A Methodical Approach on Conceptual Structural Design

Michiel Paul Horikx
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Master of Science in Structural Engineering,
Technische Universiteit Eindhoven
geboren te ’s Gravenhage
This dissertation has been approved by the promotors:
Prof.ir. A.Q.C. van der Horst and Prof.dr.ir. H.A.J. de Ridder

Composition of the doctoral committee:
Rector Magnificus chairman
Prof.ir. A.Q.C. van der Horst Delft University of Technology
Prof.dr.ir. H.A.J. de Ridder Delft University of Technology

Independent members:
Prof.ir. F.S.K. Bijlaard Delft University of Technology
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Prof.dr.ir. W.P. De Wilde Vrije Universiteit Brussel, Belgium

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To my love Mia,

and our children Marieke, Boudewijn, and Gieljan
Preface

“It should be noted that the greatest complexity is found at the borders between dissimilar things” (Jonathan J. Dickau, 2006)

Structural design consists of three major sequential design phases: conceptual, basic, and detailed design.

With detailed design - a phase of code checking, detailing, and specifying - all common material applications have been extensively researched and recorded in numerous textbooks and design codes of practice.

For basic design - a phase of deepening and optimisation - the main tools are applied mechanics-based and since Isaac Newton widespread available as textbook material.

Conceptual design - the creation phase with a complex and partly intuitive process and numerous complex interfaces between different fields of practice - is little touched by technological progress.

Complexity of design  Design is to optimise the performance/cost ratio of the life cycle. For design, it is mostly the outcome that counts, rather than the followed path. The design path, however, does control both duration and flexibility of the complex design process.
The art of design, striving for the ultimate solution, is the process of getting oversight by abstracting complexity and crossing borders.

**Abstracting complexity** The standard engineering practice of handling complex reality is modelling this reality with an abstract and approximate representation. Besides structural modelling, which is the core of structural engineering, process modelling can attribute to a clarification of the complex cyclic design process.

**Crossing borders between dissimilar things** Scientific education in structural design and corresponding research is compartmented to such an extent that the interface between applied mechanics and material applications is underdeveloped. The interfaces between structural demand, performance demand, and construction demand are even less visible.

Both professionals and higher education programmes will benefit from crossing borders and clarification of these interfaces by the research community.

**Conceptual structural design** Conceptual design is the first and decisive phase of design, providing the overall integrated system. Here, the proverbial “DNA” of the solution is constructed.

The search for a methodical approach on conceptual structural design is partly a completion of required conceptual structural design parameters and partly a matter of systematic arrangement of these parameters. The problem, however, is more the matter of systematic arrangement than the completion of missing parameters.
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Acknowledgements
Executive summary

The subject of this academic research thesis is a methodical approach on the complex problem-solving process of structural conceptual design. Both professionals and higher education programmes will benefit from such an approach.

**Problem**  A lack of insight of the professional into structural engineering is considered to be a main obstacle for an overall performance/cost optimisation of the built environment.

For a better understanding and an effective methodical approach this lack of insight can be divided into the two partial problems, “lack of insight into conceptual structural design” and the underlying “lack of insight into structural performance”.

**Solution approach**  For this relatively unexplored problem, an exploratory research is conducted by systematically zooming in from the whole to the part and from coarse to fine. The so explored methodical approach on conceptual structural design leads to a controlled build-up of insight into the behaviour of the structure and supports the actual successive design decisions during the conceptual design phase on the basis of the following coherent set of solution components:

**Structural design cycle**  Independent of life cycle phase, complexity of design, and contractual commitments, the structural engineering
practice can be outlined by a fundamental structural design cycle: creation, optimisation, and specification. Within each of the major design phases conceptual design, basic design, and detailed design, this fundamental structural design cycle is applicable. On this basis, a professional profile of structural engineering is determined.

**Basic structural forms** One of the main conceptual structural design activities is the determination of the structural form, based on “understanding” and “order of magnitude” of basic structural forms. Characterisation of structural forms, with regard to the capacity to bear and resist, and with regard to the interfaces with the built environment, turns out to be feasible on a two-dimensional subsystem level.

**Structural design path** The structural design process can fundamentally be characterised by the two simultaneous processes of specification and decomposition of the structural form from system to element. These two processes can be visualised together in a two-dimensional matrix in which the structural design can be explored. The design path follows the fundamental dimensioning routine from structural integrity, via load distribution, to failure mechanisms.

**Structural design loops** In order to have a successful solution to a complex design problem, a cyclic design process is inevitable. Every cycle goes through the phases of creation, optimisation, and specification. The cyclic convergent optimum strategy aims for an optimisation of both quality of design outcome and number of design cycles. The individual design loops are appointed and the corresponding basic principles clarified.

**Shared knowledge-based integral design** For an optimisation of the performance/cost ratio of the life cycle of a structure, an integral approach on conceptual design is a necessity. Control of the interfaces between all participating disciplines is largely dependent on experience and intuition. Definition and collection of the fundamental conceptual design parameters of the most influential par-
participating disciplines serve as a concurrent-based breeding ground for integral design solutions.

**Conceptual structural design parameters** Both for understanding structural performance and for an effective knowledge exchange with the other participating disciplines, a balanced set of conceptual structural design parameters is conditional. On a two-dimensional subsystem level, approximation parameters for conceptual structural design are determined on the basis of timeless applied mechanics.

**Validation** The applicability of the methodical approach on conceptual structural design with respect to these solution components and their coherence is validated with three studies: a professional profile of structural engineering, material demand diagrams, and an actual conceptual design.

**Conclusion** In this research thesis a relatively high level of abstraction is utilised to secure coherence and completeness of the methodical approach. On a more operational level some, but certainly not all parameters and their interrelations, are determined. Especially, the multitude of complex integral processes is hard to qualify; let alone to quantify. This is a first step towards an untangled and operationalised conceptual structural design process.
I  Problem, analysis and solution approach  

2  Introduction to part I  

3  Present-day problems in structural engineering  
   3.1  Lack of insight of the professional  
   3.1.1  Structural (un)safety in the Netherlands  
   3.1.2  Problems, causes and effects  
   3.1.3  General requirements structural engineering  
   3.1.4  Recommendations structural design  
   3.2  Present-day solutions’ field of practice  
   3.2.1  Copying reality  
   3.2.2  Planning and control  
   3.2.3  Numerical power  
   3.2.4  A need for research  
   3.2.5  Professional higher education  
   3.3  Historical perspective  
   3.3.1  Developments professional structural engineering  
   3.3.2  Homo universalis  
   3.3.3  Expanding depth and breadth  
   3.3.4  On-going expanding depth and breadth  

4  Problem definition and research goal  
   4.1  Problem definition  
   4.1.1  The merit of a proper problem definition  
   4.1.2  An interface control approach  
   4.1.3  Structural engineering activities and missing tools  
   4.1.4  Definition of structural performance  
   4.1.5  Definition of conceptual structural design  
   4.2  Complexity of the research domain  
   4.2.1  Complexity  
   4.2.2  Complex systems and processes  
   4.2.3  Complexity of interdisciplinary interfaces  
   4.3  Research goal  
   4.3.1  Research on conceptual structural design  

CONTENTS
4.3.2 Initial goal of the methodical approach . . . . . 42
4.3.3 Ultimate design method . . . . . . . . . . . . . . . 42

5 Learning from the past 43
5.1 Writings in the field of structural design . . . . . . . . 43
  5.1.1 Famous structural engineers . . . . . . . . . . . . . 43
  5.1.2 Early master builders . . . . . . . . . . . . . . . . 44
  5.1.3 Modern structural engineers . . . . . . . . . . . . . 45
5.2 Writings in early times . . . . . . . . . . . . . . . . . . . 45
  5.2.1 Marcus Vitruvius Pollio (1st century BC) . . . . . 45
  5.2.2 Leonardo Da Vinci (1452-1519) . . . . . . . . . . . . 46
  5.2.3 Simon Stevin (1548-1620) . . . . . . . . . . . . . . 47
5.3 Writings in modern times . . . . . . . . . . . . . . . . . . 48
  5.3.1 Pier Luigi Nervi (1891-1979) . . . . . . . . . . . . 48
  5.3.2 Eduardo Torroja y Miret (1899-1961) . . . . . . . . 49
  5.3.3 Mario Salvadori (1907-1997) . . . . . . . . . . . . . 50
  5.3.4 Other publications in the field of structural design . . 51
5.4 Applicability of writings . . . . . . . . . . . . . . . . . . 52
  5.4.1 Applicability of writings of early times . . . . . . . 52
  5.4.2 Applicability of writings in modern times . . . . . . 52

6 Directions for the future 55
6.1 System theories . . . . . . . . . . . . . . . . . . . . . . . 55
  6.1.1 Promising developments . . . . . . . . . . . . . . . . 55
  6.1.2 Classification by characteristics . . . . . . . . . . . . 55
6.2 Real system-based methods . . . . . . . . . . . . . . . . . 56
  6.2.1 Stochastic search techniques . . . . . . . . . . . . . . 56
  6.2.2 Genetic algorithms . . . . . . . . . . . . . . . . . . . 57
6.3 Modelled system-based methods . . . . . . . . . . . . . . . 58
  6.3.1 Expert systems . . . . . . . . . . . . . . . . . . . . 58
  6.3.2 Case-based reasoning . . . . . . . . . . . . . . . . . 60
  6.3.3 Sequential-based reasoning . . . . . . . . . . . . . . . 60
  6.3.4 Rule-based reasoning . . . . . . . . . . . . . . . . . 61
  6.3.5 Fuzzy logic . . . . . . . . . . . . . . . . . . . . . . 61
6.4 Decomposition-based methods . . . . . . . . . . . . . . . . 63
## 6.4.1 Systems engineering

63

## 6.4.2 Concurrent engineering

65

## 6.5 Technologies

67

### 6.5.1 Collaborative engineering

67

### 6.5.2 Building information modelling

69

## 6.6 Applicability of system theories

72

### 6.6.1 History

72

### 6.6.2 Applicability of system methods

73

### 6.6.3 Applicability of system technologies

74

### 6.6.4 Present-day approach

74

## 7 Research framework

77

### 7.1 In search of a methodical approach

77

#### 7.1.1 Solution approach

77

#### 7.1.2 Guiding research principles

78

### 7.2 T-shaped professional

79

#### 7.2.1 Modern demands

79

#### 7.2.2 T-shaped professional structural engineer

79

### 7.3 Applied mechanics

80

#### 7.3.1 Necessity of insight into structural performance

80

#### 7.3.2 Timeless applied mechanics

81

### 7.4 Designing with progressive insight

82

#### 7.4.1 General problem approach

82

#### 7.4.2 Progressive insight from estimation to accuracy

83

### 7.5 Decomposition

84

#### 7.5.1 Abstractions of a decomposed system

84

#### 7.5.2 Decomposition of complex systems

85

#### 7.5.3 Physical decomposition

86

#### 7.5.4 Process decomposition

86

#### 7.5.5 Aspect decomposition

87

### 7.6 Level of abstraction

87

#### 7.6.1 Level of control

87

#### 7.6.2 Defined levels of abstraction

88

### 7.7 Durability of a methodical approach

88

#### 7.7.1 Research framework boundaries

88
II The art of conceptual structural design 91

8 Introduction to part II 93

9 Conceptual design 97
  9.1 Determination of the structural form 97
  9.1.1 Conceptual structural design 97
  9.1.2 Design process 100
  9.1.3 Flow diagram 101
  9.1.4 Experience and intuition 102
  9.2 How to capture the intangible 104
  9.2.1 Abstracting conceptual design 104
  9.2.2 Directing parameters of conceptual design 105
  9.2.3 Sharing the knowledge of the built environment 106
  9.2.4 Back to the fundamentals of conceptual design 107
  9.3 Shared knowledge-based conceptual design 108
  9.3.1 Splitting process and technical breadth 108
  9.3.2 Principal disciplines of the built environment 110
  9.3.3 Concurrent-based shared knowledge 110
  9.3.4 Conceptual structural design parameters 112
  9.3.5 Qualification and approximate quantification 114

10 Process decomposition 115
  10.1 Fundamental design cycle 115
  10.1.1 Structural life cycle phases 115
  10.1.2 Structural design phases 115
  10.1.3 Cyclic design process 117
  10.1.4 Fundamental structural design cycle 118
  10.2 Level of accuracy 120
  10.2.1 Level of specification 120
  10.2.2 Fib Model Code 2010 121
  10.2.3 Accuracy fundamental structural design phases 124
10.3 Fundamental design process . . . . . . . . . . . . . . . . . . . 125
  10.3.1 Structural design characteristics . . . . . . . . . . . . . 125
  10.3.2 Fundamental structural design process . . . . . . . . . 126

11 Physical decomposition 129
  11.1 Qualification of the structural form . . . . . . . . . . . . . 129
    11.1.1 Classification . . . . . . . . . . . . . . . . . . . . 129
    11.1.2 Form follows function . . . . . . . . . . . . . . . . 130
    11.1.3 Interfaces with the built environment . . . . . . . . 131
  11.2 Decomposition of the structural form . . . . . . . . . . . . 131
    11.2.1 System decomposition . . . . . . . . . . . . . . . . 131
    11.2.2 Structural form on subsystem level . . . . . . . . . 133
    11.2.3 Basic structural forms . . . . . . . . . . . . . . . . 133

12 Cyclic process control 137
  12.1 Exploration of the solubility space . . . . . . . . . . . . . 137
    12.1.1 Creation-process requirements . . . . . . . . . . . . . 137
    12.1.2 Design strategies . . . . . . . . . . . . . . . . . . . 138
  12.2 Linear design . . . . . . . . . . . . . . . . . . . . . . . . . 139
    12.2.1 Linear process . . . . . . . . . . . . . . . . . . . . 139
    12.2.2 Specification of the structural form . . . . . . . . . 140
  12.3 Cyclic design . . . . . . . . . . . . . . . . . . . . . . . . . . 140
    12.3.1 Cyclic process . . . . . . . . . . . . . . . . . . . . 140
    12.3.2 Fundamental structural design path . . . . . . . . . 141
    12.3.3 Structural design path . . . . . . . . . . . . . . . . 144
  12.4 Cyclic convergent design . . . . . . . . . . . . . . . . . . . 144
    12.4.1 Volume of complexity . . . . . . . . . . . . . . . . . 144
    12.4.2 Three steps in conceptual design . . . . . . . . . . 147
    12.4.3 Definition step . . . . . . . . . . . . . . . . . . . . 147
    12.4.4 Creation step . . . . . . . . . . . . . . . . . . . . . 148
    12.4.5 Selection step . . . . . . . . . . . . . . . . . . . . . 148
  12.5 Cyclic optimum design . . . . . . . . . . . . . . . . . . . . 149
    12.5.1 Modelling loops . . . . . . . . . . . . . . . . . . . . 150
    12.5.2 Typical design loops . . . . . . . . . . . . . . . . . 151
    12.5.3 Optimal design cycle . . . . . . . . . . . . . . . . . 151
III  Understanding structural performance 155

13 Introduction to part III 157

14 Structural performance 161
  14.1 Legitimation 161
     14.1.1 Applied mechanics in an academic research thesis 161
     14.1.2 Conceptual structural design practice 162
     14.1.3 Balanced set of conceptual design parameters 163
     14.1.4 Professional practice factors 163
  14.2 Present-day structural performance 164
     14.2.1 Structural requirements 164
     14.2.2 Modern developments 164
  14.3 Force and deformation-driven parameters 165
     14.3.1 Equilibrium and strength 165
     14.3.2 Deformation-driven parameters 167
     14.3.3 Determination of deformation-driven parameters 169
  14.4 Approximate dimensioning 170
     14.4.1 Conceptual structural design approximations 170
     14.4.2 Conceptual structural design parameters 171
     14.4.3 Dimensioning routine 171

15 Structural integrity 175
  15.1 Conceptual design on system level 175
     15.1.1 Creation phase of the conceptual design 175
     15.1.2 Structural integrity 175
  15.2 Load path design 176
     15.2.1 Load path design on system level 176
     15.2.2 Truss-analogy in load path design 177
     15.2.3 Modelling the system decomposition 178
     15.2.4 Dimensioning routine of the load path 178
  15.3 Conceptual structural design 179
     15.3.1 Principal details 179

12.5.4 Risk analysis 153
15.3.2 System configuration . . . . . . . . . . . . . . . . . . . . . 180
15.3.3 Material properties of conceptual design . . . . . . . . . 181

16 Fundamental parameters of load distribution . . . . . . . . . . 185
   16.1 Conceptual design on subsystem level . . . . . . . . . . . . 185
      16.1.1 Load distribution phase of the conceptual design . . 185
      16.1.2 Load distribution . . . . . . . . . . . . . . . . . . . 185
      16.1.3 Parallel load distribution . . . . . . . . . . . . . . 186
   16.2 Load distribution in basic structural forms . . . . . . . . . 188
      16.2.1 Load distribution in a frame . . . . . . . . . . . . . 188
      16.2.2 Load distribution in a floor slab . . . . . . . . . . 190
      16.2.3 Load distribution in a cable-stayed beam . . . . . 191
      16.2.4 Load distribution in a truss . . . . . . . . . . . . . 194
      16.2.5 Load distribution in an arch . . . . . . . . . . . . 196
      16.2.6 Load distribution in a shear wall . . . . . . . . . . 198
   16.3 Parallel load distribution on detailed level . . . . . . . . . 199
   16.4 Induced deformation . . . . . . . . . . . . . . . . . . . . . . 203
      16.4.1 Principle of induced deformation . . . . . . . . . . 203
      16.4.2 Induced deformation on subsystem level . . . . . . . . 203
      16.4.3 Induced deformation on system level . . . . . . . . . 204

17 Fundamental parameters of failure mechanisms . . . . . . . . . 207
   17.1 Conceptual design on element level . . . . . . . . . . . . . 207
      17.1.1 Dimensioning phase of the conceptual design . . . 207
      17.1.2 Failure mechanisms . . . . . . . . . . . . . . . . . . . 207
   17.2 Shear . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 209
      17.2.1 Shear strength . . . . . . . . . . . . . . . . . . . . 209
      17.2.2 Shear deformation . . . . . . . . . . . . . . . . . . . 210
      17.2.3 Shear deformation on subsystem level . . . . . . . . . 212
   17.3 Stability . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 214
      17.3.1 Stability of the equilibrium . . . . . . . . . . . . . . 214
      17.3.2 Euler-based design approximations . . . . . . . . . . 215
      17.3.3 Combined compression and bending . . . . . . . . . . 218
   17.4 Bending and compression . . . . . . . . . . . . . . . . . . . . 219
      17.4.1 Conceptual design of concrete in bending . . . . . . . 219
17.4.2 Conceptual design of concrete in compression . . . 221
17.4.3 Conceptual design of steel in bending . . . . . . . . 222
17.4.4 Conceptual design of steel in compression . . . . . 224
17.4.5 Conceptual design of foundations . . . . . . . . . . 224

IV Validation and conclusion 227

18 Introduction to part IV 229

19 Professional profile of structural engineering 235
  19.1 Validation of the process decomposition . . . . . . . . 235
    19.1.1 Professional profile of structural engineering . . . 235
    19.1.2 Conclusion professional profile . . . . . . . . . . 236
    19.1.3 Conclusion validation process decomposition . . . 237
  19.2 Structural engineering activities . . . . . . . . . . . . . 237
  19.3 A) Creation of a system outline . . . . . . . . . . . . . . 237
    19.3.1 From requirements to performance-based solutions 237
    19.3.2 A.1) Determination of fundamental requirements . 240
    19.3.3 A.2) Secure and optimise structural needs . . . . 241
    19.3.4 A.3) Facilitate interfaces built environment . . . 242
    19.3.5 A.4) Design of principal details . . . . . . . . . . 243
    19.3.6 A.5) Variant study of performance-based solutions 243
    19.3.7 A.6) Specification and risk analysis . . . . . . . . 244
  19.4 B) Optimisation of the structural action . . . . . . . . . 245
    19.4.1 From performance-based solutions to design . . . 245
    19.4.2 B.1) Structural system analysis and modelling . . . 246
    19.4.3 B.2) Load distribution analysis . . . . . . . . . . 248
    19.4.4 B.3) Optimisation of parallel load distribution . . 249
    19.4.5 B.4) Analysis of failure mechanisms . . . . . . . 250
    19.4.6 B.5) Structural variant study . . . . . . . . . . . 252
    19.4.7 B.6) Overall structural system check . . . . . . . 252
  19.5 C) Final dimensioning and specification . . . . . . . . . 253
    19.5.1 From design to specification . . . . . . . . . . . . 253
    19.5.2 C.1) Loads and load combinations . . . . . . . . . 254
19.5.3 C.2) Load distribution and displacements . . . . . 254
19.5.4 C.3-C.8) Code check and detail dimensioning . . . 255
19.5.5 C.9) Specification and monitoring . . . . . . . . . . 255
19.6 D) Process management . . . . . . . . . . . . . . . . . . . . . . 255
  19.6.1 Structural engineering process management . . . . . . 255
  19.6.2 D.1) Problem-solving management . . . . . . . . . . 256
  19.6.3 D.2) Project management . . . . . . . . . . . . . . 256
  19.6.4 D.3) Self-management . . . . . . . . . . . . . . . . . 257
19.7 Body of knowledge . . . . . . . . . . . . . . . . . . . . . . . . . . 257
  19.7.1 General . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 257
  19.7.2 Body of knowledge creation of a system outline . . . 258
  19.7.3 Body of knowledge structural action . . . . . . . . . 259
  19.7.4 Body of knowledge process management . . . . . . . 260
  19.7.5 Complexity of structural engineering activities . . 261
  19.7.6 Professional levels . . . . . . . . . . . . . . . . . . . . . . 261
  19.7.7 Body of knowledge scheme . . . . . . . . . . . . . . . . 263

20 Material demand for conceptual design 265
  20.1 Validation of the physical decomposition . . . . . . . . . . . . 265
    20.1.1 2-D material demand . . . . . . . . . . . . . . . . . . . . 265
    20.1.2 Conclusion 2-D material demand . . . . . . . . . . . 266
    20.1.3 Conclusion validation physical decomposition . . . . 267
  20.2 Validity boundaries . . . . . . . . . . . . . . . . . . . . . . . . 267
    20.2.1 Minimisation of the material demand . . . . . . . . . . 267
    20.2.2 Standardisation . . . . . . . . . . . . . . . . . . . . . . . . 267
    20.2.3 Choice of cross-section . . . . . . . . . . . . . . . . . . . 268
  20.3 Capacity of main span elements . . . . . . . . . . . . . . . . . . . 268
    20.3.1 Section properties of a square RHS . . . . . . . . . . . 268
    20.3.2 Transition slenderness of a square RHS . . . . . . . . . 269
    20.3.3 Required section area . . . . . . . . . . . . . . . . . . . . 269
  20.4 Material demand cable-stayed fixed . . . . . . . . . . . . . . . . 270
    20.4.1 Cable-stayed beam with fixed foundation . . . . . . . . 270
    20.4.2 Material demand of the cables in the ULS . . . . . . . . 271
    20.4.3 Material demand of the pylon in the ULS . . . . . . . . 271
    20.4.4 Material demand of the floor elements in the ULS . . 272
20.4.5 Material demand of the cables in the SLS . . . . 273
20.5 Material demand cable-stayed symmetry . . . . . 274
20.5.1 Cable-stayed beam with symmetrical configuration 274
20.5.2 Material demand cables and pylon in the ULS . . 274
20.5.3 Prismatic I-beam . . . . . . . . . . . . . . . . . . . 275
20.5.4 Sensitivity to non-uniform loading . . . . . . . . . 276
20.5.5 Material demand per beam in the ULS . . . . . . 277
20.5.6 Material demand per beam in the SLS . . . . . . 277
20.6 Design diagrams for conceptual design . . . . . . 277
20.6.1 Design diagrams . . . . . . . . . . . . . . . . . . . 277
20.6.2 Design diagram of a cable-stayed beam . . . . . . 280
20.6.3 Design diagram of a cable-stayed beam grade S355 282

21 Case study trusses Maeslant storm surge barrier 285
21.1 Validation of the cyclic process control . . . . . . . 285
21.1.1 A case study of conceptual structural design . . . 285
21.1.2 Conclusion case study conceptual structural design 286
21.1.3 Conclusion validation of the methodical approach . 287
21.2 Maeslant storm surge barrier . . . . . . . . . . . . . . 288
21.2.1 Final piece of the Delta works . . . . . . . . . . . 288
21.2.2 Requirements . . . . . . . . . . . . . . . . . . . . 289
21.2.3 Conceptual design Maeslant storm surge barrier . 289
21.2.4 Performance/cost optimisation . . . . . . . . . . 291
21.3 Creation of a system outline . . . . . . . . . . . . . . . 292
21.3.1 Load-path design on system level . . . . . . . . . 292
21.3.2 Principal details . . . . . . . . . . . . . . . . . . . 293
21.3.3 Circular hollow section elements . . . . . . . . . 294
21.3.4 Decomposition in subsystems . . . . . . . . . . . 295
21.4 Optimisation of the structural action . . . . . . . . . . 298
21.4.1 Optimisation on horizontal subsystem level . . . . 298
21.4.2 Optimisation on vertical subsystem level . . . . . 299
21.4.3 Induced deformation . . . . . . . . . . . . . . . . . 299
21.5 Dimensioning . . . . . . . . . . . . . . . . . . . . . . 300
21.5.1 Cross-sectional area of the lower chord . . . . . . 300
21.5.2 Global stability . . . . . . . . . . . . . . . . . . . 300
21.5.3 Cross-sectional area of web and upper chord . . . . . . . . . 301
21.5.4 Induced deformation of web members . . . . . . . . . . . . 301
21.5.5 Section dimensions of conceptual design . . . . . . . . . 303
21.6 Specification and risk analysis . . . . . . . . . . . . . . . . . 304
  21.6.1 Material demand . . . . . . . . . . . . . . . . . . . . 304
  21.6.2 Dimensioning and cost weighting . . . . . . . . . . . . 305
  21.6.3 Uncertainties and coverage by dimensioning . . . . . . 306
  21.6.4 Reserves and optimisations . . . . . . . . . . . . . . 306
21.7 Further optimisations during basic design . . . . . . . . . . 308
  21.7.1 Basic design . . . . . . . . . . . . . . . . . . . . . 308
  21.7.2 Extensive modelling . . . . . . . . . . . . . . . . . . 309
  21.7.3 Coupling truss . . . . . . . . . . . . . . . . . . . . . 309
  21.7.4 Geometry and Section dimensions . . . . . . . . . . . . 310

22 Conclusion and recommendations 311
  22.1 Thesis conclusion . . . . . . . . . . . . . . . . . . . . . . 311
    22.1.1 Initial research goal . . . . . . . . . . . . . . . . . 311
    22.1.2 Research process . . . . . . . . . . . . . . . . . . . 312
    22.1.3 Actual research outcome . . . . . . . . . . . . . . . 314
  22.2 Recommendations for further research . . . . . . . . . . . . 315
    22.2.1 In-depth research . . . . . . . . . . . . . . . . . . . 315
    22.2.2 Conceptual design parameters built environment . . . . 316
    22.2.3 Fundamental behaviour of structural materials . . . . 317
    22.2.4 Transition of stocky to slender beam theory . . . . . 317
    22.2.5 Adjustment factor of buckling strength . . . . . . . . 318
  22.3 Recommendations for higher education . . . . . . . . . . . . 318
    22.3.1 Present-day higher education . . . . . . . . . . . . 318
    22.3.2 Quality versus quantity . . . . . . . . . . . . . . . 319
    22.3.3 Professional profile-based programme . . . . . . . . 321
    22.3.4 T-shaped based programme . . . . . . . . . . . . . . 322

Bibliography 325

Curriculum Vitae 331
List of Figures

1.1 Research domain ........................................ 1
1.2 Partition of the thesis outline ......................... 9

2.1 Reading guide for part I ............................... 14
2.2 Timeline .................................................. 15

3.1 Expanding depth and breadth ............................ 28

4.1 Structural design as an interface control approach .... 32

7.1 T-shaped professional structural engineer ............... 80
7.2 Problem approach ........................................ 83
7.3 Levels of abstraction .................................... 89

8.1 Reading guide for part II ............................... 94

9.1 Conceptual structural design process .................... 98
9.2 Directing parameters of conceptual design .............. 105
9.3 T-shaped professional for conceptual design .......... 107
9.4 T-shaped professional technical breadth ............... 108
9.5 Environment and object level ........................... 110
9.6 T-shaped conceptual structural design ................. 113
9.7 Qualitative and approximate quantitative modelling .... 114

10.1 Structural design process ............................. 118
10.2 Fundamental structural design cycle .................... 119
10.3 Level of specification ......................... 121
10.4 Fundamental structural design process .......... 127

11.1 Assembly of an arch bridge .................... 132
11.2 Subsystem level ............................... 133
11.3 Basic structural forms ......................... 134

12.1 Design strategies ............................. 139
12.2 Linear structural design ........................ 139
12.3 Fundamental structural design path ............ 142
12.4 Structural design path ......................... 145
12.5 Limited volume of complexity per design phase . 146
12.6 Fundamental structural design loops ............ 149
12.7 Structural design loops ....................... 152

13.1 Reading guide for part III ..................... 158

14.1 Developments of structural performance .......... 165
14.2 Force and deformation-driven parameters .......... 166
14.3 Dimensioning routine of the conceptual structural design . 173

15.1 Load path design ............................. 177
15.2 Truss-analogy in load path design .............. 177
15.3 Modelling the system effects .................... 178
15.4 Dimensioning routine .......................... 179
15.5 Conceptual structural design .................... 180

16.1 Statically determinate structure ............... 186
16.2 Statically indeterminate structure ............. 187
16.3 Parallel bending and axial force ............... 188
16.4 Load distribution in a two-way spanning floor slab . 190
16.5 Redistribution in a cable-stayed beam .......... 192
16.6 Load distribution in a truss ................... 194
16.7 Load distribution in an arch ................... 196
16.8 Bending moments in an arch ................... 198
16.9 Stiffener plate in a beam-to-column joint ....... 200
LIST OF FIGURES

16.10 Bending deformation of the flange .................... 201
16.11 Axial deformation of the stiffener .................... 201
16.12 Shear deformation of the stiffener .................... 202
16.13 Induced deformation torsional clamped beam .......... 204
16.14 Induced deformation in a truss bridge ................. 205

17.1 Shear strength ........................................ 209
17.2 Bending and shear deformation ......................... 211
17.3 Transition slenderness for stocky to slender beams .... 212
17.4 Shear deformation in a cantilevered truss .............. 213
17.5 Stability of the equilibrium ............................ 214
17.6 Buckling length ........................................ 216
17.7 Arch and truss analogy in concrete beams .............. 219
17.8 Bending strength of a concrete member ................. 219
17.9 Bending strength of a steel member .................... 223
17.10 Failure mechanism of a spread foundation ............ 225
17.11 Failure mechanism of a pile foundation ............... 226

18.1 Reading guide for part IV .............................. 231

20.1 Section properties of a square RHS .................... 268
20.2 Cable-stayed beam with fixed foundation ............... 270
20.3 Cable-stayed beam with symmetrical configuration .... 274
20.4 Cross section prismatic I-beam ........................ 275
20.5 Cable-stayed beam with non-uniform load .............. 276
20.6 Design diagram format ................................ 278
20.7 Material demand of a cable-stayed beam ............... 281
20.8 Material demand of a cable-stayed beam steel grade S355 283

21.1 Maeslant storm surge barrier ............................ 290
21.2 Hydraulic load .......................................... 292
21.3 Principal joint .......................................... 294
21.4 Section properties of a CHS ............................. 294
21.5 Decomposition in subsystem planes .................... 296
21.6 Triangular cross-sectional truss configuration ........ 297
21.7 Optimisation of the supports of the retaining wall .... 298
21.8 Induced deformation of the Maeslant storm surge barrier . 302
21.9 Truss dimensions . . . . . . . . . . . . . . . . . . . . . . . . . . . 304

22.1 Additional approximate quantitative modelling . . . . . . 316
22.2 Partitioning of the professional T-profile . . . . . . . . . . 323
List of Tables

4.1 Structural engineering activities and tools . . . . . . . . . 34
4.2 Research on conceptual structural design . . . . . . . . . . . 41
6.1 Classification of system theories . . . . . . . . . . . . . . . 56
8.1 Solution components for conceptual structural design . . . 96
9.1 Principal disciplines of the built environment . . . . . . . 111
10.1 Life cycle phases . . . . . . . . . . . . . . . . . . . . . . . 116
10.2 Design phases . . . . . . . . . . . . . . . . . . . . . . . . 117
10.3 Fib design phases . . . . . . . . . . . . . . . . . . . . . . . 122
10.4 Level of accuracy . . . . . . . . . . . . . . . . . . . . . . . 124
10.5 Structural engineering characteristics . . . . . . . . . . . 125
13.1 Solution components for structural performance . . . . . 160
14.1 Misfit of design parameters in education . . . . . . . . . . 169
14.2 Conceptual structural design parameters . . . . . . . . . . 172
15.1 Material properties for conceptual design . . . . . . . . . . 182
17.1 Conceptual design parameters of failure mechanisms . . . 208
17.2 Critical buckling stress comparison . . . . . . . . . . . . . 217
18.1 Validation scheme . . . . . . . . . . . . . . . . . . . . . . . 230
19.1 Structural engineering activities .................................. 238
19.2 Creation of a system outline ........................................... 239
19.3 Functional requirements ................................................ 240
19.4 Optimisation of the structural action ................................. 245
19.5 Final dimensioning and specification .................................. 254
19.6 Process management ..................................................... 256
19.7 Complexity of structural engineering ................................. 261
19.8 Body of knowledge per professional level ............................ 264

21.1 Dike reinforcement versus barrier ..................................... 289
21.2 Requirements for the Maeslant storm surge barrier ................. 290
21.3 Risk analysis: dimensioning and cost weighting ..................... 305
21.4 Risk analysis: uncertainties and coverage by dimensioning 307
21.5 Risk analysis: reserves and optimisations ............................ 308

22.1 Professional higher education programme ......................... 323
Chapter 1

Introduction

1.1 Aim of the research

1.1.1 Research on conceptual structural design

The aim of this research is the intersection of professional structural engineering and the conceptual design of the built environment as shown in figure 1.1.

Figure 1.1: Research domain
Present-day conceptual design of regularly complex structures with numerous boundary conditions, require a thorough understanding of design parameters and extensive experience in design.

Understanding conceptual structural design as a problem-solving process is underrepresented in higher education and corresponding research programmes.

1.1.2 Relevance of the research question

A lack of insight of the professional into structural engineering is considered to be one of the main causes for the notable amount of structural failures during the last decades, causing broad social and subsequent professional commotion. Furthermore, corresponding failure costs endanger the overall performance/cost optimisation of the built environment.

A proceeding increase in complexity of conceptual structural design contributes to a further decline of this indispensable insight. Consequently, conceptual structural design and its conceptual structural design parameters are in need of clarification by the research community.

The problem of a lack of insight in structural engineering and the corresponding causes and effects will be further substantiated in chapter 3.

1.2 Methodology

1.2.1 Depth versus breadth

With respect to the degree of scaling there are two basic kinds of research:

**In-depth research** Mostly characterised by a small scale, and by being focused, profound, and well-organised.
1.2 Methodology

**General research** Mostly characterised by a large scale, by getting an overview, and by being extensive and complex.

The need for more insight in, and control over conceptual structural design typically requires a process-based general research, rather than an additional in-depth research on one of the individual phenomena.

1.2.2 **Scientific method**

Scientific research has to comply with the basic principles of the scientific method. The essence of the scientific method is to test a hypothesis, and replication of this testing should get the same response; this response can be measured and recorded.

The following five steps can outline the scientific method:

1. State a problem and define a corresponding research question.
2. Investigate what is already known and structure the solution finding by means of a research framework.
3. Formulate a hypothesis as a solution to the problem.
4. Test the hypothesis and analyse the results on whether to accept, adjust, or reject the hypothesis.
5. Conclude, with recommendations for further research, and publish the results.

The underlying goal or purpose of science to society and individuals is to produce useful models of reality. To achieve this, one can form hypotheses based on observations of reality. By analysing a number of related hypotheses, scientists can form general theories. These theories benefit society and individuals who make use of them.
1.2.3 Hypothesis development

A hypothesis is defined as an open, presupposed and general rule or law, which can be checked against new facts or observations.

The subject of this research thesis is large scaled and comprises numerous parameters and complex interactions between the various disciplines involved. This complexity is further substantiated in section 4.2.

The corresponding large scaled complex research domain is relatively unexplored which makes it difficult to define an unambiguous empirical hypothesis. Thus, an enhanced variety of hypotheses can be distinguished. Given the aim of this research, an exploratory research methodology and corresponding hypothesis is adopted:

Exploratory research is conducted for a problem that has not been clearly defined. It often occurs before we know enough to make conceptual distinctions or posit an explanatory relationship [43].

The following fundamental characteristics clarify this exploratory research methodology:

- “Exploratory research tends to tackle new problems on which little or no previous research has been done” [6].
- Key variables, and in this case specifically key relationships, are therefore not defined.
- Explorative research often relies on qualitative approaches.
- An exploratory research outcome can provide a basis for an explanatory framework; in order to explain and predict we need a theoretical statement, a connection between two or more concepts.
- Its focus is on the discovery of insights and corresponding concepts as opposed to collecting statistically accurate data.

The objective of this research thesis is to generate such insights and concepts. In this case, the exploratory research is used primarily to gain a greater understanding of conceptual structural design:
1.2 Methodology

• Gain Insight into and develop concepts of the overall qualitative design process, individual qualitative design routines and quantitative conceptual design approximations.

• By systematically zooming in from the whole to the part and from coarse to fine as clarified in section 7.4.

• Within clear defined levels of abstraction as clarified in section 7.6.

• To prepare conceptual theories in order to pave the way for explanatory relationships.

An extensive clarification of the utilised guiding research principles is given in chapter 7.

1.2.4 Hypothesis testing

In essence, hypothesis testing verifies robustness - the characteristic of being strong enough to withstand intellectual challenge. All fundamental conditions of robust research have to be met such as purposiveness, rigour, testability, replicability, accuracy, objectivity, generalisability, and parsimony.

For a hypothesis there are various degrees of testability. The strongest requirement is that it should be falsifiable; it should be possible to prove the hypothesis wrong. The exploratory hypothesis is not unambiguously falsifiable; it should nevertheless be testable as a hypothesis that cannot be tested is not worth postulating from an empirical point of view.

The exploratory hypotheses and their components will be cyclic, and thus replicable, and tested after which it must be decided whether to accept, adjust, or reject them. The following main general scientific and more exploratory methodology-dependent criteria are applicable:

Relevance of the research question in combination with an increased understanding of the topic.
Rigorous research being correct, complete, clear and consistent with measurable criteria, within the accuracy of the scale.

Qualitative accuracy to which the qualitative, mostly process-related modelling corresponds to reality.

Quantitative accuracy to which the quantitative, mostly applied-mechanics related modelling corresponds to reality.

Generalisability meaning the extent to which the research findings can be applied to settings other than conceptual structural design, initially within the field of structural engineering.

Parsimony as a principle of using the least resources and explanations to postulate the hypothesis, generally known as Occam’s razor.

1.2.5 Verification versus validation

Both verification and validation are processes of confirming that data are correct and comply with predefined specifications. The difference between both is generally process-phase related:

Verification Is it true? To make certain or prove the accuracy, and generally comes first-done before validation.

Validation Is it valid? To make it officially approved, and generally follows after verification.

In design and engineering practice, verification and adjustment cycles are the standard and involve verifying the correctness of the structural modelling and accuracy of the structural engineering calculations.

In scientific research practice, the scientific method can be executed with explicit verification and adjustment cycles or implicit iterative verification and adjustment cycles followed by an explicit final validation.

For clarity and efficiency reasons, the development of an appropriate hypothesis is performed with an implicit cyclic iterative verification and
adjustment process. So the individual in-between verification and adjustment cycles are not included in this research thesis. Instead, the so-developed final hypothesis and a corresponding validation are recorded.

1.3 Researched areas

1.3.1 Bibliography

With respect to structural design in general and conceptual structural design in particular, no design strategy or even design routine was available as a basis for further development. Considering the nature of this explorative research, most of the findings and modelling are therefore personal observations, unless noted otherwise.

Furthermore, all individual conceptual structural design parameters are based upon basic applied mechanics, which are scientifically accepted as textbook material.

Consequently, the list of referred sources is relatively short and all figures are original.

1.3.2 Fields of research for hypothesis development

The following performed research studies have more or less contributed to the development of an appropriate hypothesis:

Present-day structural engineering In search of a fundamental design cycle, detailed present-day professional structural engineering activities are classified.

Integral design of the built environment Successes and developments of integral design are aiming at an optimisation of the performance/cost ratio over the life cycle of a structure.
Writings on structural design Classical and contemporary writings in the field of structural engineering and specifically conceptual structural design, are studied.

System theories Applicability of system theories in general, and decomposition techniques in particular, can contribute to an effective breakdown of the complex conceptual design routines.

Design approximations Basic applied mechanics-based conceptual design approximations are determined for both load distribution and failure mechanisms.

1.3.3 Less successful fields of research

The following performed research studies did not contribute to a coherent solution and were therefore not recorded in this thesis:

Overall conceptual design routine Qualifying the overall conceptual structural design with unambiguous flowcharts did not result in solutions, due to numerous complex interfaces with other disciplines.

Quantified costs Quantifying cost with unambiguous cost estimating algorithms and corresponding flowcharts is small-scale, limited, and highly place and time dependent.

Energy minimisation Optimising material demand by minimising strain energy turns out to be valid for costly optimised varying cross-sections rather than common prismatic beams.

Conceptual design parameter buckling strength An approximation of the buckling strength within required reliability boundaries results in an empirical-based black box formula with insufficient insight into structural behaviour.
1.4 Reading guide

1.4.1 Partition of the thesis outline

The analysis and definition of the problem, the solution in the form of a combined physical and process decomposition, the quantification of the individual design parameters and a validation of the solution and corresponding parameters are divided in four identifiable partitions as shown in figure 1.2.

![Partition of the thesis outline](image)

Figure 1.2: Partition of the thesis outline

**Part I Problem definition**  For effective problem solving, the problem is divided into two partial problems “lack of insight into conceptual structural design” and the underlying “lack of insight into structural performance”.

**Part II Conceptual structural design**  The solution to the lack of insight into conceptual structural design consists of a combined physical and process decomposition.
Part III Structural performance  The solution to the lack of insight into structural performance consists of qualification and quantification of the structural engineering fundamentals in the form of conceptual structural design parameters.

Part IV Validation and conclusion  Both qualified and quantified solutions are tested by means of applying physical and process decompositions, and a case study.

1.4.2 Introductions

Each part starts with a chapter “Introduction” which describes the reason for its existence and a chapter guide of the specific part within this research thesis.

Accompanying figures and descriptions clarify the coherence between chapters and the content of individual chapters.
Part I

Problem, analysis and solution approach
Chapter 2

Introduction to part I

A lack of insight of the professional into structural engineering is considered to be a main obstacle for an overall performance/cost optimisation of the built environment.

Research on effective solutions to this lack of insight is the subject of this academic research thesis. The research question, orienting analysis and a solution approach in the form of a research framework are described in part I with a chapter arrangement as shown in figure 2.1.

Present-day problems High-end computer programs, numerous interfaces with other disciplines, and a tendency towards more implicit performance-based provisions increasingly dominate daily practice of the present-day professional structural engineer. Due to this on-going expanding depth and breadth, the simplification and decomposition techniques of the experienced structural engineer are steadily disappearing from practice training and higher education programmes.

Because of this, the understanding and reliability of the young professional in structural engineering is on the decline. Computerised designing without sufficient insight, particularly in the conceptual design phase,
is a dangerous operation both out of economical and safety points of view.

**Problem definition and research goal** A thorough definition of the problem is a crucial step in the problem-solving process, because an effective problem definition is directing the solution approach.

For a better understanding, and effective problem solving, the lack of insight of the professional into structural engineering can be divided into the two partial problems, “lack of insight into conceptual structural design” and the underlying “lack of insight into structural performance”.

Both the initial goal of a qualified methodical approach, and the ultimate goal of a quantified design method, are discussed.
Analysis  In the search for an appropriate design methodology we can learn from famous early architects, present-day excellent structural engineers, and on-going developments.

The analysis is limited to writings, securing an accessible and shared source of knowledge. The corresponding demarcated timeline from the start of written history up to the current state of Structural Engineering (SE), including promising system theories, is shown in figure 2.2.

The analysis is practically divided into the two following chapters:

Learning from the past By studying written history from imperial Rome up to the present-day professional practice. The search is for clearly stated design methodologies or at least design philosophies; and above all, the accessibility of reliable information. The objective is to find one or more viable design methods, not to strive for completeness.

Directions for the future Going beyond the current state of Structural Engineering into the obvious direction of artificial intelligence. For a better understanding of the feasibility for conceptual struc-
tural design, individual system theories in engineering and their subsequent applications are researched.

**Research framework**  In general, complex problems can be effectively approached on a relatively high level of abstraction with an elaborate knowledge of the fundamentals and a simultaneous working “from the whole to the part” and “from coarse to fine”.

The methodical approach is aimed to be a conceptual design tool for experienced structural engineers, rather than a black box operated by data typists. Therefore, the research is carried out in the field of abstractions of a decomposed system instead of algorithm-based numerical power.

In order to secure durability of the design method, the research is focused on being overall applicable to construction types and the use of timeless elements such as mechanics.
Chapter 3

Present-day problems in structural engineering

3.1 Lack of insight of the professional

3.1.1 Structural (un)safety in the Netherlands

In the Netherlands, there has been a notable amount of structural failures over the last decades. For example, a lot of roofs and parking decks have collapsed while in use, as well as complete buildings, mostly during construction.

Some news-breaking structural failures include:

**Theatre Het Park, Hoorn, 2001** Collapse of the theatre tower during construction due to a combination of multiple engineering and construction errors.

**Hotel Van der Valk, Tiel, 2002** Parking deck collapse due to a lateral torsional instability and subsequent horizontal displacement of the supporting beams.
Bos en Lommerplein, Amsterdam, 2006  Near collapse of supporting parking garage beneath a residential complex due to missing concrete reinforcement.

Stadium De Grolsch Veste, Enschede, 2011 Roof collapse during construction due to a loading of the incomplete stabilised roof structure.

Queen Juliana bridge, Alphen aan den Rijn, 2015 Pontoon-based crane collapse during construction due to severe shortcomings in construction engineering and management.

There are but few statistics on collapses and their causes, however. In recent years, in-depth investigations of a number of specific disasters have been undertaken by the Inspectorate for Housing, Spatial Planning and the Environment, research organisations, the Dutch Safety Board, university professors, expertise firms, and specially convened committees of enquiry.

These investigations reveal that it is almost never possible to identify one single cause for a disaster. Mostly, it is a combination of factors and circumstances - which are an inherent part of the participants of the building process - that can be identified. All these participants influence the structural safety of a building with their actions and interdependencies. Many failures, however, arise in the design phase.

Structural collapse in the Netherlands appears to be mainly a combination of the lack of supervision during all project phases and a lack of insight of the professional into structural engineering, as recorded in the problem statement “Castle or House of Cards” under the management of the Ministry of Housing, Spatial Planning and the Environment [45].

For the lack of insight of the professional into structural engineering this problem statement addresses some major perceptions of the Ministry of Housing, Spatial Planning and the Environment:

- Many in the construction industry realise that the level of professional skill among structural engineers, but also among other
3.1 Lack of insight of the professional players, is on the decline.

- University professors in the field are noticing a general erosion of knowledge and command of applied mechanics, the mainstay of the structural engineering profession.

- The “black box” character of calculation software will further diminish people’s understanding of the subject.

Eight organisations, including the Inspectorate for Housing, Spatial Planning and the Environment, the Concrete Association, and structural engineers and builders’ organisations have published the joint Compendium for a Structural Safety Strategy [46].

This compendium contains a detailed description of how structural safety can be guaranteed in the various phases of the design and building process and what roles the various participants in the building process can play with regard to structural safety.

3.1.2 Problems, causes and effects

The overall problem of structural unsafety in the Netherlands is caused by many shortcomings and developments. This thesis will discuss the problem of a lack of insight of the professional into structural engineering, with corresponding causes and effects, as recorded in the problem statement [45].

Two partial problems For a better understanding, the lack of insight of the professional into structural engineering can be divided into two partial problems:

1. Lack of insight into structural performance on micro level; human error and inadequacies of people working on building projects.

2. Lack of insight into conceptual structural design on macro level; problems relating to the structure and culture of the building sector.
Structural performance  The lack of insight into structural performance is generally accepted to be caused by the following:

- General erosion of knowledge and command of applied mechanics, the mainstay of the structural engineering profession.
- Present-day extensive use of calculation software, essentially a “black box”, further diminishing people’s understanding of the subject.

Conceptual structural design  The lack of insight into conceptual structural design is generally accepted to be caused by the following:

- Increasing number and complexity of interfaces with other disciplines and corresponding collaboration processes.
- Increasing complexity of contractual models such as the Design, Build, Finance, Operate, Transfer (DBFOT) model and the Value for Money (VfM) model.

Safety and costs  Foregoing causes can have considerable effects on both safety and costs:

- The lack of insight and especially improper use of advanced computer programs can put structural safety at severe risk.
- An uncontrolled design process can bring about insufficient performance/cost optimisation and a lot of failure costs.
- Besides a tendency for excessive numerous functional requirements, process control and reliability of a tender build-up is obviously endangered by a lack of insight of participating professionals.

3.1.3  General requirements structural engineering

For competent structural engineering, the compendium [46] outlines the following general requirements:
3.1 Lack of insight of the professional

- Experience with like projects.

- Adequate knowledge about the required type of structure with regard to the structural behaviour: actions, materials, structural action, fire resistance and, if applicable, dynamic effects and fatigue.

- Adequate knowledge about the required type of structure with regard to the integral aspects: construction, architecture, durability, maintainability, and sustainability.

- With attention to the geotechnical engineering, including interactions between structure, foundation, construction activities, and structural environment.

- The ability to judge the results of automated design tools.

- Insight into the interaction between detailed design and the behaviour of the structure.

3.1.4 Recommendations structural design

With regard to structural design, the compendium [46] outlines the following recommendations:

- Aim for an as-clear-as-possible structural design concept, with regard to the overall load distribution and the decisive failure mechanisms.

- Predicated on safety, e.g. structures must not collapse without due warning.

- Be aware of the potential consequences of a structural failure and design a second method of support to ensure that the forces are dispersed elsewhere when a vital structural component can give way.

- Apply comprehensive approximated design calculations as a check for black box automated complex design tools.
3.2 Present-day solutions’ field of practice

3.2.1 Copying reality

Most of the present-day solutions reducing failure and corresponding costs are aimed at a complete and an as-accurate-as-possible procedure capturing reality.

The most thorough procedure capturing reality is copying reality:

1. Qualify the complete set of structural engineering aspects, including all the related interfaces with the built environment.

2. Quantify all these aspects.

3. Describe all the interfaces between these quantified aspects with unambiguous processes.

4. Combine these processes in one converging flow diagram.

Most of the present-day solutions aim at such a copy of reality, as accurate as possible, often in one of the following forms:

**Planning and control** A data-driven approach concerned with planning and controlling all aspects of a process.

**Numerical power** Mostly in the form of advanced structural analysis applications or even a modest expert system, capturing an expert’s knowledge by encoding it in a computer program.

3.2.2 Planning and control

The most usual present-day approach to reduce failure and corresponding costs is by establishing elaborate planning and corresponding control activities.
**PDCA cycle**  The concept of planning and control is based on the scientific method of “hypothesis, experiment, and evaluation” or “plan, do, and check”. Later developed into the present-day customary Plan, Do, Check, and Act (PDCA) cycle as an iterative four-step management method for the control and improvement of processes and products.

For an effective planning-control relationship, an accurate adjustment of the control activities to the planning is of importance:

- Establishing measurable standards together and corresponding with the objectives.
- An interaction between planning and control leading to changes occurs when taking corrective action with the final step of the control. This can take several forms, but two of the most effective are to change the objectives or alter the plan.
- A design plan must provide the framework for the design team control system. When objectives and plans change for whatever reason, control standards should change accordingly.

**Systems engineering**  Systems engineering is a world-wide practised interdisciplinary planning and control approach and a means for enabling the realisation and deployment of successful systems. Systems engineering and corresponding techniques with respect to decomposition, integration, and verification are further discussed in subsection 6.4.1.

**Building information modelling**  Building information modelling (BIM) as a digital representation of physical and functional characteristics of a facility is worldwide the most upcoming planning and control approach and implemented on a large scale.

Traditional design is reliant upon two-dimensional (2-D) drawings. BIM extends this beyond the three-dimensional (3-D) physical geometry with time as the fourth dimension (4-D) and costs as the fifth (5-D). BIM is further discussed in subsection 6.5.2.
3.2.3 Numerical power

Numerous sophisticated high-end automated design tools increasingly support daily practice of the present-day professional structural engineer.

**Finite element method** Present-day form-free complex architectural designs require an elaborate and profound structural analysis on a three-dimensional level. For a corresponding analysis on stress level, three-dimensional finite elements are applicable.

Advanced structural analysis may examine:

- Dynamic analysis; natural frequencies and frequency response.
- Geometric nonlinear analysis of second-order behaviour; linear stress-strain relationship and large displacements.
- Material nonlinear analysis of plastic load-carrying capacity; nonlinear stress-strain relationship and small displacements.
- Induced deformation analysis of the structure, based upon geotechnical failure mechanisms and corresponding deformations.

Because of the present-day availability and self-evidence of these sophisticated high-end automated structural analysis tools, utilisation of these tools for even the simplest structural problem seems appealing.

**Parametric design** Parametric design is a type of rule-based modelling where geometric constraints and also scripting are used to ensure that the main objectives of the design intent within a project are preserved. It is about the use of variables and algorithms to generate a hierarchy of mathematical and geometric relations to explore the whole range of possible solutions that the variability of the initial parameters may allow. As a result, design teams are able to generate innovative forms.
Parametric design is not limited to only constraining geometry; it can also be used to define and constrict relationships such as thermal properties and material strength. With the coupling of finite elements, modelling material dimensions and even optimised organic structural load paths can be obtained.

The shift from using BIM software as a representation tool to a parametric design tool is further discussed in subsection 6.5.2.

**Expert systems**  An expert system models how a human expert analyses a particular situation by applying rules to the facts, or by comparing the current case with similar cases in order to reach a conclusion. The underlying concept of an expert system is that it is possible to capture an expert’s knowledge and to encode it in a computer system.

Present-day application of expert systems is still small-scaled and immature and is therefore in full discussed as a direction for the future in subsection 6.3.1.

### 3.2.4 A need for research

As with a lot of complex design problems, the standard planning and control mode is not enough to guaranty a satisfying solution as this formalistic, more bookkeeping-like approach only supports basic process control.

With regard to the quality of the design solution even planning and control with elaborate procedures and explicit supervision protocols - as proposed in the joint Compendium for a Structural Safety Strategy [46] - merely gives an illusion of control and reliability.

Furthermore, elaborate process control with an overkill of numerous regulations and control systems stifles creativity, progress and cooperation. Especially process control and reliability of a conceptual design - and in particular the preceding tender build-up - is endangered by a present-
day tendency towards excessive numerous functional requirements and control procedures.

On the other hand, effective proven design tools such as systems engineering and BIM do offer control and clarity to open the way to creativity, progress and cooperation. Individual components of these applications, such as decomposition techniques and applied mechanics-based calculation routines can be very useful for a methodical approach on conceptual structural design.

3.2.5 Professional higher education

In the hands of experienced conceptual designers, present-day availability of sophisticated high-end automated structural analysis tools can contribute to conceptual structural design on a detailed scale such as an exploratory analysis of complex structural action.

In the hands of inexperienced young professionals however, the conceptual design capabilities of these sophisticated tools diminish rather than improve. Computerised designing with insufficient insight - particularly in the conceptual design phase - is a dangerous operation both from an economical and a safety point of view.

Due to the on-going expansion of high-end automated design tools, the simplification and decomposition techniques of the experienced structural engineer are steadily disappearing from practice training and higher education programmes.

University professors in the field are noticing a general erosion of knowledge and skills of applied mechanics, the mainstay of the structural engineering profession [45].

Furthermore, education about structural design in general, and conceptual structural design in particular, lacks an integral approach of the educational programme and corresponding emphasis on the interfaces between the disciplines.
3.3 Historical perspective

3.3.1 Developments professional structural engineering

With increasing complexity of structures and corresponding design, the master builder of ancient times inevitably altered into a team of specialists, as shown in figure 3.1 and clarified in the following subsections:

**Homo universalis** Master builder with expertise on the fields of architectural, structural, and construction engineering. This master builder is figured as the “Vitruvian Man” by Leonardo Da Vinci [52], based on the correlations of ideal human proportions with geometry described by the ancient Roman architect Marcus Vitruvius Pollio [53].

**Expanding depth and breath** Structural engineering as a separated formalised discipline.

**On-going expanding depth and breath** Specialisations within the professional field of structural engineering.

3.3.2 Homo universalis

Structural engineering has existed since mankind started to construct its own structures. Throughout ancient and medieval history all architectural, structural and construction design was carried out by one person; often an artisan in the role of master builder. Structural comprehension was extremely limited and almost entirely empirically based.

The physical sciences underlying structural engineering began to be understood during the Renaissance in the late 15th century. It was then that architectural, structural, and construction design evolved into a more profound and controllable knowledge level but was still in the hands of one person, then called “Homo universalis”.

The Latin expression “Homo universalis” can be translated to “Universal
person”, meaning a person with a broad knowledge of several fields and often with proficiency or accomplishments in at least some of these fields. Many notable universal persons lived during the Renaissance period such as Leonardo da Vinci and Michelangelo.

Until the 19th century, only one person was needed to integrally oversee the design, a generalist with profound expertise on the fields of architectural, structural, and construction engineering. The term “Generalist” is used to contrast this general approach to knowledge to that of the “Specialist”.

### 3.3.3 Expanding depth and breadth

With the development of specialised knowledge of structural theories, which emerged during the industrial revolution in the late 19th century,
3.3 Historical perspective

structural engineering came into existence as a more defined and formalised discipline.

The volume of knowledge of materials, technologies, and construction methods was increasing and structures became more complex. Due to the limited ability of comprehension of each individual professional, the field of building engineering was inevitably split into the separate disciplines of architecture, structural engineering, and construction engineering.

The modern structural engineer can rely on a long history of constant validation of theoretical approaches, building up extensive knowledge databases such as applied mechanics-based structural analyses, previous designs, design rules, design codes of practice, and numerous researches.

To complete any project, it now takes a team of professionals that includes structural engineers working with other disciplines such as mechanical, geotechnical, electrical, and civil engineers, and urban planners and architects.

3.3.4 On-going expanding depth and breadth

The volume of knowledge of materials, technologies and building methods is still increasing enormously. Furthermore, there is a tendency away from the explicitly deemed to satisfy provisions towards more implicit performance-based contracting. This inevitably asks for corresponding expertise and brings with it ever more in-depth specialisation.

Within the field of structural engineering alone there is so much expertise that a structural engineer can never master it fully, resulting in specialisations such as geotechnical engineering, pre-stressed concrete engineering, finite elements engineering, and bridge engineering.

Numerous sophisticated high-end automated design tools increasingly support the daily practice of the present-day professional structural engineer. In spite of, or perhaps just because of these extensive design
tools, the understanding and reliability of young professionals in structural engineering decreases dramatically.

They lack a fundamental understanding of structural behaviour, and they lack an overview and insight into the conceptual design process and related interfaces. In short, they lack the ability to abstract the basic design parameters of form, material, and dimension.
Chapter 4

Problem definition and research goal

4.1 Problem definition

4.1.1 The merit of a proper problem definition

Albert Einstein is quoted as having said that if he had one hour to save the world he would spend fifty-five minutes defining the problem and then five minutes solving it [7].

Furthermore, he is quoted as having said that the significant problems we face could not be solved at the same level of thinking we were at when we created them [10].

So finding a methodical approach for the complex conceptual structural design requires an elaborate problem definition on a high abstraction level. Subsequently, working out the solution is merely a derivative activity.
4.1.2 An interface control approach

For a better understanding, and effective problem solving, the lack of insight of the professional into structural engineering is divided into the two partial problems “lack of insight into structural performance” and “lack of insight into conceptual structural design”, as appointed in subsection 3.1.2 and clarified in figure 4.1.

![Diagram](Image)

**Figure 4.1**: Structural design as an interface control approach
4.1 Problem definition

Where the applied “Requirements & conditions” subheadings in general, and the “Construction demand” subheadings in particular, are based on the lecture notes of Van der Horst [16].

The relation of performance, structural, and construction demand with the performance/cost optimisation of the built environment will be clarified in figure 9.1 on page 98 and corresponding explanatory text.

The problem of structural performance Present-day understanding of structural performance is characterised by a constant expansion of complex analysis tools, without an adequate control of the fundamental interface between applied mechanics and the material applications.

The problem of conceptual structural design Present-day conceptual structural design is characterised by a constant expansion of requirements, related interfaces, and collaboration models, without an adequate organisation of the brought about possibilities by controlling the fundamental interface between the body of knowledge of the built environment and the demands of the customer.

4.1.3 Structural engineering activities and missing tools

Professional structural engineering encompasses both analysis and design; where analysis is related to structural performance and design is related to requirements, conditions, and interfaces with the built environment.

An effective structural design process will be characterised by convergence and optimisation, based on a progressive insight into the behaviour of the structure, and an integral control of all influential boundary conditions.

The corresponding structural engineering activities and tools as listed in table 4.1 reveal an obvious deficiency with regard to conceptual structural design tools.
The interface between applied mechanics and material applications is underdeveloped and the interface between structural demand and the built environment is not yet developed.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Subject</th>
<th>Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Code checking</td>
<td>Static scheme:</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td></td>
<td>- Load distribution</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Displacement SLS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Code check:</td>
<td>Design codes of practice</td>
</tr>
<tr>
<td></td>
<td>- Sectional strength</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Stability</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Optimisation:</td>
<td>Computerised frame analysis and code checking</td>
</tr>
<tr>
<td></td>
<td>- Trial and error</td>
<td></td>
</tr>
<tr>
<td>Structural analysis</td>
<td>Fundamental insight into structural performance:</td>
<td>Applied mechanics</td>
</tr>
<tr>
<td></td>
<td>- Equilibrium</td>
<td>Background documents</td>
</tr>
<tr>
<td></td>
<td>- Force-driven parameters</td>
<td>design codes of practice</td>
</tr>
<tr>
<td></td>
<td>- Deformation-driven parameters</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Durability driven parameters</td>
<td></td>
</tr>
<tr>
<td>Conceptual</td>
<td>Fundamental overview of basic interfaces with the built environment:</td>
<td>Interfaces between structural demand and performance and construction demand are not developed</td>
</tr>
<tr>
<td>structural design</td>
<td>- Performance demand</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Structural demand</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Construction demand</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1: Structural engineering activities and tools
4.1.4 Definition of structural performance

Structural performance and its difference from structural action, is clarified by the following definitions.

**Structural performance** Structural performance is a collective term for the following structural requirements:

**Structural safety - ULS** The safety of a structure or structural member is prescribed by its Ultimate Limit State (ULS). If structural behaviour is beyond this undesired state, one of the following failure mechanisms may occur: collapse due to loss of equilibrium of the structure; fracture due to excessive internal stresses or fatigue; or instability due to insufficiency or unbalance of the ground.

**Serviceability - SLS** The functionality of a structure or structural member is prescribed by its Serviceability Limit State (SLS). Serviceability in structural design includes the following cases: deflection of a beam under loads; deformation like swing during vibration; or tilting of a column under external actions.

**Durability - DLS** The durability of a structure or structural member is prescribed by its Durability Limit State (DLS). The ability of structural members to perform adequately for normal use during the characteristic working life can among others be endangered by material deterioration that can within time decrease the strength capacity and serviceability of these members.

These specifically in the structural design codes of practice prescribed structural requirements ULS, SLS, and DLS, are part of a more overall sustainability objective to minimise the negative environmental impact by enhancing efficiency and moderation in the use of materials and energy.

**Structural action** Structural action can be characterised by the way in which a structure resists the loads acting on it - incorporating the
load distribution within the structure; the corresponding deformation of the structure; and the strength of structural members to resist these loads.

The typifications “structural action” and “structural performance” show a high degree of similarity, except for the modern more specific contractual specifications with regard to functional behaviour and durability aspects. For this reason, both typifications are distinguished from each other, and the broader-ranging structural performance is therefore deliberately included in the problem definition.

When principally applied mechanics calculations are addressed, the typification “structural action” instead of “structural performance” will be used. Particularly, optimisation calculations with respect to load distribution, deformation, and strength will be addressed as an optimisation of the structural action.

4.1.5 Definition of conceptual structural design

Conceptual structural design and the identical integral design are clarified by the following definitions.

**Conceptual structural design** Conceptual design refers to the creation phase of the design of the built environment or objects within this built environment such as buildings and civil works. Particularly, this design phase is characterised by a multitude of co-operating disciplines and mutual interfaces.

Within this multi-disciplinary design phase, all disciplines in general are responsible for an overall optimisation of the performance/cost-ratio of the life cycle; the structural engineer in particular is responsible for a safe and efficient structural design within this overall optimisation.

With regard to a safe and efficient structural design, it should be emphasised that understanding structural performance is the starting point and an absolute prerequisite for conceptual structural design.
**Integral design**  Integral design for the benefit of overall optimisation should ideally completely take place during conceptual design in general, and conceptual structural design in particular. In this thesis therefore, conceptual design is completely synonymous with integral design and “conceptual structural design” automatically implies full integrality of design.

## 4.2 Complexity of the research domain

### 4.2.1 Complexity

Complexity describes the behaviour of a system or model whose components interact in multiple ways and follow local rules, meaning there is no reasonable higher instruction to define the various possible interactions [22].

These are typically large collections of connected elements that influence each other. Examples are the brain; society; traffic; the financial system; interacting institutions; climate; ecosystems; interacting atoms or molecules; the World Wide Web. These diverse examples have surprisingly many features in common. As a rule, they show various properties that make complex systems more than the sum of their parts.

Complexity is generally used to characterise something with:

1. Many components.
2. Where those components interact with each other in multiple ways.
3. Culminating in a higher order of emergence greater than the sum of its parts.

However, many simple components interacting with each other in multiple simple ways cannot be characterised as a complex system. Therefore the definition of complex systems by Herbert Simon as a “large number of parts that interact in a non simple way. In such systems the whole is
more than the sum of the parts” [44], clarifies the higher order characterisation.

4.2.2 Complex systems and processes

Design is an activity that plays a fundamental part in the creation of the built environment. The interdisciplinary design of the built environment consists of cyclic design processes, culminating in a physical system.

In the ISO 9000:2015 a system is defined as a “set of interrelated or interacting elements” and a process is defined as a “set of interrelated or interacting activities that use inputs to deliver an intended result” [18].

**Complex system** The traditional approach to dealing with complexity is to reduce or constrain it. Typically, this involves decomposition: dividing a large system into separate elements. The actual physical system itself - although consisting of numerous physical elements - is not complex.

The individual system elements of the built environment, however, can be classified as physical or non-physical. For example architectural demands can include non-physical elements, as aesthetics can neither be classified as physical, nor as a process.

Particularly the interacting of these non-physical elements such as aesthetics, load paths, and constructability becomes complex when the corresponding traditional disciplinary boundaries have to be crossed.

**Complex process** It is important to study how the design is organised in practice, and especially the ways in which designers with different disciplinary expertise are able to work together, collaboratively in teams. A motivation in these studies is not only to improve design processes but also the designed system.
4.2 Complexity of the research domain

4.2.3 Complexity of interdisciplinary interfaces

For an integral conceptual structural design, the main contributing disciplines and corresponding interfaces have to be considered. Architectural design is par excellence - besides construction engineering - an important and much discussed interface.

In order to get hold on the complexity of interdisciplinary interfaces in general, some fundamental characteristics of the interface between structural and architectural demand are researched; the creation of utilitarian space with materialised forms as a main influential architectural design interface with the structural form.

**Fundamental architectural demand**  The following terms can serve as directional guidance for the research on architectural demand for conceptual structural design:

**Architectural concept**  A guiding concept implies an idea or range of ideas, a design intent or a development approach. It resolves the issues of “what” and “how much” and begins to set the stage for understanding “how”.

**Architectural imaging**  In architecture, imaging often stands for a physical or digital visualisation. On a more conceptual level, it is related to aesthetics, interpretations, and perspectives.

**Structural form**  “The resistant virtues of the structures that we seek depend on their form; it is through their form that they are stable, not because of awkward accumulation of material” as stated by Eladio Dieste [11].

**Space in architecture**  The search for a definition which covers the basic idea of architecture, and corresponds with the enclosure of space with three-dimensional structural forms, results in the following more or less common definitions:
Function, structure, and aesthetics Architecture is a combination of function, structure, and aesthetics; these factors moving together through time creates architecture. A building exists as a crystallisation of a given moment of society, technology, and art.

Utilitarian space Architecture is a conscious creation of utilitarian spaces and construction of materials in such a way that the whole is both technically and aesthetically satisfying.

Utilitarian art Frank Gehry and Santiago Calatrava design in three dimensions. They create art that is tailored to provide shelter. Their designs also serve certain programmatic needs.

An introduction to architecture and space in architecture is given by Frank Ching in his book “Architecture: Form, Space, and Order” [9].

Complexity of the interdisciplinary interface Architectural decisions are those that need to be made from an overall system perspective. Essentially, these decisions identify the key structural elements of the system and their externally visible properties and relationships.

Further, they define how the architecturally significant requirements will be achieved. During the conceptual design phase, the architectural designer should focus on the capacity to bear and resist, in addition to the architectural requirements.

Nowadays, both disciplines are seldom combined in one person, so mutual cooperation is necessary. Although organising the physical meeting in an early stage of the design process is a necessity, it is not enough; a mental meeting for mutual understanding has to be arranged as well.

An architectural design is often concept-based, whereas a structural design is form-based: a materialised structural form with the emphasis on the internal distribution of the loads. In order to connect these manifest differences in design attitude between architects and structural engineers, a recognisable intersection of both disciplines has to be defined.

Furthermore, consumer ideology has turned architecture into fast cycles
of fashion and signature styles. Successive architectural movements claiming an avant-garde position have emerged, one after the other, including Minimalism, High Tech, Deconstructionism, and most recently, computer generated Blobitecture.

Consequently, a workable intersection of architectural concepts and structural forms can be characterised as a complex interface.

4.3 Research goal

4.3.1 Research on conceptual structural design

The same unambiguous procedure as used for copying reality, as discussed in subsection 3.2.1, can be followed; however, based upon abstractions of a decomposed system as listed in table 4.2.

<table>
<thead>
<tr>
<th>Step</th>
<th>Research procedure</th>
<th>Level of control</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Qualify the basic parameters for conceptual design, including the usually most influential interfaces with the built environment</td>
<td>Underdeveloped or missing parameters</td>
</tr>
<tr>
<td>2</td>
<td>Complete the set of necessary basic parameters</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Describe the likely decisive inter-relations between these parameters with unambiguous processes</td>
<td>Methodical approach; objective of this dissertation</td>
</tr>
<tr>
<td>4</td>
<td>Quantify all parameters and inter-relations with approximated values for conceptual design</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Combine all processes in one converging flow diagram</td>
<td>Design method</td>
</tr>
</tbody>
</table>

Table 4.2: Research on conceptual structural design
4.3.2 Initial goal of the methodical approach

The initial goal is an unambiguous qualified methodical approach, with qualified parameters in coherent flow diagrams, which can be obtained by the following three research steps, in conformity with table 4.2 on page 41:

1. Qualify existing conceptual design parameters with respect to load distribution, failure mechanisms, and usually, most influential interfaces within the body of knowledge of the built environment.

2. Improve underdeveloped and replenish missing parameters up to a complete set of basic conceptual structural design parameters.

3. Describe the likely decisive interrelations between these qualified parameters with unambiguous processes.

4.3.3 Ultimate design method

The ultimate goal in the near future is an unambiguous quantified design method, with quantified parameters in one converging flow diagram with mathematical functions and a numbered answer, which can be obtained by the following complementary two research steps, in conformity with table 4.2 on page 41:

4. Quantify these basic parameters and their interrelations with the help of calculation algorithms into approximated values for conceptual design.

5. Combine these processes into one converging flow diagram.
Chapter 5

Learning from the past

5.1 Writings in the field of structural design

5.1.1 Famous structural engineers

This chapter discusses the past in search of viable solutions to the problem statement of this thesis.

The basic idea of this discussion is learning from famous structural engineers by studying their writings in the field of structural engineering in general, and structural design in particular. Writings on structural design can best be found by structural engineers with a broad engineering and corresponding integral design interest.

The following requirements will be considered in the research:

- It is of great importance finding clearly stated design methodologies or at least design philosophies.
- At a time that sophisticated design tools were surely not available.
- Particularly, excellent engineers who had competence in multiple fields, especially in the field of structural, architectural, and civil
learning from the past

engineering, are of interest.

- Or excellent engineers, who worked in an interdisciplinary team, and had the interests and the skills to look “out of the box”.
- And above all, the accessibility of reliable information, straight or based upon personal writings.

The objective is a feasibility exploration whether writings on structural engineering in general, or structural design in particular, provide solutions to the lack of insight of the professional into structural engineering, rather than a complete and profound analysis of early and modern writings.

5.1.2 Early master builders

Originally, engineering was a military activity. As time passed, the benefit of engineering in non-military activities was recognised and engineering subsequently split into Military engineering and Civil engineering.

Until the 19th century, the design could be integrally overseen by one master builder who was a generalist with profound expertise on the fields of architectural, structural, and construction engineering. The term “Generalist” is used to contrast this general approach to knowledge to that of the “Specialist”.

The following famous early master builders and writers are researched:

Marcus Vitruvius Pollio (1st century BC) Probably not excellent, but one of the few ancient engineers writing about ancient Rome and Greece.

Leonardo Da Vinci (1452-1519) A typical Italian Renaissance “Homo universalis” epitomising the Renaissance humanist ideal as recorded in his comprehensive notebooks.

Simon Stevin (1548-1620) One of the leading scientists and engineers of his time and writer of an elaborate treatise on architecture,
town planning, and civil engineering.

5.1.3 Modern structural engineers

With the development of specialised knowledge of structural theories, which emerged during the industrial revolution in the late 19th century, the professional structural engineer came into existence as a more defined and formalised specialist.

The following famous modern structural engineers and writers are researched:

Pier Luigi Nervi (1891-1979) An integral architectural and structural designer with elaborate writings about art and technology of designing.

Eduardo Torroja (1899-1961) A philosophical and innovative structural designer whose writings on engineering and building construction include the philosophy of structures.

Mario Salvadori (1907-1997) Architect, structural engineer, and professor with numerous popular textbooks on structural and architectural design.

5.2 Writings in early times

5.2.1 Marcus Vitruvius Pollio (1st century BC)

The power of the Roman Empire cannot only be attributed to the Roman warlords and rulers, but also to their engineers. In spite of this, there is little known about the works of Roman engineers. In ancient times craftsmanship was not held in great esteem, so it was not a dignified topic for writing. But there is one striking exception to this rule.
In the first century Before Christ Marcus Vitruvius Pollio was a chief engineer of the Roman Empire. Vitruvius began as an architect and engineer under Julius Caesar. Later, he took charge of Octavian’s siege engines.

**Writings** Toward the end of his life, Vitruvius wrote a ten-volume account “Architectura Libri X” [53] of known technology under Octavian’s patronage.

The ten books of Vitruvius deal with city planning, building materials, acoustics, water clocks, sundials, pumps, astronomy, medicine, music, arts, and contract law. Most of his design regulations are on the level of global dimensioning. Besides technical detailing, Vitruvius considered theoretical education and practical experience as the essentials of engineering.

Vitruvius was a historian as much as an engineer. Besides imperial Rome, his books look back to classical Greece and Egypt. His writing cannot be regarded as highly preserved documents, because his books came down through medieval copyists, who saw them as a living handbook.

### 5.2.2 Leonardo Da Vinci (1452-1519)

Leonardo Da Vinci was an Italian Renaissance “Homo universalis”; painter, sculptor, architect, musician, scientist, mathematician, engineer, inventor, anatomist, geologist, cartographer, botanist, and writer whose genius, perhaps more than that of any other figure, epitomised the Renaissance humanist ideal.

Da Vinci has often been described as the archetype of the Renaissance Man, a man of unquenchable curiosity and feverishly inventive imagination.

During his lifetime, Da Vinci was valued as an engineer. When he fled to Venice in 1499 he found employment as an engineer and devised a
system of moveable barricades to protect the city from attack. He also had a scheme for diverting the flow of the Arno River.

Da Vinci’s journals include a vast number of inventions, both practical and impractical. They include musical instruments, hydraulic pumps, reversible crank mechanisms, finned mortar shells, and a steam cannon.

**Writings**  Most of what we know about Leonardo Da Vinci is recorded in his notebooks [52]. Some 6,000 sheets of notes and drawings survived, perhaps one-fifth of what he actually produced. With an artist’s eye and a scientist’s curiosity, he recorded in these pages his observations on the movement of water and the formation of rocks, the nature of flight and optics, anatomy, architecture, sculpture, and painting.

He jotted down fables, epigrams, and letters and developed his belief in the sublime unity of nature and man. Through his notebooks we can get an insight into his thoughts and his approach to work and life.

In 1502, Da Vinci produced a drawing of a single span 240 m bridge as part of a civil engineering project for Ottoman Sultan Beyazid II of Istanbul. The bridge was intended to span an inlet at the mouth of the Bosporus known as the Golden Horn. Beyazid did not pursue the project, because he believed that such a construction was impossible.

Da Vinci’s vision was resurrected in 2001 when a smaller bridge based on his design was constructed in Norway. On May 17, 2006, the Turkish government decided to construct Da Vinci’s bridge to span the Golden Horn.

### 5.2.3 Simon Stevin (1548-1620)

Originally from the Flemish city of Bruges, Simon Stevin was one of the leading scholars of his day. As a scientist and engineer, he carved a career for himself in the breakaway Dutch Republic of the Northern Low Countries, developing theoretical innovations in mathematics and
physics as well as practical innovations in civil engineering and military technology.

**Writings**  Somewhat less well known is the project that Stevin worked on during the last twenty years of his life, a treatise on architecture and town planning. The earliest mention of his “Huysbou” occurs in the first volume of his work on mathematics and other natural sciences, published in 1605 [49].

Under the auspices of the Royal Netherlands Academy of Arts and Sciences, architectural historian Charles van den Heuvel has revealed Stevin’s complete and mostly unpublished elaborate written work “De Huysbou” [15].

This treatise on architecture, town planning, and civil engineering deals with the like-sidedness of buildings, underground structures, façades, stairs, ceilings and vaults, roofs, the layout of the parts of a house, and finally, the layout of towns.

### 5.3 Writings in modern times

#### 5.3.1 Pier Luigi Nervi (1891-1979)

Pier Nervi was born in Sondrio, Lombardy in 1891. He began to work as an engineer and contractor in 1923, after an education in engineering at Bologna University. In the 1940s he developed ideas for a reinforced concrete that allowed him to create structures of “strength, simplicity and grace”. His services as an engineering consultant were highly sought after as a result of his experimentation with structural concrete.

From the very start of his career, Nervi combined excellent mathematical knowledge with sound intuition to become a master designer of concrete at a time when concrete was beginning to be accepted as the new building material in Europe.
Nervi believed that architecture and engineering were two connected parts of a whole. To produce good buildings, he felt that knowledge of materials, nature, and construction were essential to understanding architecture. His work as a theorist attracted a wide following.

**Writings**  
Nervi’s elaborate writings about his thoughts and work include various books about the art and technology of designing and building in reinforced concrete: “Structures” [32], “Buildings, projects, structures” [33], and “Aesthetics and Technology in Building” [34].

Nervi’s books cover his work over a period of more than 30 years, presented with numerous drawings and photographs, including plans, interesting details, various stages of construction, and both interior and exterior views. Moreover, he reveals his ideas, his hopes, and even his mistakes, including a treatise on the necessity of intuitive understanding of structures and the general lack of this understanding.

Referring to most of his important projects, Nervi discusses solutions to various functional and construction requirements where he used precast and cast-in-place concrete. He stresses the advantages of reinforced concrete, which, he said, allows greater flexibility and makes it easier to satisfy his triple demand of economy, technical correctness, and aesthetic satisfaction.

### 5.3.2 Eduardo Torroja y Miret (1899-1961)

Eduardo Torroja y Miret was a Spanish structural engineer, pioneer in the design of concrete-shell structures and one of the few great engineers and architects of our time. He pioneered new techniques and exploited shell structures to produce new forms whose strength comes from shape and whose beauty springs from mathematical curves possible only in modern reinforced concrete.

Torroja y Miret was fond of walking his institute visitors under the sickle-shaped ribs of the pergola that sprang from the outside wall and curved
elegantly overhead like jets of water frozen in a high wind, explaining with professional pride that they were actually Bernoullian lemniscates with zero end curvature. Quoting Torroja y Miret, “Every mathematical curve has a nature of its own, the accuracy of a law, the expression of an idea, the evidence of a virtue” [51].

**Writings**  Torroja y Miret’s books include “Philosophy of Structures” (1958) [51]: building construction, load distribution and material strength, philosophic contemplations of stressing, the beauty of structures, and designing.

Most technical literature on structural engineering abounds with theoretical works of a mathematical nature, but few publications are concerned with the various kinds of structures and their fundamental reasons for existence. Torroja y Miret developed new ways of looking at structures as well as ways to increase the strength of the structures without dimming aesthetics.

Torroja y Miret’s book “Philosophy of Structures” illustrates his at times philosophic visions on engineering and art, often incorporated into his structures as reflected in his treatise on the beauty of structures. Besides that his book contains structural engineering learning on materials, structural forms, load distribution, construction methods, and some design process characteristics.

### 5.3.3 Mario Salvadori (1907-1997)

Mario Salvadori was an architect, structural engineer, and professor of both civil engineering and architecture at Columbia University. He earned doctoral degrees in both civil engineering and mathematics from the University of Rome in 1930 and 1933 respectively.

He turned down a job offer to become a CEO and took up teaching at Columbia University where he has taught for 50 years. He founded the Salvadori Educational Centre on the Built Environment (since renamed...
5.3 Writings in modern times

the Salvadori Center), a non-profit educational centre on the campus of the City College of New York, dedicated to helping inner-city youth to learn appreciating mathematics and science.

During his time as a professor at Columbia, from 1945 to 1960, Salvadori worked as a consultant at Weidlinger Associates in New York City. As a structural engineer, he strived for great architecture in all of his projects.

Writings Salvadori authored numerous textbooks on structural engineering in general and structural design in particular:

- “Structure in architecture” (1963) [39]: The building of buildings.
- “Structural Design in Architecture” (1967) [40]: Simplified methods of analysis required for preliminary design of structures.
- “Why Buildings Stand Up” (1980) [41]: An introduction to building methods from ancient times to the present day, revealing a revolution in technology, materials, and structures.
- “Why Buildings Fall Down” (1992) [26]: The history of architectural and structural catastrophes, whether caused by natural disaster or human error, or both.

5.3.4 Other publications in the field of structural design

A selection of well-known authors and corresponding modern textbooks on structural engineering:


Tony Hunt “Tony Hunt’s Structures Notebook” (2003) [17] and other
books: Building construction and structural behaviour, simply explained by pen drawings.

Jaap Oosterhoff “Kracht en vorm” (1990) [35] and other books: Building construction and structural behaviour, simply explained by pen drawings.

Derek Seward “Understanding Structures” (1994) [42]: Applied mechanics and structural behaviour.

5.4 Applicability of writings

5.4.1 Applicability of writings of early times

Early master builders understood the behaviour of structures by studying mathematics, physics, successful attempts and structural collapses. They were thus enlarging, step by step, a beginning knowledge base of structural performance.

The researched historical writings describe down to earth rules of thumb on the one hand and abstract design philosophies on the other hand, rather than the in-between actual design methods. Such an abstract design philosophy often consists of an ideal image based on mathematics, applied physics, and at the time current philosophies.

Therefore, it is not plausible that writings of early times will give direction to a methodical approach on conceptual structural design and certainly not in relation to the present-day complex computational modelling, interdisciplinary interfaces, and collaboration processes.

5.4.2 Applicability of writings in modern times

The researched modern writings in the field of structural engineering describe applied mechanics, material strength, building construction, and
5.4 Applicability of writings

the design philosophy, rather than the actual design method. Mostly, applied mechanics are the principal part.

Some authors are able to capture the behaviour of structures in a more broadening sense, including interactions with the built environment such as construction and architecture. Usually, the design phase is not mentioned at all or only touched upon with some remarks about the complex and ambiguous intuitive character of this phase.

Numerous publications also address modern developments and corresponding challenging consequences for conceptual structural design. In these publications, however, the actual operationalisation of the partly intuitive conceptual design is not elaborated.

This analysis is not pretended to be complete, but within the field of conceptual structural design no writings were found about an actual design method or even a coherent design approach.
Chapter 6

Directions for the future

6.1 System theories

6.1.1 Promising developments

This chapter discusses promising technologies in search of viable solutions to the problem statement of this thesis.

Directions for the future are going beyond the current state of structural engineering into the obvious direction of artificial intelligence as shown on the timeline in figure 2.2 on page 15.

The objective is a feasibility exploration as to whether artificial intelligence in general, and system theories in particular, can be a solution to the lack of insight of the professional into structural engineering, rather than a complete and profound analysis of this specific field.

6.1.2 Classification by characteristics

System theories in engineering such as stochastic search techniques, expert systems, systems engineering, concurrent engineering, collaborative
engineering, and building information modelling, can be divided into methods and technologies, as listed in table 6.1.

<table>
<thead>
<tr>
<th>Classification of system theories by characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methods</td>
</tr>
<tr>
<td>Whole system</td>
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<tr>
<td>Reality</td>
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<tr>
<td>Stochastic search techniques:</td>
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<tr>
<td>- Genetic algorithms</td>
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Table 6.1: Classification of system theories

6.2 Real system-based methods

6.2.1 Stochastic search techniques

Stochastic Search Techniques is a collective name for a group of algorithms that can be used to search for solutions using techniques that contain an element of randomness. Many search algorithms have the problem that they can become trapped on a sub-optimal solution. Although there are techniques to help these algorithms overcome this premature convergence there is still a strong chance that the result will be sub-optimal. Stochastic Search Techniques try to avoid this by including a degree of randomness in their search and often the search is undertaken in many different directions at the same time, thus improving the chances of success.
6.2 Real system-based methods

6.2.2 Genetic algorithms

Genetic algorithms are currently the most prominent and widely used computational models of evolution in artificial life systems. These decentralised models provide a basis for understanding many other systems and phenomena in the world.


Benefits In contrast to more traditional numerical techniques, which iteratively refine a single solution vector as they search for optima in a multi-dimensional landscape, genetic algorithms operate on entire populations of candidate solutions in parallel. In fact, the parallel nature of a genetic algorithm’s stochastic search is one of the main strengths of the genetic approach.

The parallel nature implies that genetic algorithms are much more likely to locate a global peak than traditional techniques, because they are much less likely to get stuck at local optima. Also, due to the parallel nature of the stochastic search, the performance is much less sensitive to initial conditions and hence a genetic algorithm’s convergence time is rather predictable.

In fact, the problem of finding a local optimum is greatly reduced because genetic algorithms, in effect, make hundreds, or even thousands, of initial guesses. This implies that a genetic algorithm’s performance is at least as good as a purely random search.

Points of attention As appealing as a genetic algorithm may seem, the parallel nature of the stochastic search is not without consequences. Although the prospects of finding global optima make it robust, the convergence of a genetic algorithm is usually slower than traditional tech-
niques. In fact, with a good initial guess close to the global optimum, a numerical technique will likely be much faster and more accurate than a genetic search because, in essence, the genetic algorithm will be wasting time testing the fitness of sub-optimal solutions.

Furthermore, due to the stochastic nature of a genetic algorithm, the solution, although more likely to estimate the global optimum, will only be an estimate. Users must realise that genetic algorithms will only by chance find an exact optimum, whereas traditional methods will find it exactly, assuming, of course, they find it at all. The user must then determine whether the solution found by a genetic algorithm is close enough. In many cases it is, but the question of “How close is close enough?” is somewhat arbitrary and application-dependent.

**Practitioners** Genetic algorithms have been used in a large number of scientific and engineering problems. Genetic algorithms are used to study how learning and evolution interact, and to model ecosystems, immune systems, cognitive systems, and social systems.

The first known application of genetic algorithms to building design is the work of Rafiq and Mathews with the development of a Conceptual Building Design system [37]. This system enables the designer to trace the design evolution process throughout a whole run of a genetic algorithms operation. This was an important facility that added transparency to the otherwise “black box” genetic algorithms operation.

### 6.3 Modelled system-based methods

#### 6.3.1 Expert systems

An expert system represents information and searches for patterns in that information. They are known as expert systems because they model how a human expert analyses a particular situation by applying rules to
6.3 Modelled system-based methods

the facts, or compares the current case with similar cases, in order to reach a conclusion.

The underlying concept of an expert system is that it is possible via a series of carefully structured interviews, to capture an expert’s knowledge and to encode it in a computer system in such a way that the system is able to mimic the decision-making behaviour of the expert.


Benefits  Expert systems capture scarce expert knowledge and render it archival. Distributing the expert knowledge enhances employee productivity by offering necessary assistance to make the best decision. Expert systems are capable of handling complex tasks and activities as well as a rich knowledge-database structure and content. Expert systems can reduce production downtime and, as a result, increase output and quality. Additionally, expert systems facilitate the transfer of expertise to remote locations using digital communications.

Practitioners  The early expert systems mostly concerned the field of medical diagnosis. To a growing extent, expert systems are also being developed in technical fields.

In the field of civil engineering there are several applications of expert systems such as flood management and the designing of bridges and retaining walls.

The study of a “Sequence-Based Prediction in Conceptual Design of Bridges” [54] explores the application of a machine learning technique in knowledge support systems in civil engineering design. It presents a sequence-based prediction method for engineering design and demonstrates its utility in the conceptual design of bridges. A model of sequence-based prediction is developed and carries out a number of experiments. It is then applied to a set of standard data and the results of the use
of the sequence-based prediction method are compared with other methods. The empirical results show the potential applications of the method in engineering design.

**Types of expert systems**  Expert systems can include different types of reasoning such as case based, sequential based, rule based, and fuzzy logic.

### 6.3.2 Case-based reasoning

The underlying idea of case-based reasoning is that if you build up a repository of previous designs, when a new design brief is received, this repository can be searched and amended to suit the new situation. Case-based reasoning has been formalised for purposes of computer reasoning.

The general inference process proceeds in the following steps:

**Retrieve**  Given a target problem, retrieve cases from memory that are relevant to solving it. A case consists of a problem, its solution, and, typically, annotations about how the solution was derived.

**Reuse**  Map the solution from the previous case to the target problem. This may involve adapting the solution as needed to fit the new situation.

**Revise**  Having mapped the previous solution to the target situation, test the new solution in the real world or a simulation and, if necessary, revise.

**Retain**  After the solution has been successfully adapted to the target problem, store the resulting experience as a new case in memory.

### 6.3.3 Sequential-based reasoning

The basic idea of sequential-based reasoning is that the most recent numbers of similar design cases are used in predicting the characteristics
of the next design and more recent cases are given stronger influence on
decision-making in the new design situation than older ones.

6.3.4 Rule-based reasoning

Rule-based reasoning uses “if-then-else” rule statements. Rules are simply
patterns and an inference engine searches for patterns in the rules that
match patterns in the data. The “if” means “when the condition is true”,
the “then” means “take action A” and the “else” means “when the condi-
tion is not true take action B”.

Rules can be forward chaining, also known as data-driven reasoning,
because they start with data or facts and look for rules that apply to the
facts until a goal is reached. Rules can also be backward chaining, also
known as goal-driven reasoning, because they start with a goal and look
for rules that apply to that goal until a conclusion is reached.

6.3.5 Fuzzy logic

To date, fuzzy expert systems are the most common use of fuzzy lo-
gic. A fuzzy expert system is an expert system that uses a collection
of fuzzy membership functions and rules, instead of Boolean logic, to
reason about data.

Uncertainty is crucial for the management of real systems. Fuzzy logic
is a formal mathematical methodology for the representation of uncer-
tainty. A superset of conventional Boolean logic has been extended with
values between “completely true” and “completely false”. In this way any
specific theory can be generalised from a discrete to a continuous “fuzzy”
form. The in-between values are precise numbers, so fuzzy logic is a
logic of fuzziness, not a logic which itself is fuzzy. Just as the laws of
probability are not random, so the laws of fuzziness are not vague.

The general inference process proceeds in the following steps:
Fuzzification  The membership functions defined on the input variables are applied to their actual values, to determine the degree of truth for each rule premise.

Inference  The truth value for the premise of each rule is computed, and applied to the conclusion part of each rule. This results in one fuzzy subset to be assigned to each output variable for each rule. Usually “min” or “product” is used as an inference rule. In “min” inference, the output membership function is clipped off at a height corresponding to the rule premise’s computed degree of truth. In “product” inference, the output membership function is scaled by the rule premise’s computed degree of truth.

Composition  All of the fuzzy subsets assigned to each output variable are combined together to form a single fuzzy subset for each output variable. Usually “max” or “sum” is used. In the “max” composition, the combined output fuzzy subset is constructed by taking the point wise maximum over all of the fuzzy subsets assigned to the output variable by the inference rule. In the “sum” composition, the combined output fuzzy subset is constructed by taking the point wise sum over all of the fuzzy subsets assigned to the output variable by the inference rule.

Optional Defuzzification  When it is useful to convert the fuzzy output set to a discrete number, there are techniques such as “centroid” and “maximum” methods. In the “centroid” method, the discrete value of the output variable is computed by finding the variable value of the centre of gravity of the membership function for the fuzzy value. In the “maximum” method, one of the variable values at which the fuzzy subset has its maximum truth-value is chosen as the discrete value for the output variable.
6.4 Decomposition-based methods

6.4.1 Systems engineering

Systems engineering is an interdisciplinary approach and is used for enabling the realisation and deployment of successful systems. Systems engineering integrates other disciplines and specialty groups into a team effort, forming a structured development process that spans the whole system lifecycle.

Systems engineering became synonymous with the overarching responsibility for the development of the complete end product and enabling products. This role has increasingly expanded until the present; it now also being responsible for the interface between the complete device and the user, and even with the system’s eventual disposal. Interface design and specification are concerned with assuring that the pieces of a system connect and interoperate with other parts of the system, and with external systems when necessary.

In general, systems engineering proceeds in the following steps:

1. Formalise the approach.
2. Control the overall system, regarding the entire life cycle, all interfaces included.
3. Apply explicit, clear and provable selection processes.
4. Define interactions between requirements, objects and organisations.


The ISO/IEC/IEEE 15288:2015 standard [19] establishes a common framework of process descriptions for describing the life cycle of systems cre-
ated by humans. It defines a set of processes and associated terminology from an engineering viewpoint. These processes can be applied at any level in the hierarchy of a system’s structure. Selected sets of these processes can be applied throughout the life cycle for managing and performing the stages of a system’s life cycle.

**Benefits** Systems engineering reduces the risk of schedule and cost overruns and increases the likelihood that the implementation will meet the user’s needs. In addition to providing these overall benefits the systems engineering process can provide:

- Improved stakeholder participation.
- Shorter project cycles.
- More adaptable and resilient systems.
- Verified functionality and fewer defects.
- Better documentation.

**Systems development** Systems development often requires a contribution from diverse technical disciplines. Each of these disciplines is normally focused on its own particular contribution to the system. Systems engineering’s vantage point is a holistic perspective on the system, and from this perspective integrates all of these technical efforts to ensure that their various subsystems work with one another.

By providing a system’s view of the development effort, systems engineering helps conflating all the technical contributors into a unified team effort, forming a structured development process that proceeds from concept to production to operation and, in some cases, through to termination and disposal. Systems engineering is usually directly responsible for any engineering function that is not deemed sufficiently necessary on a project to require a full-time, specialist engineer, although consultants may be enlisted as needed.
6.4 Decomposition-based methods

**Systems engineer** Whereas civil engineers might design buildings, systems engineers deal with abstract systems, and rely on other engineering disciplines to design and deliver the tangible products that are the realisation of those systems. The systems engineer is especially concerned with the engineering “-ilities”.

Taking an interdisciplinary approach to engineering systems is inherently complex, since the behaviour of, and interaction among system components are not always well defined or understood. Defining and characterising such systems and subsystems, and the interactions among them, is the primary aim of systems engineering.

**Practitioners** Since the 1970s, U.S. military have acquired to using systems engineering techniques. Partly as the result of this long history of systems engineering development in the military, the use of military weapons subsequent to the Vietnam war have generally proved to be spectacularly successful, with little unexpected failure of complex weapons systems.

In addition, the major advances of the telecommunications industry in recent years were largely made possible by the use of systems engineering techniques, resulting in the successes of the industry as we know it today.

Nowadays, systems engineering is widely applied in the engineering practise in general, and structural engineering practises in particular, especially in complex projects.

6.4.2 Concurrent engineering

Concurrent engineering is a systematic approach to integrated product development that emphasises the response to customer expectations. It embodies team values of co-operation, trust and sharing in such a manner that decision-making is by consensus, involving all perspectives in parallel, from the beginning of the product life cycle.
Essentially, concurrent engineering provides a collaborative, co-operative, collective and simultaneous engineering working environment. The concurrent engineering approach is based on the five key elements of process, multidisciplinary team, integrated design model, facility and software infrastructure.

Concurrent engineering is recognised as a strategic weapon that businesses must use for effective and efficient product development. It is not a trivial task, but a complex strategic plan that demands full corporate commitment, and therefore strong leadership and teamwork go hand in hand with successful concurrent engineering programmes.

Prasad gives an introduction on concurrent engineering in his book “Concurrent Engineering Fundamentals” [36] and Anumba, Kamara, and Cutting-Decelle collected various research efforts on the implementation of concurrent engineering in construction in their book “Concurrent Engineering in Construction Projects” [2].

**Benefits** There are several benefits that concurrent engineering can bring, although it is difficult to quantify many of these benefits by using spreadsheets and numbers. These are not only benefits that the participating company will experience, but ultimately the end users or customers as well as by having a quality product which fits their needs and in many cases, costs them less to purchase. Therefore, concurrent engineering produces a unified profitable corporation and a satisfied consumer.

The majority of a product’s costs are committed very early in the design and development process. Therefore, companies must apply concurrent engineering at the onset of a project. This makes concurrent engineering a powerful development tool that can be implemented early in the conceptual design phase where the majority of the product’s costs are committed.

Companies recognise that concurrent engineering is a key factor in improving the quality, development cycle, production costs, and delivery
time of their products. It enables the early discovery of design problems, thereby enabling them to be addressed up front rather than later in the development process. Concurrent engineering can eliminate multiple design revisions, prototypes, and re-engineering efforts and create an environment for designing right the first time.

**Practitioners**  
Spacecraft design is based on mathematical models, which make use of custom software and linked spread sheets. By this means, a consistent set of design parameters can be defined and exchanged throughout the study, and any changes which may have an impact on other disciplines can immediately be identified and collectively assessed. In this way, a number of design iterations can be performed, and different design options can easily be analysed and compared.

Concurrent Design Facilities activities are conducted in sessions: plenary meetings in which representatives of all space engineering domains participate, from the early phases (requirement analysis) to the end of the design (costing). Even those disciplines that were traditionally involved at a later stage of the process are given the opportunity to participate from the beginning and identify trends that might later invalidate the design.

### 6.5 Technologies

#### 6.5.1 Collaborative engineering

Collaborative engineering aims at providing concepts, technologies, and solutions for product development in dispersed engineering teams. The increased industrial demand for this innovative approach is based on the fact that networked organisation structures are common practice in numerous industry sectors like automobile, aerospace, electronics, or construction. Collaboration has become a key issue for agile and flexible engineering processes.

**Collaboration technologies**  Collaboration technology allows people, or groups of people, to work together from remote sites. Design sessions, product reviews, supplier meetings, and customer reviews no longer require travel and time away from daily work. Depending on the software being used everything from two-dimensional drawings to Microsoft office documents to three-dimensional model assemblies can be viewed, marked-up, manipulated, and modified in an interactive session by computer.

**Benefits**  Some of the many potential benefits of using collaboration technologies include:

- A design project team no longer needs to be co-located. They can collaborate on a design online in a virtual meeting with their counterparts across town, within company divisions across the nation, or with resources across the world.

- They improve designs, shorten design cycles, and reduce time to production and market by improving communications without requiring travel.

- They allow companies to take advantage of resources within their own company divisions, external resources and expertise, and low cost suppliers that otherwise would be too far away to use effectively.

- Design and marketing reviews of a three-dimensional model concept can be held across a company’s division, or with divisions and customers across the globe linking up multiple sites.
• Companies can compete for business across long distances by offering the ability to regularly meet with their customer and collaborate on projects without incurring the expense and lost work time of travel to their site.

• There are tremendous savings in travel costs, combined with the savings of employee downtime while travelling, which face-to-face meetings require. None of the involved parties in these sessions are required to spend more than the length of a normal meeting away from their company or their primary job.

**Practitioners** Fisher Controls, Marshalltown, IA. (control valves, valve-related instrumentation, regulators):

• Hold interactive design sessions with engineering at other global Fisher design centres.

• Collaborate with suppliers online to convey requirements, and design parts to best fit the process creating them.

• Hold design, marketing, and manufacturing reviews involving personnel from other Fisher divisions and sites.

### 6.5.2 Building information modelling

Building Information Modelling (BIM) is a digital representation of physical and functional characteristics of a facility. A building information model is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle.

A basic premise of BIM is collaboration by different stakeholders at different phases of the life cycle of a facility to insert, extract, update, or modify information in the BIM to support and reflect the roles of that stakeholder.

For the professionals involved in a project, BIM enables a virtual information model to be handed from the design team to the main contractor
and subcontractors and then on to the owner/operator; each professional adds discipline specific data to the single shared model. This reduces information losses, which traditionally occurred when a new team took “ownership” of the project, and provides more extensive information to owners of complex structures.

Traditional design was largely reliant upon two-dimensional (2-D) drawings. BIM extends this beyond the three-dimensional (3-D) physical geometry with time as the fourth dimension (4-D) and costs as the fifth (5-D), etc. BIM therefore covers more than just geometry. It also covers spatial relationships, light analysis, geographic information, and quantities and properties of building components.

In addition, sensor-based monitoring systems within a Plan Do Check Act (PDCA) cycle can be used in structural and seismic monitoring projects ranging from simple beam-fatigue analysis, to structural mechanics research, to continuous monitoring of various structures such as buildings, bridges, and retaining walls.


**Benefits**  
BIM is a process involving the generation and management of digital representations of physical and functional characteristics of a facility. The resulting building information models become shared knowledge resources to support decision-making about a facility from earliest conceptual stages, through design and construction, to its operational life and eventual demolition.

The building information models are constantly accessible to all participants and up to date. In principle, all data have to be imported only once thus diminishing superfluous multiple input and corresponding mismatches. Data management of both modelling and revising, however, is a crucial prerequisite for an effective application of BIM.
Design tools  BIM design tools allow extraction of different views from a building model for drawing production and other uses. These different views are automatically consistent, being based on a single definition of each object instance. BIM software also defines objects parametrically; that is, the objects are defined as parameters and relations to other objects, so that if a related object is amended, dependent ones will automatically also change.

Structural engineering related applications include the following:

- Initial sizes of all load-bearing elements with indicative dimensions.
- Foundation elements like bored piles, spread footing, retaining walls, mat slabs, and soil stabilisation like jet grouting columns.
- A digital terrain model, showing existing soil conditions and properties; soil contour and profile. Modelling terrain relief is a powerful tool in the Geographic Information System (GIS).
- A design object library with commonly used elements including structural objects as columns, trusses, and unique objects like precast, post-tension, and built-up steel sections cut from plates.
- Finite element modelling and code checking for foundation, structural system, slab, member and detail design.
- Parametric design modelling for an elaborate exploration of possible solutions with regard to geometry and load path optimisation.

Practitioners  BIM is an upcoming design tool and nowadays quite customary for complex projects worldwide. With respect to the collaboration of structural engineering with other disciplines, the following applications are operational:

- Architectural engineering: grids, usage with respect to loading, floor levels, column and wall positions, ceiling height with respect to structural beams and slabs, floor openings, cladding.
Directions for the future

- Civil engineering: site plan, digital terrain model, soil report, existing utilities, adjacent properties, and roads.

- Mechanical and electrical engineering: lift, escalator, mechanical ventilation, drive unit for movable bridges, equipment weight, and layout.

- Construction engineering: 4-D time structural model, 5-D costs structural model, temporary structures, formwork, and alteration works, as built.

- Clash detection: finding “clashes” where elements of separate models occupy the same space or with parameters that are incompatible, or in 4-D BIM modelling a time sequence that is out of order.

6.6 Applicability of system theories

6.6.1 History

The initial impact of information technology came in the area of analysis and especially with the introduction of finite element analysis. This fitted well with the initial concept of the computer as a high-speed calculating machine and finite element analysis has saved many man-hours, reducing the need for hand calculations and allowing far more complex structures to be analysed.

Another development in information technology applications was the introduction of computer aided design and subsequently building information modelling. Furthermore, the spreadsheet with its adaptability and flexibility has become a widely used asset.

One of the few areas of design that is little touched by technological progress is conceptual design. This lack of tools is not due to any lack of interest by the research community. For more than 30 years, there have been reports of research prototype information technology systems
for conceptual design. The early attempts mostly focussed on so-called “expert systems”.

6.6.2 Applicability of system methods

For design, a search space can be defined as all the possible solutions. All these solutions have to be linked to one or more variables, for example costs. To look for solutions amongst the combinations of options is to search the space of possible solutions.

The search space can be expressed in terms of the variables. The boundaries of the search space are determined by constraints. Some of the variables in the search space may be continuous and some may be discrete. Typically, search spaces are multi-dimensional and as such, viewing them in their entirety in our three-dimensional world is not yet feasible.

Because of the multitude of parameters and the complexity of interrelations, a workable and to optimisation leading numerical power-based design method seems far ahead. Besides, a system that absorbs information and then gives an answer is just not acceptable for designers; the structural designer is responsible for the structural performance and needs to control the risks.

Expert systems for conceptual structural design Computers do not possess common sense, so when an expert system is pushed outside the bounds of its knowledge, it has no way of judging whether or not something is sensible.

Much of the knowledge that an expert possesses is in a form that cannot be expressed clearly. Also the sheer volume and depth of the information is such that it is just not possible to capture it all. Maintaining and updating knowledge bases is a demanding task that requires specialist staff.

In reality, matching a previous design to new design requirements is more complex than can be achieved by simple techniques. Also, automatically
modifying the design proved to be a very difficult task.

**Concurrent engineering for conceptual structural design**  When for the complexity of the interdisciplinary interfaces, as defined in subsection 4.2.3, the loss of information at the borders of the partitioned disciplines will be unacceptable large, then decomposition cannot be applied effectively and concurrent engineering, as discussed in subsection 6.4.2, will be an appropriate solution.

6.6.3 **Applicability of system technologies**

With strategic implementation, system technologies will significantly improve the design, construction, management, and maintenance process by securing clarity and initiating cooperation. So BIM as such is an extremely effective tool for unambiguous information transfer and management during the complete life cycle of a facility.

However, this uncompromising clarity of system technologies in general, and BIM in particular, is a necessary but by definition not adequate condition for obtaining insight and integrality of design. The capability of the professional using the modelling tools remains decisive for success.

6.6.4 **Present-day approach**

Present-day system theories development is aiming at tools and methods to better comprehend and manage the complexity of the total system life cycle. Modern developments include performance-based design, multidimensional modelling management, and quantitative risk management.

Because of the multitude of parameters and the complexity of interrelations, a workable and to optimisation leading numerical power-based overall design method seems far ahead.
In the long run, however, the ultimate artificial intelligent expert system is surely a possibility.

The time gap between present-day short-term needs and future successful applications of artificial intelligence will probably be large enough to excuse for a more simplified methodical approach on conceptual structural design.
Directions for the future
Chapter 7

Research framework

7.1 In search of a methodical approach

7.1.1 Solution approach

Insight into both structural performance and conceptual structural design is the primary requirement for a solution, based on universal fundamental understanding instead of specific applicability.

Present-day innovative accurate and integral design programmes such as expert systems are still small-scaled, insufficiently developed, and unreliable. The black-box character of such systems makes this lack of reliability worse.

So the methodical approach on conceptual structural design will focus on fundamental insight, by appointing and organising all factors that have been identified as important to the problem and to corresponding relationships. A research framework offers a model of how to make logical sense of these relationships.
7.1.2 Guiding research principles

In response to the problem definition and subsequent analysis, starting points and guiding principles for the methodical approach are searched for, in order to get hold of a coherent research framework.

The following highly-correlated research framework components can substantiate a methodical approach:

**T-shaped professional** A balanced combination of in-depth understanding of structural performance and an in-breadth understanding of conceptual structural design, directly in line with the problem definition as expressed in figure 4.1 on page 32.

**Applied mechanics** Insight through simplification by way of an approximate mechanics-based modelling - the mainstay of the structural engineering profession - and corresponding conceptual structural design parameters.

**Designing with progressive insight** A need for understanding - from a safety and an economical point of view - based upon a controlled built-up of insight by working “from the whole to the part” and “from coarse to fine”.

**Decomposition** Working “from the whole to the part” through a physical decomposition of the system and “from coarse to fine” through a process decomposition of the conceptual structural design process.

**Levels of abstraction** A controlled exploratory research within well-defined levels of abstraction with respect to qualitative and quantitative modelling and the corresponding degree of quantitative accuracy.
7.2 T-shaped professional

7.2.1 Modern demands

The problem of present-day collapses can be attributed to a lack of insight of the professional into structural performance and integral design as discussed in section 3.1.

The upcoming call for the return of the old-fashioned structural engineer can be part of the solution. After all, such an engineer has sufficient fundamental insight into structural performance to secure structural safety during conceptual design. Furthermore, this fundamental insight could prove to be an effective guide to acquire and utilise present-day complex software tools, codes, and research results.

However, the old-fashioned structural engineer would not be equipped for present-day and future performance-based integral design, with complex interfaces, contractual conditions, and collaboration processes. For an effective performance/cost optimisation with regard to service life and environment, one has to comply with modern demands.

7.2.2 T-shaped professional structural engineer

The problem definition of structural design as an interface control approach, as shown in figure 4.1 on page 32, represents these modern demands.

Therefore, within the integral Body Of Knowledge of the Built Environment (BOK BE), the present-day professional in structural engineering should possess a so-called “T-profile” as given in figure 7.1.

This T-profile consists of sufficient in-depth understanding of structural performance to secure the structural safety, and sufficient in-breadth understanding of conceptual structural design to function effectively within an integral design team.
7.3  Applied mechanics

7.3.1  Necessity of insight into structural performance

Structural performance has to comply with structural safety, serviceability, durability, and sustainability over the life cycle of a structure as defined in subsection 4.1.4.

Non-conformities with respect to these structural requirements have to at the least be detected and corrected but preferably prevented by a preliminary insight into the structural performance.

**Structural failure**  Every failure could lead to a catastrophic structural collapse. And therein lies the problem for structural engineers: engineering is the most unforgiving of professions.

Structural collapse is often a combination of causes and even if there is a single cause, it can lead to a progressive collapse. Usually, the causes can be attributed to human error: mistakes, misunderstandings, incompetence, ignorance, dishonesty; every facet of human failing is represented in construction failure.
Disaster is most likely when new designs are based purely on successful precedents and basic lessons of past failures are ignored, or not foreseen; for example the Tacoma Narrows Bridge. Other forces can be at work such as new materials, competitive pressure, and economical constraints.

Other non-conformities With structural safety being a self-evident prerequisite, serviceability is an upcoming contractual requirement to be met with regard to a controlled functional behaviour of the structure.

The further addition of durability as a contractual requirement is initiated through performance-based design as a logical step towards an integral performance/cost optimisation of the built environment of the entire life cycle. As a result, durability is extending to sustainability by minimising a negative environmental impact.

Necessity of insight Present-day sophisticated automated black-box design tools are an upcoming threat with respect to non-conformities. A black box permits no insight into the process; the quality of the process and the design outcome is completely dependent on the understanding and overall insight of the programmer and at that time current knowledge, practices, and perceptions.

Computerised designing with insufficient insight, particularly in the conceptual design phase, is a dangerous operation both from an economical and a safety point of view. Insight into the conceptual structural design process is a necessity for structural designers, who are directly responsible for the structural performance.

7.3.2 Timeless applied mechanics

Especially the lack of insight of the young professional during the design phase can be seen as a shortcoming of present-day professional education.
During the entire design process there must be a constant built-up of insight into the load distribution in combination with decisive failure mechanisms of the structure as a whole.

Insight into the load distribution and decisive failure mechanisms can primarily be based on a thorough knowledge and application of mechanics. The visibility of this application highly contributes to an insightful controlled structural design process during all design phases, but emphatically during the conceptual structural design.

Applied mechanics-based modelling is and will be the mainstay of the structural engineering profession.

In order to secure durability of the design method, this research will be focused on an overall applicability for construction types, and the use of timeless elements and particularly applied mechanics.

### 7.4 Designing with progressive insight

#### 7.4.1 General problem approach

Conceptual structural design is such a complex problem solving process that it is in urgent need of increased accessibility to the field of practice.

In general, complex problems can be effectively approached on a relative high level of abstraction, with an elaborate knowledge of the fundamentals and a simultaneous working “from the whole to the part” and “from coarse to fine” as shown in figure 7.2.

The vertical and horizontal axes can be formulated somewhat more abstract as “level of decomposition” respectively “level of specification”.
7.4 Designing with progressive insight

7.4.2 Progressive insight from estimation to accuracy

An effective structural design process is characterised by convergence and optimisation, based on a progressive insight into the behaviour of the structure, and an integral control of all influential boundary conditions.

Working with an increasing number of related interfaces and using complex computational analysis and code checking asks for insight and oversight during all design phases.

The three phases of a global structural design process are designing the primary purpose of the structure, designing the basic structural concept, and the calculation process.

Progressive insight from estimation to accuracy on (sub)system level:

1. Determination of the structural form and the choice of material.
2. Approximate dimensioning by manual calculation of the load distribution and failure mechanisms with basic applied mechanics.
3. Computerised two-dimensional framework calculation of the load
distribution and post-processed code checking.

For most buildings this will normally be sufficient, but high-rise buildings and civil structures may need a more thorough investigation:

4. Computerised three-dimensional framework calculation of the load distribution (three-dimensional torsion effects) and post-processed code checking.

5. Computerised Finite Elements calculation on stress level of the load distribution and post-processed code checking.

6. Computerised Finite Elements calculation on stress level for both load distribution and material strength, code checking is no longer applicable.

7.5 Decomposition

7.5.1 Abstractions of a decomposed system

Decomposition is a standard technique when dealing with complex systems and allows for certain abstractions. One way of decomposing may allow for natural and elegant abstraction in further system description, whereas other decompositions allow for less natural abstraction. So the decomposition has to be chosen with respect to the possible abstractions later.

Completeness When decomposing a system we need an argument that the composition of all decomposed components makes the whole system and its functionality complete again. For certain kinds of decompositions the completeness argument is easier than for others.

Loss of information When designing with abstractions of a decomposed system, the unavoidable loss of information to the system reality
7.5 Decomposition

needs to be taken into account. Decomposing a system inevitably results in loss of information at the borders of the partitioned subsystems. Conscientiously chosen locations for the interfaces between subsystems - often a natural way of decomposing - will decrease insight and reduce loss, however.

Natural descriptions We use formal language to describe systems. This language can be based on different disciplines in the formal, mathematical world:

- There are logics, where we have basic properties and propositional and temporal operators to relate basic properties. Theorem provers are suitable tools that require a logic-based system description.

- There are process algebras, wherein processes and different ways of synchronisation between processes are the elementary bricks, and wherein model checkers are the tools corresponding to the process-algebraic way of system description.

- A physical system can also be described as a set of differential equations, and classical mathematics forms the basis for solving sets of differential equations and arguments about the functionality described.

Additionally, the composition mechanism that corresponds to the chosen decomposition is relevant. On the one hand, when this composition mechanism is reflected by a language primitive of the description language, the corresponding decomposition fits this language best. On the other hand, each decomposition corresponds to a most ideal way of system description.

7.5.2 Decomposition of complex systems

Particularly the complexity of the interdisciplinary interfaces makes both the design process and the overall behaviour of a structural system - and corresponding research domain - complex as discussed in section 4.2.
For an effective analysis of such a complex system, the following coherent decomposition approach can be applied as brought up by Kickert [25] and further substantiated by De Ridder [38]:

**Physical decomposition** Decomposing the physical parts of a system as the most natural way of decomposition.

**Process decomposition** Decomposing the process phases of a system such as design, construction, and operation.

**Aspect decomposition** Decomposing the aspect parts of a system such as strength, aesthetics, and durability.

### 7.5.3 Physical decomposition

This way of decomposition follows the physical parts of a system. Often, it is a very natural way of decomposition because we easily “see” all the physical parts.

The completeness criterion of physical parts is easy to check: when we have processed all physical parts, we have the whole system. Also, failure of physical parts can be located naturally and therefore described more straightforwardly.

The actual physical decomposition of a structural system into basic structural forms is further elaborated in chapter 11.

### 7.5.4 Process decomposition

When looking at chemical plants or production plants a recipe or a production plan forms the “essence” of their functionality. In this case, process decomposition is the most natural way and allows for the most effective abstractions.

The focus in the process decomposition lies in the form of causal chains that are relevant in the system to model.
7.6 Level of abstraction

The actual process decomposition of conceptual structural design into individual fundamental structural design phases is further elaborated in chapter 10.

7.5.5 Aspect decomposition

Particularly the interacting of the numerous aspect parts of the built environment such as functionality, costs, aesthetics, strength, redundancy, constructability, flexibility, durability, maintainability, and sustainability becomes complex when crossing disciplinary boundaries.

Although an integral conceptual design is a highly cyclic process, the complexity lies in the interdisciplinary aspects rather than the process itself.

As a result of this complexity of the interdisciplinary interfaces, the loss of information at the borders of the partitioned disciplines will be unacceptably large and decomposition cannot be applied effectively.

So concurrent engineering will be an appropriate solution as discussed in subsection 6.6.2. This utilisation of concurrent engineering and corresponding preconditions is further elaborated in section 9.3.

7.6 Level of abstraction

7.6.1 Level of control

Primarily, the research will focus on controlling the conceptual design process, using elementary abstractions in a decomposed system. The strategy, both for the structural performance part and for the conceptual structural design is only pointing out the most fundamental solutions instead of trying to link up with all the possibilities. In doing so, it is inevitable to make choices on the basis of probability.

The quality of the design method will be governed by these choices:
• The reality value and the controllable number of the fundamental solutions. Make up a basis of design for the all-round structural engineer in the field of both building and civil engineering.

• The arrangement of, the interaction between, and the possibility of optimisation of the fundamental solutions. In short, the choice of system theory.

• The measure of insight into the fundamental solution influences the quality assurance of the structural performance.

7.6.2 Defined levels of abstraction

From the beginning, the full spectrum will be researched in order to optimise further specification. However, an extensive and profound study of applied mechanics does not converge to a suitable solution.

A high level of abstraction is needed while searching for a suitable decomposition of the structural system. The load distribution in the system and the capacity of the parts of the system are main elements in the search for converging. Non-physical but influential boundary conditions such as construction demand and architectural demand have to be incorporated, thus optimising the structural system.

For an effective and clear distinction between the initial qualitative modelling and the subsequent approximate quantification, two corresponding basic levels of abstraction can be classified as shown in figure 7.3.

7.7 Durability of a methodical approach

7.7.1 Research framework boundaries

To secure durability of the design method, the research will be focused on an overall applicability for construction types, and the use of timeless elements as mechanics.
7.7 Durability of a methodical approach

The research framework components are chosen for reasons of effectiveness, affecting the main research questions such as insight into structural performance and insight into conceptual structural design.

As a direct consequence, possible complementary research framework components are excluded subjects of research so that the explicitly chosen research framework components outline the validity area of this research.

7.7.2 New techniques

Until recently, the structural form was restricted to complex differential mathematics leading to surfaces as a hyperbolic paraboloid. With present computational design modelling, however, almost every structural form has become accessible. Will these new techniques lead to an acceleration of structural engineering and construction in the order of magnitude of computational engineering itself? An extrapolation of even recent history should then be considered with great care.

It is, however, not likely that these new techniques will accelerate the
development of structural engineering considerably as structural safety and reliability are applicable for the whole life cycle of approximately 50 years. Besides that, designing and building complex unique structures increases the risk of unforeseen costs. Structural engineering is with reason a cautious profession.

7.7.3 On-going developments

The solution tends towards a more technical approach, including basic interfaces with the built environment. In order to secure the feasibility of this thesis, some limitations have to be determined. Particularly, on-going developments concerning life cycle design and serviceability limit state design cannot be fully incorporated. The basics will be incorporated in the methodology, with the possibility of a future extension.
Part II

The art of conceptual structural design
Chapter 8

Introduction to part II

Both principal and design team are in search of an overall performance/cost optimisation. A lack of insight of the professional into structural engineering is considered to be a main obstacle for such an optimisation.

For this relatively unexplored problem, an exploratory research is conducted by a systematically zooming in from the whole to the part and from coarse to fine. The so explored methodical approach on conceptual structural design consists of a process control component and an underlying structural performance component. The process control component is discussed in this Part II, “The art of conceptual structural design”. The underlying structural performance component is discussed in the following Part III, “Understanding structural performance”.

Part II starts with present-day complex and ambiguous conceptual structural design.

Then the conceptual structural design process is subdivided into the individual components process decomposition, physical decomposition, and a cyclic control of the process, as shown on the axes in figure 8.1.
Conceptual design  Conceptual structural design is a creative and dimensioning process in which the structural form, the materials and the basic dimensions are determined, taking into account all influential aspects such as aesthetics, constructability, sustainability, and costs.

Until the present day, it appears challenging to capture performance-based solutions out of the multitude of aspects and their complex interrelations. Modelling these interrelations is capturing intuition; the most ambiguous, and therefore the most intangible aspect of conceptual design.

A definition and collection of the fundamental conceptual design parameters of the most influential participating disciplines can serve as a
joint breeding ground for a concurrent “shared knowledge-based integral
design”.

For a controlled conceptual design process, both process and physical
decomposition techniques are inevitable.

**Process decomposition**  Capturing structural design by breaking
down this complex process into the essential absolute minimum, res-
resulting in a “structural design cycle” as an effective characterisation of
both the overall design process and the individual design phases.

**Physical decomposition**  A structure as a three-dimensional physical
system can be decomposed in clear two-dimensional “basic structural
forms”, with each individual structural form being an assembly of directly
connected one-dimensional structural elements, designed to act together
to resist loads.

**Cyclic process control**  A complete control of the present-day com-
plex and highly cyclic conceptual design process is still out of reach.
Success in this design phase is dependent on the level of experience and
intuition of the conceptual structural designer.

Structural design can be explored on a “structural design path”, following
the fundamental dimensioning routine from structural integrity, via load
distribution, to failure mechanisms.

A cyclic optimum design with regard to optimisation of both the quality
of design outcome, and the number of design cycles can be supported
by “structural design loops” such as analysis, check, orientation, and
correction loops.

**Solution components**  The so-obtained coherent set of solution com-
ponents for conceptual structural design, and corresponding chapter ar-
rangement, is listed in table 8.1.
# Chapter arrangement and solution components

<table>
<thead>
<tr>
<th>No.</th>
<th>Chapter</th>
<th>Solution component</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Conceptual design</td>
<td>- Shared knowledge-based integral design</td>
</tr>
<tr>
<td>10</td>
<td>Process decomposition</td>
<td>- Structural design cycle</td>
</tr>
<tr>
<td>11</td>
<td>Physical decomposition</td>
<td>- Basic structural forms</td>
</tr>
<tr>
<td>12</td>
<td>Cyclic process control</td>
<td>- Structural design path</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Structural design loops</td>
</tr>
</tbody>
</table>

Table 8.1: Solution components for conceptual structural design
Chapter 9

Conceptual design

9.1 Determination of the structural form

9.1.1 Conceptual structural design

A conceptual design team consists of a representative of the principal and representatives of each discipline with a major design involvement with regard to feasibility and the performance/cost ratio of the specific required system.

After a reduction of the mostly numerous requirements and contractual conditions into a controllable set of presumably dominant requirements and conditions, the first conceptual draft on system level can be executed. Only on this three-dimensional level an integral design is feasible. The process of creating system outlines by the conceptual design team is shown in figure 9.1.

Customary, this creation is a composition of basic structural forms on object level. More innovative structural design, however, requires a system creation on aspect level. On such an aspect level, a set of functional requirements is directing the design of possible load paths instead of just combining basic forms.
Performance demand:
- Functional reliability
- Structural reliability
- Redundancy
- Architectural demand
- Flexibility
- Durability
- Maintainability
- Sustainability

Structural demand:
- Structural safety ULS
- Serviceability SLS
- Durability DLS
- Material demand

Construction demand:
- Material demand
- Temporary structures
- Equipment demand
- Manpower demand
- Time demand

Added value design:
Performance surplus

Performance/Cost optimisation

Performance / Cost optimisation may lead to modification of the requirements

Requirements & conditions

Iterative design loop

Code check

As built

Conformity between As built and requirements should be secured through conceptual structural design

Form, material & dimension

Construction

Code check may lead to correction of the conceptual structural design
For a coherent and complete integral design all fundamental demands, namely performance demand, structural demand, and construction demand, have to be complied with. Moreover, these three demands are, one by one, indispensable:

**Performance demand** A system derives its reason for existence from its function. Principally, performance demand has to secure this function by means of explicit reliability demands. Furthermore, architectural expression, future customisation, service life, and environmental sustainability can be demanded.

**Structural demand** The safety and serviceability of the structure are inevitably conditional for a safe and functional use of the system. Failing structural safety has proved to cause serious civil disturbances.

**Construction demand** Design engineers optimise cost drivers of the scheme - such as simplicity, uniformity, repetition, and phasing - to be executed with respect to manpower, equipment, and material demand. The cost optimisation of the execution is implicitly part of the life cycle costs and is, among other things, dependent on location and the individual contractor. Constructability in itself, and corresponding construction time are inevitably conditional for coming into existence of the system.

These functional demands in general and the construction demand in particular are based on the lecture notes of Van der Horst [16].

The quality of the system can best be valued by its performance/cost ratio; with a performance in the broadest sense, including structural and construction demands.

Due to the large amount of design freedom, the performance/cost ratio can best be established and optimised in the creation phase. In the process of further specification, an optimisation of the performance/cost ratio will turn out to be increasingly limited.

The system outlines that only comply with the requirements are so-
called “performance-based” solutions. On the basis of these requirements, striving for full optimisation of the performance/cost ratio will lead to a performance-based cost minimisation.

However, such a minimisation is not automatically the ultimate goal of a principal and the design team; sometimes, supplementary added-value solutions offer a considerable added-value for a relatively small cost increase. Then, a real performance/cost optimisation, despite the earlier established requirements, is preferable.

9.1.2 Design process

Conceptual structural design is a creative and dimensioning process, in which the structural form, the materials, and the basic dimensions are determined. The structural engineer should be involved in the project from the start of the conceptual design phase because of the influence of complex aspects such as functionality, costs, aesthetics, constructability, and sustainability.

The structural form One of the main conceptual structural design activities is the determination of the structural form, based on “understanding” and “order of magnitude” of standard structural forms, fundamental insight into structural behaviour, and an overview of the basic interfaces with the built environment.

Materialisation The choice of material is dependent on a combination of structural, construction, and architectural demand parameters; structural demand with respect to reliability, redundancy, and durability; construction demand parameters for both permanent and temporary structures such as construction time, mass, simplicity, and uniformity; and finally, architectural demand, which can span a wide spectrum of expressions from power and massiveness to minimalism and transparency.
Dimensioning Dimensioning of a materialised structural form is a quantification process. The load distribution on the system, through the subsystems into the elements, is one of the flow parameters. The second parameter in a reversed flow is the determination of the approximated capacity of the materialised elements, the subsystems, and the system.

The starting point in this process is usually the adoption of dimensions derived from similar projects. Final dimensioning is obtained through a “trial and error” procedure involving repeated analysis of the structure. Only in some uncomplicated cases this process can be rationalised using an algorithm flow diagram.

9.1.3 Flow diagram

The framework of procedures in conceptual structural design can be modelled by flow diagrams, giving an unambiguous solution.

Flow diagrams can support structured analysis and design, by showing the flow of data from external entities into the system, and how the data move from one process to another, as well as its logical storage. Within processes, optimisation loops can be implemented. There are common modelling rules creating flow diagrams:

- All processes must have at least one data flow in and one data flow out.
- All processes should modify the incoming data, producing new forms of outgoing data.
- Each data store must be involved with at least one data flow.
- Each external entity must be involved with at least one data flow.
- A data flow must be attached to at least one process.

All influential aspects are known in conceptual structural design, the basic interfaces with the built environment included. The interrelation
and interaction between all these aspects, however, is so complicated that besides experience, intuition has to be used frequently.

Using a flow diagram is a way of making effective choices out of all we already know. In doing so, throwing away aspects that cannot be captured in this way - such as the ambiguous but vital intuition - is unavoidable.

9.1.4 Experience and intuition

In many cases the interacting of the numerous aspects of the built environment such as functionality, costs, aesthetics, strength, redundancy, constructability, flexibility, durability, maintainability, and sustainability becomes complex when crossing disciplinary boundaries.

Then a lot of experience is advisable, and furthermore and more intangibly, intuition becomes a necessity as stated by famous engineers:

**Eduardo Torroja** In his book “Philosophy of Structures” [51]: “The achievement of the final solution is largely a matter of habit, intuition, imagination, common sense, and personal attitude. Only the accumulation of experience can shorten the necessary labour or trial and error involved in the selection of one among the different possible alternatives.” “The calculation of stresses can only serve to check and to correct the sizes of structural members as conceived and proposed by the intuition of the designer. The work itself is never born from calculation.”

**Pier Luigi Nervi** In his book “Structures” [32]: “It is highly regrettable that some of the highest qualities of the human mind, such as intuition and direct apprehension, have been banned from our schools and have been overwhelmed by abstract and impersonal mathematical formulas... The essential part of the design of a building consists in conceiving and proportioning its structural system... then and only then we can and we should apply the formulas of mathematical theory of elasticity to specify with greater accuracy
9.1 Determination of the structural form

Modern structural engineers can rely on a long history of constant validation of theoretical approaches, building up an immense database of knowledge.

Until the present day, it appears challenging to capture performance-based solutions out of the multitude of aspects and their complex interrelations. The unsolved topic in modelling these interrelations is capturing intuition, the most ambiguous, and therefore the most intangible aspect of conceptual design.

Furthermore, some unambiguous structural aspects such as serial effects, induced deformation, and the stability of the equilibrium are difficult to insert in a linear optimisation process. At a certain level, decomposition and a linear approach to modelling the design process is no longer feasible.

Consequently, the determination of the structural form is partly a qualification process. The field of application, and the characteristics of the structural forms with respect to the individual relations with the built environment, are the variables in this partly unambiguous and partly ambiguous process.

The ambiguous part is often specified as experience and intuition. The most tangible of the two - experience - consists of conscious and subconscious knowledge.

It is a reasonable assumption that intuition is nothing more than the subconscious part of experience. After all, there is a noticeable difference between the intuitive capacities of a young professional and an experienced engineer. This difference is contradictory to the sometimes-suggested idea of a cosmic consciousness.

It is worthwhile revealing the experienced-based subconscious knowledge, keeping in mind never to take something for granted.


9.2 How to capture the intangible

9.2.1 Abstracting conceptual design

In general, communication can be divided in three basic levels of abstraction: object, experience, and concept. Going up the levels of abstraction, ideas increase while reality decreases:

At the object level Communication is about tangible material or an unambiguous representation of it.

At the experience level Communication is about (common) experience. Although reality is the point of departure, it has the abstraction of interpretation.

At the concept level Communication is about ideas and thoughts. Concepts can be accepted or rejected.

Considering the levels of abstraction in conceptual structural design, the basic levels of communication are applicable. The experience level in engineering practice, however, is mainly restricted to physical behaviour, described with physical laws.

These laws are scientific generalisations that have become accepted universally within the scientific community. Describing the observable laws of nature is based on observations and repeated scientific experiments.

Some extremely important physical laws are simply definitions of the observable laws of nature, such as the mathematical definition of force by Newton’s second law of mechanics. Some laws are only approximations of other more general laws, with a restricted domain of applicability.

Modelling Due to the complexity of load distribution and above all material behaviour, structural analysis is completely dependent on abstract representations of the actual structure.

As an abstract representation, modelling has its limitations. For a
reliable application of structural modelling, awareness of these limita-
tions is of great importance, for example when shear deformation is
dominant.

### 9.2.2 Directing parameters of conceptual design

During the conceptual design phase, the individual participants of the
integral design process such as the structural engineer, the architect, and
the contractor, measure, so to speak, with different scales:

**Form** The structural engineer designs in terms of materialised structural
forms, static schemes, and dimensioning processes; in brief “form”.

**Concept** The architect designs in terms of architectural concepts, design
philosophy, space, and expression; in brief “concept”.

**Process** The contractor designs in terms of building techniques, plan-
ning, phasing, and repetition; in brief “process”.

Dependent on the discipline, the parameters “form”, “concept”, and “pro-
cess” give direction to the design solution as shown in figure 9.2.

![Diagram of Directing parameters of conceptual design]

Figure 9.2: Directing parameters of conceptual design

Present-day misunderstanding between professional disciplines within an
integral design process can partly be ascribed to these almost perpen-
dicular oriented areas of attention.
Participation in this process requires a certain level of abstraction. Particularly, the architect is used to abstraction, considering the nature of architectural designing. On the contrary, both the structural engineer and the contractor have to deal with a lot of down-to-earth activities in the field of code checking and execution. For an effective cooperation, it is of the utmost importance that every discipline contributes on the required conceptual design level of abstraction.

9.2.3 Sharing the knowledge of the built environment

For an optimisation of the performance/cost ratio over the life cycle of a structure, an integral approach and control of all participating influential disciplines is an absolute necessity. In many cases, the interacting of the numerous aspects of the built environment is so complex that an unambiguous flow diagram cannot be applied. Then, a lot of experience and intuition becomes advisable.

In consequence of gathering the required information for both the conscious and sub-consciousness of participants of conceptual design, an accessible knowledge base is to be researched. For this purpose, the immense complete body of knowledge of the built environment is totally unsuitable and consequently, resulted in the present-day numerous disciplines and specialisations.

Nevertheless, the ability to have insight in multiple fields of discipline is the most effective way of crossing borders between disciplines and thus more effectively handles the design interfaces between these disciplines. It is of importance to determine and bring together the required fundamental knowledge of these disciplines as an effective basis for conceptual design.

A mutual knowledge base is possibly feasible, determining the absolute required minimum:

1. Sharing the knowledge of the built environment on an approximation level suitable for conceptual design;
2. and restricted to only the knowledge of the disciplines involved with a major interface during conceptual design.

### 9.2.4 Back to the fundamentals of conceptual design

The required T-profile of the professional structural engineer as shown in figure 7.1 on page 80, can be refined by a visualisation of the overlap between the in-depth and the in-breadth understanding. This overlap, being the conceptual design parameters, is visualised in figure 9.3.

![Figure 9.3: T-shaped professional for conceptual design](image)

**Conceptual design parameters** The conceptual design parameters are the specific part of the in-depth understanding that contributes to the conceptual design. These conceptual design parameters have to encompass all fundamental aspects of structural engineering. After all, the inherent quality of a design is established during conceptual design, taking into account all influential interfaces with the other disciplines.

Although subsequently a lot of optimisation, detailing, and verification has to be carried out, conceptual design and corresponding approximate parameters establish, so to say, the “DNA” of the final design.
Discipline fundamentals  Therefore, the conceptual design parameters represent the fundamentals of the discipline, in this specific case the professional field of structural engineering. In view of the nature of conceptual design, this generalisation is applicable to all disciplines within the built environment.

9.3  Shared knowledge-based conceptual design

9.3.1  Splitting process and technical breadth

For a better understanding of the typical conceptual design activities, the in-breath understanding of conceptual design can furthermore be divided into a technical breadth of the built environment and the integral process control of conceptual design as shown in figure 9.4.

Figure 9.4: T-shaped professional technical breadth

Integral process control  The ability to work in a multi-disciplinary manner with the profile to be “integrator” - besides the standard required process control abilities with respect to problem solving, project management, and self-management - includes the following:
• Functional requirements as starting point for conceptual design.

• Decomposition techniques as used in systems engineering.

• Collaboration models such as concurrent engineering and building information modelling.

**Technical breadth**  The combined technical breadth and depth of the Built Environment (BE) encompasses the complete Body Of Knowledge (BOK) as indicated in figure 9.4 with the abbreviation “BOK BE”, applicable to all design phases of conceptual, basic, and detailed design.

A part of this body of knowledge, indicated in figure 9.4 as “Technical breadth”, refers only to the conceptual design phase. On the level of conceptual design, the technical breadth of the built environment specifically encompasses a fundamental understanding and application of the conceptual design parameters of all disciplines.

This understanding and application includes an understanding and control of the relevant interfaces between the individual disciplines with attention to constructability, safety, and durability.

However, due to the complexity of present-day design and the limited extrapolation capacities of previous designs, the consequences of design decisions in the early phase of conceptual design are difficult to oversee.

This underlines both the necessity to have insight in multiple fields of discipline, and to develop numerous concepts in order to bring them to a lower degree of complexity as further elaborated in section 12.4.

**Technical depth structural engineering**  The technical depth equals the in-depth understanding of structural performance. This depth encompasses the complete body of knowledge of professional structural engineering as practiced during all design phases of conceptual, basic, and detailed design.
9.3.2 Principal disciplines of the built environment

For an integral conceptual design, the main contributing, and thus principal disciplines and corresponding interfaces, have to be considered. With respect to the quantity and character of the interfaces between the participating disciplines within a conceptual design team, a distinction between environment and object level as shown in figure 9.5 is appropriate.

![Figure 9.5: Environment and object level](image)

Besides this distinction between environment and object level, an effective classification of principal disciplines can be based upon obvious requirements such as value, functionality, safety, aesthetics, and realisability. The so-classified principal disciplines for the built environment are listed in table 9.1.

9.3.3 Concurrent-based shared knowledge

On object level, the interfaces of the object-related structural engineering with the other object-related disciplines are within the system functionality of the object and are further substantiated as follows:

**Property management** The performance/cost ratio is the main driver for the overall optimisation of conceptual design. Regarding life cycle costs, maintenance, and management are gaining importance, and are therefore substantial input for conceptual design.

**Installation engineering** Particularly, the main ducts of air conditioning systems have the same scale as girders and are preferably de-
Table 9.1: Principal disciplines of the built environment

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Environment level</th>
<th>Object level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>Property Development</td>
<td>Property Management</td>
</tr>
<tr>
<td>Functionality</td>
<td>Transportation Engineering</td>
<td>Installation Engineering</td>
</tr>
<tr>
<td>Safety</td>
<td>Hydraulic Engineering</td>
<td>Structural Engineering</td>
</tr>
<tr>
<td>Aesthetics</td>
<td>Urban Planning</td>
<td>Architectural Engineering</td>
</tr>
<tr>
<td>Realisability</td>
<td>Environmental Engineering</td>
<td>Construction Engineering</td>
</tr>
</tbody>
</table>

signed parallelly. Smaller scaled installations normally have minor to no influence at all on structural dimensioning.

**Architectural engineering** Architecture is a conscious creation of utilitarian space and construction of materials in such a way that the whole is both technically and aesthetically satisfying. Creation of utilitarian space with materialised forms is a main influential design interface with the structural form.

**Construction engineering** The practical feasibility of the execution focuses on avoiding unnecessary complexity, on influences on dimensions and tolerances, and on possible choices between alternatives.

On environmental level, the interfaces with the object-related structural engineering mainly consists of geometrical and loading constraints such as free space profiles, road cross sections, traffic loads, and hydraulic loads.

So for the determination of the fundamental shared knowledge with respect to conceptual structural design, the emphasis is on the object-

9.3 Shared knowledge-based conceptual design
related disciplines.

Because of the complexity of the interdisciplinary interfaces between these object-related disciplines, concurrent engineering will be an appropriate solution as discussed in subsection 7.5.5 of the research framework.

After all, the concurrent engineering approach provides a collaborative, co-operative, collective and simultaneous engineering working environment, based on the five key elements of process, multidisciplinary team, integrated design model, facility and software infrastructure.

9.3.4 Conceptual structural design parameters

Both for understanding structural performance and sharing our fundamental knowledge with the other directly related interface disciplines, a set of conceptual structural design parameters has to be established.

For professional Structural Engineering (SE), the applied mechanics-based conceptual structural design parameters can be split into the structural integrity on system level via the load distribution on subsystem level to the failure mechanisms on element level, as shown in figure 9.6.

Structural integrity  The system as a whole can only be captured on the corresponding three-dimensional system level. A typical three-dimensional system effect such as overall torsion has to be incorporated here. Insight into and control of the load distribution within the three-dimensional system is merely feasible with axial forces on the level of load paths.

For a more accurate insight into the structural action and corresponding analysis of load distribution and dimensioning, the three-dimensional system is too complex and has to be decomposed into more accessible two-dimensional subsystems.
Load distribution  On the two-dimensional subsystem level, a more accurate load distribution can be executed, including insight into optimisation, redistribution and possibly induced deformation of statically indeterminate structures. Consequently, a distribution of the prime actions can be executed to determine the individual element forces and corresponding required capacity.

Failure mechanisms  The failure mechanisms on a one-dimensional element level represent the ability of materialised elements or cross sections to resist the distributed loads per element. These failure mechanisms are dependent on resistance of materials, resistance of cross sections, and stability of elements.

The deformation of the individual, materialised elements culminates in a deformation and corresponding displacements of the subsystems and subsequently, the whole system.
9.3.5 Qualification and approximate quantification

The T-shaped in-breadth understanding in general - consisting of the technical breadth of the built environment and the integral process control of conceptual design - and the conceptual structural design process control in particular, is qualitatively modelled in part II of this thesis as shown in figure 9.7.

Subsequently, the conceptual structural design parameters as discussed in the previous subsection 9.3.4, are approximately quantified in part III of this thesis as shown in figure 9.7.
Chapter 10

Process decomposition

10.1 Fundamental design cycle

10.1.1 Structural life cycle phases

In the life cycle of a structure, the following phases and corresponding structural engineering activities can be chronologically distinguished as listed in table 10.1: initiation, design and specification, construction, operation and maintenance, and demolition.

10.1.2 Structural design phases

Out of the functional requirements and boundary conditions, a system is created and the performance/cost ratio is optimised, taking into account the interfaces with the built environment. Specifications for construction are prepared. This process can be divided into three major design phases with increasing accuracy, as listed in table 10.2: conceptual design, basic design, and detailed design.
### Life cycle phases of a structure

<table>
<thead>
<tr>
<th>Life cycle phases</th>
<th>Structural engineering activities</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initiation</strong></td>
<td>User needs are secured by a set of functional requirements, which define what the system is ultimately supposed to do. At this level of abstraction, structural requirements are not directly referred to.</td>
</tr>
<tr>
<td><strong>Design and specification</strong></td>
<td>Out of the functional requirements, a system is created and the performance/cost ratio is optimised, taking into account the interfaces with the built environment. Specifications for construction are prepared.</td>
</tr>
<tr>
<td><strong>Construction</strong></td>
<td>Feasibility and cost optimisation of construction is secured by design, including temporary structures. Structural site engineers operate on the level of postponed design activities, including corrective actions in case of non-conformities.</td>
</tr>
<tr>
<td><strong>Operation and maintenance</strong></td>
<td>After a maintenance or flexibility demand, structural engineers design the reconditioning or rebuilding of the structure or parts of it, and again operate on the level of design activities.</td>
</tr>
<tr>
<td><strong>Demolition</strong></td>
<td>A controlled structural collapse is based upon a structural action analysis and structural engineers operate on the level of partial design activities.</td>
</tr>
</tbody>
</table>

Table 10.1: Life cycle phases

**Conceptual structural design** The conceptual design phase is of special interest with respect to the problem definition of this thesis. The starting point in this phase is usually the adoption of conceptual structural design solutions derived from similar projects. Any new type of structure, however, requires an extended lead-time to obtain a thorough understanding of the structural action.
10.1 Fundamental design cycle

<table>
<thead>
<tr>
<th>Design phases</th>
<th>Structural engineering activities</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conceptual design</strong></td>
<td>The purposes of conceptual design of any structure are to obtain a clear picture of the structural action, approximated dimensions of the structure, principal details, quantities of materials for making estimates of costs, and a reliable prediction of the basic and detailed design.</td>
</tr>
<tr>
<td><strong>Basic design</strong></td>
<td>The purposes of basic design are to obtain exact dimensions of the structure and approximated dimensions of the details.</td>
</tr>
<tr>
<td><strong>Detailed design</strong></td>
<td>The purposes of detailed design are to obtain exact dimensions of the details and specifications for construction.</td>
</tr>
</tbody>
</table>

Table 10.2: Design phases

It is not expected that corresponding conceptual design calculations and estimated costs be precise, but rather within accepted tolerance. The level of acceptance has at least to be qualified, and preferably be quantified, with a risk analysis of the costs of the conceptual design.

10.1.3 Cyclic design process

The immense number of individual parameters and mutual interactions cannot be unambiguously controlled and will inevitably lead to a highly cyclic process as shown in figure 10.1.

In the process of materialisation from requirements to construction, ongoing design and check activities can influence foregoing activities with regard to choice of geometry, material, and matching dimensions. In an effective converging process, however, the number of optimisation loops will diminish during the process of further specification.

Both principal and design team are in search of an overall perform-
ance/cost optimisation. In some cases, this performance/cost optimisation may even lead to a modification of the requirements.

The conformity between the as-built situation after completion of the construction and the requirements should be secured through conceptual design.

10.1.4 Fundamental structural design cycle

The objective is capturing structural design by breaking down this complex and unambiguous process to the essential absolute minimum, resulting in a fundamental design cycle as an effective characterisation of both the design process as a whole, and the individual design phases.

The major contribution of professional structural engineering to the over-
all life cycle of a structure is on the level of design activities as clarified in table 10.1 on page 116.

Each individual design activity starts with requirements as to what the (part of the) structure is supposed to do and ends with a specification for construction. Independent of the life cycle phase, complexity of design, and contractual commitments, structural engineering practice can be outlined by the fundamental structural design cycle as shown in figure 10.2.

**Figure 10.2: Fundamental structural design cycle**

**Creation of a system outline** The most directing functional requirements and contractual conditions are interpreted into an overall geometry, choice of materials, and approximate material dimensions. All influential interfaces with other disciplines are taken into account and overall performance/cost is optimised.
Optimisation of the structural action  Within the boundaries of the overall integral design, a more thorough analysis of the structural action leads to optimisation of this structural action and a further accuracy of the material dimensions. An overall structural system check and compliance with all functional requirements and contractual conditions is carried out.

Final dimensioning and specification  Final material and detail dimensioning is determined on the basis of code checks with respect to structural safety, serviceability, and durability. Specification for construction is prepared.

10.2  Level of accuracy

10.2.1  Level of specification

To meet a client’s demand, functional requirements will specify the starting point for the design process. Functional requirements, with function as a higher order, can lead to form and material. Functional requirements are decisive with respect to the quality of a durable structure, boundary conditions included, and therefore fixed.

The process from functional requirements to as-built can be divided into identifiable phases as shown in figure 10.3: conceptual design, basic design, detailed design, and construction.

Time schedule  The time schedule on the horizontal axis consists of the three major design phases and the subsequent construction phase. These major design phases - conceptual, basic, and detailed design - can be substituted by the fundamental structural design cycle-based phases “exploration & creation”, “selection & optimisation”, and “verification & specification”.
Level of reliable specification The corresponding achieved level of specification per individual design phase is strongly dependent on the time schedule. Particularly, in the conceptual design phase during exploration and creation most of the design is specified. This phase is decisive for both quality of design and a prosperous completion of subsequent phases.

For an effective decision supporting, the reliability of each design phase outcome requires a corresponding accuracy. A feasibility study of this accuracy per design phase is provided by the International Federation for Structural Concrete.

10.2.2 Fib Model Code 2010

The International Federation for Structural Concrete fib, “fédération internationale du béton”, is a pre-normative organisation. “Pre-normative” implies pioneering work in codification. This work has been realised in 2012 with the fib Model Code 2010 [13].
The fib Model Code 2010 includes the whole life cycle of a concrete structure, from design and construction to conservation and dismantlement, in one code for buildings, bridges, and other civil engineering structures.

In this code, subsection 3.5.3, “Quality Management in Design”, a serious study is reported on the feasible accuracy of individual design phases. These individual phases, compatible with the decision process employed by the owner, are listed in table 10.3.

<table>
<thead>
<tr>
<th>Fib Model Code 2010 design phases of a structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design phases</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Scouting</td>
</tr>
<tr>
<td>Basis of design</td>
</tr>
<tr>
<td>Project specification</td>
</tr>
<tr>
<td>Final design</td>
</tr>
<tr>
<td>Detailed design</td>
</tr>
</tbody>
</table>

Table 10.3: Fib design phases

**Scouting phase** The “Scouting Phase” is an initial feasibility scan of the scheme. From an abstract level of perception, global functional requirements are specified. In common practice, the design effort expenses will then be limited, because the feasibility of the project will usually
still be uncertain. At this stage, the target accuracy for the estimate of overall project costs might typically be ±30%.

**Basis of Design phase** During this phase, the functional requirements, basic data, and design criteria will be developed and the service criteria agreed upon. A conceptual design will also be developed to support a more accurate budget estimate. Quite some effort is required as the “Basis of Design” should be agreed upon, fixed and frozen upon completion. At this stage, the target accuracy for the estimate of overall project costs might typically be ±20%.

**Project Specification phase** With the “Basis of Design” as starting point, the design will be developed into a preliminary design. Alternative structural concepts will generally be developed and evaluated against each other. Specifications for workmanship, materials, and detailed design will then be developed. Significant effort is generally required. At this stage, the target accuracy for the estimate of overall project costs might typically be ±10%.

**Final Design phase** During this phase, all primary structural members will be specified and typical details will be designed. The structural analysis should consider the behaviour of the structure in relation to the envisaged dimensioning situations, taking into account the relevant factors that significantly influence the potential performance of the structure concerned. At this stage, the target accuracy for the estimate of overall project costs might typically be ±5%.

**Detailed Design phase** The output of this phase shall allow construction of the project. The level of detail of drawings and specifications and site instructions shall allow unambiguous understanding by the contractor of what is required and how the scheme must be executed, as well as how compliance with the documents must be demonstrated.
**Target accuracies costs** The target accuracies for the estimate of overall project costs, however, could also be applied to other factors such as environmental impact and the evaluation sustainability parameters.

10.2.3 **Accuracy fundamental structural design phases**

The fib Model Code 2010 study on the feasible accuracy of corresponding individual design phases can easily be transformed into the required accuracy of the individual major design phases and structural phases of the fundamental structural design cycle, as listed in table 10.4.

<table>
<thead>
<tr>
<th>Structural design phases and corresponding accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural phases</td>
</tr>
<tr>
<td>Creation of a system outline</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Optimisation of the structural action</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Final dimensioning and specification</td>
</tr>
</tbody>
</table>

Table 10.4: Level of accuracy
10.3 Fundamental design process

10.3.1 Structural design characteristics

Independent of life cycle phase, complexity of design, and contractual commitments, the structural engineering practice can be most effectively outlined by the structural design characteristics as listed in table 10.5, directly based upon the fundamental design cycle as shown in figure 10.2 on page 119.

<table>
<thead>
<tr>
<th>Professional structural engineering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural design characteristics</td>
</tr>
<tr>
<td><strong>Conceptual design: Creation of a system outline</strong></td>
</tr>
<tr>
<td>- Overall geometry</td>
</tr>
<tr>
<td>- Choice of materials</td>
</tr>
<tr>
<td>- Approximate section characteristics: ±20%</td>
</tr>
<tr>
<td>- Conceptual variant studies of performance-based solutions</td>
</tr>
<tr>
<td>- Main optimisation of the performance/cost ratio</td>
</tr>
<tr>
<td>- Open mind for ideas and innovative design</td>
</tr>
<tr>
<td><strong>Basic design: Optimisation of the structural action</strong></td>
</tr>
<tr>
<td>- Thorough analysis of the structural action</td>
</tr>
<tr>
<td>- Optimisation of the structural action</td>
</tr>
<tr>
<td>- Further dimensioning with an accuracy of ±5%</td>
</tr>
<tr>
<td>- Overall structural system check with the complete set of functional requirements and contractual conditions</td>
</tr>
<tr>
<td><strong>Detailed design: Final dimensioning and specification</strong></td>
</tr>
<tr>
<td>- Final section and detail dimensioning</td>
</tr>
<tr>
<td>- Check calculations structural safety ULS</td>
</tr>
<tr>
<td>- Check calculations serviceability SLS</td>
</tr>
<tr>
<td>- Check calculations durability DLS</td>
</tr>
<tr>
<td>- Specification for construction</td>
</tr>
<tr>
<td>- Monitoring decisive parameters</td>
</tr>
</tbody>
</table>

Table 10.5: Structural engineering characteristics
These structural design characteristics can be an effective guide for structuring structural engineering activities and a corresponding professional profile of structural engineering.

10.3.2 **Fundamental structural design process**

Within each of the major design phases of conceptual design, basic design, and detailed design, the fundamental structural design cycle as shown in figure 10.2 on page 119 is applicable. Consequently, the structural design process as shown in figure 10.1 on page 118, can be filled in as shown in figure 10.4.

In the process of increasing insight into the system’s functionality, each design phase is characterised by a change of both accuracy and character of the activities.

The corresponding increasing level of specification is reflected by the required accuracy of the material dimensioning from ±20%, via ±5%, to final specification for construction.
10.3 Fundamental design process

Conceptual design:
- Creation of a system outline
- Optimisation of the structural action
- Dimensioning ±20% and specification

Basic design:
- Creation of a system outline
- Optimisation of the structural action
- Dimensioning ±5% and specification

Detailed design:
- Creation of a system outline
- Optimisation of the structural action
- Final dimensioning and specification

Construction

Requirements & conditions

Figure 10.4: Fundamental structural design process
Chapter 11

Physical decomposition

11.1 Qualification of the structural form

11.1.1 Classification

A physical decomposition of a structure requires a methodical classification as a guidance for the partition of the system into subsystems.

There are numerous possibilities of classifying structural systems. The two most notable classification techniques are the following:

- Classification by physical appearance; in this case structural form.
- Classification by behaviour; in this case structural action.

The majority of applied classifications are directly based on the structural form with clear identifiable structural elements as beams, columns, floors, walls, arches, and trusses.

Oskar Büttner und Erhard Hampe performed an extensive study and reported it in the corresponding publication “Bauwerk, Tragwerk, Tragstruktur, Band 2: Klassifizierung, Tragqualität, Bauwerkbeispiele” [5] of a structural action-based classification.
In this classification, specifically the bending flexibility of linear and plane structural elements is distinguished. These elements are then assembled into one-dimensional linear elements, and two-dimensional and three-dimensional structural systems. De facto it is a distinction between tensile structures and all other structures dominated by bending.

11.1.2 Form follows function

The starting point of the design process is the function expressed by a set of functional requirements. In order to successfully conceive and plan a structure it is necessary to investigate and well know its reason for existence, and its major and minor loads to resist and to bear. The function, however, is not a static specification but can vary during the life cycle of a structure.

**Eduardo Torroja** Stated in his book “Philosophy of Structures” [51]: “The primary functions of all structure can be summarised as follows: To enclose a certain space and to protect it from the natural elements of wind, rain, and snow, from changes in temperature, and from noise. This function is achieved by the use of walls and roofs. To provide passageways for the movement of persons and vehicles; floors, staircases, and ramps of buildings, and bridges and viaducts are used for these functions. To resist the lateral thrust of earth, water, or other fluids; included in this category are dams, dikes, reservoirs, storage tanks, silos, and retaining walls.”

**Eladio Dieste** Stated in his book “La Estructura Cerámica” [11]: “The resistant virtues of the structures that we seek depend on their form; it is through their form that they are stable, not because of awkward accumulation of material. There is nothing more noble and elegant from an intellectual viewpoint than this: to resist through form.”
11.1.3 Interfaces with the built environment

The main interfaces with the built environment, which are decisive with respect to influencing the feasibility in general and the overall performance/cost ratio in particular, are: reliability, architectural demand, air conditioning system, constructability (practical feasibility), and relative life cycle costs.

To secure a clear recognisable interface between conceptual structural design and the mainly form-oriented other conceptual design disciplines of the built environment, a structural form-based, rather than structural action-based classification is preferable.

Furthermore, a structural action-based classification can vary completely on different levels. For example, the global load distribution of a truss consists of bending moments and shear forces. The corresponding local load distribution within the truss consists completely of axial compression and tension forces in the individual members of the truss.

11.2 Decomposition of the structural form

11.2.1 System decomposition

Physical decomposition follows the physical parts of a system. Often, it is a very natural way of decomposition, because we easily “see” all the physical parts. Also, the completeness criterion above is easy to check; when we have all physical parts, we have the whole system.

The whole structure is a three-dimensional system such as a frame building, multi-storey building, barrier, bridge, and tunnel.

The three-dimensional system can be disassembled in two-dimensional (plane) subsystems such as a frame, floor slab, cable-stayed beam, truss, arch, and shear wall.
The two-dimensional subsystems can subsequently be assembled in one-dimensional (linear) elements such as a compression and tension bar, a bending beam, and a (shear) corbel.

The system “Arch bridge” as shown in figure 11.1 for example, can be seen as an assembly of the subsystems frame, truss, arch, and orthotropic deck.

A two-dimensional subsystem is an assembly of directly connected structural elements, designed to act together to resist loads.
11.2 Decomposition of the structural form

11.2.2 Structural form on subsystem level

Characterisation of a problem is part of the solution. But characterisation of a bridge, barrier or building as a whole is nearly impossible due to the variety and complexity of possible structural forms. Characterisation of individual forms with regard to the capacity to bear and resist, and with regard to the interfaces with the built environment, appears feasible. It is plausible that on this subsystem level, as shown in figure 11.2, enough insight and oversight can be gathered to produce performance-based solutions.

![Figure 11.2: Subsystem level](image)

11.2.3 Basic structural forms

On subsystem level the following basic structural forms can be distinguished as shown in figure 11.3: frame, floor slab, cable-stayed beam, truss, arch, and shear wall.

**Global and local load distribution** On the basis of uniformly distributed loads the global load distribution of all basic structural forms consists of bending moments and shear forces. Dependent on the individual basic form this global load distribution is internally transferred...
differently into a local load distribution.

Each individual basic structural form is characterised by its corresponding local load distribution. This characteristic local distribution of the loads is described in the following paragraphs, whereby members subjected to axial compression or tension, are relatively stronger and generally more economical than those designed for pure bending.

**Frame**  Frames consist of bending beams and supporting columns. The local load distribution of a beam consisting of one element equals the global load distribution and is therefore subjected to bending and shear. The supporting columns are subjected to compression. The load distribution in a frame is worked out in subsection 16.2.1.

**Floor slab**  The local load distribution of a floor slab equals the global load distribution and is therefore subjected to bending and shear. A
two-way spanning floor slab, whether concrete slab or orthotropic steel
deck, is subjected to bending and shear in both spanning directions. The
load distribution in a floor slab is worked out in subsection 16.2.2.

**Cable-stayed beam**  A supporting cable diminishes the supported
length and corresponding local load distribution of beams; by each half,
strength - the effect of section modulus $W$ - is quadrupled and stiffness
- the effect of moment of inertia $I$ - is eight-fold.

The effectiveness of the local load distribution in a cable-stayed, stat-
ically indeterminate continuous beam is dependent on the stiffness of
the cable. The cross-sectional area of the cable is therefore governed by
both tension strength and supporting stiffness. The load distribution in
a cable-stayed beam is worked out in subsection 16.2.3.

**Truss**  Every member of the truss is in pure compression or pure ten-
sion. Shear, bending moments, and other more complex stresses are all
practically zero. This makes trusses physically stronger and stiffer than
other ways of arranging material. Some or all of the joints may be fixed
rather than pinned but the main contribution to the strength and stiff-
ness is provided by the triangulation. The load distribution in a truss is
worked out in subsection 16.2.4.

**Arch**  The form is more or less parabolic and usually, the horizontal
reaction forces are resisted by a tension rod. Uniformly loaded, the entire
arch is in compression and has little bending moments and shear. This
makes arches relatively stronger than other ways of arranging material,
resulting in smaller cross-sectional dimensions. However, an arch requires
a more than average amount of structural space.

So-called “false” arches, when bending is dominant over compression, are
unfavourable: they are circular instead of parabolic arches and/or have
highly-concentrated loads, instead of more or less uniform loads. The
load distribution in an arch is worked out in subsection 16.2.5.
Shear wall  The most common application of shear walls is securing the global stability of a system. For non-sway buildings, these can be in the form of concrete shear walls or steel wind bracing. The load distribution of a stocky shear wall consists of dominant shear in combination with minor bending. The load distribution in a shear wall is worked out in subsection 16.2.6.
Chapter 12

Cyclic process control

12.1 Exploration of the solubility space

12.1.1 Creation-process requirements

During the creation process, the structural engineer is creating a materialised form out of the functional requirements and taking into account the fundamental related interfaces with the built environment.

Key words in the search for a structural form are “insight”, “overview”, and “breeding ground”.

Insight  Insight into each individual aspect of the design process such as reliability, structural form, load distribution, choice of material, failure mechanisms, dimensioning, architectural demand, constructability, and costs.

Overview  Overview of the interrelations of the aspects, such as:
• Reliability versus form, load distribution, material, failure mechanisms, and dimensions.
• Architectural demand versus form, material, and dimensions.
• Constructability versus form, material, and dimensions.
• Costs versus reliability, architectural demand, and constructability.

Breeding ground The way of presenting and visualising the individual aspects and their interrelations can serve as a fertile breeding ground for design solutions. All data do not necessarily have to be quantified to fulfil their function. Therefore, hardly quantifiable phenomena such as intuition, imagination, common sense, and personal attitude can be implemented in the creation process.

12.1.2 Design strategies

Four typical design strategies with increasing complexity can be distinguished as shown in figure 12.1:

**Linearity** The simplest design strategy describes designing as an unambiguous one-way movement among the design activities. This strategy is only working for the design of extremely simple structures.

**Cyclic** For most of the design problems, a cyclic design process is inevitable. Every time the designed structure turns out to be insufficient a new cycle is appropriate.

**Cyclic Convergent** In a converging process, the number of loops will diminish during the process of further specification by making goal-oriented design choices. Convergence, however, does not automatically mean optimisation.

**Cyclic Optimum** Optimisation of both quality of design outcome and number of design cycles is dependent on how strong the initial idea
is and the improvements one chooses to make. For the most successful possible outcome, corresponding fundamental design choices have to be searched for.

Figure 12.1: Design strategies

12.2 Linear design

12.2.1 Linear process

Each individual design activity starts with requirements as to what the structure or part of the structure is supposed to do and ends with a specification for construction. Independent of life cycle phase, complexity of design, and contractual commitments, structural engineering practice can be outlined by the fundamental structural design cycle as shown in figure 10.2 on page 119.

Linear design describes designing as an unambiguous one-way movement among these design phases as shown in figure 12.2. This strategy is only working for the design of extremely simple structures.

Figure 12.2: Linear structural design
12.2.2 Specification of the structural form

Essentially, the design process of a structure is a process of composing the structural form. For an effective control of this composition process both the level of specification and the level of composition have to be considered.

The integral composition process of a conceptual draft of the system outline will inevitably lead to a process of decomposing the structure in controllable basic structural forms, mostly on a two-dimensional subsystem level.

The immense number of individual parameters and mutual interactions cannot be unambiguously controlled and will inevitably lead to a cyclic process.

12.3 Cyclic design

12.3.1 Cyclic process

In order to have a successful solution to a complex structural design problem a cyclic design process is inevitable. Every cycle goes through the phases of creation, optimisation, and specification. Then, the concept is reviewed with respect to the functional requirements in particular, and a performance/cost optimisation over the life cycle in general.

When the reviewed concept turns out to be insufficient, a new cycle is appropriate. In the process of materialisation from requirements to construction, on-going design and check activities can influence foregoing activities with regard to choice of geometry, material, and matching dimensions.

The number of cycles depends on how strong the initial idea is, and on the improvements one chooses to make; intelligent improvements will reduce the number of times that one has to go through the cyclic design process.
The cyclic design process evolves over time in order to produce the most successful possible outcome but at least a performance-based solution. In an effective converging process, the number of optimisation loops will diminish during the process of further specification.

An example of this cyclic design process is when the famous Thomas Edison, who designed more than ten thousand prototypes of the light bulb until he was satisfied and knew it worked, said: “I have not failed 10,000 times, I have successfully found 10,000 ways that will not work” [56].

12.3.2 Fundamental structural design path

The structural design process can fundamentally be characterised by two simultaneous processes:

**Specification** The process of specification of the structural form from approximate to accurate.

**Composition** The process of composition or rather decomposition of the structural form from system to element.

These two processes can be visualised together in a two-dimensional matrix as shown in figure 12.3. Within this matrix, the cyclic structural design can be explored.

**Level of specification** On the horizontal axis, the phases of specification are arranged from creation of the system outline, via optimisation of the structural action, to dimensioning and specification.

**Level of decomposition** On the vertical axis, the phases of decomposition of the structural form are arranged from three-dimensional system, via two-dimensional subsystem, to one-dimensional element.
Figure 12.3: Fundamental structural design path

**Design path**  Complex structures can effectively be analysed “from system to element” and “from approximate to accurate”. The corresponding design path is directed by the effectiveness of this combination of breadth and depth. For an effective converging process, this combination has to be well balanced.

The design path follows the fundamental dimensioning routine from structural integrity, via load distribution, to failure mechanisms:
• Structural integrity; three-dimensional system design and decomposition in subsystems.

• Load distribution; distribution of the actions within the subsystem on element level.

• Failure mechanisms; distributed actions can be resisted by materialising the elements.

Outside the boundaries of this design path, ineffectiveness such as inaccurate modelling or even uncontrollable complexity can be found.

**Inaccurate modelling**  The integral creation of a system outline requires a three-dimensional modelling. Due to the huge degree of freedom and the complexity of interfaces with other disciplines, this three-dimensional modelling and corresponding dimensioning is only approximating and without great detail.

For a more refined dimensioning, load distribution and capacity calculations on element level are appropriate. The required data for an accurate calculation on element level are not available in such an early conceptual design stage.

Therefore, a creation of a system outline on element level inevitably leads to inaccurate and thus unusable modelling.

**Uncontrollable complexity**  The specification of the design is determined on element level in order to get the required detailed depth and accuracy. Solely on system level, it is not achievable to control the multitude of information and interrelations from creation, via optimisation, to specification.

So inevitably, designing the structure on system level only results in uncontrollable complexity of the dimensioning and specification.
12.3.3 Structural design path

Out of the functional requirements, a system is created and the performance/cost ratio is optimised, taking the interfaces with the built environment into account. Then, specifications for construction are prepared. This process can be divided into three major design phases with increasing accuracy: conceptual design, basic design, and detailed design, as shown in figure 10.4 on page 127.

The fundamental structural design path as shown in figure 12.3 on page 142 is applicable for all these three design phases. Furthermore, this fundamental path is also applicable for the structural design process as a whole - from creation to specification - as shown in figure 12.4.

In this case, the standard level of decomposition is combined with a level of specification over the major structural design phases of conceptual, basic, and detailed design:

**Conceptual design** Creation of a system outline with the help of truss analogy.

**Basic design** Optimisation of the structural action with the help of a Finite Element Method (FEM) analysis.

**Detailed design** Dimensioning with the help of code checking, followed by a specification for construction.

These include the ineffectiveness that can be found outside the boundaries of the design path, as mentioned before, in the form of inaccurate modelling or uncontrollable complexity.

12.4 Cyclic convergent design

12.4.1 Volume of complexity

The number of interdependent parameters that can be simultaneously controlled is limited and subject to the complexity of the individual
parameters, the complexity of the interdependency between the parameters, and the level of abstraction of both parameters and interdependency.

The limitation of the complexity of either the individual parameters, or the interdependency between the parameters, has a similarity with communicating vessels. On the one hand, the control of processes with complex interdependencies will unavoidably lead to a limitation of the
quantity and/or complexity of the individual parameters. On the other hand, control of processes with large quantities and/or complex parameters, will unavoidably lead to a limitation of the complexity of the interdependency between the parameters.

Due to the limited volume of complexity per design phase, the integral design process with complex interdependencies inevitably has to be separated from the individual architectural, structural, and construction design processes with complex parameters as shown in figure 12.5.

Figure 12.5: Limited volume of complexity per design phase
12.4 Cyclic convergent design

12.4.2 Three steps in conceptual design

In order to control the conceptual design phase, we can consider three steps:

**Definition step**  Defining the design problem.

**Creation step**  Structural engineering-based creation; diverging into a rough overview of possible solutions.

**Selection step**  Value engineering-based selection; a more refined checking of the boundary conditions, converging into a solution.

12.4.3 Definition step

Common practice during conceptual design is formulating a quick definition of the problem in order to save time for a heated search for performance-based solutions.

Albert Einstein is quoted as having said that if he had one hour to save the world he would spend fifty-five minutes defining the problem and then five minutes solving it [7].

Einstein’s wisdom with regard to the problem-solving process is directly applicable to the conceptual structural design process. Thoroughly formulating the definition of the design problem during the problem definition phase is a time-consuming but crucial effort before starting the search for performance-based solutions.

Besides an effective partition of available time, it is a misconception that extending the duration of the search would lead to a better solution. It is far more effective to optimise available time, than stretching it.

The conceptual design team has to evaluate the complete set of functional requirements and contractual conditions, in order to determine a workable reduced set of fundamental requirements and conditions: presumably dominant, required performances and aspects - including interfaces with the adjacent built environment and prerequisite constraints.
The so-determined set of fundamental functional requirements will then be the starting point of the creation of concepts by the conceptual integral design team.

Effective functional requirements should be defined on an as-high-as-possible level of abstraction in order to serve as a starting point for creative freedom, rather than stifling restriction.

Furthermore, on such a high abstraction level, market tendencies and other undesirable influences are neutralised.

12.4.4 Creation step

First of all, it is important to create concepts that are likely to meet the performance requirements. It is hard enough to create a materialised form out of the functional requirements, and to take the fundamental related interfaces as reliability, architectural demand, constructability, and costs, into account.

To be secured of at least one performance-based solution at the end of the conceptual design process, it is advisable to create numerous concepts and develop them to a lower degree of complexity for a considered selection. Dependent on the complexity one has to cope with during the selection phase, the number of initial concepts can be reduced.

12.4.5 Selection step

The goal is convergence by optimising the cost-drivers such as the complexity of execution - shape, repetition and planning, maintenance, and possibilities regarding future extension capability.

Striving for an optimisation of the performance/cost ratio will lead to a performance-based cost minimisation. Sometimes, supplementary added-value solutions offer a considerable added value for a relatively small cost increase. Then, a real performance/cost optimisation - despite the earlier established requirements - will be executed.
12.5 Cyclic optimum design

Design cycles encompass complete updates of design. Within a design cycle, individual design loops can be distinguished representing particular design actions. Independent of life cycle phase, complexity of design, and contractual commitments, fundamental design loops can be identified as shown in figure 12.6.
In principal, design loops can occur at any level of specification, at any level of decomposition, in any direction, and with any range. Usually, in design practice however, most frequently occurring design loops can be identified:

**Modelling loops** Vertical calculation-based loops with regard to structural safety and serviceability.

**Typical design loops** Diagonal creation-based loops with regard to a controlled build-up of the structural system.

### 12.5.1 Modelling loops

Modelling loops are the backbone of structural design. Within each specification phase from creation to specification, the complexity of reality has to be modelled with the help of calculation models with regard to structural safety and serviceability of the structure, or a specific part of the structure.

Although the point of attention differs per specification phase, for research on the structural integrity, the whole system or a specific part of the system is involved, covering all the levels of decomposition from system to element.

Such modelling loops are vertically orientated in the fundamental structural design loops as shown in figure 12.6 on page 149.

Refinement requires an analysis loop, whereas keeping the integrity of the whole system in mind requires check loops.

**Analysis loop** Going to a higher level of decomposition, complexity increases and further analysis is necessary to get a grip on the more detailed structural action.

**Check loop** With increasing level of decomposition and corresponding further analysis, checking the calculation model on a lower level of
decomposition - preferably the whole system - is necessary in order to secure the integrity of the structure.

### 12.5.2 Typical design loops

Typical design loops are directing the design process. Within each specification phase from creation to specification, requirements-based design choices are made. Although the point of attention differs per specification phase, each design choice has to be valued and made ready for further refinement.

These design loops are diagonally orientated in the fundamental structural design loops as shown in figure 12.6 on page 149. On-going, more detailed specification requires an orientation loop, whereas diagnosed inaccuracies require correction loops.

**Orientation loop**  Going to a higher level of specification in combination with a higher level of decomposition, complexity increases and research is necessary in order to orientate on possible further design refinements.

**Correction loop**  With on-going detailing, insight into the structural action increases. With this increasing insight, foregoing structural design approximations and decisions can turn out to be insufficient or even incorrect. Such diagnosed inaccuracies require correction.

### 12.5.3 Optimal design cycle

The cyclic character of the conceptual structural design process is a continuous process of zooming in and zooming out with (diagonal) design loops, thus constantly changing both the level of decomposition and the level of specification.
In between, the dimensioning with the help of calculation models is a process of zooming in and zooming out with (vertical) modelling loops, changing only the level of decomposition. This process from creation to dimensioning is shown in figure 12.7.

![Figure 12.7: Structural design loops](image)

The clearly directed fundamental design loops result in small-scaled and thus shorter, more clarifying individual design cycles. Furthermore, these small-scaled clarifying cycles potentially lead to a reduction of the total
amount of cycles.

It should be noted that an effective optimal design cycle is a process of reduction rather than exclusion and limitation. This process of reduction, however, is completely dependent on known and explicitly unknown parameters. In the case of implicitly unknown parameters, there is automatically an unwanted exclusion and consequently uncontrollable risk with corresponding uncertainties in cost estimation.

12.5.4 Risk analysis

The specification of a conceptual design demarcates the concerning project phase. Dependent on the contractual arrangement, this specification can be used as internal transfer documentation or for tenders. In both cases, a risk analysis is essential.

A risk analysis of the material demand gives an accuracy estimate of the material quantities and corresponding unit cost indications. The risk analysis has to be executed on the level of individual components of a decomposed system, principal details included.

For an effective risk analysis the following, preferably quantified data have to be determined:

**Performed structural analysis** Depth and breadth of the structural analysis are dependent on the complexity of the structural action and the available time schedule, financing, and resources of the conceptual structural design phase.

**Dimensioning** The result of the performed structural analysis is an approximate section-dimensioning of the materialised overall geometry. This dimensioning of the conceptual design is specified by a list of material quantities.

**Cost weighting** The cost weighting equals the material quantities times the unit cost indications, and is a measure for cost optimisation opportunities and corresponding risk.
**Uncertainties**  The difference between the performed approximate structural analysis for conceptual design and the required depth and breath to meet the in-use requirements for structural safety and serviceability, can be defined as uncertainties of the conceptual design. The difference in depth and breath generally concerns load combinations, load distribution, and failure mechanisms.

**Coverage by conceptual dimensioning**  The uncertainties of the performed approximate structural analysis with respect to the required depth and breath can be partially, or even not at all, covered. The corresponding status of the coverage gives an indication of the risk influence of uncertainties on conceptual design.

**Reserves**  Reserves can be intentionally incorporated or are the result of rounding-up to the nearest standardised product dimensions. Occasionally, an optimisation of requirements during the conceptual design phase can result in a reserve.

**Optimisations**  Foreseen but time-consuming cost optimisations can be postponed to basic design but registered as a potential reserve with regard to the completed conceptual design.
Part III

Understanding structural performance
Chapter 13

Introduction to part III

The methodical approach on conceptual structural design consists of a process control component and an underlying, structural performance component. The process control component has been discussed in the previous Part II, “The art of conceptual structural design”. The underlying, structural performance component is discussed in this Part III, “Understanding structural performance”.

Although the individual, conceptual structural design parameters are fully applied mechanics-based, it is choice, combination, and balanced depth of these parameters that define their professional applicability. It is thereto that this part derives its reason for existence within this academic research thesis.

Part III starts with a qualification of structural performance.

The fundamental structural design path, as shown in figure 12.3 on page 142, gives the basic arrangement of the required conceptual structural design parameters “3-D structural integrity”, “2-D load distribution”, and “1-D failure mechanisms”. The quantification of these design parameters as described in part III is subdivided into the individual parameters as shown on the diagonal in figure 13.1.
Figure 13.1: Reading guide for part III

**Structural performance**  Structural performance is a collective term for structural safety, serviceability, and durability. As a major part of structural performance, structural action with regard to load distribution, corresponding deformation, and strength is researched.

For an effective and efficient conceptual structural design, approximations and especially deformation-driven parameters have to be determined. The choice and combination of these parameters, however, define their professional applicability.
**Structural integrity**  In the course of the conceptual design, and particularly in the first design loops, the insight into the structural action has to be built up step by step. Due to the huge degree of freedom and the complexity of interfaces with other disciplines, conceptual structural designing requires simple and clear, three-dimensional modelling.

This is possible on the level of axial forces, directly or with a truss analogy for modelling bending action and more complex forms.

**Load distribution**  The load distribution on the system through the subsystems into the elements, can best be determined on subsystem level with design approximations of the load distribution in two-dimensional, basic structural forms.

For the basic structural forms, the design parameters concerning load distribution and deformation are determined and guides are given for the design of parallel load distribution with regard to optimisation, redundancy, and induced deformation.

**Failure mechanisms**  With the determined forces in the individual one-dimensional elements, the required dimensions of these elements can be determined by means of design approximations of the load-carrying capacity with regard to the ultimate limit state.

With the determined deformations, the required dimensions of these elements can be determined by means of design approximations of the deformation with regard to the serviceability limit state.

For the elements of basic structural forms, the design parameters concerning material properties, sectional strength, stability, and deformation are determined.

**Solution components**  The so obtained coherent set of solution components for structural performance, and corresponding chapter arrangement, is listed in table 13.1.
<table>
<thead>
<tr>
<th>No.</th>
<th>Chapter</th>
<th>Solution component</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>Structural integrity</td>
<td>- Load path design</td>
</tr>
<tr>
<td>16</td>
<td>Load distribution</td>
<td>- Load distribution parameters</td>
</tr>
<tr>
<td>17</td>
<td>Failure mechanisms</td>
<td>- Dimensioning parameters</td>
</tr>
</tbody>
</table>

Table 13.1: Solution components for structural performance
Chapter 14

Structural performance

14.1 Legitimation

14.1.1 Applied mechanics in an academic research thesis

Understanding structural performance is nearly impossible without a thorough conception and application of basic applied mechanics. Hence, there is a strong urge for an actual implementation of applied mechanics in order to achieve a methodical approach on conceptual structural design.

Although based upon standard textbook material, applied mechanics have to be transformed and rearranged into a new application as a balanced set of conceptual structural design parameters. For this, more or less autonomous scientific fields such as mechanics, materials, and design have to be interconnected.

Therefore, it is legitimate and essential to incorporate the applied mechanics-based conceptual design parameters in this academic research thesis.
14.1.2 Conceptual structural design practice

Structural design and especially conceptual structural design is highly dependent on an effective merge of the three concerning fields of knowledge, namely “applied mechanics”, “material applications”, and “conceptual structural design practice”. However, every field has its own particular routine and areas of interest.

Applied mechanics  Applied mechanics bridges the gap between physical theory and its application to technology in general, and building technology in particular. Much of modern engineering mechanics is based on Newton’s laws, while the modern practice of their application can be traced back to Timoshenko.

Within the theoretical sciences, applied mechanics is primarily occupied with formulating new theoretical applications and developing computational tools such as the finite element method.

Material applications  Present-day applications of structural building materials include concrete, steel, timber, masonry, and aluminium. Improvements on these materials vary from high strength materials to new reinforcement materials for concrete. New technologies generate upcoming structural materials such as carbon fibre composites and structural adhesive connections.

Discovery and testing of new materials demand a thorough and conscientious research in compliance with strict scientific principles and methodologies. Final goal is standardisation through design codes of practice.

Conceptual structural design practice  Structural engineers must ensure their designs satisfy given design criteria with respect to structural safety, serviceability, and performance.
Especially conceptual structural design is for the greater part a decision-making process with a large number of design variables and demands to comply with. There is a strong resemblance with playing chess on multiple boards or even three-dimensional chess on interrelated, multiple boards.

### 14.1.3 Balanced set of conceptual design parameters

To get and stay in control of the numerous design variables requires a set of applied mechanics-based conceptual structural design parameters that are effectively customised, arranged and restricted:

**Customised** Applied mechanics for approximated design parameters secure the necessary insight but can sometimes lack the required accuracy. Then, supplemental professional practice factors based on more refined design codes of practice or professional experience, improve the approximation accuracy to an acceptable level.

**Arranged** Specifically, structural performance parameters serve both as conceptual structural design parameters and as a knowledge base with a controlled build-up of insight into governing force and above all deformation-driven structural action.

**Restricted** The set of parameters has to be well balanced with respect to depth, breadth and quantity. Therefore, the set has to be restricted to a manageable quantity with just enough depth and breadth to fulfil the basic needs for reliable conceptual design approximations.

### 14.1.4 Professional practice factors

Supplemental professional practice factors for improvement of approximation accuracy to the required level for conceptual structural design are mostly based on design codes of practice or elaborate professional experience.
When based on design codes of practice, verification of qualification and corresponding quantification is directly reducible from and conformable to the concerning code of practice.

When based on professional experience, however, explicit scientific verification has not taken place. When available, a reference is included in the bibliography.

14.2 Present-day structural performance

14.2.1 Structural requirements

Structural performance is a collective term for the following structural requirements as defined in subsection 4.1.4:

**Structural safety** The safety of a structure or structural member is prescribed with its Ultimate Limit State (ULS).

**Serviceability** The functionality of a structure or structural member is prescribed with its Serviceability Limit State (SLS).

**Durability** The durability of a structure or structural member is prescribed with its Durability Limit State (DLS).

These specifically in the structural design codes of practice prescribed structural requirements ULS, SLS, and DLS, are part of a more overall sustainability objective to minimise the negative environmental impact.

14.2.2 Modern developments

The three structural requirements, structural safety, serviceability, and durability, combined with corresponding directions of development are shown in figure 14.1.

With structural safety being a self-evident prerequisite, serviceability is an upcoming contractual requirement with regard to controlled func-
ational behaviour of the structure. Due to the absence of an additional safety factor for serviceability, the outcome of measurement results typically is sensitive to downward crossing.

Particularly, the recent addition of a durability limit state to the ultimate and serviceability limit states, is initiated through performance-based building design as a logical step towards an integral performance/cost optimisation of the built environment of the entire life cycle. As a result, durability is extending to sustainability by minimising negative environmental impact, and further to the Triple Bottom Line (TBL) accounting framework with a social, environmental, and financial partition.

Due to the amount of structural failures, however, society is shifting its focus back towards structural safety.

14.3 Force and deformation-driven parameters

14.3.1 Equilibrium and strength

For an effective and efficient determination of the capacity to bear and resist, a fundamental insight into structural behaviour is necessary. The four subjects to be considered profoundly are equilibrium, strength, deformation, and parallel load distribution.
Further qualification and coherence of these four subjects as shown in figure 14.2 will be clarified subsequently.

Figure 14.2: Force and deformation-driven parameters
Equilibrium  Equilibrium is the first, most obvious aspect and an absolute necessity for each building and all civil work; otherwise the structure or parts of the structure will translate, rotate, or just tumble down.

Strength  Strength is the second most obvious aspect and also an absolute necessity; without enough strength the functional requirements with respect to the ultimate limit state, and particularly the structural safety, can never be met.

The two failure mechanisms concerning the strength are sectional strength and stability. Sectional strength is force-driven, whereas the stability of the equilibrium - from element up to system level - is deformation-driven.

This deformation-driven stability is subject to many parameters such as length, cross-sectional bending stiffness, boundary conditions, deformation due to fabrication, residual stresses, and material faults. Therefore, the stability analysis is often merely based upon iterative blind code checking, without availing the opportunity of essence-based deformation-driven designing.

The necessity of both equilibrium and strength is described thoroughly in built environment related legislation by structural safety regulations.

14.3.2 Deformation-driven parameters

One of the main pitfalls in conceptual designing, however, is focusing mainly on the combined equilibrium and strength, just because it is an obvious necessity.

As for stability, deformation-driven parameters in structural designing are somewhat underexposed in higher education as well as in common, modern structural engineering practices.
Especially the conceptual designer needs to comprehend the deformation-driven parameters as shown in figure 14.2 on page 166, in addition to the standard engineering basics such as applied mechanics, design codes, and related background documents.

**Deformation** In case of functional requirements with regard to the serviceability limit state, displacements of parts of the structure and the structure as a whole have to be met.

**Parallel load distribution** Foregoing strength and deformation parameters have to meet the requirements concerning structural safety in the ultimate limit state, and displacements in the serviceability limit state. The extent of compliance with these requirements determines the effectiveness of the design.

Nowadays, a lot of structures are statically indeterminate out of economical efficiency and redundancy considerations. Corresponding parallel load distribution in the ultimate limit state is largely determined by deformation parameters.

**Statiscal indeterminacy** The structural system is statically indeterminate when the static equilibrium equations are not sufficient for determining the internal forces and reactions on the structure. A difference in deformation will influence the load distribution. Consequently, the behaviour can be deformation-driven, besides force-driven.

The distribution of the load in detailed design will be on the level of stress and strain. Due to a high degree of parallel behaviour - statistical indeterminacy - the stress distribution is proportional to the stiffness distribution, which is inversely proportional to the strains.

**Optimisation of the performance/cost ratio** The optimisation of the stiffness distribution is a main factor in the optimisation of the performance/cost ratio. Focusing mainly on the strength will produce a safe
14.3 Force and deformation-driven parameters 

Design but not automatically an economical efficient one. Therefore, it
is of great importance that the structural designer, besides perform-
ance and construction demand, focuses on deformation in addition to
strength.

14.3.3 Determination of deformation-driven parameters

The relative small group of conceptual structural design practitioners
does not have the time to analyse its mainly intuition-based designing in
order to make its knowledge accessible for both professionals and higher
education programmes.

Scientific education is compartmented to such an extent that the in-
terface between applied mechanics and material applications is under-
developed. The interfaces between the structural engineering and archi-
tectural demand, constructability and life cycle engineering are even less
visible.

The practice of conceptual structural design with regard to deformation-
driven parameters, is not covered by most of the higher education pro-
grammes, as listed in table 14.1.

<table>
<thead>
<tr>
<th>Misfit of structural design parameters in education</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural design parameters: Force-driven</td>
</tr>
<tr>
<td>Field of practice</td>
</tr>
<tr>
<td>Higher education programmes</td>
</tr>
</tbody>
</table>

Table 14.1: Misfit of design parameters in education

Therefore, a missing set of deformation-driven design parameters has
to be determined as a basis for conceptual structural design in higher
education programmes.
14.4 Approximate dimensioning

14.4.1 Conceptual structural design approximations

It is of the utmost importance that design assumptions during conceptual structural design are based on insight into the behaviour of the structure to assure structural safety and to facilitate design optimisation.

Effective conceptual structural design approximations should address, and give insight into all influential structural parameters namely material properties, geometry, support conditions, and loading.

**Ineffective approximations**  So-called “rules of thumb” when solely based on geometric properties and therefore load indifferent, do not address all influential structural parameters, have a low accuracy and are almost never provided with a clear and comprehensive insight into the application boundaries.

High-end black box application programs, on the other hand, address all structural parameters and have a high accuracy but do not give a direct insight into the behaviour of the structure.

**Modified applied mechanics-based approximations**  Applied mechanics-based approximations give a calculated insight into load distribution and likely decisive failure mechanisms. Furthermore, it facilitates an overview of the optimisation possibilities of the structural design.

For realistic approximations of complex material behaviour, applied mechanics approximations can be modified with identifiable empirical data.

On the level of integral conceptual design, geometrical parameters should be related to outer dimensions.
14.4 Approximate dimensioning

14.4.2 Conceptual structural design parameters

Although applied mechanics are textbook material-based, defining an adequate set of conceptual structural design parameters is appropriate within this research thesis.

This set of conceptual structural design parameters has to fulfil the following requirements:

- Be applied mechanics-based to assure structural insight.
- Have clear and unambiguous applicability.
- Have performance-based approximation depth for conceptual design.
- Be balanced with respect to deformation-driven parameters.
- Have manageable limited overall size.

The fundamental structural design path, as shown in figure 12.3 on page 142, gives the basic arrangement of the required conceptual structural design parameters:

- Load path design on a three-dimensional system level.
- Load distribution on a two-dimensional subsystem level.
- Failure mechanisms on a one-dimensional element level.

This basic arrangement can be extended into an effective set of applied mechanics-based conceptual structural design parameters as listed in table 14.2.

14.4.3 Dimensioning routine

In conformity with the fundamental structural design cycle as shown in figure 10.2 on page 119, the dimensioning routine of the conceptual structural design can be constructed as shown in figure 14.3.
### Conceptual structural design parameters

<table>
<thead>
<tr>
<th>Structural integrity</th>
<th>Load distribution</th>
<th>Failure mechanisms</th>
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<tbody>
<tr>
<td>3-D system level</td>
<td>2-D subsystem level</td>
<td>1-D element level</td>
</tr>
<tr>
<td>System design on load path level and decomposition in subsystems</td>
<td>Distribution of the prime actions within the subsystem on element level</td>
<td>Distributed actions can be resisted by materialising and dimensioning</td>
</tr>
</tbody>
</table>

### Basic applied mechanics based

<table>
<thead>
<tr>
<th>System design:</th>
<th>Distribution:</th>
<th>Capacity:</th>
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<tbody>
<tr>
<td>- Rigidity</td>
<td>- Basic structural forms</td>
<td>- Material strength and stiffness</td>
</tr>
<tr>
<td>- System effects</td>
<td>- Parallel load distribution</td>
<td>- Sectional strength and stiffness</td>
</tr>
<tr>
<td>- Principal details</td>
<td>- Induced deformation</td>
<td>- Stability</td>
</tr>
</tbody>
</table>

Table 14.2: Conceptual structural design parameters
Figure 14.3: Dimensioning routine of the conceptual structural design
Chapter 15

Structural integrity

15.1 Conceptual design on system level

15.1.1 Creation phase of the conceptual design

The creation phase of a system outline starts with requirements and conditions of what the system is supposed to do and ends with one or more materialised structural schemes as shown in figure 14.3 on page 173.

15.1.2 Structural integrity

Structural integrity is the term used for the performance characteristics of a structure with regard to the ability to support designed loads and the redundancy capacity of the whole system.

In an integral conceptual design process, the performance/cost-ratio of the life cycle has to be optimised. Every structure will have its own process of creation, influenced by its bearing capacity and resistance, its economy, its construction site, and last but not least a more or less pronounced aesthetic concept and appearance.
Its structural integrity, however, will always be an undoubted demand and has to be unambiguously secured by a clear, three-dimensional basic structural concept.

The vertical imposed loads, the self-weight of the structure and natural impacts such as snow loads have to be borne. In addition to these vertical loads, other equally essential horizontal loadings must be taken into account due to wind actions and global initial sway imperfections.

On system level, the static resistance and equilibrium during the life cycle of the structure have to be secured. Particularly, the design of additional stabilising elements to resist the horizontal loads requires attention and insight on a three-dimensional system level.

Furthermore, the redundancy of the structural system with respect to accidental loads has to be secured, based on a risk analysis and dependent on specific structural performance demands.

### 15.2 Load path design

#### 15.2.1 Load path design on system level

Due to the huge degree of freedom and the complexity of interfaces with other disciplines, conceptual structural designing requires simple and clear three-dimensional modelling. This is merely possible on the level of axial forces, directly, with a truss-analogy or an arch depending on the structural form.

Axial forces-based, a rough three-dimensional outline of the load paths can be constructed as shown in figure 15.1.

These load paths are directly caused by the prime actions, by-passing the free space profiles, and borne by the available points of support.

Load path design during the creation phase of conceptual design is the process of determination and optimisation of the load paths, in close collaboration with all the influential participating disciplines.
15.2 Load path design

15.2.2 Truss-analogy in load path design

Modelling bending action in more complex forms can be axial forces-based with the help of a truss-analogy, as shown in figure 15.2.

The complex form can be filled out by a statically determinate truss configuration, two-dimensional or when appropriate three-dimensional. The load distribution in the truss can then easily be calculated using the method of sections. The strength-based dimensioning results in sectional properties and corresponding construction heights. The rigidity of the truss can further be optimised with a minimal potential energy-based
15.2.3 Modelling the system decomposition

Getting a grip on possible three-dimensional load distribution effects in an early stage of the conceptual design process requires retention of three-dimensional effects during decomposition of the three-dimensional system in two-dimensional subsystems. This system decomposition can be principally done either by defining the compatibility functions between the subsystems; or by separating the three-dimensional effect as shown in figure 15.3.

![Figure 15.3: Modelling the system effects](image)

Defining the compatibility functions to such an extent that they can be used for a neat quantification of the three-dimensional load distribution is too complex and time-consuming for a conceptual dimensioning. Therefore, qualification and approximate quantification of a separated three-dimensional effect is the remaining feasible option.

For example, the three-dimensional system effect of a double track truss bridge can be separated by defining the overall torsion due to one track loading, with the help of basic applied mechanics.

15.2.4 Dimensioning routine of the load path

The load distribution on the system, through the subsystems into the elements can best be determined on subsystem level with design ap-
proximations of the load distribution in basic structural forms. Possible overall three-dimensional system effects then have to be separately evaluated, estimated and added to the load distribution of the subsystem. The result is an approximate determination of the forces in each individual element.

With these forces, the dimensions of the individual elements can be determined by means of design approximations of the load-carrying capacity of elements with regard to sectional strength and element stability. The dimensioning routine, in conformity with figure 14.3 on page 173, is shown in figure 15.4.

![Diagram of Dimensioning Routine]

Figure 15.4: Dimensioning routine

This determination of the approximated capacity of the elements, the subsystems and the system is a reversed flow resulting in a dimensioning of the whole structural system.

15.3 Conceptual structural design

15.3.1 Principal details

The materialisation of the structural form is not only dependent on the choice of material and corresponding dimensioning, but also on the design of influential architectural and cost dictating details of the structure, the so-called “principal details” as shown in figure 15.5.
The design approach of these often three-dimensional details is identical to that of the structural system.

The choice of material and the matching dimensions of the principal detail can influence the foregoing qualification process with regard to the field of application and characteristics of the chosen structural form; then, an optimisation loop is applicable.

15.3.2 System configuration

Independent of requirements and performance/cost optimisation of the conceptual design, structural design should keep the following more generic rules in mind with regard to a simple and clear structural system configuration:

**Structural economy** Members subjected to axial compression or tension are relatively stronger than other ways of arranging material and generally more economical than those designed for pure bending.

**Structural safety** In a simple and clear structure, which is rigorously functional, the transmission of forces in the whole structure and in each of the elements will be simple, clear, and without twist.

**Instinctive security** A structure with few and strong elements always gives an impression of ease and security.
15.3 Conceptual structural design

15.3.3 Material properties of conceptual design

In conceptual design, clear and concise material properties are strived for. The strength of structural elements loaded by axial forces or bending moments, is based on the material-dependent normal stress strength $f_d$. For concrete and its reinforcement, the design material strength $f_c$ respectively $f_s$, incorporates a material safety. For structural steel, the design material strength equals the yielding stress $f_y$.

Other material properties such as shear strength $f_v$, normal stiffness $E$ and shear stiffness $G$, can be expressed in this basic strength property $f_d$ or are constant.

The material properties are based upon the applicable Eurocodes for concrete [28] and structural steel [30].

Elementary material properties for the conceptual structural design of reinforced concrete and steel structures are listed in table 15.1.

**Normal stress strength for reinforced concrete**  Common material grades from conventional to high strength, and their normal stress strengths $f_c$, are as follows:

<table>
<thead>
<tr>
<th>Concrete grade</th>
<th>$f_c \left[ \frac{N}{mm^2} \right]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C30</td>
<td>20</td>
</tr>
<tr>
<td>C45</td>
<td>30</td>
</tr>
<tr>
<td>C60</td>
<td>40</td>
</tr>
<tr>
<td>C90</td>
<td>60</td>
</tr>
</tbody>
</table>

Higher concrete grades offer increasing strength and corresponding increasing stiffness in order to reduce structural dimensions and increase available space. Furthermore, a shorter cure time allows for quick removal of formwork, and subsequently, putting it into use.

**Normal stress strength for structural steel**  Common material grades from conventional to high strength, and their normal stress
### Material properties for conceptual design

<table>
<thead>
<tr>
<th>Property:</th>
<th>Reinforced concrete</th>
<th>Structural steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal stress strength $f_d \left[ \frac{N}{mm^2} \right]$</td>
<td>$f_c = \frac{Concrete grade}{1.5}$</td>
<td>$f_y = Steel grade$</td>
</tr>
<tr>
<td>Shear stress strength $f_v \left[ \frac{N}{mm^2} \right]$</td>
<td>$f_v = 0.2f_c$</td>
<td>$f_v = \frac{f_y}{\sqrt{3}}$</td>
</tr>
<tr>
<td>Normal stiffness modulus $E \left[ \frac{N}{mm^2} \right]$</td>
<td>$E_c = \frac{f_c}{1.75 \cdot 1000}$</td>
<td>$E = 2.1 \cdot 10^5$</td>
</tr>
<tr>
<td>Shear stiffness modulus $G \left[ \frac{N}{mm^2} \right]$</td>
<td>$G_c = \frac{f_c}{1.75 \cdot 1000 \cdot 2.4}$</td>
<td>$G = 8.1 \cdot 10^4$</td>
</tr>
</tbody>
</table>

Table 15.1: Material properties for conceptual design

Strengths $f_y$, are as follows:

<table>
<thead>
<tr>
<th>Structural steel grade</th>
<th>$f_y \left[ \frac{N}{mm^2} \right]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S235</td>
<td>235</td>
</tr>
<tr>
<td>S355</td>
<td>355</td>
</tr>
<tr>
<td>S460</td>
<td>460</td>
</tr>
<tr>
<td>S690</td>
<td>690</td>
</tr>
</tbody>
</table>

Higher steel grades offer increasing strength in order to reduce strength-driven structural dimensions.

**Shear stress strength for reinforced concrete**  The shear stress strength $f_v$ for most materials is linearly proportional to the normal stress strength $f_d$ and considerably lower. For reinforced concrete, the
shear stress strength is approximately 20% of the normal stress strength: $f_v = 0.2f_c$.

**Shear stress strength for structural steel**  The shear stress strength for structural steel can be derived from the Huber Hencky and Von Mises yield criterion:

$$\sqrt{\sigma^2 + 3\tau^2} \leq f_y \Rightarrow \tau \leq \frac{f_y}{\sqrt{3}} = f_v$$  (15.1)

**Normal stiffness modulus for reinforced concrete**  For concrete, the normal stiffness modulus or Young’s modulus $E_c$ is dependent on the material grade and its corresponding normal stress strength $f_c$. This modulus $E_c$ can be derived from the simplified bi-linear modelled stress strain relationship of concrete with an elastic strain limit of $1.75\%$ [28], combined with the practical usage for the modulus $E_c$, including the influence of time related effects [3]:

$$E_c = \frac{f_c}{1.75 \times 1000}$$  (15.2)

**Normal stiffness modulus for structural steel**  For steel, the normal stiffness modulus or Young’s modulus $E$ has a constant value of $2.1 \cdot 10^5 \, \text{N/mm}^2$.

**Shear stiffness modulus for reinforced concrete**  For uncracked concrete the shear modulus $G_c$ is dependent on the material grade and its corresponding normal stress strength $f_c$:

$$G_c = \frac{E_c}{2(1 + \nu)} = \frac{\frac{f_c}{1.75 \times 1000}}{2(1 + 0.2)} = \frac{f_c}{1.75 \times 1000 \cdot 2.4}$$  (15.3)
Shear stiffness modulus for structural steel For steel the shear modulus \( G \) has a constant value of approximately \( 8.1 \cdot 10^4 \frac{N}{\text{mm}^2} \):

\[
G = \frac{E}{2(1 + \nu)} = \frac{2.1 \cdot 10^5}{2(1 + 0.3)} \approx 8.1 \cdot 10^4 \frac{N}{\text{mm}^2}
\]  

(15.4)
Chapter 16

Fundamental parameters of load distribution

16.1 Conceptual design on subsystem level

16.1.1 Load distribution phase of the conceptual design

The load distribution phase starts with materialised structural schemes and ends with element forces and displacements as shown in figure 14.3 on page 173.

16.1.2 Load distribution

The distribution of the loads within a two-dimensional subsystem is dependent on the geometrical characteristics of the subsystem. For the two-dimensional basic structural forms as defined in figure 11.3 on page 134, the approximated load distribution for conceptual design has to be determined.

In search of a basic set of knowledge and approximation parameters for
conceptual structural design in general, and load distribution in particular, the following principles are employed:

**Applied mechanics-based** to secure insight and durability. Basic applied mechanics textbook material, being established knowledge, is not included in the bibliography.

**Professional practice factors** for improvement of approximation accuracy, including reference in the bibliography or verification in this treatise.

**Emphasis on deformation-driven aspects** in accordance with the force and deformation-driven parameters as shown in figure 14.2 on page 166.

**Performance-based** and well-balanced with respect to depth and breadth of underlying knowledge and applicability for conceptual design.

### 16.1.3 Parallel load distribution

**Statically determinate structures** An assembly of directly connected elements is defined “statically determinate” when the static equilibrium equations are sufficient for determining the internal forces and reactions: \( \Sigma H = 0, \Sigma V = 0, \) and \( \Sigma M = 0.\)

A common statically determinate structure is a simply supported beam as shown in figure 16.1.

![Serial system](image)

Figure 16.1: Statically determinate structure
Practically, a statically determinate structure has just enough (internal) members and (external) supports to secure structural form and fixation, in analogy to a serial system.

As a consequence, the behaviour is completely force-driven and failure of only one random element immediately leads to failure of the structure.

**Statically indeterminate structures** An assembly of directly connected elements is defined “statically indeterminate” when the static equilibrium equations are not sufficient for determining the internal forces and reactions on the structure.

A common statically indeterminate structure is a continuous beam as shown in figure 16.2.

![Figure 16.2: Statically indeterminate structure](image)

Practically, a statically indeterminate structure has more (internal) members and/or (external) supports than necessary for structural integrity, in analogy to a parallel system.

As a consequence, the behaviour can be stiffness-driven, besides force-driven. A difference in stiffness will influence the load distribution within the parallel system.

Parallel load distribution can be effectively utilised with regard to the following:

**Redundancy** Design a second method of support to ensure that the forces are dispersed elsewhere when a vital structural component
can give way.

**Optimisation** Optimisation through redistribution by altering the stiffness of the individual elements.

**Induced deformation** Deformation of a primarily statically indeterminate structure can cause unwanted loading of secondary structures.

### 16.2 Load distribution in basic structural forms

#### 16.2.1 Load distribution in a frame

Frames consist of bending beams and supporting columns. The local load distribution of a beam consisting of one element equals the global load distribution and is therefore subjected to bending and shear. The supporting columns are subjected to compression.

The effects of bending moments versus axial forces can be analysed with a statically indeterminate frame structure, consisting of a combined cantilever beam and supporting column as shown in figure 16.3.

![Figure 16.3: Parallel bending and axial force](image-url)
Axial versus bending strength  The strength of the individual cantilever beam, the individual column and the ratio between both, can be determined:

\[
\sigma_{bm} = \frac{M}{W_{bm}} = \frac{F_{bm} \cdot l_{bm}}{\frac{1}{6} \cdot b_{bm} \cdot h_{bm}^2} \quad \Rightarrow \quad F_{bm} = \frac{\sigma_{bm} \cdot b_{bm} \cdot h_{bm}^2}{6 \cdot l_{bm}} \quad (16.1)
\]

\[
\sigma_{cln} = \frac{N}{A_{cln}} = \frac{F_{cln}}{b_{cln} \cdot h_{cln}} \quad \Rightarrow \quad F_{cln} = \sigma_{cln} \cdot b_{cln} \cdot h_{cln} 
\quad (16.2)
\]

\[
F_{cln} = \frac{\sigma_{cln} \cdot b_{cln} \cdot h_{cln} \cdot 6 \cdot l_{bm}}{\sigma_{bm} \cdot b_{bm} \cdot h_{bm}^2} 
\quad (16.3)
\]

When both beam and column are equally homogeneous materialised and dimensioned □ 300 \cdot 300 \text{ mm}^2 with lengths of 3 m:

\[
\frac{F_{cln}}{F_{bm}} = \frac{\sigma \cdot b \cdot h \cdot 6 \cdot l}{\sigma \cdot b \cdot h^2} = \frac{6 \cdot l}{h} = \frac{6 \cdot 3}{0.3} = 60 
\quad (16.4)
\]

The axial strength exceeds the bending strength by far. In general, members subjected to axial compression, or tension, are relatively stronger than other ways of arranging material.

Axial versus bending stiffness  The distribution of a load in a statically indeterminate structure, will be on the basis of the ratio between the axial stiffness and the bending stiffness:

\[
F = F_{cln} + F_{bm} 
\quad (16.5)
\]

\[
\delta = \frac{F_{cln} \cdot l_{cln}}{E \cdot A_{cln}} = \frac{F_{bm} \cdot l_{bm}^3}{3 \cdot E \cdot I_{bm}} \Rightarrow \frac{F_{cln}}{F_{bm}} = \frac{E \cdot A_{cln} \cdot l_{bm}^3}{3 \cdot E \cdot I_{bm} \cdot l_{cln}} 
\quad (16.6)
\]

When both beam and column are equally homogeneous materialised and dimensioned □ 300 \cdot 300 \text{ mm}^2 with lengths of 3 m:

\[
\frac{F_{cln}}{F_{bm}} = \frac{E \cdot b \cdot h \cdot l^3}{3 \cdot E \cdot \frac{1}{12} \cdot b \cdot h^3 \cdot l} = \frac{4 \cdot l^2}{h^2} = \frac{4 \cdot 3^2}{0.3^2} = 400 
\quad (16.7)
\]

Because axial stiffness mostly exceeds the bending stiffness by far, a combined load distribution will result in a domination of the axial forces.
16.2.2 Load distribution in a floor slab

The local load distribution of a floor slab equals the global load distribution and is therefore subjected to bending and shear. A two-way spanning floor slab, whether concrete slab or orthotropic steel deck, is subjected to bending and shear in both spanning directions.

The effect of parallel bending can be analysed with a homogeneous two-way spanning floor slab with a simplified load distribution as shown in figure 16.4.

![Figure 16.4: Load distribution in a two-way spanning floor slab](image)

The load distribution in statically indeterminate structural systems with parallel bending is dependent on the length of the load paths; the effectiveness of the load paths is linearly proportional to the difference in stiffness.

An approximation of the distribution of the loads in the short span ($F_1$)
respectively long span \((F_2)\) of the floor slab:

\[
F = F_1 + F_2
\]  
\((16.8)\)

\[
\delta = \frac{F_1 l_1^3}{48EI} = \frac{F_2 l_2^3}{48EI} \Rightarrow \frac{F_1}{F_2} = \left( \frac{l_2}{l_1} \right)^3
\]  
\((16.9)\)

For example, a rectangular two-way spanning slab with spans of \(l\) respectively \(2l\):

\[
\frac{F_1}{F_2} = \left( \frac{2l}{l} \right)^3 = 8
\]  
\((16.10)\)

The short load path is eight times as effective as the long load path, due to the proportional difference in stiffness.

The outcome is directly appropriate for a slab of reinforced concrete. The usually low reinforcement percentage has after all a negligible influence on the stiffness \(E_cI\) of a reinforced concrete slab.

### 16.2.3 Load distribution in a cable-stayed beam

A supporting cable diminishes the supported length and corresponding local load distribution of beams; by each half, strength - the effect of section modulus \(W\) - is quadrupled and stiffness - the effect of moment of inertia \(I\) - is eight-fold. The required section modulus \(W\), and moment of inertia \(I\), are worked out in subsection 17.4.3.

The effectiveness of the local load distribution in a cable-stayed statically indeterminate continuous beam is dependent on the stiffness of the cable. The cross-sectional area of the cable is therefore governed by both tension strength and supporting stiffness.

In such a statically indeterminate structure, optimisation by redistribution within the deformation-driven parallel load distribution can be utilised. An example of such an optimisation by a controlled redistribution is the cable-stayed continuous beam as shown in figure 16.5.
The effectiveness of the beam is governed by the stiffness of the cable; the strength of the cable has no influence at all with regard to the redistribution.

Regardless of the required cross-sectional area of the cable with respect to the strived-after redistribution, the structural strength and serviceability always remain prerequisite requirements.

**Optimisation**  An optimisation of the moment distribution in the continuous beam can be accomplished by sagging the middle support:

\[
\delta = \frac{5}{12} ql \cdot \frac{l^3}{3EI} - \frac{ql^4}{8EI} = \frac{ql^4}{72EI_{bm}} \tag{16.11}
\]

The corresponding recommended cross-sectional area of the cable with
16.2 Load distribution in basic structural forms

respect to the stiffness (ULS) amounts to:

\[
\delta = \frac{ql^4}{72EI_{bm}} = \frac{\Delta l_{cable}}{\sin \alpha} = \frac{N_{cable} \cdot l_{cable}}{E A_{cable} \cdot \sin \alpha} = \frac{\frac{7}{6}ql \cdot \sqrt{l^2 + h^2}}{E A_{cable} \cdot \sin \alpha}
\]

\[\Rightarrow A_{cable, stiffness\ ULS} = \frac{84 \cdot I_{bm} \cdot \sqrt{l^2 + h^2}}{l^3 \cdot \sin^2 \alpha} \cdot \frac{E_{bm}}{E_{cable}} \quad (16.12)\]

**Structural strength**  The required cross-sectional area of the cable with respect to the strength (ULS) amounts to:

\[
A_{cable, strength\ ULS} \approx \frac{7 q_d \cdot l}{\sin \alpha \cdot f_y} \quad (16.13)
\]

No redistribution and both spans under extreme loading amounts to:

\[R_{mid} = \frac{5}{4} q_d l \neq \frac{7}{6} q_d l \quad (16.14)\]

Using high-strength steel cables, the required stiffness usually will be decisive due to the same Young’s modulus for all steel grades.

**Serviceability**  The required cross-sectional area of the cable with respect to the displacements (SLS) amounts to:

\[
\delta_{tot} \approx \frac{1}{150} \cdot \frac{q_k l^4}{E I_{bm}} + \frac{1}{2} \cdot \frac{\frac{7}{6} q_k l \cdot \sqrt{l^2 + h^2}}{E A_{cable} \cdot \sin \alpha} \leq \frac{l}{250}
\]

\[\Rightarrow A_{cable, stiffness\ SLS} \approx \frac{146 \cdot q_k \cdot \sqrt{l^2 + h^2}}{E_{cable} \cdot \sin^2 \alpha \cdot \left(1 - \frac{5q_k l^3}{3EI_{bm}}\right)} \quad (16.15)\]

Concerning the displacements of the beam, the stiffness of the beam \(I_{bm}\) influences the required stiffness of the cable \(A_{cable}\).
16.2.4 Load distribution in a truss

Every member of a truss is in pure compression or pure tension. The main contribution to the strength and stiffness is provided by the triangulation. Shear and bending moments, and other more complex stresses are all practically zero. This makes trusses relatively strong and stiff.

The load distribution in a simply supported simplified parallel chord truss is shown in figure 16.6.

![Figure 16.6: Load distribution in a truss](image-url)
The global load distribution consists of bending moments and shear forces. The local load distribution within the truss consists completely of axial compression and tension forces in the individual truss members.

A simply supported truss with a uniform load results in the following maximum axial forces in the main and the web members:

\[ N_{\text{main, max}} = \frac{M}{h} = \frac{1}{8} q_d l^2 \tag{16.16} \]

\[ N_{\text{web, max}} = \frac{V \cos \alpha}{\cos \alpha} = \frac{1}{2} q_d l \tag{16.17} \]

A non-uniform load still results in local axial forces only, with the possibility of a change of compression and tension in the web members near the shear transition point.

The global stiffness of the truss can be approximated as follows:

\[ I_{\text{truss}} \approx 0.8 \cdot 2 \cdot A_{\text{main}} \cdot \left(\frac{1}{2} h\right)^2 \tag{16.18} \]

The moment of inertia \( I_{\text{truss}} \) has an approximated loss of 0.2 because of global shear deformation of the truss due to elastic deformation of the individual web members, as substantiated by studies of Arie Romeijn, Delft University of Technology.

During conceptual design this stiffness parameter \( I_{\text{truss}} \) can be applied to determine the global bending deflection (SLS):

\[ \delta = \frac{5}{384} \cdot \frac{q_k l^4}{E I_{\text{truss}}} \quad \text{and} \quad I_{\text{truss}} \approx 0.8 \cdot 2 \cdot A_{\text{main}} \cdot \left(\frac{1}{2} h\right)^2 \tag{16.19} \]

Furthermore, this stiffness parameter \( I_{\text{truss}} \) can be applied to determine the global buckling strength (ULS) as discussed in subsection 17.3.2.
16.2.5 Load distribution in an arch

The form of an arch is more or less parabolic and usually, the horizontal reaction forces are resisted by a tension rod. Uniformly loaded, the entire arch is in compression and has little bending moments and shear; this makes arches relatively strong.

The load distribution in a simply supported arch is shown in figure 16.7.

Figure 16.7: Load distribution in an arch
The subsystem as a whole is simply supported and therefore globally statically determinate. The corresponding global load distribution consists of bending moments and shear forces.

The tied arch, consisting of an arch and a tie-rod, is locally statically determinate. When loaded with a uniform load per m\(^1\) span length, the corresponding local load distribution within a tied parabolic arch consists solely of axial compression in the arch and axial tension in the tie-rod.

A uniform load results in the following maximum axial forces in the tie-rod and the arch:

\[
H = \frac{M}{h} = \frac{1}{8} q d l^2
\]

\[
N_{arch, max} = \sqrt{\left(\frac{1}{2} q d l\right)^2 + H^2}
\]

When the uniform load is dominant, the arch more or less follows the line of compression. Loaded with a uniform load per m\(^1\) span length it equals a parabola. Loaded with a uniform load per m\(^1\) arch length it equals a hyperbola (hyperbolic cosine function), the so-called “catenary”.

A non-uniform load results in additional bending of the arch, besides the axial compression. So-called “false” arches, where local bending is dominant over compression, are unfavourable:

- They have circular instead of parabolic arches.
- And/or they have highly concentrated loads, instead of more or less uniform loads.

A practical design value for the maximum bending moment within the arch can be obtained by half the variable uniform loading as shown in figure 16.8.

The so-obtained practical design value for the maximum bending moment within the arch amounts to:

\[
M_{arch, max} \approx \frac{1}{64} q d l^2
\]
The corresponding variable axial forces in tie-rod and arch amount to:

\[ H = \frac{M}{h} = \frac{1}{16} q d l^2 \quad \text{for} \quad h \]  

\[ N_{arch} = \sqrt{\left(\frac{3}{8} q d l\right)^2 + H^2} \quad \text{(16.24)} \]

### 16.2.6 Load distribution in a shear wall

A most common application of shear walls is securing the global stability of a system against wind actions and global initial sway imperfections. For non-sway buildings these can be in the form of concrete shear walls or steel wind bracing.
The load distribution of a stocky shear wall consists of dominant shear in combination with minor bending.

**Concrete shear wall** The load distribution within the shear wall takes place on element level. For conceptual design, the approximate calculation of shear strength and deformation in subsection 17.2.1 respectively 17.2.2 is applicable.

**Steel wind bracing** The load distribution within the steel wind bracing takes place on subsystem level as discussed in subsection 16.2.4 on the load distribution in trusses.

Because of the stocky dimensions, shear is governing. For conceptual design, the approximate calculation of shear strength and deformation in subsection 17.2.3 on the shear deformation in cantilevered trusses is applicable.

### 16.3 Parallel load distribution on detailed level

The distribution of the load in detailed design will be on the level of stress and strain. Due to the high degree of complexity of common three-dimensional details, these details reveal a corresponding high degree of statically indeterminacy. The stress distribution within the details is proportional to the stiffness distribution, which is inversely proportional to the strains.

Conceptual design of principal details can be interpreted as the design of a small-scaled system. Thus, an identical methodical approach such as for system design, with a decomposition in subsystems and elements, is appropriate.

Because both axial and shear stiffness mostly exceed the bending stiffness by far, a combined load distribution will result in a domination of the axial and shear forces.
A study on the optimum design of a stiffening plate in a beam-to-column joint shows the difference between bending and combined axial/shear deformation. In this specific case, it is by far preferable to connect the plate only to the loaded flange, thus avoiding high fitting costs of each individual stiffener. Both options are given in the same figure 16.9.

![Stiffener plate in a beam-to-column joint](image)

Figure 16.9: Stiffener plate in a beam-to-column joint

When the contribution of the flange turns out to be a negligible factor, the stiffener plate only needs to be connected to the loaded flange for force transition.

By calculating the deformation of each individual (parallel) failure mechanism, the decisive mechanism can be determined under the condition that there is an order of magnitude difference in deformation. When the deformations lie in the same range, an accurate finite elements calculation has to be executed.

In this specific case the following failure mechanisms are applicable:

- Bending of the flange.
- Axial force on the stiffener.
- Shear force on the stiffener.
Bending of the flange  The bending deformation of the flange is shown in figure 16.10.

\[ \delta = \frac{F l^3}{3 E I} = \frac{100 \cdot 10^3 \cdot 50^3}{3 \cdot 2.1 \cdot 10^5 \cdot \frac{1}{12} \cdot 100 \cdot 10^3} = 2.38 \text{ mm} \] (16.25)

Axial force on the stiffener  The axial deformation of the stiffener is shown in figure 16.11.
The displacement, due to axial deformation of the stiffener, amounts to:

\[ \sigma = \varepsilon \cdot E \Rightarrow \frac{N}{A_N} = \frac{\delta}{l} \cdot E \]
\[ \Rightarrow \delta = \frac{N \cdot l}{E \cdot A_N} = \frac{1}{2} \cdot \frac{100 \cdot 10^3 \cdot 150}{2.1 \cdot 10^5 \cdot 80 \cdot 10} = 0.04 \text{ mm} \quad (16.26) \]

Shear force on the stiffener  The shear deformation of the stiffener is shown in figure 16.12.

The displacement, due to shear deformation of the stiffener, amounts to:

\[ \tau = \gamma \cdot G \Rightarrow \frac{V}{A_V} = \frac{\delta}{h} \cdot G \]
\[ \Rightarrow \delta = \frac{V \cdot h}{G \cdot A_V} = \frac{100 \cdot 10^3 \cdot 50}{8.1 \cdot 10^4 \cdot 150 \cdot 10} = 0.04 \text{ mm} \quad (16.27) \]

The deformation due to bending of the flange is an order of magnitude higher; consequently, the contribution of the flange is negligible.
16.4 Induced deformation

16.4.1 Principle of induced deformation

An induced deformation may only occur in a statically indeterminate and thus deformation-driven structure.

Problem of induced deformation  Within a statically indeterminate subsystem, a stiff element can cause an induced deformation of an adjacent relatively flexible element. The same can occur on a higher system level with an induced deformation of a relative flexible subsystem within a statically indeterminate system.

As a result this induced deformation can cause a structural failure of the concerning relatively flexible element, respectively subsystem.

Solution to the problem of induced deformation  Failure is commonly opposed by an increase of the cross-sectional strength and accompanying stiffness. When the stiffness and corresponding structural action increases more than the strength of the structure, the solution is to reduce the stiffness.

16.4.2 Induced deformation on subsystem level

An example of induced deformation on subsystem level is a concrete floor slab on a torsional clamped steel beam as shown in figure 16.13.

When the problem of possible torsional failure is force-driven, the only solution is the necessary increase of the torsional strength to oppose structural failure.

However, when the problem of possible torsional failure is deformation-driven, the solution is to reduce the torsional stiffness to prevent structural failure.
16.4.3 Induced deformation on system level

Within a statically indeterminate system a stiff subsystem can cause an induced deformation of a relatively flexible subsystem.

A common application is, for example, a bridge with a top lateral bracing as shown in figure 16.14. The effect of the induced deformation, however, also appears in other types of bending systems.

The position of the neutral axis is dependent on the difference in stiffness between the top lateral bracing and the bottom deck.

The shortening of the neutral axis $\Delta l_{\text{neutral axis}}$ due to the pure mathematical deflection is a negligible factor with regard to the mechanical deformations $\Delta l_{\text{bottom edge}}$ and $\Delta l_{\text{top edge}}$ related to the cross-sectional and material stiffness parameters.
The lengthening of the bottom edge $\Delta l_{\text{bottom edge}}$ gives an induced displacement of the bearings. The shortening of the top edge $\Delta l_{\text{top edge}}$ gives an induced deformation of the top lateral bracing.

**Triangular bracing** When the system as a whole is statically determinate, induced deformations cannot occur. The matching deformation of a triangular hinged top lateral bracing is shown in figure 16.14.

Normally however, the upper chord is continuous over the truss span length, making the structure statically indeterminate and inducing a deformation of the top lateral bracing. When designing a stiff truss...
bracing, the compressed members will probably fail due to this induced deformation.

**K-bracing** Therefore, a more flexible K-bracing is an effective design to reduce the overall bracing stiffness by introducing flexible bending elements among the stiff axial elements, thus reducing the load on all bracing elements. The deformation of the top lateral K-bracing is shown in figure 16.14.
Chapter 17

Fundamental parameters of failure mechanisms

17.1 Conceptual design on element level

17.1.1 Dimensioning phase of the conceptual design

The dimensioning phase starts with element forces and displacements, and ends with the required section properties for conceptual design, as shown in figure 14.3 on page 173.

17.1.2 Failure mechanisms

Failure mechanisms typically include structural failures in the Ultimate Limit State (ULS) and serviceability failures in the Serviceability Limit State (SLS). Corresponding minimum required section properties have to be defined to comply with functional requirements and contractual conditions.

In search of a basic set of knowledge and approximation parameters
for conceptual structural design in general, and failure mechanisms in particular, the following principles are employed:

**Applied mechanics-based** to secure insight and durability. Basic applied mechanics textbook material is considered established knowledge and is therefore not included in the bibliography.

**Professional practice factors** for improvement of approximation accuracy, including reference in the bibliography or verification in the treatise.

**Emphasis on deformation-driven aspects** in accordance with the force and deformation-driven parameters as shown in figure 14.2 on page 166.

**Performance-based** and well-balanced with respect to depth and breadth of underlying knowledge and applicability for conceptual design.

The following appropriate applied mechanics-based knowledge and approximation parameters are discussed as listed in table 17.1.

<table>
<thead>
<tr>
<th>Conceptual design parameters of failure mechanisms</th>
<th>Shear strength</th>
<th>Shear deformation</th>
<th>Stocky beam</th>
<th>Stability</th>
<th>Principle</th>
<th>Euler based</th>
<th>Buckling</th>
<th>Bending &amp; axial</th>
<th>Concrete elements</th>
<th>Steel elements</th>
<th>Foundations</th>
</tr>
</thead>
</table>

Table 17.1: Conceptual design parameters of failure mechanisms

The material properties are based upon the applicable Eurocodes for concrete [28] and structural steel [30].
17.2 Shear

17.2.1 Shear strength

For a reliable determination of the shear strength it is essential to comprehend the two major parameters $f_v$ and $A_v$ as shown in figure 17.1.

![Figure 17.1: Shear strength](image)

**Material shear strength** $f_v$ The shear strength $f_v$ for most materials is linearly proportional to the axial strength $f$ and considerably lower. For reinforced concrete the shear strength is approximately 20% of the axial strength. Decisive for this global shear strength is the local compressive strength of the concrete diagonals in the truss-like load distribution of the global shear force, provided that the shear reinforcement is sufficient. For structural steel the shear strength is approximately 60% of the axial strength.

**Effective shear area** $A_v$ The stiffness contribution of the perpendicular to shear force orientated material such as flanges, is negligible with regard to the material parallel to the shear force. Therefore, the shear force will be borne solely by the shear area $A_v$ parallel to this force. Failure will result in rupture of the shear area before the flange material will
contribute, resulting in a propagating shear rupture of the whole cross section.

The required effective shear area $A_v$ can be calculated as follows:

$$\frac{V_d}{V_u} = \frac{V_d}{A_v \cdot f_v} \leq 1 \Rightarrow A_v \geq \frac{V_d}{f_v}$$

Reinforced concrete $A_v \geq \frac{V_d}{0.2f_c}$, steel $A_v \geq \frac{V_d}{0.6f_y}$ \quad (17.1)

For standard slender beams, however, bending strength is mostly decisive over shear strength.

### 17.2.2 Shear deformation

A beam as shown in figure 17.2 is subjected to a combined bending and shear deformation.

For slender beams the bending deformation is decisive and the shear deformation may be neglected, for stocky beams the shear deformation is decisive and the bending deformation may be neglected.

For a slender beam, the bending deformation is in general:

$$\delta_{bending} = \int \frac{M}{EI} \quad (17.2)$$

And in this specific case:

$$\delta_{bending} = \frac{Fl^3}{3EI} \quad (17.3)$$

For a stocky beam, the shear deformation is in general:

$$\delta_{shear} = \int \frac{V}{GA} \quad (17.4)$$
And in this specific case:

\[ \delta_{\text{shear}} = \frac{Fl}{GA} \]  \hspace{1cm} (17.5)

The transition from “stocky” to “slender” depends on the bending versus shear stiffness of the material. The transition slenderness cannot be determined by an equilibrium of foregoing shear and bending formulae, because the abstraction of bending is based upon slender beam theory and the transition slenderness is beyond the validity range of this theory.
In mechanics-based analyses of the transition slenderness from “stocky” to “slender” of a simply supported beam, the span-over-height ratio \( \frac{l}{h} \) varies between 3 and 4. The Dutch National Annex to the Eurocode 2 [29] defines this transition slenderness for simply supported concrete beams explicitly at a span-over-height ratio of \( \frac{l}{h} = 3 \).

Considering the relatively small difference in \( \frac{E}{G} = 2 \left(1 + \nu\right) \) between concrete and steel, \( 2 (1 + 0.2) = 2.4 \) respectively \( 2 (1 + 0.3) = 2.6 \), the corresponding transition slenderness of the two will be approximately similar, resulting in span-over-height ratios \( \frac{l}{h} \) as shown in figure 17.3.

![Figure 17.3: Transition slenderness for stocky to slender beams](image)

**17.2.3 Shear deformation on subsystem level**

Shear deformation on subsystem level occurs in cantilevered truss structures. For a comprehensible conceptual design, the shear contribution on element level has to be appointed. An example of a usual, present-day cantilevered parallel chord building design is showed in figure 17.4.

Because of the usually heavy dimensioned floor-carrying chord members in combination with the nearby stocky dimensions of this cantilevered truss, the displacement at the cantilevered end of the truss will be dominated by shear deformation, rather than bending deformation. To realise this, the design in the serviceability limit state should focus on shear deformation and the corresponding required section properties of the web members.
17.2 Shear

The linearity of deformation is based on a strength-optimised design of the web members.

Approximated loads (ULS):

\[ N_{\text{main}, \text{max}} = H = \frac{1}{2} q_d l^2 \frac{1}{h} \]  
\[ N_{\text{web}, \text{max}} = q_d \cdot \left( n_{\text{panel}} - \frac{1}{2} \right) \cdot \frac{l}{\sin \alpha} \]  
(17.6)

(17.7)

Displacement due to shear deformation (SLS):

\[ \delta = n_{\text{panel}} \cdot \frac{\Delta l}{\sin \alpha} = n_{\text{panel}} \cdot \frac{N_{\text{web}, k} \cdot l_{\text{web}}}{E A_{\text{web}} \cdot \sin \alpha} \]  
\[ = n_{\text{panel}} \cdot \frac{q_k \cdot \left( n_{\text{panel}} - \frac{1}{2} \right) \cdot l}{E A_{\text{web}} \cdot \sin \alpha} \cdot \frac{n_{\text{panel}}}{E A_{\text{web}} \cdot \sin \alpha} \leq \delta_{\text{required}} \]  
(17.8)

Required cross-sectional area with regard to shear deformation (SLS):

\[ A_{\text{web}, \text{max}} \geq \frac{q_k \cdot \left( n_{\text{panel}} - \frac{1}{2} \right) \cdot l}{E} \cdot \frac{\sqrt{\left( \frac{l}{n_{\text{panel}}} \right)^2 + h^2}}{n_{\text{panel}} \cdot E \cdot \sin \alpha} \]  
(17.9)
17.3 Stability

17.3.1 Stability of the equilibrium

The basic principles of the stability of the equilibrium can be demonstrated by the uncomplicated structural element as shown in figure 17.5.

A body may be in one of three states of equilibrium: stable, unstable, and neutral. Analysis on the state of stable equilibrium can be effectively executed by a displacement over a slight distance $\delta$. The structural element is in stable equilibrium if it returns to its equilibrium position.

Driving moment leading to an instability failure mode:

$$N_u \cdot \delta$$  \hspace{1cm} (17.10)

Resisting moment providing a possible equilibrium:

$$H \cdot l = k \cdot \delta \cdot l$$  \hspace{1cm} (17.11)
17.3 Stability

Equilibrium and corresponding ultimate failure load:

\[ N_u \cdot \delta = (k \cdot \delta) \cdot l \Rightarrow N_u = k \cdot l \]  

(17.12)

What we can learn from the equilibrium of this uncomplicated structural element is applicable for stability problems in general:

**Stability is deformation-driven** The ultimate failure load \( N_u \) with respect to stability has no relation whatsoever with strength parameters, but is solely determined by flexural stiffness parameters such as length, cross-sectional bending stiffness and boundary conditions.

Cross-sectional strength is naturally determined by the cross-sectional area in combination with the material strength: \( N_u = A \cdot f_d \).

In addition, this analysis shows that every rule has its “field of application” to be considered; in this case, the assumption \( \sqrt{l^2 - \delta^2} \approx l \) is valid under the condition of small displacements with respect to the overall geometry.

### 17.3.2 Euler-based design approximations

The ultimate failure load with respect to stability, is defined by Euler as follows:

\[ N_{Euler} = \frac{\pi^2 EI}{L_{cr}^2} \]  

(17.13)

Where \( L_{cr} \) is the buckling length with design approximations as shown in figure 17.6.

For braced frames, a buckling length of \( l \) is a safe approximation. For unbraced frames, there is no absolutely safe approximation; for common frames a buckling length of \( 2.5 l \) is appropriate [23].

For in-plane buckling of arches, a buckling length of \( 0.5 l_{arch} \) is appropriate [50]. For out-of-plane buckling the overall arch length is appropriate,
which is normally reduced by adding lateral supports, such as bracings between the arches.

The mathematical formula of Euler is valid for a slender, perfectly straight member of homogeneous material that is free from initial stress. Because of deformation, material inhomogeneity, and residual stress due to fabrication, the Euler critical load has to be reduced by an adjustment factor $k$:

$$N_u = \frac{\pi^2 EI}{kL_{cr}^2} \quad (17.14)$$

Whereby the lowest $N_u$ of both axes is decisive for the failure load.

In the professional practice, the value for the adjustment factor $k$ can be set at 1.7, based on experimental results of buckling failure as included in Eurocode 3 [30] and listed in table 17.2.

For both an adjustment factor $k = 1.7$ and a buckling curve $b$, the critical buckling stress $\sigma_{cr}$ is determined for structural steel grade S355. The accuracy of the adjustment factor $k$ in relation to the Eurocode-based experimental results amounts to $\pm 30\%$.

The sectional strength-related, basic applied mechanics-based, design approximations have an accuracy far within the required $\pm 20\%$ as listed in table 10.5 on page 125.
17.3 Stability

<table>
<thead>
<tr>
<th>Critical buckling stress steel grade S355</th>
<th>EC3 buckling curve b</th>
<th>Adjustment factor $k = 1.7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$</td>
<td>$\sigma_{cr}$</td>
<td>$\sigma_{cr}$</td>
</tr>
<tr>
<td>0</td>
<td>355</td>
<td>355</td>
</tr>
<tr>
<td>20</td>
<td>347</td>
<td>355</td>
</tr>
<tr>
<td>40</td>
<td>310</td>
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<td>60</td>
<td>260</td>
<td>339</td>
</tr>
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<td>201</td>
<td>190</td>
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<tr>
<td>100</td>
<td>150</td>
<td>122</td>
</tr>
<tr>
<td>150</td>
<td>77</td>
<td>54</td>
</tr>
</tbody>
</table>

Table 17.2: Critical buckling stress comparison

The stability-related design approximations, however, are more difficult to capture. Probably the most sensitive is the buckling design approximation with an accuracy of $\pm 30\%$.

Global buckling strength Whether it is local buckling on element level or global buckling on subsystem level, the same conceptual design formulae for buckling strength $N_u$ and buckling length $L_{cr}$ are applicable. Both the moment of inertia $I$ and buckling length $L_{cr}$ have to be related to the subsystem as a whole.

Lateral torsional buckling strength Lateral torsional buckling of a beam in bending is dependent on both buckling failure of the compressed flange and opposing effects such as torsional resistance and stabilisation of the tensioned flange.

As a safe approximation for conceptual design, opposing effects can be neglected. Lateral torsional buckling can then be determined on the basis of the buckling of the compressed flange. The same conceptual design formulae for buckling strength $N_u$ and buckling length $L_{cr}$ can then be applied.
Lateral buckling restraints  All lateral restraints of buckling-sensitive structures or parts of structures have the function of a stiffener since stability in general, and buckling in particular, is deformation-driven.

However, the required stiffness can be obtained with a strength-driven design approximation \( F_d \) for the lateral restraint: \( F_d = 1\% \cdot N_d \) [31].

It should be noted that a lateral restraint is not just a detailing matter but a noticeable structural element, which has to be connected to a fixed support.

17.3.3 Combined compression and bending

The combination of compression and bending with respect to stability is too complex to handle on the level of conceptual design approximations.

However, when possibly decisive, this combination can be designed on stress level, including the estimation of an initial deformation \( e_0 \). Considering the relative complex calculation, such an analysis functions more as a check than as a design.

On stress level, the combined compression and bending can be described with the following equation:

\[
\sigma = \frac{N_d}{A} + \frac{n}{n-1} \cdot \frac{N_d \cdot e_0}{W} + \frac{n}{n-1} \cdot \frac{M_d}{W} \leq f
\]

\[
\text{and } n = \frac{N_{Euler}}{N_d} = \frac{\pi^2 EI}{L_{cr}^2} \quad (17.15)
\]

The following corresponding unity check is equivalent:

\[
\frac{N_d}{A \cdot f} + \frac{n}{n-1} \cdot \frac{N_d \cdot e_0}{W \cdot f} + \frac{n}{n-1} \cdot \frac{M_d}{W \cdot f} \leq \frac{f}{f}
\]

\[
\Rightarrow \frac{N_d}{N_u} + \frac{n}{n-1} \cdot \frac{N_d \cdot e_0}{M_u} + \frac{n}{n-1} \cdot \frac{M_d}{M_u} \leq 1 \quad (17.16)
\]
17.4 Bending and compression

17.4.1 Conceptual design of concrete in bending

**Bending strength of concrete members**  Because of the insignificant tensional strength of concrete, global bending moments and shear forces in a concrete member cannot be resisted through homogeneous material behaviour.

The local load distribution within a concrete beam consists of axial compression and tension forces in the concrete and the reinforcement, respectively, in complete analogy with the load distribution in an arch for stocky beams and a truss for slender beams, as shown in figure 17.7.

![Figure 17.7: Arch and truss analogy in concrete beams](image)

A design approximation of the ultimate strength of the usually governing bending rather than shear, can be effectively modelled by a lever arm with an approximated value of $0.8h$ between the centres of gravity of the compressed concrete zone and the reinforcement [4] as shown in figure 17.8.

![Figure 17.8: Bending strength of a concrete member](image)

Within the cost optimal limits of reinforcement percentage, the strength
of the reinforcement will be decisive for the bending strength of concrete members. As a professional practice-based average for cost optimal concrete design for an individual reinforcement direction and layer, a reinforcement percentage of 0.5% of the gross concrete cross section $b \cdot h$ will be applied.

Consequently, the amount of reinforcement $A_s$ to provide the required bending strength $M_d$ can be based on the reinforcement strength $f_s$ and the lever arm of $0.8h$:

$$\frac{M_d}{M_{u}} = \frac{M_d}{(A_s \cdot f_s) \cdot 0.8h} \leq 1 \Rightarrow A_s \geq \frac{M_d}{f_s \cdot 0.8h}$$  \hspace{1cm} (17.17)

The required section height $h$, relative to the member length $l$, for a simply supported beam under a uniform load can be derived as follows:

$$A_s \geq \frac{1}{8} q_d l^2 \cdot f_s \cdot 0.8h = \frac{0.5}{100} bh \Rightarrow \frac{h}{l} \geq \sqrt[2]{\frac{1}{8} q_d} \cdot b \cdot 0.8 \cdot \frac{0.5}{100}$$  \hspace{1cm} (17.18)

The required section height can be adjusted to resist load distributions due to non-uniform loading or beam end restraints, for example for the end field of a continuous beam:

$$A_s \geq \frac{1}{10} q_d l^2 \cdot f_s \cdot 0.8h = \frac{0.5}{100} bh \Rightarrow \frac{h}{l} \geq \sqrt[2]{\frac{1}{10} q_d} \cdot b \cdot 0.8 \cdot \frac{0.5}{100}$$  \hspace{1cm} (17.19)

The width $b$ of a poured-in-place concrete beam will mostly be adapted to the supporting concrete structure for reasons of formwork economics. In any case, lateral torsional failure must be prevented. A common value for the $\frac{b}{h}$-ratio is between $\frac{1}{2}$ and $\frac{3}{4}$ [3].

For a floor slab, the load $q_d$ is directly proportional to the width $b$, so usually, the reinforcement design will be executed per $m^1$ unit width.
Displacement of concrete members  For the displacement of a concrete member, the material and cross-sectional related stiffness $EI_c$ has to be approximately determined. The material stiffness $E_c$ is derived from the simplified bi-linear modelled stress-strain relationship of concrete with an elastic strain limit of 1.75%/perthousandzero, including the influence of time-related effects, as discussed in subsection 15.3.3 about material properties for conceptual design. The cross-sectional stiffness $I_c$ is based on an uncracked cross-section in the serviceability limit state.

$$\delta = \frac{5}{384} \cdot \frac{q_k l^4}{EI_c} \quad \text{and} \quad EI_c = \frac{f_c}{175} \cdot \frac{1}{12} bh^3$$  (17.20)

The required section height $h$, relative to the member length $l$, for a simply supported beam can be derived as follows:

$$\delta = \frac{5}{384} \cdot \frac{q_k l^4}{f_c \cdot \frac{1}{12} bh^3} \leq \frac{l}{250}$$

$$\Rightarrow h \geq \sqrt[3]{\frac{5}{384} \cdot 250 \cdot 0.021 \cdot \frac{q_k}{b \cdot f_c}}$$  (17.21)

The required section height can be adjusted to resist load distributions due to non-uniform loading or beam end restraints, as for the end field of a continuous beam:

$$\delta = \frac{1}{150} \cdot \frac{q_k l^4}{f_c \cdot \frac{1}{12} bh^3} \leq \frac{l}{250}$$

$$\Rightarrow h \geq \sqrt[3]{\frac{1}{150} \cdot 250 \cdot 0.021 \cdot \frac{q_k}{b \cdot f_c}}$$  (17.22)

17.4.2 Conceptual design of concrete in compression

Axial strength  The axial strength capacity of a more or less homogeneous material is dependent on the strength $f_d$ of the material in combination with the area $A$ of the cross section.
The required area of concrete can simply be calculated as follows:

\[
\frac{N_d}{N_u} = \frac{N_d}{A \cdot f_c} \leq 1 \Rightarrow A \geq \frac{N_d}{f_c}
\]  

(17.23)

This simple model can also be applied as a design approximation for reinforced concrete whereby the contribution of the reinforcement may be neglected.

**Buckling strength of concrete members** For concrete members with a rectangular cross section, the slenderness \( \lambda \) can be defined as follows:

\[
\lambda = \frac{L_{cr}}{h}
\]  

(17.24)

Where \( L_{cr} \) is the buckling length and \( h \) is the sectional height in the decisive buckling direction.

For reinforced concrete the Euler critical load has to be reduced by an adjustment factor of \( k = 1.7 \).

The required sectional height can be derived as follows:

\[
\frac{N_d}{N_u} = \frac{N_d}{\frac{1}{k} \cdot \frac{\pi^2 E_c}{L_{cr}^2} \frac{bh^3}{12}} \leq 1 \Rightarrow h_{weak\ axis} \geq \sqrt[3]{\frac{N_d \cdot \frac{1.7 \cdot L_{cr}^2}{\pi^2 E_c \cdot b}}{\frac{1}{12}}} \frac{bh^3}{12}
\]  

(17.25)

**17.4.3 Conceptual design of steel in bending**

**Bending strength of steel members** Global bending moments and shear forces in a steel member can be resisted through nearly homogenous material behaviour with a plastic stress distribution for standard rolled sections with the lowest steel grade S235 and a mostly elastic stress distribution for higher grades [30] as shown in figure 17.9.
Due to material costs and weight of structural steel, the design of cross-sectional areas has to be fully optimised. In order to support this optimisation process, design approximations have to be based upon the section modulus $W$:

$$\frac{M_d}{M_u} = \frac{M_d}{W \cdot f_y} \leq 1 \Rightarrow W \geq \frac{M_d}{f_y} \quad (17.26)$$

The required section modulus for a simply supported beam under a uniform load is as follows:

$$W \geq \frac{1}{8} q_d l^2 \frac{1}{f_y} \quad (17.27)$$

The required section modulus can be adjusted to resist load distributions due to non-uniform loading or beam end restraints, for example for the end field of a continuous beam:

$$W \geq \frac{1}{10} q_d l^2 \frac{1}{f_y} \quad (17.28)$$

**Displacement of steel members**  For the displacement of a steel member, the material and cross-sectional related stiffness $EI$ is governing. For steel, the material stiffness $E$ has a constant value of $2.1 \cdot 10^5 \frac{N}{mm^2}$ and is completely independent of the steel grade.
The required cross-sectional stiffness or moment of inertia $I$ for a simply supported beam can be derived as follows:

$$
\delta = \frac{5}{384} \cdot \frac{q_k l^4}{EI} \leq \frac{l}{250} \Rightarrow I \geq 250 \cdot \frac{5}{384} \cdot \frac{q_k l^3}{E}
$$

(17.29)

The required moment of inertia can be adjusted to resist load distributions due to non-uniform loading or beam end restraints, for example for the end field of a continuous beam:

$$
\delta = \frac{1}{150} \cdot \frac{q_k l^4}{EI} \leq \frac{l}{250} \Rightarrow I \geq 250 \cdot \frac{1}{150} \cdot \frac{q_k l^3}{E}
$$

(17.30)

17.4.4 Conceptual design of steel in compression

**Axial strength**  The axial strength capacity of a more or less homogeneous material is dependent on the strength $f_d$ of the material in combination with the area $A$ of the cross section.

The required area of steel can simply be calculated as follows:

$$
\frac{N_d}{N_u} = \frac{N_d}{A \cdot f_y} \leq 1 \Rightarrow A \geq \frac{N_d}{f_y}
$$

(17.31)

**Buckling strength of steel members**  For structural steel, the Euler critical load has to be reduced by an adjustment factor of $k = 1.7$.

The required moment of inertia can be derived as follows:

$$
\frac{N_d}{N_u} = \frac{N_d}{\frac{1}{1.7} \cdot \frac{\pi^2 E l}{L_{cr}^2}} \leq 1 \Rightarrow I_{\text{weak axis}} \geq N_d \cdot 1.7 \cdot \frac{L_{cr}^2}{\pi^2 E}
$$

(17.32)

17.4.5 Conceptual design of foundations

**Spread foundation strength**  The structural action of a spread foundation consists of a load spread, a stabilisation by a possibly present top
loading, and a complex failure mechanism of slipping soil particles as shown in figure 17.10.

Figure 17.10: Failure mechanism of a spread foundation

Soil failure occurs with the formation of a load and soil dependent slip surface, characterised by the slope of the slip surface and the shear strength along this slip surface.

A safe and considerably simplified, ultimate limit state design approximation is a maximum of uniform assumed soil stresses at the foundation contact area of \(0.2 \frac{N}{\text{mm}^2}\).

This professional practice-based conceptual design approximation is based on a common foundation type on sand ground, a base width of about 1 metre and a minimal embedment depth of 0.3 metre.

In combination with horizontal loading, intermediate layers or adjacent (future) excavations, a more deepening analysis is required.

**Pile foundation strength** The structural action of a pile foundation consists of a pile head bearing capacity, a pile shaft friction-bearing capacity and a complex failure mechanism of slipping soil particles as shown in figure 17.11.
Soil failure occurs with the formation of a load and soil dependent slip surface, characterised by the slope of the slip surface and the shear strength along this slip surface.

A safe and considerably simplified ultimate limit state design approximation is a maximum of uniform assumed soil stresses at the pile head area of $5 \frac{N}{mm^2}$.

This professional practice-based conceptual design approximation is based on a common typical Dutch foundation type on a deeper sand layer with substantial base resistance, partial shaft resistance, and partial negative skin friction.

This design approximation can even be applied to the conceptual design of tension piles, despite the difference in failure mechanism.
Part IV

Validation and conclusion
Chapter 18

Introduction to part IV

Part IV discusses the validation (final hypothesis testing) of the proposed solution (hypothesis) to the research problem.

The validation process consists of three steps with increasing professional complexity:

1. Arrangement of inter alia conceptual structural design activities:
   Professional profile of structural engineering (Ch.19).

2. Composition of tools for conceptual structural design:
   Material demand for conceptual design (Ch.20).

3. Actual realisation of a conceptual structural design:
   Case study trusses Maeslant storm surge barrier (Ch.21).

The solution to the research problem is postulated in Part II “The art of conceptual structural design” and Part III “Understanding structural performance”.

Solution components  The individual solution components of part II and III, and corresponding chapter arrangement, are listed in table 8.1 on page 96 respectively table 13.1 on page 160.
These solution components are validated, per corresponding chapter, as listed in table 18.1.

<table>
<thead>
<tr>
<th>Validation of the proposed solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter and subject matter</td>
</tr>
<tr>
<td>-------------------------------------</td>
</tr>
<tr>
<td>The art of conceptual structural design</td>
</tr>
<tr>
<td>Ch.10 Process decomposition</td>
</tr>
<tr>
<td>Ch.11 Physical decomposition</td>
</tr>
<tr>
<td>Ch.12 Cyclic process control</td>
</tr>
<tr>
<td>Understanding structural performance</td>
</tr>
<tr>
<td>Ch.15 Structural integrity</td>
</tr>
<tr>
<td>Ch.16 Load distribution</td>
</tr>
<tr>
<td>Ch.17 Failure mechanisms</td>
</tr>
</tbody>
</table>

Table 18.1: Validation scheme

The chapters of “The art of conceptual structural design” are specifically individually coupled and so explicitly validated as displayed with closed bullets in table 18.1. The open bullets represent actual validation relations that are not preconceived.

The underlying conceptual structural design parameters as discussed in the chapters of “Understanding structural performance” are already implicitly validated, as all these parameters are fully textbook applied
mechanics-based. The choice and combination of these parameters, however, define their professional applicability and can best be validated with an actual design case study as displayed with closed bullets in table 18.1. Again, the open bullets represent actual validation relations that are not preconceived.

The resulting chapter arrangement is visualised in figure 18.1. Each individual chapter starts with a justification, an overview and a corresponding conclusion of the executed verification.

![Figure 18.1: Reading guide for part IV](image)

**Professional profile**  As a major solution component of the proposed methodical approach, validation of the process decomposition, and in particular the fundamental design cycle, is essential. On the basis of the fundamental design cycle, a universally applicable professional profile of structural engineering is determined.
In order to capture the profession of structural engineering, typical present-day structural engineering activities - typical in the sense that the professional profile covers the average professional activities of the medium to higher segment of the structural engineering field - are classified, process management activities included.

Material demand As a major solution component of the proposed methodical approach, validation of the physical decomposition, and in particular the distinction in two-dimensional basic structural forms, is essential. On this two-dimensional subsystem level, the material demand of an example is modelled with the help of design diagrams.

For a cable-stayed beam, the conceptual structural design parameters concerning minimising the material demand are presented in design diagrams with regard to span, load, and material strength.

This method is meant as a variable and customisable design tool for experienced structural engineers, rather than a set of standard diagrams for designers, whether architects or inexperienced structural engineers.

Case study The purpose of this specific case study is to validate whether the proposed methodical approach leads to a controlled build-up of insight into the behaviour of the structure and supports the actual successive design decisions during the conceptual design of the trusses of the Maeslant storm surge barrier.

The load paths, overall geometry, and principal detailing on the basis of performance, structural, and construction demands, are determined. Subsequently, the structural action in this outlined structure is optimised and the elements are dimensioned. Finally, a thorough risk analysis is conducted as a demarcation of the conceptual structural design phase.

Overall conclusion and recommendations This scientific research thesis discusses the methodical approach on conceptual structural design
on an abstract superficial level, but coherent and complete. Quality and coherence are verified by an afterwards hypothesis-testing, in conformity with main general scientific and more exploratory methodology-dependent criteria.

It is always justified questioning completeness; an on-going, more deepening research on conceptual structural design is valuable and recommendations for further research are given.
Introduction to part IV
Chapter 19

Professional profile of structural engineering

19.1 Validation of the process decomposition

19.1.1 Professional profile of structural engineering

As a major solution component of the proposed methodical approach, validation of the process decomposition, and in particular the fundamental design cycle as shown in figure 10.2 on page 119, is essential. On the basis of the fundamental design cycle, a universally applicable professional profile of structural engineering is determined.

In order to capture the profession of structural engineering, typical present-day structural engineering activities - typical in the sense that the professional profile covers the average professional activities of the medium to higher segment of the structural engineering field - are classified, process management activities included.

So inevitably for some practitioners, it describes the desired rather than the existing situation. Furthermore, the applicability of the typical struc-
tural engineering activities is determined by the complexity of the design and the kinds of contractual commitments.

19.1.2 Conclusion professional profile

Structural design is a complex and highly cyclic process. Modelling this process is dependent on abstract representations of the actual professional activities and their interrelations. Modelling has its limitations and can be diversely interpreted. For a reliable professional profile, validation by the (inter)national professional field of structural engineering is essential.

The following expert professionals in the field of structural engineering executed the validation:

**Building engineering** Ir. A.G. (Anne) van der Sluis, Director Van Rossum Raadgevende Ingenieurs Amsterdam.

**Civil engineering** Ir. R.P. (Roy) Dayala, Team manager Urban structures Ingenieurs Bureau van Amsterdam.

**Geotechnical engineering** Prof. dr. ir. ing. A.E.C. (Almer) van der Stoel, Director CRUX Engineering BV, Professor Civil Engineering University of Twente.

**International building and civil engineering** David Millar BSc(Eng) CEng FICE FIStructE MIEAust, Associate Director Arup Scotland, former Chairman Scottish Branch The Institution of Structural Engineers.

**International contractor** Ing. A.C. (Jan) Versluis, Design leader and member of the Management Team BAM Infraconsult.

The result is an adequate and complete set of professional structural engineering activities.
19.1.3 Conclusion validation process decomposition

The proposed process decomposition, and in particular the underlying fundamental design cycle as a simplified representation of present-day extensive and diverse professional engineering activities, turns out to be effective and complete.

Both effectiveness and completeness of the individual process phases of the fundamental design cycle successfully support a professional profile of structural engineering. Therefore, this fundamental design cycle can be applied to the field of structural engineering in general.

19.2 Structural engineering activities

Independent of life cycle phase, complexity of design, and contractual commitments, the structural engineering practice can most effectively be outlined by the structural engineering characteristics as listed in table 10.5 on page 125, which are directly based on the fundamental design cycle as shown in figure 10.2 on page 119. A set of corresponding individual, structural engineering activities is determined and listed in table 19.1.

Justification and further detailing of this professional structural engineering outline, including a corresponding body of knowledge, is worked out in this chapter.

19.3 A) Creation of a system outline

19.3.1 From requirements to performance-based solutions

A conceptual design team has to be composed, consisting of a representative of the principal and representatives of each discipline with a major
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<thead>
<tr>
<th>Professional structural engineering activities</th>
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Table 19.1: Structural engineering activities
design involvement with regard to feasibility and the performance/cost ratio of the specific required system.

Dependent on objective, scale and complexity of the required system, the following disciplines can be involved: structural engineering, construction engineering, architectural engineering, mechanical engineering, electrical engineering, environmental engineering, hydraulic engineering, traffic engineering, materials engineering, urban engineering, logistics engineering, and systems engineering.

Out of a selection of functional requirements, the conceptual design team creates rough system outlines. Customary, this creation is just a composition of basic structural forms on object level. More innovative structural design, however, requires a system creation on aspect level.

The rough system outlines that only comply with the requirements are so-called “performance-based” solutions. Supplementary added value solutions offer a considerable added value for a relatively small cost increase.

The structural engineering activities, which can be distinguished during the creation of a system outline, are listed in table 19.2.

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<th>Professional structural engineering activities</th>
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<td>A.6</td>
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Table 19.2: Creation of a system outline
19.3.2 A.1) Determination of fundamental requirements

Any coherent and reasonable project must have requirements that define what the system is ultimately supposed to do. The initiation phase results in functional requirements, which have to be met during the life cycle of the structure. With regard to structural engineering, the functional requirements are particularly prominent during the creation of a system outline.

The following functional requirements can be distinguished and are characterised in table 19.3: performance requirements, interface requirements, aspect requirements, and prerequisite constraints.

<table>
<thead>
<tr>
<th>Functional requirements</th>
<th>Types of requirements</th>
<th>Characteristic requirements</th>
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<tbody>
<tr>
<td>Performance requirements:</td>
<td>directly contributing to the primary function</td>
<td>- To bear or to resist: qualification and quantification</td>
</tr>
<tr>
<td>Interface requirements</td>
<td></td>
<td>- Interfaces with the adjacent built environment</td>
</tr>
<tr>
<td>Aspect requirements:</td>
<td>specific requirements not directly contributing to the primary functions</td>
<td>- Architecture</td>
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<td>- Construction</td>
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<td>- Life cycle</td>
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<td>- Environment</td>
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<td>RAMS:</td>
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<td></td>
<td></td>
<td>- Reliability</td>
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<td>- Availability</td>
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<td></td>
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<td>- Maintainability</td>
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<td>- Safety</td>
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<tr>
<td>Prerequisite constraints:</td>
<td>explicit constraints of the solubility space</td>
<td>- Planning</td>
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<td></td>
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<td>- Costs</td>
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<td>- Legislation</td>
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<td>- Available technologies</td>
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Table 19.3: Functional requirements
For an effective performance/cost control during conceptual design, the following directives with regard to the functional requirements are recommendable:

1. An as-low-as-possible number of functional requirements, with a focus on required performances.

2. An as-high-as-possible level of functional requirements, on system level and preferably independent of economical cycles.

3. SMART quantification of the individual functional requirements:
   S = Specific, clear and unequivocal
   M = Measurable, verifiable
   A = Acceptable
   R = Realistic
   T = Time related

The conceptual design team evaluates the contractual commitments, and particularly the complete set of functional requirements, in order to determine a workable reduced set of fundamental functional requirements: presumably dominant, required performances and aspects including interfaces with the adjacent built environment and prerequisite constraints.

The so-determined set of fundamental functional requirements will be the starting point of the creation of system outlines.

19.3.3 A.2) Secure and optimise structural needs

Fundamental structural demand determines the three-dimensional outline of materialised load paths, based upon the fundamental functional requirements: dominant loads, points of support, free-space profiles, load-path geometry, equilibrium and deformation, materialisation and global dimensioning, and design of principal structural details.

For a simple and clear determination and optimisation of the load paths, an axial force-based analysis is appropriate: truss and tied arch analogy.
19.3.4 A.3) Facilitate interfaces built environment

The determined set of fundamental functional requirements directs the structural demand and its most influential interfaces with the built environment: construction demand and performance demand.

**Construction demand**  Design engineers optimise the cost drivers of the scheme to be executed. The cost optimisation of the execution is implicitly part of the life cycle costs and is, among other things, dependent on location and individual contractor. The practical feasibility of the execution focuses on avoiding unnecessary complexity, on influences on dimensions and tolerances, and on possible choices between alternatives.

Construction demand determines the influence of construction on structural form, material, dimension, and principal details: material demand of temporary structures, equipment demand, manpower demand, and time demand.

**Performance demand**  As with construction demand, performance demand determines the influence of required performances on structural form, material, dimension, and principal details:

**Functional reliability**  Heat, Ventilation, and Air-Conditioning (HVAC).

**Structural reliability**  Required minimum is the reliability-level design codes of practice.

**Redundancy**  Design a second method of support to ensure that the forces are dispersed elsewhere when a vital structural component can give way.

**Architectural demand**  The demanded specific architectural expression of buildings and bridges have to be translated into a materialised structural form.
19.3 A) Creation of a system outline

Flexibility  Predict new functions and take possible function changes into account.

Durability  The ability of a structure, its parts and materials to perform its required functions over a period of time without unforeseen need for maintenance.

Maintainability  The ease and speed with which a structure can be restored to operational status after a failure occurs.

Sustainability  Minimise the negative environmental impact by enhancing efficiency and moderation in the use of materials and energy.

Demolition  Foundation methods and reuse of structural materials.

19.3.5  A.4) Design of principal details

Principal details are in general details that strongly dictate costs and/or the architectural expression of a structure.

Structural engineering is primarily focused on structural reliability. In an integral design process, however, principal details are determined by an optimisation of all influential design parameters: constructability, structural reliability, redundancy, architectural expression, durability, maintainability, and sustainability.

19.3.6  A.5) Variant study of performance-based solutions

An effective selection process requires a variety of integral concepts and numerous performance-based solutions; each future, necessary design loop demands for alternatives to fall back upon.

The outcome of the conceptual design is a set of performance-based and possibly added-value solutions for a more profound structural analysis and further dimensioning during the optimisation of the structural action.
The selection of this set of performance-based solutions is based on an optimisation of the performance/cost ratio, preferably with regard to the entire life cycle.

The performance/cost ratio is the main driver for the overall optimisation of structural design. For this purpose, it is a necessity that all performances can be quantified into costs. Besides structural demand, the commonly most influential parameters are: architectural demand, construction demand, and durability.

Awareness of the order of magnitude of life cycle costs, implicitly related to all involved disciplines, is of great importance.

An early assessment of particularly durability in design is very important in the decision to invest and in achieving long-term value-for-money.

19.3.7 A.6) Specification and risk analysis

The specification of a concept demarcates the concerning project phase. Dependent on the contractual arrangement, this specification can be used as internal transfer documentation or for a tender. In both cases, a risk analysis of the specified material demand is essential.

A risk analysis of the material demand gives an accuracy estimate of material quantities and corresponding unit cost indications. The analysis has to be executed on the level of individual components of a decomposed system, principal details included.

For an effective analysis the following data have to be determined: performed analysis, uncertainties, coverage by conceptual dimensioning, and reserves and optimisations.

A risk analysis of the material demand is not general, structural engineering practice, although the benefits are obvious.
19.4 B) Optimisation of the structural action

19.4.1 From performance-based solutions to design

A fundamental set of functional requirements and the concerning disciplines have been contributed to integral performance-based solutions.

Per individual discipline, a thorough check of these integral system outlines, optimisation analyses and further dimensioning have to be performed.

An analysis of the structural action is based on modelling with a simplified representation of load distribution and strength so that the order of magnitude of paramount loads and capacity can be determined.

An effective analysis and optimisation requires a profound insight into the behaviour of the structural system, based upon fundamental structural action parameters and underlying structural phenomena.

The outcome of the optimisation of the structural action, and particularly an overall structural system check, can lead to the necessity of a system re-design.

The structural engineering activities that can be distinguished during the optimisation of the structural action are listed in table 19.4.

<table>
<thead>
<tr>
<th>Professional structural engineering</th>
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<tr>
<td>Structural engineering activities</td>
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<tr>
<td>B.1 Structural system analysis and modelling</td>
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<td>B.2 Load distribution analysis</td>
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<td>B.3 Optimisation of parallel load distribution</td>
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<td>B.4 Analysis of failure mechanisms and dimensioning of elements</td>
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<td>B.5 Structural variant study</td>
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<td>B.6 Overall structural system check</td>
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Table 19.4: Optimisation of the structural action
19.4.2 B.1) Structural system analysis and modelling

A fundamental insight into the behaviour of the structural system requires a solution strategy with regard to analysis and modelling: an effective decomposition and appropriate analysis tools.

**Modelling**  Due to the complexity of material behaviour, structural analysis is completely dependent on abstract representations of the actual structure.

As an abstract representation, modelling has its limitations. For a reliable application of structural modelling, awareness of these limitations is of great importance; for example, when shear deformation is dominant.

**Physical decomposition**  Decomposition of a problem into various sub-problems can diminish the level of complexity. The optimality condition is a minimum of interaction between the section interfaces.

Physical decomposition follows the physical parts of a structure. Because we can easily identify physical parts, it is a very natural way of decomposition, usually in planar structural forms.

Basic planar structural forms are frame, floor slab, cable-stayed beam, truss, arch, and shear wall.

**Structural analysis**  To perform an accurate analysis, the structural engineer must determine information about structural loads, geometry, material properties and support conditions. The results of such an analysis typically include support reactions, member forces, and displacements. This information is then compared to criteria that indicate the conditions of failure.

Hand calculations of the structural action are based on analytical formulations that mostly apply to simple linear-elastic and ideal-plastic
analysis models.

Computer calculations of the structural action are generally based on the finite element method, including the most commonly used displacement method. It is a numerical method generated by theories of mechanics and is applicable to structures of arbitrary size and complexity. The finite element method also helps in producing stiffness and strength visualisations.

Regardless of approach, the formulation is based on the same three fundamental relations of equilibrium, constitutive - stress-strain relationship, and compatibility - strength and stiffness transfer between elements. The solutions are approximate when any of these relations are only approximately satisfied, or an approximation of reality.

For standard structural systems, an automated linear-elastic load distribution analysis is customary:

**2-D Frame** Two-dimensional framework calculation.
For most buildings this will normally be sufficient; high-rise buildings and civil structures, however, may need a more thorough load distribution analysis.

**3-D Frame** Three-dimensional framework calculation, including overall torsion effects.

**FEM Stress** For analysis on stress level, two- and three-dimensional finite elements are applicable.

The load-carrying capacity parameters of the individual elements are incorporated in the rules of the applicable design codes; two-dimensional action, non-linear behaviour, including stability, fatigue, and prevention of dynamic response.

Advanced structural analysis may examine:

**Dynamic analysis** Natural frequencies and frequency response.

**Geometric non-linear analysis of second-order behaviour**
Linear stress-strain relationship and large displacements.
Material non-linear analysis of plastic load-carrying capacity
Non-linear stress-strain relationship and small displacements.

Induced deformation analysis of the structure Based upon geo-
technical failure mechanisms and corresponding deformations.

Applied mechanics For both load distribution in a structural system
and load-carrying capacity of materialised structural elements, applied
mechanics are the main means for modelling structural behaviour:

Forces Newton’s laws, equilibrium, and internal and external forces.

Stress-strain relations and deformation Geometric section proper-
ties, elastic bending relationships, shear-stress distribution, beam
bending and deflection formulae, work and strain energy, and plastic
deforation and redistribution.

Continuous structures Force or flexibility method, displacement or
stiffness method, and finite element method.

Special topics Elastic bedded structures, structural dynamics, and frac-
ture mechanics.

Applied mathematics Applied mathematics facilitates other domains
such as physics in general, and applied mechanics in particular, with
mathematical techniques for the required abstraction and logical reason-
ing:

Calculus Differentiation, integration, and differential equation.

Linear algebra Gaussian elimination, determinant and inverse matrix
calculation.

19.4.3 B.2) Load distribution analysis

Every system will be loaded by primary loads, mostly variable actions, as
a result of the functional requirements: floor, traffic, hydraulic (including
ground water), and soil loading.

When materialising the system, the self-weight of the structure and other secondary loads will be unavoidably supplemented: weight, wind, temperature, and induced deformation.

The determination of the real expected loading for each design is an endless exercise. The loads and load combinations in a design code of practice are a conservative approximation of the real expected loading. These code-prescribed quasi-static loads and combinations can be simplified to a set of approximate quasi-static basic design loads. In case of possible decisive dynamic loading, dynamic analysis is appropriate.

The loads on the system will be distributed within the system over the individual elements. Depending on the degree of statical indeterminacy, this distribution will be determined by strength and/or stiffness.

The further distribution of the load within an individual element, on detailed level, will be on the level of stress and strain. Due to a high degree of statical indeterminacy within an element - although this expression is only applied for the load distribution between elements - the stress distribution in an element is proportional to the stiffness distribution, which is inversely proportional to the strains.

19.4.4 B.3) Optimisation of parallel load distribution

An assembly of directly connected elements is defined as statically determinate when the static equilibrium equations are sufficient for determining the internal forces and reactions. Consequently, the behaviour is completely force-driven.

When the static equilibrium equations are not sufficient for determining the internal forces and reactions on the structure, a difference in deformation will influence the load distribution. Consequently, the parallel load distribution in these statically indeterminate structures can be deformation-driven, besides force-driven.
Nowadays, a lot of structures are statically indeterminate out of economical efficiency and redundancy considerations. The optimisation of the parallel load distribution is a main factor in the optimisation of the performance/cost ratio. Focusing on the equilibrium will produce a safe design but not necessarily an efficient one from an economical point of view.

Deformation-driven structural action parameters:

**Deformation** Normal, bending and shear deformation, and strain energy.

**Stability** Stability of the equilibrium, buckling, lateral torsional buckling, and plate buckling.

**Parallel load distribution** Parallel bending, shear and axial force, redistribution, redundancy, and induced deformation.

### 19.4.5 B.4) Analysis of failure mechanisms

The results of the foregoing load distribution analysis will be compared to criteria that indicate the conditions of failure: when the loading reaches the ultimate strength of the material, a failure mechanism will occur resulting in a collapse of the element.

This comparison between loading and required strength, provides approximated required section properties.

**Dimensioning approximations** In order to meet the required sections properties, the actually approximated dimensioning can be executed:

**Standard structures based** The approximate dimensioning rules contain only variables of the overall geometry of the structure, and particularly the span. Irregular structures with irregular loads are not covered by the field of application of this simplified dimensioning.
19.4 B) Optimisation of the structural action

**Applied mechanics based** The approximate dimensioning formulas will be based upon applied mechanics with correction factors based on research, available through background documents of design codes of practice. The use of applied-mechanics formulas implies the influence of both geometry and load. Furthermore, it provides a fundamental insight into the structural phenomena.

**Code check based** Trial and error procedure, involving repeated use of automated framework calculation of the load distribution and post processed code checking. Drawback of this procedure is the black-box character with regard to the fundamental structural action.

**Analysis of failure mechanisms and dimensioning** The analysis of failure mechanisms and the subsequent approximate dimensioning of the materialised structures include the following subjects:

**Material properties** Concrete, structural steel, reinforcing steel, prestressing steel and connecting devices, timber, masonry, and soil and rock.

**Effects of deformation** Shrinkage, creep and relaxation.

**Classification and analysis of structures** A braced system, an unbraced system, and a bracing system.

**Cross-sections** Tension, compression and bending, shear and torsion, and combined bending, shear and axial force.

**Members in compression** Buckling, lateral torsional buckling, combined axial compression, and bending and arch buckling.

**Flat slabs and plates** Effective width for elastic shear lag, effective width for plate buckling, and punching shear.

**Joints** Joint reinforcement details of concrete elements, connections for concrete precast elements, structural joints connecting steel H or I sections, steel hollow section joints, and glued and mechanically jointed timber elements.
Geotechnical structures  Shallow foundation, bearing pile foundation, tension element, retaining wall (horizontal loading $\perp$ plane, || plane and vertical loading), reinforced soil structures, influence of construction activities on the geotechnical environment, and influence of geotechnical construction activities on the structural environment.

Structural fire design  Fire exposure and design resistance of members at elevated temperatures.

Fatigue  Traffic data, S-N curves and load models, internal forces and stresses for fatigue verification, and damage equivalent stresses for fatigue verification.

19.4.6  B.5) Structural variant study

A selection of a structural design, out of the performance-based solutions, is based upon the foregoing analysis and optimisation of the structural action and implicitly the performance/cost ratio.

During the optimisation per discipline, the interfaces with the other participants in the integral design process have to be reviewed.

19.4.7  B.6) Overall structural system check

Before the selected structural design can be submitted to final dimensioning and specification, the following overall structural system checks have to be executed: does the design meet the client’s complete set of functional requirements and is the reliability of the overall structural system covered by the foregoing analysis?

Complete set of functional requirements  Foregoing creation and optimisation of the structural system are based upon a workable reduced set of fundamental functional requirements. The presumed dominancy of the applied requirements has to be checked with the complete set of functional requirements.
Reliability of the overall structural system  When the structural system and/or the structural action is complex to extraordinary complex, the effectiveness of the applied decomposition and structural analysis has to be verified. An approximated check, with a simplified model of the overall system behaviour has to be carried out, based upon the build up design-specific knowledge.

19.5 C) Final dimensioning and specification

19.5.1 From design to specification

During final dimensioning, the selected structural design is subject to an automated trial and error fine-tuning and final check with an applied-mechanics calculation of the load distribution and the displacements in combination with a post-processed code check.

Levels of load distribution analysis and code check:

2-D Frame  Two-dimensional framework calculation of the load distribution and post-processed code check.

3-D Frame  Three-dimensional framework calculation of the load distribution and post-processed code check.

FEM Stress distribution  Finite Elements calculation of the load distribution on stress level and post-processed code check.

FEM Stress strength  Finite Elements calculation on stress level for both load distribution and material strength; code checking is no longer applicable.

Major design decisions with regard to constructability and the performance/cost ratio have been made during the creation of the system outline, and some during the optimisation of the structural action. Even during final dimensioning a major deficiency, leading to an inevitable adjustment of the structural action or even the system outline, may occur.
In an effective converging process, however, the number of optimisation loops will diminish during the process of further specification.

The structural engineering activities that can be distinguished during the final dimensioning and specification are listed in table 19.5.

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<th>Professional structural engineering</th>
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<td>Structural engineering activities</td>
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Table 19.5: Final dimensioning and specification

19.5.2 C.1) Loads and load combinations

The loads and load combinations in a design code of practice are a conservative approximation of the real expected loading.

If a structural model is linear, the principle of superposition can be applied. After the section forces for each load case are computed, each load combination can be linearly superposed.

19.5.3 C.2) Load distribution and displacements

Common practice is an automated applied-mechanics calculation of the load distribution and the displacements:
Ultimate limit state Forces per element and stresses within an element.

Serviceability limit state Vertical deflections, horizontal deflections, and dynamic effects.

19.5.4 C.3-C.8) Code check and detail dimensioning

Common practice is an automated post-processed code check and detail dimensioning.

General index, with reference to the applicable codes: material properties, structural modelling for analysis, ultimate limit states, serviceability limit states, and structural detailing, including common constructability.

19.5.5 C.9) Specification and monitoring

For a transfer from the structural design to the construction phase, the following deliverables are required: material specification and geometrical specification (fabrication drawings).

The precise geometrical specification is input for a geometrical validation: a free space profile and a clash-check analysis.

During the life cycle of the structure, performance quality has to be insured: monitoring and control of determinate parameters.

19.6 D) Process management

19.6.1 Structural engineering process management

The structural engineering activities, which can be distinguished during an effective control of the structural engineering process, are listed in table 19.6.
Professional structural engineering

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<th>Structural engineering activities</th>
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Table 19.6: Process management

19.6.2 D.1) Problem-solving management

Problem solving requires a practical solution-driven academic attitude, analytical skills, creativity, and applied research as a fundamental tool in the professional field.

Applied research can be defined as an objective and systematic search for solutions to present or foreseen practical problems. Successfully applied research requires a methodical approach of the research activity. Research methodology is a systematic way to solve a problem with procedures by which researchers go about their work of describing, explaining, and predicting phenomena with the help of analytical, experimental, and simulation methods.

The methods and strategies by which researchers can effectively direct their activities toward the achievement of objectives include academic attitude, problem definition, research framework, research methodology, modelling, lateral thinking, and academic communication.

19.6.3 D.2) Project management

Project management is a carefully planned and organised effort to accomplish a specific and usually one-time objective, for example constructing a building. Project management includes developing a project plan, which includes defining and confirming the project goals and objectives, identifying tasks and how goals will be achieved, quantifying the resources
needed, and determining budgets and timelines for completion.

The methods and strategies by which project teams can effectively direct their activities toward the achievement of objectives include communication and presentation, information management, quality management, project planning and monitoring, risk management, team work and decision-making, and system theories in engineering.

System theories in engineering include systems engineering, concurrent engineering, collaborative engineering, expert systems, and stochastic search techniques.

19.6.4 D.3) Self-management

Self-management is about planning professional development that will involve setting short-range and long-range goals, and investigating different ways to reach these goals. Education, training, and experience help make goals become a reality. To achieve goals, choose the best path and make a commitment to it, while remaining flexible enough to deal with changes and new opportunities.

The methods and strategies by which individuals can effectively direct their own activities toward the achievement of objectives include time management, being proactive, goal setting and prioritisation, seeking and actively using feedback, continued professional development, making judgments, adjustment capacity, and taking account of the environmental context one is operating within.

19.7 Body of knowledge

19.7.1 General

The body of knowledge is a term used to represent the complete set of activities, concepts and terms that make up a professional domain.
A description of the professional activities in combination with the applicable design tools and knowledge sources is an effective abstract of the body of knowledge of professional structural engineering.

A differentiation of this body of knowledge per professional level - undergraduate entry professional, graduate entry professional, and expert professional - outlines the particular corresponding professional bodies of knowledge.

19.7.2 Body of knowledge creation of a system outline

Structural engineering activities The structural engineering activities, which can be distinguished during the creation of a system outline, are listed in table 19.2 on page 239.

Levels of comprehension The following levels of comprehension of the integral design process can be distinguished:

Awareness of the process and its participants.

Qualification of parameters and interrelations with the help of expressing algorithms; flow charts with a natural language or pseudo code.

Quantification of parameters and interrelations with the help of calculation algorithms; flow charts with mathematical functions and a numbered answer.

Knowledge sources The overall process of an integral design is only superficially available by means of publications; mainly by involved participants such as public authorities and main contractors. Especially, the benefits of this method of working are elaborately highlighted.

The knowledge of the mainly experience and intuition-based expert conceptual structural design practitioners is only accidentally and fragmentedly accessible for professionals and higher education programmes.
19.7 Body of knowledge

19.7.3 Body of knowledge structural action

Structural engineering activities The structural engineering activities, which can be distinguished during the optimisation of the structural action, are listed in table 19.4 on page 245. The structural engineering activities, which can be distinguished during the final dimensioning and specification, are listed in table 19.5 on page 254.

Levels of structural complexity The level of structural complexity is best measured by the complexity of the structural action, with respect to geometry, loads, load distribution, and failure mechanisms.

Levels of complexity of the structural action: simple structural action, medium structural action, complex structural action, and extraordinary complex structural action.

Complexity of structures The level of complexity of the structural action is, to some extent, related to corresponding structures:

Simple structural action Single-storey frame buildings.


Complex structural action Unbraced multi-storey buildings, medium-span bridges, and water/ground barriers.

Extraordinary complex structural action High-rise buildings, large-span bridges, storm surge barriers, underground structures, and off-shore structures.

Complexity of the structural analysis The level of complexity of the structural action is evidently directly related to the required level of structural analysis and modelling: approximate manual analysis, two-dimensional framework analysis, three-dimensional framework analysis, and two- and three-dimensional finite elements analysis.
Knowledge sources  The following knowledge sources are available:

Textbook material  Textbooks applied-mathematics, textbooks applied-mechanics, and structural materials related textbooks by the concerning trade organisations.

Research material  Educational research material and professional publications.

Design codes of practice  Structural design codes of practice and related background documents.

19.7.4  Body of knowledge process management

Structural engineering activities  The structural engineering activities, which can be distinguished during an effective control of the structural engineering process, are listed in table 19.6 on page 256.

Levels of complexity of process management activities  Most engineering activities with respect to project control and personal development are ultimately related to process control.

Levels of complexity of process control: simple process control, medium process control, complex process control, and extraordinary complex process control.

Knowledge sources  The following knowledge sources are available:

Textbook material  Basic to advanced textbook material of process and research management methods and strategies.

Research material  Educational research material on system theories in general, and systems engineering and building information modelling in particular.
19.7.5 Complexity of structural engineering activities

The complexity of design activities and the corresponding necessity of professional profundity vary considerably per design activity creation of a system outline, optimisation of the structural action, and final dimensioning and specification as listed in table 19.7.

<table>
<thead>
<tr>
<th>Activities</th>
<th>Degree of complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Creation of a system outline</td>
<td>The creation of a system outline requires a high level of abstraction and a corresponding level of professional expertise and ample experience with regard to fundamental understanding of the structural action and the numerous interfaces with the built environment.</td>
</tr>
<tr>
<td>Optimisation of the structural action</td>
<td>An optimisation of the structural action requires a medium to high level of abstraction and a corresponding level of professional expertise and experience with regard to profound understanding of the structural action.</td>
</tr>
<tr>
<td>Final dimensioning and specification</td>
<td>Final dimensioning and specification requires a low level of abstraction and a corresponding level of professional depth. The present-day complex final dimensioning and code checking is an automated fine-tuning routine.</td>
</tr>
</tbody>
</table>

Table 19.7: Complexity of structural engineering

19.7.6 Professional levels

With regard to structural engineering the following professional levels can be distinguished:

- Entry professional on vocational education and training level.
• Entry professional on undergraduate bachelor level.
• Entry professional on graduate master level.
• Professional expert.

Entry professional on vocational education and training level
The vocational education and training focuses mainly on the material and geometrical specification of the structure during design, construction, and maintenance.

Entry professional on undergraduate bachelor level
The focus of a bachelor education is on the standard parameters of structural engineering and can vary from a more profound knowledge of structural action to a more profound practice of the numerous automated standard engineering tools.

Contrary to the vocational education and training, the bachelor computer-aided drafting and design programme focuses more on visual design communication, rather than specification for construction and as-built.

Entry professional on graduate master level
Generally, a professional master focuses more on a direct practical relevance and a master of science focuses on an in-depth academic research relevance.

Within both professional and science graduate education, the focus can vary from extensive and profound understanding of all the fundamental parameters of the structural action of standard structures, to extraordinary structural action parameters of complex structures.

Professional expert
The professional expert experience is on the level of complex to extraordinary complex structures with complex to extraordinary complex structural action parameters.
The required knowledge is obtained by experience, self-education, and post-master courses.

19.7.7 Body of knowledge scheme

The body of knowledge scheme as listed in table 19.8 presents the structural engineering activities in combination with the applicable levels of knowledge and the knowledge sources per professional level.
<table>
<thead>
<tr>
<th>Body of knowledge of professional structural engineering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undergraduate entry professional</td>
</tr>
</tbody>
</table>

**Creation of a system outline: Integral design process**

- **Knowledge level:**
  - Awareness
  - Integral design process

- **Knowledge source:**
  - Open mind observations

**Optimisation of the structural action: Structural action**

- **Knowledge level:**
  - Medium structural action

- **Knowledge source:**
  - Textbook material

**Final dimensioning and specification: Design codes of practice**

- **Knowledge level:**
  - Superficial knowledge of codes of practice

- **Knowledge source:**
  - Calculation examples

---

Table 19.8: Body of knowledge per professional level
Chapter 20

Material demand for conceptual design

20.1 Validation of the physical decomposition

20.1.1 2-D material demand

As a major solution component of the proposed methodical approach, validation of the physical decomposition, and in particular the distinction in two-dimensional basic structural forms, is essential. On this two-dimensional subsystem level, the material demand of an example is modelled with the help of design diagrams.

For a cable-stayed beam, the conceptual structural design parameters concerning minimising the material demand are presented in design diagrams with regard to span, load, and material strength.

This method is meant as a variable and customisable design tool for experienced structural engineers rather than a set of standard diagrams for designers, whether architects or inexperienced structural engineers.
20.1.2 Conclusion 2-D material demand

Primary goal of this validation is the viability of two-dimensional structural forms; secondary goal is testing the underlying design approximations in the form of conceptual structural design parameters of load distribution and failure mechanisms.

Viability basic structural forms The viability of structural forms on a two-dimensional subsystem level can be effectively researched with the application of material demand-based conceptual design diagrams. Normative for this viability is the degree of insight into, and optimisation of the structural form with respect to the structural action.

The design diagrams are based on a structural analysis of strength, deformation, and sensitivity to non-uniform loads. They generate an optimised material demand regarding system outline, refined configuration, and material grade.

Accuracy of the underlying design approximations The required accuracy of the conceptual structural design approximations is ±20% as listed in table 10.5 on page 125.

The sectional strength-related, basic applied mechanics-based, design approximations have an accuracy far within this required ±20%.

The stability related design approximations, however, are more difficult to capture. Probably the most sensitive is the buckling design approximation. The accuracy amounts to ±30% for common steel grade S355, in combination with common buckling curve b as listed in table 17.2 on page 217.

Lateral torsional buckling with the help of buckling of the compressed flange: $\lambda \approx 30$ with a deviation of circa +10% due to the inaccuracy of the buckling design approximation, in combination with the negation of the positive torsional effects with a deviation of less then -20%. 
20.2 Validity boundaries

20.1.3 Conclusion validation physical decomposition

The physical decomposition into two-dimensional structural forms shows a viable insight into, and optimisation of the structural forms with respect to the structural action.

The underlying conceptual design approximations have an adequate accuracy except for the buckling strength-related conceptual design approximations.

20.2 Validity boundaries

20.2.1 Minimisation of the material demand

For a first conceptual analysis of the configuration of a cable-stayed beam, an insight into basic structural action and corresponding material demand is necessary, both for the Ultimate Limit State (ULS) and the Serviceability Limit State (SLS).

Optimising the material demand with regard to structural action is minimising the material demand per span length as a function of total span, uniform load, and material strength:

\[
\frac{Vol}{l_{span}} \propto \frac{q_{dl_{span}}}{f_d} \tag{20.1}
\]

20.2.2 Standardisation

In order to compare the individual material demands, the following has to be standardised:

- Fixed height/span ratios.
- Standardised sections for individual elements.
• Uniform loading and a quick sensitivity study for non-uniform loading.

• The calculations will be carried out with approximate design rules rather than accurate code checking.

20.2.3 Choice of cross-section

When the structural action is dominant over the interfaces with the built environment such as with large spans, rectangular hollow sections are quite effective and common structural elements. For elements in tension, compression, and combined bending and axial compression, square Rectangular Hollow Sections (RHS) are representative conceptual design elements.

For elements under dominant bending such as the continuous beam in a symmetrical configuration, prismatic I-beams are more effective.

20.3 Capacity of main span elements

20.3.1 Section properties of a square RHS

The section properties of a square RHS, with approximations based on a relatively small wall thickness, are given in figure 20.1.

\[
\begin{align*}
A & \approx 4ht \\
I & \approx \frac{2}{3} h^3 t \approx \frac{1}{6} Ah^2 \\
W & \approx \frac{4}{3} h^2 t \approx \frac{1}{3} Ah
\end{align*}
\]

Figure 20.1: Section properties of a square RHS
20.3.2 Transition slenderness of a square RHS

The slenderness $\lambda_{el} = \frac{l_{el}}{h}$, with the axial strength equalling the buckling strength, defines the transition between both failure mechanisms.

Axial strength:

$$N_u = A \cdot f_d$$

(20.2)

Buckling strength of an element in a braced structure:

$$N_u \approx 1.7 \cdot \frac{\pi^2 EI}{L_{cr}^2} \approx 1.7 \cdot \frac{\pi^2 EI}{l_{el}^2}$$

(20.3)

Transition slenderness $\lambda_{el,trans}$ square RHS:

$$A \cdot f_d \approx 1.7 \cdot \frac{\pi^2 EI}{l_{el}^2} \approx 1.7 \cdot \frac{\pi^2 E \cdot \frac{1}{6}Ah^2}{l_{el}^2} = 1.7 \cdot \frac{\pi^2 E \cdot \frac{1}{6}A}{\lambda_{el}^2}$$

$$\Rightarrow \lambda_{el,trans} = \frac{l_{el}}{h} = 1.0 \sqrt{\frac{E}{f_d}} \approx \sqrt{\frac{E}{f_d}}$$

(20.4)

20.3.3 Required section area

The required section area of a square RHS with regard to buckling strength can be determined by the required moment of inertia:

$$I \geq N_d \cdot 1.7 \cdot \frac{l_{el}^2}{\pi^2 E} \quad \text{with} \quad I = \frac{1}{6}Ah^2$$

$$\Rightarrow A = N_d \cdot \frac{1.7 \cdot l_{el}^2}{\pi^2 E} \cdot \frac{6}{h^2}$$

(20.5)
20.4 Material demand cable-stayed fixed

20.4.1 Cable-stayed beam with fixed foundation

A fixed foundation as shown in figure 20.2 stabilises the individual floor elements supported by the connected cables. Consequently, each floor element can be designed as a simply supported beam.

Replacing the individual floor elements by a beam spanning the whole \( l_{\text{span}} \) can be done for reasons of optimisation, but is not a structural necessity.

The additional costs of a fixed foundation, often based on gravity, are not a negligible factor and have to be taken into account separately.
20.4.2 Material demand of the cables in the ULS

The mid-section cable will be taken as a representative for the entire cable configuration:

\[
Vol_{\text{mid\,section}} = \frac{N_d}{f_d} \cdot l_{\text{cable}} = \frac{\sqrt{2}}{f_d} \cdot \frac{\frac{1}{10} q_d l_{\text{span}}}{f_d} \cdot \frac{1}{2} l_{\text{span}} \sqrt{2} = \frac{1}{10} \frac{q_d l_{\text{span}}^2}{f_d}
\]

\[
\Rightarrow \frac{Vol_{\text{cables}}}{l_{\text{span}}} = \frac{Vol_{\text{mid\,section}}}{\frac{1}{10} l_{\text{span}}} = \frac{q_d l_{\text{span}}}{f_d} \quad (20.6)
\]

When designing smaller configurations, efficiency considerations could lead to a uniform cable diameter based on the maximum required section area and mean cable length \(\frac{1}{2} l_{\text{span}} \sqrt{2}\):

\[
Vol_{\text{mid\,section}} = \frac{N_{d,\text{max}}}{f_d} \cdot l_{\text{cable}} = 2 \sqrt{\left(\frac{9}{10}\right)^2 + \left(\frac{1}{2}\right)^2} \cdot \frac{1}{10} q_d l_{\text{span}} \cdot \frac{1}{2} l_{\text{span}} \sqrt{2} = \frac{\sqrt{53}}{5} \frac{q_d l_{\text{span}}^2}{f_d}
\]

\[
\Rightarrow \frac{Vol_{\text{cables}}}{l_{\text{span}}} = \frac{Vol_{\text{mid\,section}}}{\frac{1}{10} l_{\text{span}}} = \frac{\sqrt{53}}{5} \frac{q_d l_{\text{span}}}{f_d} = 1.5 \frac{q_d l_{\text{span}}}{f_d} \quad (20.7)
\]

20.4.3 Material demand of the pylon in the ULS

For the strength of the pylon, both sectional strength and buckling strength can be decisive.

Sectional strength decisive:

\[
Vol_{\text{pylon}} = \frac{N_d}{f_d} \cdot l_{\text{pylon}} = q_d l_{\text{span}} \cdot \frac{1}{2} l_{\text{span}} = \frac{1}{2} \frac{q_d l_{\text{span}}^2}{f_d}
\]

\[
\Rightarrow \frac{Vol_{\text{pylon}}}{l_{\text{span}}} = \frac{1}{2} \frac{q_d l_{\text{span}}}{f_d} \quad (20.8)
\]
Buckling strength decisive:

\[
\text{For } Vol_{pylon} = \frac{l_{pylon}}{h_{pylon}} \geq \sqrt{\frac{E}{f_d}} : \\
\frac{Vol_{pylon}}{l_{span}} = \frac{A \cdot \frac{1}{3} l_{span}}{l_{span}} = \frac{1}{2} A = \frac{1}{2} N_d \cdot \frac{1.7 \cdot l_{pylon}^2}{\pi^2 E} \cdot \frac{6}{h_{pylon}^2} \\
= \frac{1}{2} q_{d \cdot l_{span}} \cdot \frac{\lambda_{pylon}^2}{E} \cdot \frac{1.7 \cdot 6}{\pi^2} = 0.5 \lambda_{pylon}^2 \frac{q_{d \cdot l_{span}}}{E}
\]

(20.9)

20.4.4 Material demand of the floor elements in the ULS

Primarily, the floor elements have to resist the bending moments as a direct result of the uniform load; secondarily, they have to resist the compression due to the global load distribution of the cable-stayed sub-system.

Material demand floor elements with respect to bending:

\[
W \geq \frac{1}{8} \frac{q d \cdot \left(\frac{1}{10} l_{span}\right)^2}{f} \quad \text{with } W = \frac{1}{3} A h
\]

\[
\Rightarrow \frac{Vol_{floor}}{l_{span}} = A = \frac{3}{80} \frac{q_d l_{span}}{f_d} \lambda_{floor} \quad \text{with } \lambda_{floor} = \frac{\frac{1}{10} l_{span}}{h}
\]

If \( \lambda_{floor} = 20 \) then

\[
\frac{Vol_{floor}}{l_{span}} = \frac{60}{80} \frac{q_d l_{span}}{f_d} = 0.8 \frac{q_d l_{span}}{f_d}
\]

(20.10)

For the material demand of the compression in the floor, the mean cumulative compression will be determined as a representative for the entire floor: the individual resulting horizontal cable forces, namely 0, 1.8, 1.6, 1.4, 1.2, 1.0, 0.8, 0.6, 0.4, and 0.2 \( \frac{1}{10} q_d l_{span} \), with corresponding cumulative compression in the floor elements, namely 0, 1.8, 3.4, 4.8, 6.0, 7.0, 7.8, 8.4, 8.8, and 9.0 \( \frac{1}{10} q_d l_{span} \), result in a mean cumulative compression of 5.7 \( \frac{1}{10} q_d l_{span} \).
Due to the required bending capacity of the floor elements, the transition slenderness will not easily be exceeded; consequently, the sectional strength will be decisive.

Material demand of the floor elements with respect to compression:

\[
\frac{Vol_{floor}}{l_{span}} = A = \frac{5.7 \cdot \frac{1}{10} q_d l_{span}}{f_d} = 0.6 \frac{q_d l_{span}}{f_d}
\]  

(20.11)

For the combination of the approximately equal bending and compression material demand, the structural action in the cross-sectional area can be optimised by allocating both web sides of the RHS section to compression capacity and both flange sides of the RHS section to an optimal bending capacity, resulting in an improvement of the section modulus \( W \) of 1.5.

Material demand of the floor elements with respect to combined bending and compression:

\[
\frac{Vol_{floor}}{l_{span}} = \left( \frac{1}{1.5} \cdot 0.8 + 0.6 \right) \frac{1}{10} \frac{q_d l_{span}}{f_d} = 1.1 \frac{q_d l_{span}}{f_d}
\]  

(20.12)

### 20.4.5 Material demand of the cables in the SLS

The elongation of the mid-section cable will be taken as a representative for the displacement of the floor; due to the elongation of the equilibrium cable the displacement of the floor will approximately be doubled:

\[
\delta_{max} = 2\sqrt{2} \frac{N l_{cable}}{EA} = 2\sqrt{2} \left( \sqrt{2} \frac{1}{10} q_k l_{span} \right) \cdot \left( \frac{1}{2} l_{span} \sqrt{2} \right) \leq \delta \cdot l_{span}
\]

with displacement ratio \( \delta = \frac{\delta_{max}}{l_{span}} \)

and \( Vol_{mid\text{section}} = A \cdot l_{cable} = \frac{\sqrt{2}}{5} \cdot \frac{1}{\delta} \cdot \frac{q_k l_{span}}{E} \cdot \frac{1}{2} l_{span} \sqrt{2} \)

\[\Rightarrow \frac{Vol_{cables}}{l_{span}} = \frac{Vol_{mid\text{section}}}{\frac{1}{16} l_{span}} = \frac{2}{\delta} \cdot \frac{q_k l_{span}}{E} \]  

(20.13)
20.5  Material demand cable-stayed symmetry

20.5.1  Cable-stayed beam with symmetrical configuration

The fixed foundation can be omitted when replaced by a counterpart cable-stayed beam, thus balancing each other. Unlike the cable-stayed beam with a fixed foundation, the symmetrical configuration is evidently sensitive to non-uniform loading just because of the balancing principle. Therefore, it is a necessity to replace the individual floor elements by a beam spanning the whole $l_{\text{span}}$ as shown in figure 20.3.

![Uniform load $q$](image)

Figure 20.3: Cable-stayed beam with symmetrical configuration

20.5.2  Material demand cables and pylon in the ULS

The material demand is the same as for the cable-stayed beam with fixed foundation.
20.5.3 Prismatic I-beam

Before applying a cable-stayed prismatic I-beam, a simply supported prismatic I-beam is researched.

The material demand for an I or H cross section will be determined for a common design dimension between the centre lines of the flanges as shown in figure 20.4.

\[
\text{Simply supported prismatic I-beam in the ULS}
\]

The function of the flanges is to provide enough bending capacity, the function of the web is to restraint the flanges and to provide enough shear capacity. The material demand can be on a summation of these separated functions:

\[
\frac{\text{Vol}_{\text{beam}}}{l_{\text{span}}} = 2A_f + A_w = 2 \frac{1}{8}q d l_{\text{span}}^2 \frac{h}{f_d} + \frac{1}{7} q d l_{\text{span}} \frac{f}{f_v} = 2 \frac{1}{8}q d l_{\text{span}}^2 \frac{1}{25} \cdot f_d + \frac{1}{7} q d l_{\text{span}} \frac{0.2 f_d}{0.2 f_d} = (6.1 + 2.1) \frac{q d l_{\text{span}}}{f_d} = 8.8 \frac{q d l_{\text{span}}}{f_d}
\]

(20.14)

With the assumption of a lower design limit of \( f_v = 0.2 f_d \), as applicable for reinforced concrete.
Simply supported prismatic I-beam in the SLS The material demand for a prismatic I-beam in the SLS can be determined as follows:

\[ \delta_{\text{max}} = \frac{5}{384} \frac{q_{k} l_{\text{span}}^4}{EI} = \frac{5}{384} \frac{q_{k} l_{\text{span}}^4}{E \cdot 2 A_f \left( \frac{h}{2} \right)^2} \]

\[ = \frac{5}{384} \frac{q_{k} l_{\text{span}}^4}{E \cdot 2 A_f \left( \frac{l_{\text{span}}}{225} \right)^2} \leq \delta \cdot l_{\text{span}} \]

with displacement ratio \( \delta = \frac{\delta_{\text{max}}}{l_{\text{span}}} \)

\[ \Rightarrow \frac{V_{\text{ol}_b e a m}}{l_{\text{span}}} = 2 A_f + A_w = 3 A_f = \frac{48.8 \cdot q_{k} l_{\text{span}}}{\delta \cdot E} \quad (20.15) \]

20.5.4 Sensitivity to non-uniform loading

The governing bending moment in the beam is based on the assumption of a non-uniform load distribution as shown in figure 20.5.

![Figure 20.5: Cable-stayed beam with non-uniform load](image)

Due to the difference in load of both spans, the bending moment will be distributed between both individual beams:

\[ M_d \approx \frac{1}{2} \cdot \frac{1}{16} q_d l^2 = \frac{1}{32} q_d l^2 \quad (20.16) \]
20.5.5 Material demand per beam in the ULS

Considering the global spanning, the prismatic I-beam is applicable:

\[ \frac{Vol_{beam}}{l_{span}} = \frac{1}{32} \left( 6\frac{1}{4} + 2\frac{1}{2} \right) \frac{qd_{l_{span}}}{f_d} = 2.2 \frac{qd_{l_{span}}}{f_d} \quad (20.17) \]

For a uniform load distribution, this material demand of the I-beam is more than sufficient for the combination of bending and compression. For a non-uniform load distribution, the corresponding reduced compression can be combined with the shear in the web of the I-beam, resulting in a negligible contribution to the material demand.

20.5.6 Material demand per beam in the SLS

The displacement of the floor will be maximised by the non-uniform load as a result of bending of both beams. The elongation of the cables is a negligible factor due to the acting-together of the total cable configuration. Considering the global spanning, the prismatic I-beam is applicable:

\[ \frac{Vol_{beam}}{l_{span}} = \frac{1}{4} \cdot 48.8 \cdot \frac{q_k l_{span}}{E} = \frac{12.2 q_k l_{span}}{E} \leq \delta \cdot l_{span} \]

with displacement ratio \( \delta = \frac{\delta_{max}}{l_{span}} \) \quad (20.18)

20.6 Design diagrams for conceptual design

20.6.1 Design diagrams

Applied mechanics calculations-based insight into the basic structural action, and corresponding material demand of a structure can be obtained by conceptual design diagrams, including possible configurations.
The basic format of the design diagram is shown in figure 20.6.

Dependent on time and location, preferences differ, and so do simplified standardisations of the parameters. Therefore, it is of the utmost importance to handle these diagrams as a variable and customisable design.
tool for experienced structural designers rather than a set of standard diagrams for architects or inexperienced structural engineers.

Due to their influence on the structural action and corresponding material demand, both force-driven and deformation-driven design parameters have to be taken into account.

**Force-driven design parameters** The material demand per span length with regard to the cross-sectional strength in the ULS, is expressed by the following parameters on the first vertical upward axis:

\[
\frac{Vol}{l_{\text{span}}} \left( \frac{qd_{\text{span}}}{f_d} \right)
\] (20.19)

**Deformation-driven design parameters** The influence of the slenderness on the buckling strength is expressed by the following parameters on the horizontal axis:

\[
\lambda_{el} = \frac{l_{el}}{h_{el}} \quad \text{with a transition slenderness of } \lambda_{el,\text{trans}} = \sqrt{\frac{E}{f_d}}
\] (20.20)

The slenderness-dependent material demand per span length with regard to the buckling strength in the ULS, is expressed by the following parameters on the second vertical upward axis:

\[
\frac{Vol}{l_{\text{span}}} \left( \frac{qd_{\text{span}}}{E} \right)
\] (20.21)

The material demand per span length with regard to the displacement in the SLS, is expressed by the following parameters on the vertical downward axis:

\[
\frac{Vol}{l_{\text{span}}} \left( \frac{qk_{\text{span}}}{E} \right)
\] (20.22)
20.6.2 Design diagram of a cable-stayed beam

The design diagram of a cable-stayed beam, both for the fixed foundation and the symmetrical configuration, is determined on the basis of foregoing standardisation and applied mechanics-based calculations as shown in figure 20.7.

This takes the following three failure modes into account:

**Section ULS** The volume of material per span length with regard to the cross-sectional strength in the ultimate limit state.

**Buckling ULS** The slenderness dependent volume of material per span length with regard to the buckling strength in the ultimate limit state. Passing the transition slenderness \( \lambda_{el,trans} \), the volume shows a further increase due to the governing, slenderness-based stability strength.

**Displacement SLS** The volume of material per span length with regard to the allowable maximum displacement in the serviceability limit state.

For each individual element - floor, beam, cables, and pylon - the required volume of material per span length is calculated. The failure mode with the highest volume is decisive.

Then, the volumes of the individual elements of the subsystem “cable-stayed beam” - both for the fixed foundation and the symmetrical configuration - are summarised into a total volume of the subsystem per corresponding span length of the subsystem.

It should be noted that even though the cable-stayed beam with a fixed foundation has by far the lowest material demand, additional costs of a gravity-based fixed foundation is a significant factor to be taken into account.

Furthermore, this is merely a flexible design tool for the experienced conceptual structural designer rather than for architects or inexperienced
Figure 20.7: Material demand of a cable-stayed beam
structural engineers. In a similar manner, this analysis can be extended by a comparison to other span types such as a truss and an arch.

20.6.3 Design diagram of a cable-stayed beam grade S355

Design diagrams can be made more specific by choosing material, material grade, and a displacement criterion; for example, foregoing cable-stayed beam in structural steel grade S355 as shown in figure 20.8.

Material properties Material properties of steel grade S355, namely the normal stress strength $f_d$ and the steel grade independent Young’s modulus $E$:

$$f_d = f_y = 355 \frac{N}{\text{mm}^2} \quad \text{and} \quad E = 2.1 \cdot 10^5 \frac{N}{\text{mm}^2} \quad (20.23)$$

Ultimate limit state The quantity of steel on the vertical axis is preliminarily based upon sectional strength and stability in the ULS. Both strength and stability can be presented on one axis, with a corresponding load expressed as $q_d$.

Serviceability limit state For an effective comparison of the influences of both ULS and SLS, one axis is advisable, expressed in $q_d$. Therefore, the displacement axis has to be converted to the strength axis, based on the assumption that both permanent and variable loads are approximately equal and a common displacement criterion:

$$\frac{q_d}{q_k} \approx \frac{1.5 + 1.2}{2} = 1.35 \quad \text{and} \quad \delta = \frac{l_{\text{span}}}{250} \quad (20.24)$$

Material demand With the actual choice of structural steel, the material demand of the individual elements, and the summarised material demand of the subsystem as a whole is directly expressed into the usual mass criterion for structural steel rather than volume.
Figure 20.8: Material demand of a cable-stayed beam steel grade S355
Material demand for conceptual design
Chapter 21

Case study trusses Maeslant storm surge barrier

21.1 Validation of the cyclic process control

21.1.1 A case study of conceptual structural design

The purpose of this specific case study is to validate whether the proposed methodical approach leads to a controlled build-up of insight into the behaviour of the structure and supports the actual successive design decisions during conceptual design.

For a clear comparison between standard practice and the proposed methodical approach, diffuse conceptual design variables such as experience, and especially intuition, have to be eliminated. Therefore, (a part of) an actual personally executed conceptual structural design such as the trusses of the Maeslant storm surge barrier is preferred rather than a new project.

The load paths, overall geometry, and principal detailing on the basis of performance, structural, and construction demands are determined.
Subsequently, the structural action in this outlined structure is optimised and the elements are dimensioned. Finally, a thorough risk analysis is conducted as a demarcation of the conceptual structural design phase.

21.1.2 Conclusion case study conceptual structural design

The actual design method at the time of the conceptual structural design of the Maeslant barrier doors can be characterised by the following:

3-D Modelling From the beginning, full three-dimensional modelling is applied for all conceptual design activities as geometry design, load distribution analysis, and code checking.

Force-driven The initial geometry design and optimisation is force-driven based. Subsequently, code-based unity checks on sectional strength, stability, and the hollow section joints are conducted.

Reactive The reactive unity check-based conceptual design indicated a severe failure problem of the web members. Analysis revealed an induced deformation problem and corresponding solution.

Risk analysis As one of the first Design and Construct contracts, a thorough risk analysis of the material demand was conducted for tendering, and subsequently, as internal transfer documentation for the basic design team.

The proposed methodical approach as practiced on the conceptual structural design of the Maeslant barrier door trusses, can be characterised by the following:

2-D Modelling Decomposition-based conceptual design ensures a controlled build-up of insight into the behaviour of the structure, with a progressive insight from two-dimensional estimations to three-dimensional accuracy.

Deformation-driven Deformation-driven conceptual design with continuous consideration of aspects such as local stability, global sta-
bility, and induced deformation.

**Pro-active** A pro-active methodical approach including principal details and foreseen induced deformation, with the help of orientation, analysis, and check loops.

**Risk analysis** For complex design and construct-based contracts - being today’s standard in the field of civil engineering - a thorough risk analysis of the material demand is inevitable as transfer documentation for basic design.

### 21.1.3 Conclusion validation of the methodical approach

The proposed methodical approach leads to a controlled build-up of insight into the behaviour of the structure and supports the actual successive design decisions during conceptual design. The following targeted solution components are validated:

**Structural design path** The structural design is effectively explored from structural integrity, via load distribution, to failure mechanisms.

**Structural design loops** Conceptual structural design is based on a progressive insight with orientation, analysis, check and, if necessary, correction loops.

**Load path design** Out of the functional requirements, an initial system outline is created based on major load paths, an order of magnitude, and principal details.

**Load distribution parameters** After a decomposition in two-dimensional subsystems, further geometrical optimisations are clarified, and the load distribution is established.

**Dimensioning parameters** On the basis of so-obtained member loads in combination with deformation-driven conditions, conceptual dimensioning can eventually be specified.
Furthermore, the following remaining solution components are not pre-conceivedly validated by this case study:

**Structural design cycle** The fundamental design cycle with the decomposed design phases creation, optimisation, and dimensioning proved to be viable and effective.

**Basic structural forms** Decomposition of the three-dimensional structural system into two-dimensional basic structural forms - in this case trusses - proved an effective basis for structural analysis.

**Shared knowledge-based integral design** The interface of structural demand with architectural, and in this case particular construction demand, relies mainly on professional experience. A successful material demand and risk analysis is conducted.

### 21.2 Maeslant storm surge barrier

#### 21.2.1 Final piece of the Delta works

After the North Sea flood of 1953, a commission was installed which had to come up with a plan to research the causes and seek measures to prevent such a disaster in future; they came up with a plan for the so-called “Delta works”.

The plan consisted of blocking the estuary mouths of the Oosterschelde, the Haringvliet, and the Grevelingen. This reduced the length of the dikes exposed to the sea by 700 kilometres. The mouths of the Nieuwe Waterweg and the Westerschelde were to remain open because of the shipping routes to the ports of Rotterdam and Antwerp. The dikes along these waterways were to be heightened and strengthened.

The construction of the Maeslantkering was the final stage of these Delta Works. The main objective was improving the safety against flooding of the Rotterdam harbour and the surrounding towns and agricultural
areas. In the original plan, this had to be carried out by the reinforce-
ment of existing dikes as far as 50 kilometres inland. During the 1980s,
it became clear that dike reinforcement would take at least 30 years
and would only have disadvantages compared to a barrier as listed in
table 21.1.

<table>
<thead>
<tr>
<th>Dike reinforcement versus barrier</th>
<th>Dike</th>
<th>Barrier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs (in billion euros)</td>
<td>0.82</td>
<td>0.45</td>
</tr>
<tr>
<td>Uncertainty costs</td>
<td>±20%</td>
<td>±10%</td>
</tr>
<tr>
<td>Delta safety schedule</td>
<td>2020</td>
<td>2000</td>
</tr>
<tr>
<td>Uncertainty schedule</td>
<td>10 years</td>
<td>2 years</td>
</tr>
<tr>
<td>Storm surges exposure</td>
<td>300 km</td>
<td>35 km</td>
</tr>
<tr>
<td>Environmental impact</td>
<td>Large scale</td>
<td>Limited</td>
</tr>
</tbody>
</table>

Table 21.1: Dike reinforcement versus barrier

Therefore, the initial plan was put aside and the Ministry of Waterways
and Public Works organised a competition in which construction com-
panies could make plans for the construction of a reliable, yet relatively
inexpensive, storm surge barrier.

### 21.2.2 Requirements

The storm surge barrier had to be located in the waterway that connects
Rotterdam with the North Sea. As this waterway is the main route to the
port of Rotterdam, a wide opening, unlimited headway, and a minimum
disturbance of ship movements, among others, were required as listed in
table 21.2.

### 21.2.3 Conceptual design Maeslant storm surge barrier

The winning barrier design with two huge hollow floating barrier doors
was put forward by the Bouwcombinatie Maeslant Kering (BMK) con-
Casestudy: Maeslant storm surge barrier

### Functional requirements for the Maeslant storm surge barrier

<table>
<thead>
<tr>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unlimited headway</td>
</tr>
<tr>
<td>360 metres’ wide opening</td>
</tr>
<tr>
<td>Barrier failure 1/1,000,000 in any one year</td>
</tr>
<tr>
<td>Minimum disturbance of ship movements</td>
</tr>
<tr>
<td>100 years’ lifetime</td>
</tr>
</tbody>
</table>

Table 21.2: Requirements for the Maeslant storm surge barrier

sortium and became one of the first large Design and Construct projects in the Netherlands.

Each barrier door consists of a 210 metres’ long retaining wall with floodable buoyancy chambers, supported by 250 metres’ long trusses and ending in a ball joint with a diameter of 10 metres, and embedded in a concrete caisson as shown in figure 21.1.

![Maeslant storm surge barrier](image)

Figure 21.1: Maeslant storm surge barrier

Under normal conditions, the barrier doors are fully opened to allow ships to sail to and from Rotterdam. However, if the water level rises by three metres above the designated norm, the barrier doors are closed and flooded with water. This causes them to sink slowly onto the sill blocks at the bottom of the waterway. The entire process takes about 90 minutes.
During a storm surge, the water level on the North Sea side rises relative to the water level on the Rotterdam side. The corresponding hydraulic design load against one door equals approximately 350 meganewton (MN).

A major advantage of this design was that construction of the storm surge barrier could take place under dry conditions, in dry docks. Other advantages were that no vital parts of the barrier had to be placed under water, and maintenance of the barrier would be easy because of the dry docks. Finally, there would be almost no inconvenience for passing ships.

21.2.4 Performance/cost optimisation

For a coherent and complete integral design, all fundamental demands - namely performance demand, structural demand, and construction demand - have to be complied with. Within a Design and Construct contract, the performance/cost optimisation within the functional requirements is up to the integral constituted conceptual design team.

With respect to performance and construction demand, the following major performance/cost optimisations are essential for the conceptual design of the trusses:

Architectural demand The functionalism-based concept of architect Wim Quist for the design of the trusses, consists of a combination of tubular offshore-like appearance and a powerful clear transmission of the enormous hydraulic forces.

Maintainability Maintenance costs are a major issue for such a functional storm surge barrier. Therefore, the conceptual design of the steel trusses demands special attention to the coating by minimising surface area and avoiding sharp edges.

Construction demand Welding is, for the construction of steel trusses, a major laborious and thus cost-dominant design parameter. The
design objective is thus an optimisation of weldability by minimising weld volume and maximising welder accessibility.

21.3 Creation of a system outline

21.3.1 Load-path design on system level

The primary design load consists of a combination of approximately 6 metres of hydraulic head and approximately 3 metres of transversing wave load, and can initially be simplifiedly modelled by a quasi-static hydraulic head design load of 9 metres, and a corresponding uniform load of $q_d = 90 \frac{kN}{m}$ in accordance with figure 21.2.

![Figure 21.2: Hydraulic load](image)

The resulting force of the ball joint amounts to 320 MN as a result of the projected hydraulic head in combination with the influence of the top and bottom of the wave.

Resisting this primary load and bridging 250 metres to the balancing concrete caisson requires a large amount of material. The corresponding self-weight of the structure is an inevitable secondary load of importance.
21.3.2 Principal details

Circular Hollow Section (CHS) members and joints are by far preferable, in analogy with offshore structures and based on the following performance/cost optimisation considerations:

Coated surface Surface area and sharp edges highly affect the influential costs of coating and corresponding maintenance. Minimisation of the coated surface, and avoiding sharp edges evidently, leads to a circular section.

Water pressure To avoid coating the inner surface, and the corresponding need for corrosion inspection and maintenance on the inside of such a complex structure, the trusses are completely watertight. Consequently, a circular section is the best way to resist the water pressure.

Drag coefficient The drag coefficient quantifies the drag or resistance of an object in a fluid environment such as air or water. A circular section has a very low drag coefficient and is therefore less prone to both wind loading and dynamic hydraulic loading when submerged.

Element buckling Circular hollow sections have an excellent element buckling strength due to their all-directional high moment of inertia, low geometrical tolerances and low residual stresses.

Plate buckling A higher moment of inertia can be obtained by making sections thin-walled. Due to their circular shape, circular hollow sections effectively combine a high moment of inertia and excellent plate buckling resistance. Plate buckling, however, imposes a limit to the extent to which sections can be made thin-walled; $\frac{d}{t} \leq 50$.

Uniformity To obtain cost-saving identical tubular gap joints and web member lengths, the trusses are designed with parallel lower and upper chords.

Joint geometry Aiming for a full capacity connection, the multi-planar gap joints are designed with canned sections and an average $\frac{d_{web}}{d_{chord}}$.
ratio $\beta$ of 0.6.

In this way, a principal joint as shown in figure 21.3 leads to a life cycle design that is both economically and architecturally satisfying.

![Figure 21.3: Principal joint](image)

21.3.3 Circular hollow section elements

For an effective design of trusses with CHS members, section properties, steel grade, and the transition between sectional strength and element buckling have to be determined.

Section properties CHS The section properties of a CHS, with approximations based on a relatively small wall-thickness, are given in figure 21.4.

\[
\begin{align*}
A & \approx \pi dt \\
I & \approx \frac{1}{8} \pi d^3 t \approx \frac{1}{8} Ad^2 \\
W & \approx \frac{1}{4} \pi d^2 t \approx \frac{1}{4} Ad
\end{align*}
\]

![Figure 21.4: Section properties of a CHS](image)

Steel grade At the time of the design of this storm surge barrier, standardised grades for structural steel varied from S235 up to S355.
21.3 Creation of a system outline

Given the functional requirements with respect to failure, this specific design is primarily force-driven instead of deformation-driven. Thus, the highest steel grade S355 is appropriate, thereby reducing the enormous self-weight of the structure.

**Transition slenderness CHS** The slenderness $\lambda_{el} = \frac{l_{el}}{d}$, where the axial strength equals the buckling strength, defines the transition between both failure mechanisms.

Axial strength:

$$N_u = A \cdot f_d$$  \hspace{1cm} (21.1)

Buckling strength of an element in a braced structure:

$$N_u \approx \frac{1}{1.7} \cdot \frac{\pi^2 EI}{L_{cr}^2} \approx \frac{1}{1.7} \cdot \frac{\pi^2 EI}{l_{el}^2}$$  \hspace{1cm} (21.2)

Transition slenderness $\lambda_{el,trans}$ CHS:

$$A \cdot f_d \approx \frac{1}{1.7} \cdot \frac{\pi^2 EI}{l_{el}^2} \approx \frac{1}{1.7} \cdot \frac{\pi^2 E \cdot \frac{1}{8} A l^2}{l_{el}^2} = \frac{1}{1.7} \cdot \frac{\pi^2 E \cdot \frac{1}{8} A}{l_{el}^2}$$

$$\Rightarrow \lambda_{el,trans} = \frac{l_{el}}{d} = 0.85 \sqrt{\frac{E}{f_d}} = 0.85 \sqrt{\frac{210000}{355}} = 20.7 \hspace{1cm} (21.3)$$

21.3.4 Decomposition in subsystems

For a clear and effective design of the primary and secondary load paths, the three-dimensional system is decomposed into two-dimensional horizontal and vertical subsystem planes, as shown in figure 21.5.
Horizontal plane  The horizontal plane directs the load paths of the primary hydraulic load. To provide a short transition of this primary hydraulic load to the ball joint, the level of this horizontal plane coincides with the resulting hydraulic design load.

The total required cross-sectional area of the lower chords per barrier door amounts to:

$$A_{\text{lower}} = \frac{l \cdot h \cdot q_d}{f_d} = \frac{210 \cdot 22 \cdot 90}{355} \cdot 10^3 = 117 \cdot 10^4 \text{ mm}^2 \quad (21.4)$$

Vertical plane  The vertical plane directs the load paths of the secondary structural self-weight. Furthermore, this plane directs the load paths caused by an eccentricity of the resulting hydraulic load due to the transversing wave.

The secondary upper chords are less loaded than the primary lower chords. Nevertheless, out of strength and fabrication considerations the preferred principal CHS joints are appropriate for both lower and upper chord joints. In combination with stability considerations, a three-dimensional truss configuration as shown in figure 21.6 is the logical consequence.

Intersection of horizontal and vertical plane  The intersecting line between the horizontal and vertical plane gives an interaction between the hydraulic load and the structural self-weight.
The maximum hydraulic load in the horizontal plane is relieved by the structural self-weight in the vertical plane. However, when submerged, the buoyancy of the lower chords will partly neutralise this relief since the buoyancy of the submerged members approximately equals their own weight.

The before mentioned eccentricity of the resulting hydraulic load on the spot of the bottom of the transversing wave, and the corresponding reduced water level also generates a relieving load with respect to the structural self-weight. Because of its temporal character, this relief will not be taken into account.

3-D system effects  Possible three-dimensional load distribution effects require retention of these effects during decomposition of the three-dimensional system into two-dimensional subsystems.

In case of such a relatively flat structural system, three-dimensional system effects, and especially overall torsion, cannot be expected to be influential.
21.4 Optimisation of the structural action

21.4.1 Optimisation on horizontal subsystem level

In search of an optimal configuration, the absolute minimum performance-based configuration will be determined first; and then the possibility of redundancy as an added value, will be explored.

Performance-based cost minimisation  The absolute minimum configuration consists of a statically determinate arrangement of two supports of the retaining wall. To secure global stability over a length of 250 metres, in plane horizontal stabilisation elements have to be designed in addition to the vertical weight bearing structures. However, the great distance between both supports requires heavy bracings.

Therefore each support is designed as a three-dimensional truss configuration. An efficient design of the retaining wall, however, requires more supports. Considering the long load path between the retaining wall and the ball joint, additional bracings instead of complete trusses are the most economical solution. Additional supporting bracings are designed as shown in figure 21.7.

![Figure 21.7: Optimisation of the supports of the retaining wall](image-url)
Added-value design  Nevertheless, one or more extra supporting trusses can be included to incorporate redundancy in this statically determinate design. However, even with four instead of two three-dimensional supporting trusses, failure of only one truss will inevitably lead to failure of the whole system due to an insurmountable loss of retaining wall capacity. So extra supporting trusses are still useless and costly.

21.4.2 Optimisation on vertical subsystem level

The vertical height $h$ and the horizontal width $w$ of the three-dimensional truss configuration as shown in figure 21.6 on page 297, have to be determined.

**Vertical truss height**  The optimal height/span ratio of trusses varies between $\frac{1}{10}$ and $\frac{1}{15}$. Because of the secondary load character of the truss design, a height/span ratio near $\frac{1}{15}$ is appropriate with a height $h$ of 18 metres.

The resulting corresponding equilateral triangle has a web member, and lower chord and upper chord lengths of approximately 20 metres.

**Horizontal truss width**  For a sufficient connection angle of both web members to the upper chord, with regard to the cross-section of the truss as shown in figure 21.6 on page 297, the width $w$ requires 15 metres.

21.4.3 Induced deformation

A timely determination of deformation-driven design parameters is of importance for an effective optimisation of the structural action during design. This statically indeterminate truss structure with primary loaded
chord members and secondary loaded web members can be potentially sensitive to induced deformation of the web members.

Because the primary loaded chord members can induce an impermissible deformation and corresponding failure of the web members, a sensitivity study, as input for final dimensioning of these web members, has to be conducted.

### 21.5 Dimensioning

#### 21.5.1 Cross-sectional area of the lower chord

In the statically determinate arrangement, the hydraulic load will be divided over $2 \cdot 2 = 4$ cross sections. Each cross section requires the following area:

$$ A_{\text{lower}} = \frac{1}{4} \cdot 117 \cdot 10^4 = 29.3 \cdot 10^4 \text{ mm}^2 $$

(21.5)

#### 21.5.2 Global stability

The bearing capacity of the truss with respect to global buckling can be approximated as follows:

$$ N_u \approx \frac{1}{1.7} \cdot \frac{\pi^2 EI}{l_{\text{sys}}^2} \quad \text{and} \quad I_{\text{truss}} \approx 0.8 \cdot 2 \cdot A_{\text{chord}} \cdot \left(\frac{1}{2} w\right)^2 $$

(21.6)

With known cross-sectional area $A_{\text{lower}}$ of the lower chord members, the minimum required truss width $w$ with respect to global buckling amounts to:

$$ w \geq \sqrt{\frac{4.25 \cdot N_d \cdot l_{\text{sys}}^2}{\pi^2 \cdot E \cdot A_{\text{lower}}}} = \sqrt{\frac{4.25 \cdot 207.9 \cdot 10^6 \cdot 250^2 \cdot 10^6}{\pi^2 \cdot 2.1 \cdot 10^5 \cdot 29.3 \cdot 10^4}} \cdot 10^{-3} $$

$$ \quad = 9.5 \leq \text{actual 15 m} \quad (21.7) $$
21.5 Dimensioning

21.5.3 Cross-sectional area of web and upper chord

The uniform structural self-weight load of the lower chords per barrier door amounts to:

\[ q_{\text{lower}} = A_{\text{lower}} \cdot \rho_s = 1.17 \cdot 78.5 = 91.8 \frac{\text{kN}}{\text{m}} \quad (21.8) \]

An additional upper chord and a three-dimensional web member configuration will approximately double this weight. On the basis of post calculation, the design value of the uniform structural self-weight load amounts to approximately \(200 \frac{\text{kN}}{\text{m}}\) per barrier door.

The uniform structural self-weight load of approximately \(100 \frac{\text{kN}}{\text{m}}\) per three-dimensional truss results in the following maximum cross-sectional areas in the upper chord and the web members:

\[ A_{\text{upper}} = \frac{1}{8} q_{dl} l^2 \cdot \frac{1}{h \cdot f_d} = \frac{1}{8} \cdot \frac{100 \cdot 250^2 \cdot 10^6}{18 \cdot 10^3 \cdot 355} = 12.2 \cdot 10^4 \text{ mm}^2 \quad (21.9) \]

\[ A_{\text{web}} = \frac{1}{2} \cdot \frac{1}{2} q_{dl} \cdot \frac{1}{\cos \alpha \cdot \cos \beta \cdot f_d} = \frac{1}{2} \cdot \frac{1}{2} \cdot \frac{100 \cdot 250 \cdot 10^3}{\cos 22.6^\circ \cdot \cos 30^\circ \cdot 355} = 2.2 \cdot 10^4 \text{ mm}^2 \quad (21.10) \]

21.5.4 Induced deformation of web members

Because the primary loaded chord members can induce an impermissible deformation and a corresponding failure of the web members, a sensitivity study is conducted.

**Phenomenon** An induced deformation on subsystem level is applicable for the web members of the trusses of the Maeslant storm surge barrier as shown in figure 21.8.
The angle $\varphi = \frac{Ml}{6EI}$ is induced because of the elastic deformation $\delta$ of the main members due to the immense horizontal water load, in combination with the stiffness of the welded tubular hollow section joints.

As a consequence of the induced angle $\varphi$, fixed web member length $l$, and fixed normal stiffness modulus $E$, the fraction $\frac{M}{l}$, is a constant.

So reducing the bending moment $M$, as caused by the induced angle, is only possible by reducing the cross-sectional moment of inertia $I$ of the web member.

**Modelling** During conceptual design the barrier door is modelled with an overall finite elements model including retaining wall, trusses, and ball joint. The load cases consist of hydraulic head, transversing wave, and the structural self-weight.

The results are imported into a computerised code check including the failure mechanisms of the individual truss members and their connection to the canned joints.
Analysis  To be on the safe side for the web members, the computerised calculation input is initially based on CHS sizes of $\varnothing 900 - 30$ mm. The corresponding load distribution within the trusses results in a cross-sectional failure of these web members, primarily due to bending.

Subsequently, the wall thickness is incremented until the bending strength of the web members is sufficient. Even with a massive section of $\varnothing 900$ mm, cross-sectional failure still occurs. This huge sectional area is completely out of proportion with the initial required axial strength.

The problem of induced deformation where the bending stiffness and the corresponding bending moments increase more than the strength of the structure, can be effectively solved by reducing the bending stiffness of the concerning member.

Reducing the bending stiffness of the web members by reducing the wall thickness to CHS sizes of $\varnothing 900 - 20$ mm, the corresponding strength proves more than sufficiently that it resists all forces including the induced deformation-driven bending moments.

Design solution  The potential induced deformation-driven problem of cross-sectional failure of CHS web members with high plate thicknesses, can be effectively prevented by applying the relatively low plate thickness of a $\varnothing 900 - 20$ mm web member.

To prevent this potential induced deformation-driven problem during further design optimisation, the cross-sectional bending stiffness of the web members may not exceed the moment of inertia of a CHS $\varnothing 900 - 20$ mm.

21.5.5 Section dimensions of conceptual design

The induced deformation-based dimensions of the web members, in combination with the average $\frac{d_{web}}{d_{chord}}$ ratio $\beta$ of 0.6, results in the dimensions as shown in figure 21.9.
21.6 Specification and risk analysis

21.6.1 Material demand

The specification of conceptual design demarcates this project phase. As a Design and Construct project with a separated competitive tendering and assignment phase, this specification is used as a risk analysis for tendering, and subsequently, as internal transfer documentation for the basic design team.

A risk analysis of the material demand gives an accuracy estimation of the material quantities and corresponding unit cost indications. The risk analysis has to be conducted on the level of individual components of a decomposed system, principal details included.

For an effective risk analysis, as discussed in subsection 12.5.5, quantified data have to be determined.
21.6.2 Dimensioning and cost weighting

The result of the performed structural analysis is an approximate section dimensioning of the materialised overall geometry. This dimensioning of the conceptual design is specified by a list of material quantities.

An executed example of the dimensioning and cost weighting during the conceptual design of the trusses of the Maeslant storm surge barrier is listed in table 21.3.

| Risk analysis conceptual design trusses Maeslant storm surge barrier Dimensioning and cost weighting |
|-------------------------------------------------|-----------------|-----------------|-----------------|
| Description                                     | Weight [ton]    | Costs indication [mhr/ton] | Weight × Costs |
| Upper chord members                             | 2550            | 15              | 12%             |
| ⊙ 1500 - approx. 30 mm                          |                 |                 |                 |
| 1 splice-weld/member                            |                 |                 |                 |
| Lower chords members                            | 5790            | 10              | 18%             |
| ⊙ 1500 - approx. 70 mm                          |                 |                 |                 |
| 1 splice-weld/member                            |                 |                 |                 |
| Web members                                     | 2830            | 35              | 31%             |
| ⊙ 900 - approx. 20 mm                           |                 |                 |                 |
| 2 splice-welds/member                           |                 |                 |                 |
| Hollow section joints in upper chord            | 600             | 60              | 11%             |
| 1 splice-weld/joint                             |                 |                 |                 |
| Hollow section joints in lower chords           | 1170            | 45              | 17%             |
| 1 splice-weld/joint                             |                 |                 |                 |
| Ball joint ⊙ 10 m                               | 1010            | 35              | 11%             |

Performed analysis:
3-D framework analysis with post-processing on stress level

Table 21.3: Risk analysis: dimensioning and cost weighting
The cost weighting equals the material quantities times the unit cost indications, and is a measure for cost optimisation opportunities and corresponding risk.

21.6.3 Uncertainties and coverage by dimensioning

The difference between the performed approximate structural analysis for conceptual design and the required depth and breath to meet the in-use requirements for structural safety and serviceability can be defined as uncertainties of the conceptual design. The difference in depth and breath generally concerns load combinations, load distribution, and failure mechanisms.

The uncertainties of the performed approximate structural analysis with respect to the required depth and breath cannot, or only partially, be covered. The corresponding status of the coverage gives an indication of the risk influence of the uncertainties of the conceptual design.

An executed example of the uncertainties and corresponding coverage by dimensioning during the conceptual design of the trusses of the Maeslant storm surge barrier is listed in table 21.4.

21.6.4 Reserves and optimisations

Reserves can be intentionally incorporated or are the result of rounding up to the nearest standardised product dimensions. Occasionally, an optimisation of requirements during the conceptual design phase can result in a reserve.

Foreseen, but time-consuming cost optimisations can be postponed to basic design, but registered as a potential reserve with regard to the completed conceptual design.
<table>
<thead>
<tr>
<th>Uncertainties</th>
<th>Coverage by dimensioning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper chord, lower chords and web members:</td>
<td></td>
</tr>
<tr>
<td>Decisive load combination head + wave based on 5% of the members</td>
<td>Average influence based on known member forces</td>
</tr>
<tr>
<td>Fatigue</td>
<td>No specific coverage, anticipation not decisive</td>
</tr>
<tr>
<td>Geometrical non-linearity</td>
<td>Average influence based on framework analysis of one load case</td>
</tr>
<tr>
<td>Serial effect</td>
<td>Assumption based on TNO report B-89-455</td>
</tr>
<tr>
<td>Global buckling</td>
<td>Average influence through enlargement factor</td>
</tr>
<tr>
<td>Hollow section joints in upper and lower chords:</td>
<td></td>
</tr>
<tr>
<td>Decisive load combination unknown</td>
<td>No specific coverage</td>
</tr>
<tr>
<td>Fatigue</td>
<td>No specific coverage, anticipation not decisive</td>
</tr>
<tr>
<td>Net area due to man holes</td>
<td>10% extra plate thickness with a length of 3 m per hole</td>
</tr>
<tr>
<td>Ball joint:</td>
<td></td>
</tr>
<tr>
<td>Load life cycle with FEM model stress distribution</td>
<td>Order of magnitude</td>
</tr>
<tr>
<td>Friction coefficient of bearing material</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 21.4: Risk analysis: uncertainties and coverage by dimensioning

An executed example of the incorporated reserves and possible optimisations during the conceptual design of the trusses of the Maeslant storm surge barrier is listed in table 21.5.
21.7 Further optimisations during basic design

21.7.1 Basic design

During conceptual design, the functional requirements and contractual conditions are evolved into a materialised overall system geometry, principal details included, with approximated modelling-based dimensions, quantities of materials, and corresponding risk analysis.

The subsequent basic design phase is characterised by a thorough analysis-based optimisation of the structural action and a thorough overall structural system check.

Furthermore, the basic design is assisted by testing of the ductility of the thermo-mechanical steel and the cast steel, the pre-stressed injection bolts, and the friction coefficient of the coating of the sliding surfaces.

Corresponding gained insight can reveal a need for adjustment and ap-
p apparently even an addition of structural elements.

### 21.7.2 Extensive modelling

During basic design, the stiffness influence of both retaining wall and ball joint on the structural action in the trusses is refined within the overall finite elements model of the barrier door:

**Retaining wall** An accurate stiffness contribution of the combined bending plate and longitudinal stiffener, the combined shear plate and longitudinal stiffener, and the transverse stiffener, is individually modelled and condensed into the model of the retaining wall. Subsequently, the tubular bracings and partition bulkheads are included.

**Ball joint** The effects of slip-stick, variation of the friction coefficient, and actual rolling instead of slipping is determined with numerous life cycle calculations with partial models and the condensed overall model.

### 21.7.3 Coupling truss

During basic design, the refined modelling of the retaining wall in combination with more refined load cases and more load combinations, revealed unacceptable high longitudinal stresses in the retaining wall. These high stresses were mainly caused by the transversing wave load, with a top and bottom of approximately ±3 metres.

For a more uniformly distributed support of the retaining wall, coupling of both supporting multi-planar trusses was required. Addition of an extra multi-planar coupling truss resulted in the necessary reduction of these longitudinal stresses.
21.7.4 Geometry and Section dimensions

During basic design, a more detailed code check was executed, including all individual failure mechanisms of the individual members, and particularly, their connection to the canned joints.

For the trusses, welding in situ was inevitable. Large lengths of the chord members could be welded on ground level and hoisted in place afterwards. However, all connections of the web members had to be welded in their permanent position.

Because of the difficultly accessible and laborious welding, a profound optimisation of geometry in combination with weld profile, volume, process, tolerances, and position was executed during basic design. This resulted in a reduction of 10% of the total weld volume and corresponding costs.

As a result of this optimisation of strength and welding of the tubular joints, the diameter of the web members was altered to 800 mm, and the diameter of the chords to 1800 mm.
Chapter 22

Conclusion and recommendations

22.1 Thesis conclusion

22.1.1 Initial research goal

Structural design consists of three major sequential design phases namely conceptual, basic, and detailed design.

With detailed design - a phase of code checking, detailing, and specifying - all common material applications are extensively researched and recorded in numerous textbooks and design codes of practice.

For basic design - a phase of deepening and optimising - the main tools are applied mechanics-based and since Isaac Newton widespread available as extending textbook material.

Conceptual design - the creation phase with a complex and partly intuitive process and numerous complex interfaces between different fields of practice - is little touched by technological progress.
This lack of progress is not the result of a lack of interest by the research community. The last decades, many small-scaled prototype information technology systems for conceptual design have been researched. Because of the multitude of parameters and complexity of interrelations, a workable and to optimisation leading design method seems far ahead.

In anticipation of future successful applications of artificial intelligence, a design method on the basis of abstractions of a decomposed system is researched here.

**Initial goal of the methodical approach**  The initial goal is an unambiguous qualified methodical approach, with qualified parameters in coherent flow diagrams, as discussed in subsection 4.3.2.

**Ultimate design method**  The ultimate goal in the near future is an unambiguous quantified design method, with quantified parameters in one converging flow diagram with mathematical functions and a numbered answer, as discussed in subsection 4.3.3.

**22.1.2 Research process**

The ultimate completely quantified design method is very appealing but rejected beforehand out of feasibility considerations. Thus, the initial goal of the qualified methodical approach on the subject is researched. The process from initial goal to actual outcome reveals why some postulated research steps are not completely met.

The process of research is a systematic analysis of information to establish facts and to reach conclusions as discussed in subsection 1.2.2. The first steps in this process, being “problem definition”, “investigate the known”, and “structure the solution finding”, appear to be common research practise. So do the last steps; “hypothesis testing” and “conclusion with recommendations”.
The crucial step in the middle, however, “formulate an hypothesis”, demands an open and general solution to this specific, large-scaled and complex problem. This probably requires an even more large-scaled and complex effort for its solution.

**Tangled complexity**  The preferred research approach is to deepen the full spectrum of the problem, step by step, until a methodical approach becomes within reach. The initial research findings, however, are fragmented and have different depths. Individual findings are difficult to interrelate into a coherent solution.

It merely seems to be analysing an existing situation rather than creating a new one. Nonetheless, there is a strong resemblance with the analysis phase of conceptual design itself; a lot of experience and intuition is required to disentangle the complexity.

The actual research process can best be compared with an enormous jigsaw puzzle; seeking for a familiar looking piece, trying to locate its possible position within the overall puzzle and making use of interrelations with other found pieces. This analogy can further be extended to the actual research outcome, in which some pieces are still missing, as discussed in the next subsection.

**In-depth research**  A complete control of the complex highly-cyclic conceptual design process, and in particular the interfaces between all participating disciplines, is still out of reach. It is challenging enough to find and formulate guiding principles, and even more challenging to organise these with a logical sequence and coherence.

In the search for guiding principles, a lot of apparently main optimisation routines such as cost estimating algorithms and optimising material demand by minimising strain energy, appear useless.

During scientific research of individual subjects, the main pitfall is an on-going in-depth research, thereby increasing the depth over breadth beyond the level of equilibrium between both.
22.1.3 Actual research outcome

The initial goal is an unambiguous qualified methodical approach, with qualified parameters in coherent flow diagrams. The research on a methodical approach consists of individual findings and their consistency. The following individual findings can be distinguished:

**Structural design cycle** Capturing structural design by breaking down this complex process into the essential absolute minimum, resulting in a fundamental design cycle as an effective characterisation of both the overall design process, and the individual design phases.

**Basic structural forms** Basic set of two-dimensional subsystems, with each individual subsystem being an assembly of directly connected structural elements, designed to act together to resist loads.

**Structural design path** The structural design can be explored in a two-dimensional matrix, in which the design path follows the fundamental dimensioning routine from structural integrity, via load distribution, to failure mechanisms.

**Structural design loops** A combination of analysis, check, orientation, and correction loops to support a cyclic optimum design with regard to optimisation of both the quality of design outcome and the number of design cycles.

**Shared knowledge-based integral design** Definition and collection of the fundamental conceptual design parameters of the most influential participating disciplines can serve as a joint breeding ground for integral design solutions.

**Load path design** A first draft of the structure’s integrity requires simple and clear three-dimensional modelling on the level of axial forces, directly or with a truss-analogy, including the three-dimensional effects.

**Load distribution parameters** Applied mechanics-based oversight of force- and deformation-driven load distribution and a matching
balanced set of conceptual design approximations.

**Dimensioning parameters** Applied mechanics-based oversight of professional practice dimensioning and a matching balanced set of conceptual design approximations.

These individual findings and their interrelations are combined into a methodical approach on conceptual structural design. To secure coherence and completeness of this methodical approach, in this research thesis a higher than intended level of abstraction is used.

The completeness is therefore restricted to the actual level of abstraction; on a deeper level some, but certainly not all parameters and their interrelations, are determined. Especially, the multitude of complex integral processes are hard to qualify and almost impossible to quantify.

Thus, it is certainly not a striking leap forward to the ultimate goal of an unambiguous quantified design method, neither is it the initial research goal of a complete qualified methodical approach; but it is a significant first step towards an untangled and operationalised conceptual structural design process.

### 22.2 Recommendations for further research

#### 22.2.1 In-depth research

This thesis discusses a methodical approach on conceptual structural design on a high level of abstraction. However, an on-going more deepening research on conceptual structural design is valuable and feasible. Recommendations for further research are given with respect to both understanding structural performance and conceptual structural design.

Out of the multitude of missing in-depth knowledge, the following most direct completing topics with respect to the proposed methodical approach are recommended for further research:

- Conceptual design parameters built environment.
• Fundamental behaviour of structural materials.
• Transition of stocky to slender beam theory.
• Adjustment factor of buckling strength.

### 22.2.2 Conceptual design parameters built environment

As given in figure 9.7 on page 114 the T-shaped in-breadth understanding in general, and the conceptual structural design process control in particular, is qualitatively modelled in part II of this thesis. Subsequently the conceptual structural design parameters are approximately quantified in part III.

Both the individual sets of conceptual design parameters of the other principal disciplines, as given in table 9.1 on page 111, and the integral process of interacting and control of these sets are in need of approximate quantitative modelling as shown in figure 22.1.

![Figure 22.1: Additional approximate quantitative modelling](image-url)
22.2 Recommendations for further research

22.2.3 Fundamental behaviour of structural materials

Design approximations of load distribution are common property through standard applied mechanics textbooks. Design approximations of strength and stiffness behaviour of common structural materials are widely accessible through numerous textbooks and design codes of practice.

Both design approximations of load distribution, and material strength and stiffness of concrete as well as of structural steel are organised and supplemented into a set of conceptual structural design parameters in this research thesis.

Approximated behaviour and strength of new structural materials, however, have to be modelled with care. Especially brittle material behaviour, and corresponding approximate conceptual modelling, is not widely accessible. Brittle material behaviour requires far more in-depth modelling to detect and prevent high-peak stresses with consequent progressive tearing failures.

In general, the relationship between the degree of ductility - quantified by the length of the ductile or plastic zone - and the required corresponding degree of in-depth modelling, has to be researched. In particular, the fundamental behaviour of such structural materials and an effective approximate modelling for conceptual design should become available.

22.2.4 Transition of stocky to slender beam theory

For slender beams, the bending deformation is decisive and the shear deformation may be neglected; for stocky beams, on the other hand, the shear deformation is decisive and the bending deformation may be neglected. The transition from “stocky” to “slender” depends on the bending versus shear stiffness of the material. This transition cannot be determined with the common abstraction of bending based upon slender beam theory.
For a better understanding and application of deformation in general, and shear deformation in particular, research on the transition slender-ness with the help of proper constructed in-depth truss-analogy and/or finite element modelling, is advisable.

22.2.5 Adjustment factor of buckling strength

The mathematical formula of Euler gives a proper insight into structural behaviour but has to be adjusted by a factor $k$ for accuracy reasons. Even then, buckling strength-related design approximations are difficult to capture and often have insufficient accuracy with regard to conceptual design.

Therefore, more thoroughly substantiating the material-dependent adjustment factor $k$, is desirable; first of all, an appropriate adjustment factor $k$ for the buckling strength of concrete members, in combination with a corresponding stiffness modulus $E_c$; and subsequently, material-dependent adjustment factors for other common structural materials.

22.3 Recommendations for higher education

22.3.1 Present-day higher education

Education about design in general, and conceptual design in particular, is poorly represented and embedded in present-day higher educational programmes.

Erosion of fundamental knowledge and skills  The number and complexity of sophisticated high-end computer programs and interfaces with other disciplines, increasingly dominate daily practice of the present-day professional structural engineer. Due to this on-going expansion of depth and breadth, the simplification and decomposition techniques of
the experienced structural engineer are steadily disappearing from practice training and higher educational programmes.

Compartmented educational programmes  Furthermore, especially scientific higher education is compartmented in disciplines and even specialisations, and corresponding research sections with nearly no overlap and cooperation whatsoever.

Education about design in general, and conceptual design in particular, is highly dependent on an integral approach of the educational programme, with emphasis on the interfaces between the disciplines.

Adaptation to the Anglo-American system  The present-day binary system in the Netherlands with respect to professional bachelor education and scientific bachelor education has to be adapted to the uniform Anglo-American system; first of all because the Anglo-American system is the world-wide standard in higher education; and furthermore, especially for structural engineering, because the necessary abstraction level requires a higher level of education than the average professional bachelor programmes offer.

Then higher education offers a mainstream bachelor in structural engineering with a professional-based programme on a scientific level of abstraction.

22.3.2 Quality versus quantity

Both quality and quantity are essential conditions and legitimate target values for viable higher education programmes.

Quality instead of quantity  During the last decades, the building industry has been struggling with complex integral design questions and increasing failure costs. In essence, however, it involves no more than a
neglected optimisation of the performance/cost-ratio over the life cycle. Despite the self-evidence of the problem and corresponding solutions, just a few developments emerge and only with small steps.

In particular, professional higher education proves to lack quality and corresponding focus. Management of universities often strive primarily for quantitative goals, and quality is merely a granted derivative. Nothing has ever proved to be granted, however, unless managed consciously and with understanding.

Even if quality is gaining significance as a serious management goal, it is hard focusing due to an increasing information density; the present-day professional in an integral building process is confronted with the availability of complex software tools, codes and research results, as well as with the presence of complex interfaces, contractual conditions, and collaboration processes.

**Quantity by quality** Striving for quantitative goals is quite a legitimate operation. After all, most of the time these are prerequisite constraints for financing the necessary quality, on the condition of a primary focus on unambiguous defined quality goals.

And because outlay must precede returns, management has to invest in advance by recruiting highly qualified personnel, and subsequently, by developing a high-quality educational programme.

The professional field is not the appropriate developer of such an educational programme because all subject material ought to be relevant, making it difficult to choose what is most relevant within such a programme. Didactic experts prove unsuitable as well, due to a tendency to didactic hypes resulting in present-day’s “overdone” project-based learning.

Successful development of an educational programme can best be accomplished using a highly qualified and specialist educational team, taking into account a balanced combination of both professional and didactic
22.3 Recommendations for higher education

considerations, and in close dialogue with the professional field, students, and didactic experts.

22.3.3 Professional profile-based programme

A professional education should strive for a professional profile-based educational programme. The professional profile of structural engineering on the level of professional activities, is an effective guide for a professional programme:

- For an identifiable validation of the educational programme by the professional community.
- As a frame of reference for the student with regard to the engineering practice.

The professional field of structural engineering lacks a detailed standard overview of typical present-day professional activities. For educational development and quality assurance purposes, the typical professional activities are classified in the professional profile of structural engineering in chapter 19.

Course content and corresponding examination criteria can directly be derived from the professional structural engineering activities in combination with the applicable levels of complexity.

Linkage professional activities and competences  The professional profile of structural engineering is based on the activities of structural engineers in the field of practice. A professional higher education programme should be focused on learning to practice these professional activities.

A competence is a standardised requirement for an individual to properly perform a specific job. It encompasses a combination of knowledge, skills, and behaviour, used to improve performance. More generally,
competence is the state or quality of being adequately or well qualified, having the ability to perform a specific role.

Professional activities are directly linked to competences. A competence is actually nothing more than the ability to fulfil a professional activity. This ability encompasses a combination of knowledge, skills, and behaviour.

22.3.4 T-shaped based programme

The required T-profile of the professional structural engineer, as shown in figure 9.4 on page 108, should be fully implemented into a professional higher education programme.

Considering the evident significance of both the in-depth and in-breadth understanding, an equal division is plausible:

- In-depth understanding: approx. 50%.
- In-breadth understanding: approx. 50%.

Furthermore, an equal partition of the in-breadth understanding in the individual components - namely conceptual design parameters, technical breadth, and integral process control - is likewise plausible. Because the conceptual design parameters are part of both in-depth and in-breadth understanding, each component amounts to $\frac{50\%}{2+\frac{2}{2}} = 20\%$:

- Conceptual design parameters discipline: approx. 20%.
- Technical breadth interfaces built environment: approx. 20%.
- Integral process control: approx. 20%.

The technical depth remains $50\% - \frac{1}{2} \cdot 20\% = 40\%$. The result of this partitioning is shown in figure 22.2.
22.3 Recommendations for higher education

Figure 22.2: Partitioning of the professional T-profile

**Four-year higher education programme** The individual components can be effectively distributed over a four-year professional higher education programme as listed in table 22.1.

<table>
<thead>
<tr>
<th>Year</th>
<th>Continuous</th>
<th>Year programme</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Discipline fundamentals (20%)</td>
<td>Technical breadth built environment (20%)</td>
</tr>
<tr>
<td>2</td>
<td>(20%)</td>
<td>Technical depth concerning discipline (20%)</td>
</tr>
<tr>
<td>3</td>
<td>Integral process control (20%)</td>
<td>Technical depth concerning discipline (20%)</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 22.1: Professional higher education programme

With increasing complexity of related interfaces and extensive computational analyses and code checks, the professional field of practice should proportionally focus on the fundamentals of its discipline. The conceptual design parameters represent these fundamentals and are therefore offered continuously during the programme, with an increasing level of difficulty.
The programme starts with an overview of the built environment, followed by an initial in-depth specialisation. Then, the integral design interfaces of the concerning discipline with the built environment, and corresponding process control, are discussed. The programme ends with a thorough in-depth specialisation.
Bibliography


Curriculum Vitae

Michiel Paul Horikx was born in 1956, in The Hague, the Netherlands. He attended the Lyceum Augustinianum in Eindhoven and completed his secondary education in 1976. Subsequently, he first studied Architectural, and later Structural Engineering at the Eindhoven University of Technology. He completed his master’s thesis in 1983.

After completing his military service he worked with the Hollansche Beton Groep, at that time the largest civil engineering contractor in the Netherlands. As a structural designer, he was involved in large scale projects, including offshore and bridge design. From 1988 up to 1992 he held the position of conceptual designer and engineering manager of the steel structures - retaining wall, trusses, and ball joint - of the Maeslant Storm Surge Barrier.

Since 1992 he has worked as a senior lecturer and manager at the Amsterdam University of Applied Sciences and has been responsible for the design, implementation and management of the following successful higher education programmes: Bachelor in Civil Engineering; Bachelor in Structural Engineering; and Master in Structural Engineering.