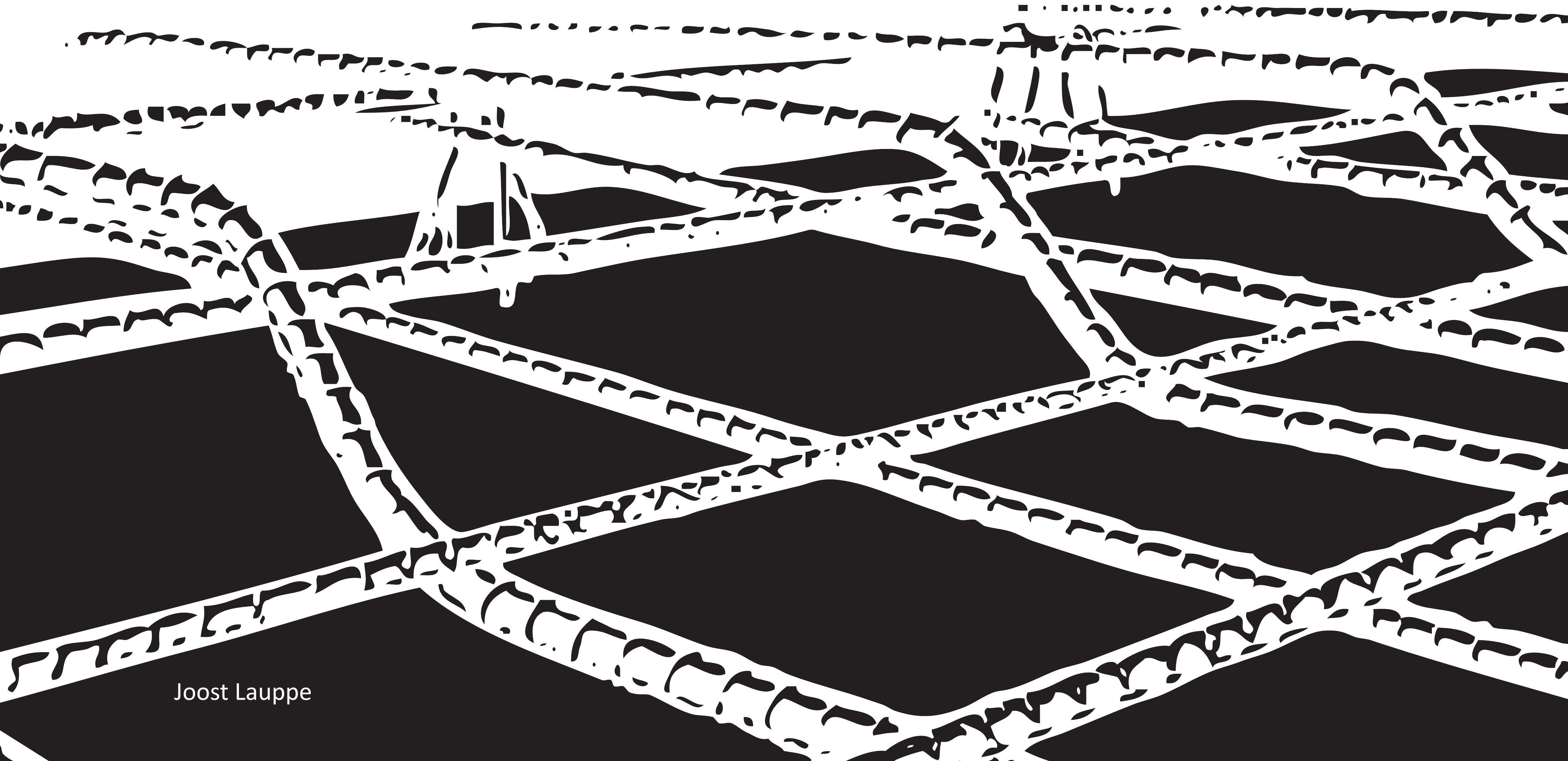
Reinforcement Toolbox

A Parametric Reinforcement Modelling Tool for Curved Surface Structures.



Joost Lauppe

Reinforcement Toolbox

A Parametric Reinforcement Modelling Tool for Curved Surface Structures.

Joost Lauppe, January 2012

Delft University of Technology
Faculty of Civil Engineering and Geosciences
Department of Design & Construction
Section Structural and Building Engineering

Arup Amsterdam

TU Delft Delft University of Technology

ARUP

Disclaimer

Published in the Netherlands

Members of the graduation committee:

Prof. dr. ir. J.G. Rots
e-mail: J.G.Rots@tudelft.nl
tel: +31 (0)15 278 3799
Delft University of Technology
Faculty of Civil Engineering and Geosciences
Department of Design & Construction
Section Structural Mechanics

Dr. ir. J.L. Coenders
e-mail: Jeroen.Coenders@arup.com
tel: +31 (0)20 305 8500
Arup Amsterdam
Delft University of Technology
Faculty of Civil Engineering and Geosciences
Department of Design & Construction
Section Structural and Building Engineering

Ir. H.R. Schipper
e-mail: H.R.Schipper@tudelft.nl
tel: +31 (0)15 278 9933
Delft University of Technology
Faculty of Civil Engineering and Geosciences
Department of Design & Construction
Section Structural and Building Engineering

Ir. A. Borgart
email: A.Borgart@tudelft.nl
tel: +31 (0)15 278 4157
Delft University of Technology
Faculty of Architecture
Department of Building Technology
Section Structural Mechanics

“All the promising developments are made possible by the progressive liberation of reinforced concrete from the bonds of wooden forms. Until these bonds are totally removed, the architecture of concrete structures is bound to be, even if briefly, an architecture of wooden planks.” P.L. Nervi

Preface

This is the final report of the MSc thesis on the development of the Reinforcement Toolbox, a parametric reinforcement modelling tool for curved surface structures. The research is part of a collaboration between the faculty of Civil Engineering and Geosciences of the Delft University of Technology, and Arup Amsterdam.

The topic arose from my personal desire to work on a practical engineering problem, preferably directly related to an actual building project. Jeroen Coenders pointed me at the challenge of designing reinforcement for complex curved surface structures, and the current lack of proper tools to assist the structural engineer in fulfilling this task.

Parallel to this thesis I have been part of the Arup Amsterdam Computation Group. This has helped me to acquire new skills, while working together with a group of enthusiastic and talented people. Working in this stimulating environment has contributed significantly to this thesis.

This final report describes the research, design and development associated to the thesis. It consists of three parts: Research; Computational Strategy and Toolbox Design; Application, Validation & Conclusions. Together they provide readers with an overview of the thought process and essential steps leading up to the development of the Reinforcement Toolbox.

Joost Lauppe,
Amsterdam, January, 2012

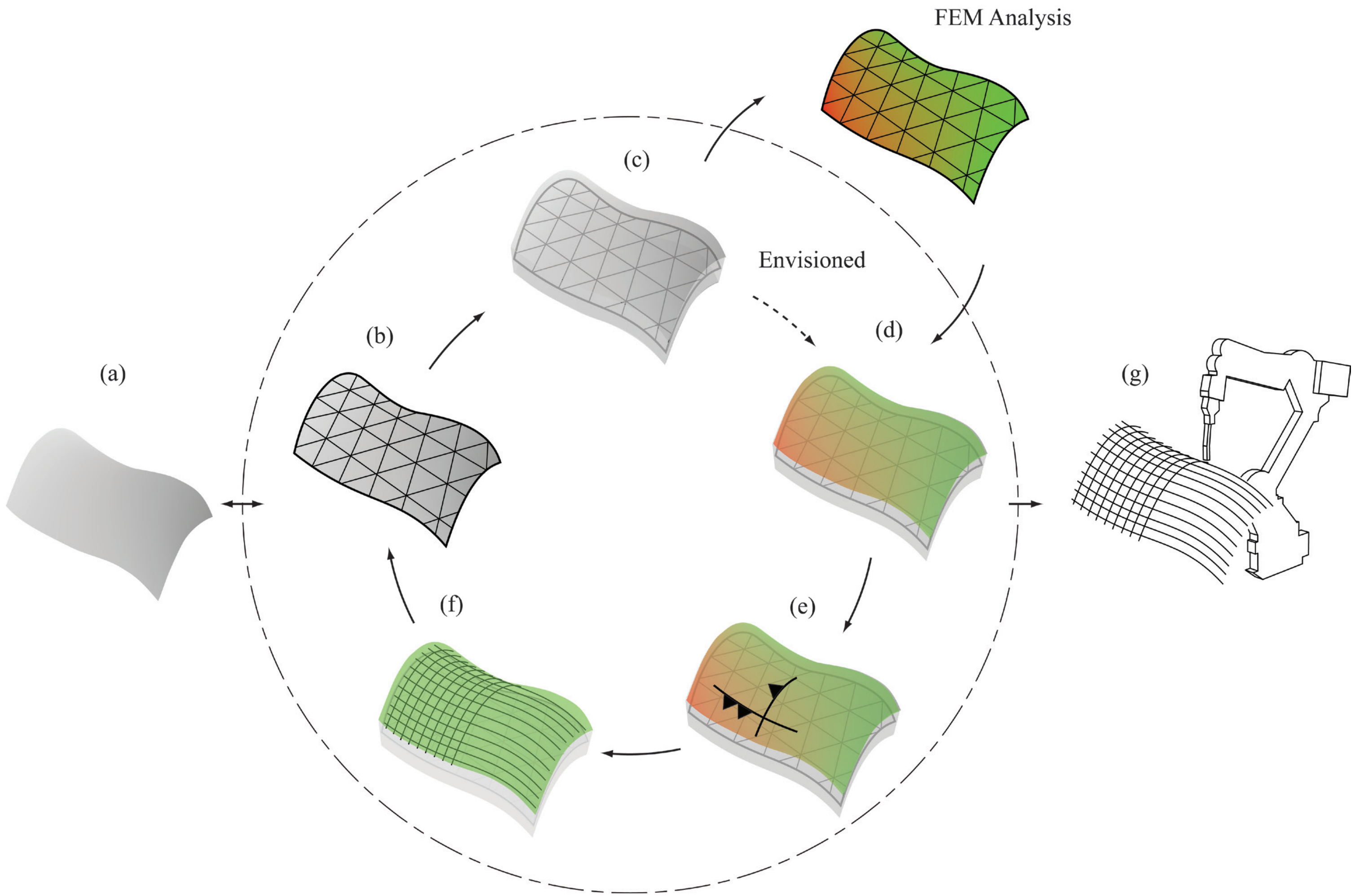
Acknowledgements

This thesis is the result of an intensive process of research, design and reflection which would not have reached its full potential without the help and support of several people. My thanks and acknowledgements go out to those who, in one way or the other, have contributed to this process.

Firstly I would like to thank my graduation committee members: prof. Jan Rots, Jeroen Coenders, Roel Schipper and Andrew Borgart. Their feedback and support has stimulated me throughout the whole process. Special thanks go out to my daily supervisor Jeroen Coenders, who, through his endless enthusiasm and stream of ideas has sparked my interest in a field which was previously unknown to me: computational design. I would also like to thank Roel Schipper and Andrew Borgart with whom I spent several hours discussing the various aspects of the thesis. It helped me to apply focus in my research.

Secondly I would like to thank Arup Amsterdam for offering me the chance to conduct my research in a stimulating professional environment. Special thanks go out to my direct colleagues of the Computation Group: Roel van de Straat, Anke Rolvink, Bastiaan van de Weerd and Tijl Uijtenhaak. Apart from being great colleagues, you have become great friends, thanks for that.

Figure 1
Subsequent steps of the computational strategy: (a) Input of a curved surface (b) Surface rationalisation (c) Creation of the SolidModel (d) Visualization of FEM Analysis results (e) Allocation of reinforcement (f) Reinforcement model (g) Production.



Summary

Recent years have witnessed the realization of multiple concrete curved surface structures. The often complex geometry of these structures led to new challenges in the final design and production phase: design of the reinforcement is one of these challenges.

3D reinforcement models are rapidly replacing 2D reinforcement drawings as the main data carrier in the design process. There are several practical reasons for this development; all involve optimization of the reinforcement process. Current reinforcement modelling software is not capable of properly dealing with NURBS curves and surfaces. The absence of proper reinforcement tools for curved surface structures renders the structural engineer less effective in designing the reinforcement. This can lead to missing out on potential through ill-informed design decisions.

The reinforcement process of curved surface structures is characterized by close cooperation between design and production industries. Control over the end product, the reinforcement, demands a clear division of responsibilities and agreed communication standards. Reinforcement for curved surface structures is often a one off product, which implies the entire process from design to production has to be repeated for each object.

The computational strategy proposed in this thesis provides a way of improving the design process. It includes all necessary steps of raising an architectural curved surface model to production level in terms of reinforcement (see Figure 1). Three design aspects have been distinguished: geometrical control, structural analysis, and production. Corresponding to these design aspects, three concepts have been developed: the SolidModel, FEM Analysis visualisation and Rebar DNA which help to control them.

The developed Reinforcement Toolbox supports the strategy by offering structural engineers a tool which can be used to control the design aspects of reinforcement in curved surface structures. It sets out to help remove the current split between draftsman and structural engineer by offering a design environment which offers the possibility to simultaneously model and verify reinforcement for curved surface structures. In addition it should serve as a lubricant, improving communications between the structural engineer – contractor, and the structural engineer – detailer/fabricator. Figure 2 shows the envisioned role of the Reinforcement Toolbox placed in the reinforcement process document flow diagram.

Functional requirements which emerged from the strategy formed an important input for the developed architecture of the Reinforcement Toolbox. Use cases helped to identify different scenarios in which the software application is likely to be used. The system

architecture of the Reinforcement Toolbox has been developed with strong attention to the multifaceted design process of reinforcement in curved surface structures. It builds on existing 3D modelling software, Rhinoceros and Grasshopper, by adding custom components. For the first version of the Reinforcement Toolbox a number of components have been developed and categorized according to the following sub-categories:

1) Conditions
2) Geometry
3) Reinforcement
4) Post-Processing

The Reinforcement Toolbox has been developed using Microsoft Visual Studio 2008 and written in C#. In accordance to the possibilities offered by this object oriented programming language, the Reinforcement Toolbox uses a collection of custom objects which can be considered the building blocks of the Toolbox. For the first version of the Reinforcement Toolbox several components have been developed. Together they offer the necessary functionality for a structural engineer or CAD draftsman to design longitudinal reinforcement groups and reinforcement meshes for curved surface structures.

At the heart of the Toolbox lie three key components: the SolidModel component, the Path component and the Allocator component. Figure 3 gives an explanation in six steps of how reinforcement is created. In a first step the averaged vectors are created in the vertices of the reference mesh, by addition of the normal vectors of the adjacent face. These are used in a second step for creating the Solids. The third step involves a start- and endpoint being assigned by the user, creating a so-called RebarPath. In the fourth step the PathPoints are determined through an algorithm which finds the plane edge intersection between the reference mesh edges and the y,z-plane of the RebarPath. The last two steps are dominated by the Allocator component which assigns the PathPoints to the correct offset layer within the SolidModel. Each PathPoint has a pointer to the reference mesh face which contains it, together with the u,v-coordinates which determine its position. The Allocator component uses this information when it creates a RebarPoint: a temporary offset face within the Solid is created on which the RebarPoint is plotted. A Rebar object contains multiple of these RebarPoints, together they form the control points of a smooth center line which defines the Rebar.

A first version of the Reinforcement Toolbox has been developed and tested. It can be applied to both complex curved surface structures as well as non-complex structures, making it a widely applicable design tool. Users can apply the Reinforcement Toolbox at their own discretion within any given stage of the reinforcement process either to quickly research different reinforcement design alternatives, or use it to build extensive reinforcement models. The parametric reinforcement models (see Figure 4) are easily adaptable to design changes, which makes them valuable throughout the entire reinforcement process. Validation of two important aspects of the solid- and reinforcement models created using the Toolbox, the mesh topology and concrete cover, revealed no inconsistencies or large deviations from the allowed tolerances.

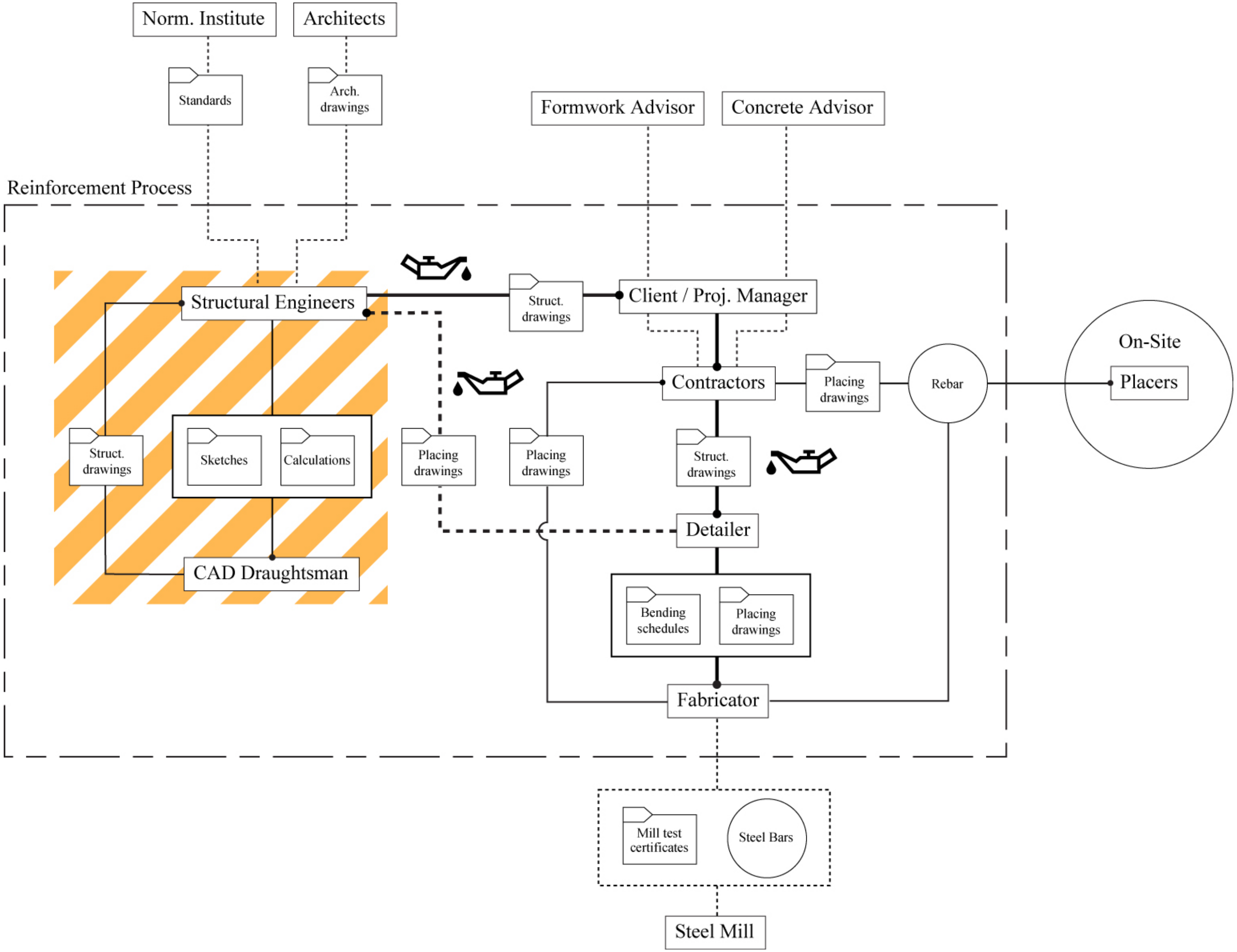


Figure 2
Envisioned role of the Reinforcement Toolbox, abolishing the divide between structural engineer and draftsman and improving the communications between stakeholders.

The Toolbox has been designed considering user friendliness, and freedom of use. The modular setup allows users to combine components at their own discretion allowing for the intended freedom when designing reinforcement. It has been demonstrated to a group of structural engineers, who recognize the potential it can bring to the reinforcement process, especially when its current functionality and scope will be expanded.

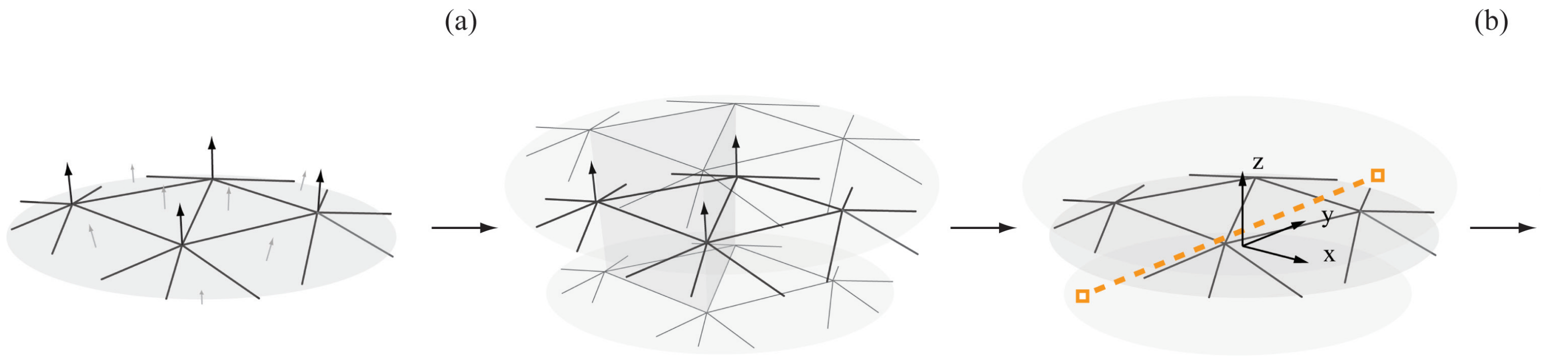


Figure 3 (Continues on next page)
The workings of the Toolbox explained according to three key components, (a) the SolidModel component, (b) the Path component and (c) the Allocator component.

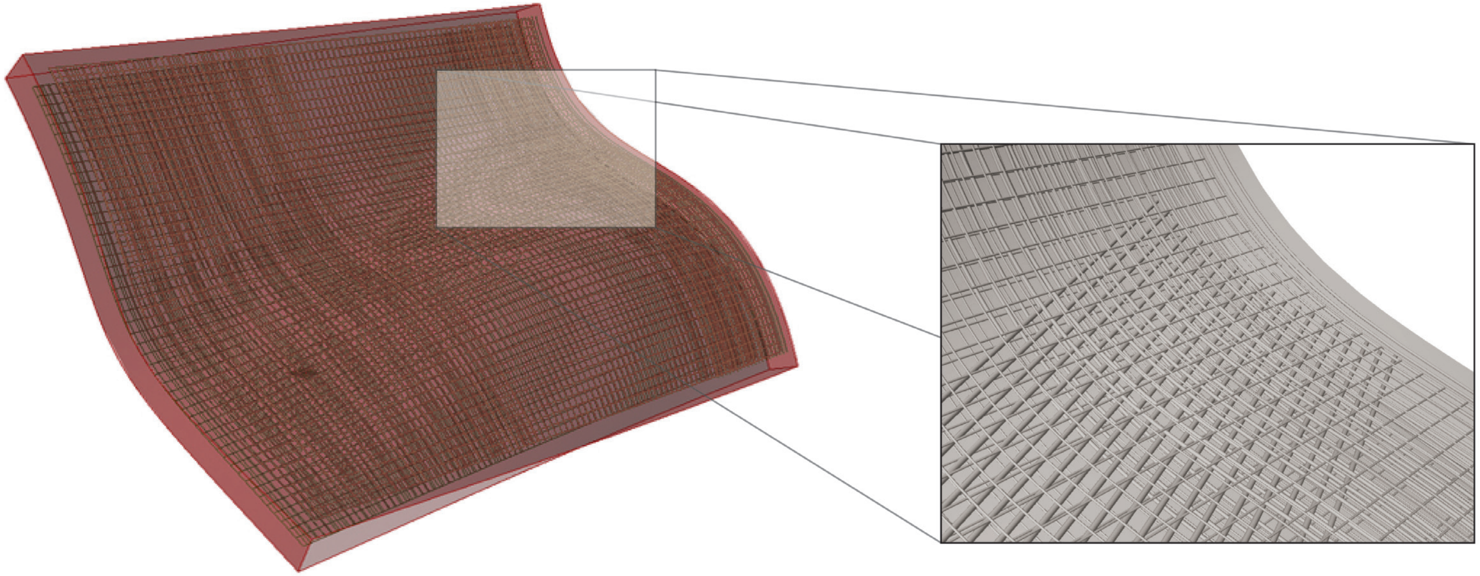
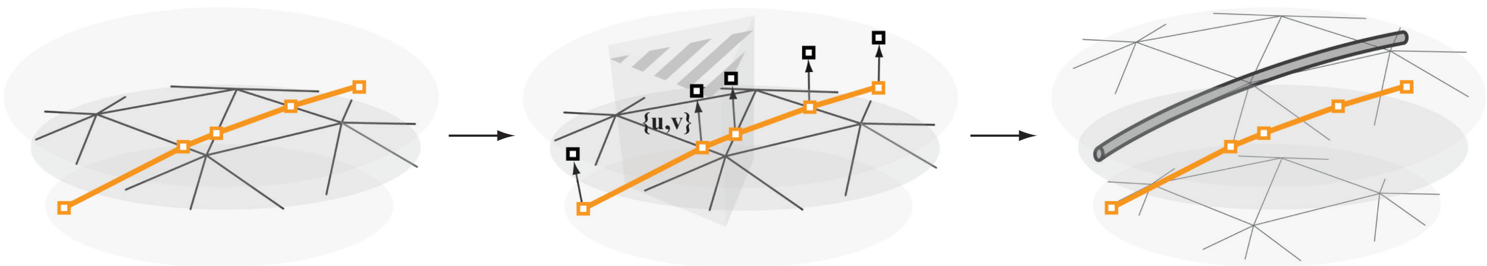


Figure 4
A parametric reinforcement model for a curved surface structure created using the Reinforcement Toolbox.

(c)



Contents

Bundles of reinforcement bars are stored outside, ATG Steel, Raamsdonksveer.

1.0 **Introduction**

This chapter introduces the most important terms and concepts used throughout this thesis and explores the state of the art of reinforcement engineering for curved concrete structures. It provides insight into fields of knowledge which are of importance to the topic of reinforcement in curved concrete structures, leading up to the problem statement and research objective of this thesis.

Section 1.1 describes the developments in the field of Computer Aided Geometrical Design (CAGD) as the main driver behind the emergence of contemporary curved surface structures. Section 1.2 introduces some of the important characteristics of reinforcement in concrete curved surface structures. The structural analysis techniques used for this type of structures are explored in Section 1.3 after which the applicability of BIM software is described in Section 1.4. The Chapter concludes with an elaboration on the problem statement and research objective.

1.1 Curved Surface Structures

Advancements made in the field of Computer Aided Geometrical Design (CAGD) have provided a solid basis for the design and engineering of curved concrete structures. It has contributed to a strong embedding of this type of structures into the current architectural discourse. Acclaimed architecture firms like Zaha Hadid Architects, Toyo Ito and UNStudio propagate the free form, and often employ concrete as the physical embodiment of their ideals. Recent projects like the Phaeno Centre and the MUMUTH music theatre are examples of buildings which would have been very hard to realize without the new methods and computational techniques provided by CAGD.

The history of the Computer Aided Geometrical Design (CAGD) discipline is inextricably linked to the emergence of the computer. Without it many of the mathematical operations required for curve and surface definition would be practically impossible to perform. The enormous computation power allows for digital representation of every conceivable shape or form. Now there exist many CAD / CAM packages, which all benefit from efforts within the field of Computer Aided Geometrical Design. They are widely adopted in architecture firms, and have rendered the representation and production of curved surface structures more feasible. Advanced CAD tools offer architects the possibility to represented complex curved surfaces structures. Figure 1.1 shows a render of the Arnhem Transfer Hall a curved surface structure design.

The origins of Computer Aided Geometrical Design are inextricably linked to developments in the automotive and aerospace industries. The demand for control over geometrically complex designs asked for new geometric concepts. Companies like Citroën

Figure 1.1
Render of the NSP Arnhem Transfer hall, an example of a curved surface structure (image courtesy of UNStudio).

and Renault attracted young mathematicians to help develop these. Two names which stand out in this history are Paul de Faget de Casteljau and Pierre Bézier. Their work laid the foundations to an entirely new discipline which would have an enormous effect on contemporary design including architecture (Farin, 2002).

Before computers, physical templates or blueprints convey the geometrical information of curves into the production process. This can be traced back as far as AD Roman times when templates, were used for the purpose of shipbuilding. These actual sized templates offered geometrical control over the shape of the curved ribs. The first recorded use of constructive geometry to define free-form shapes on construction drawings also originated from the marine industry. An instrument called 'spline' was used to define the smooth contour lines of ships. Over time industries became better equipped to accurately translate drawings into products. This led to a shift from the often impractical templates on the work floor towards blueprints on the drawing board. Parallel to the research into new ways of storing geometrical data, research was done into the automation of machine tools. Initially punch tapes provided input to motors that moved the controls of milling machines. The analogue input through punch tapes soon became replaced by computers, resulting in the first Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) systems capable of accurately producing curved elements. The work of de Casteljau and Bézier resulted in a completely new way of defining curves and surfaces. Their key insight proved to be detaching the control points from the direct shape of the curve. Their algorithms recursively construct points on a curve, through a method of repeated linear interpolation, a process which requires many computations.

The sixties witnessed different research approaches and the development of several CAD/CAM systems, but it was not until the seventies that these different approaches began to converge. An important unifying force went out from the earlier works of de Casteljau and Bézier. Their new concept for defining curves proved to be so strong that eventually it was adopted by practically all the CAD/CAM systems. Bézier helped to develop of UNISURF, a pioneering surface CAD CAM system entirely based on Bézier curves and surfaces, which was used to design car bodies. This system later evolved into CATIA, a multi-platform CAD/CAM/CAE commercial software suite which is still very popular in the automotive and aerospace industries. Gehry Technologies has used CATIA as a core engine for their Digital Project (Gehry Technologies, 2011). Similar products are developed by McNeel (McNeel, 2009) and Autodesk (Autodesk, 2011).

Nowadays practically all architecture and engineering firms employ advanced CAD systems in their daily business. 3D models are rapidly replacing 2D drawings as the main data carrier in the design process, and working with them is part of the regular skill set of the contemporary engineer.

1.2 Reinforcement

Reinforced concrete is the most widely used man made construction material in the world. Production currently adds up to 7.5 cubic kilometres each year, representing a bit more than one cubic meter for every person each year (‘Concrete’, Wikipedia: The Free Encyclopedia). The success of this composite material has several reasons, most importantly the fact that its components complement each other in terms of structural behaviour. Concrete performs particularly well under compression, but poor under tension. Cracking occurs when, due to applied loads, positive or negative thermal expansion, or shrinkage, the concrete tensile strength is reached. The tensile strength of concrete is about 10 to 15% of its compressive strength (Walraven, 2002) and therefore adding reinforcement becomes necessary when applying concrete structurally.

Although new types of reinforcement, like fibre- and fabric reinforcement have emerged, the use of steel reinforcing bars is still the most commonly used reinforcement in both non-complex as well as complex concrete structures. Its success can be explained according to three distinct physical characteristics in the interplay between reinforcement steel and concrete:

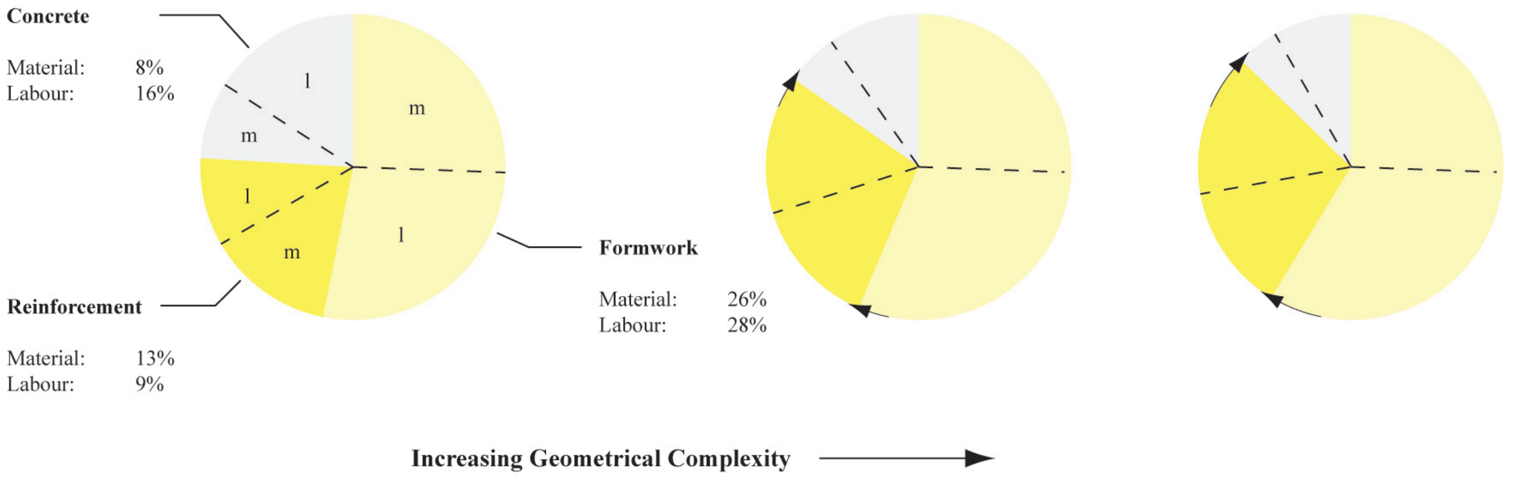
- The thermal expansion coefficient of steel and concrete are almost similar, which prevents the formation of internal stresses due to thermal expansion or contraction.

Figure 1.2
Production costs of a cast in situ continuous footing and wall specified in terms of material- (m) and labour (l) costs. Increased geometrical complexity leads to a rise in labour costs.

- Hardened cement has an excellent bond to the steel surface of the reinforcement bars, allowing for an efficient load transfer between the components.
- Due to the highly alkaline environment of concrete, a thin protective layer is formed around the reinforcing steel during the cement hydration. This forms a natural protection against corrosion.

This thesis focuses on steel reinforcing bars in a specific subset of concrete structures: curved surface structures. Their complex geometry generally leads to higher design and production costs. Research on the distribution of production costs of a standard concrete element (a cast in situ continuous footing and wall) reveals that reinforcement and formwork together make up around seventy five per cent of the total production costs (Popescu, 2003). In case of curved surface structures the share of these two production aspects further increases due to a significant rise in labour costs, see Figure 1.2. Increased geometrical complexity demands more design time and more time on site.

Despite the higher production costs, recent years have witnessed the realization of multiple concrete curved surface structures (see Appendix A). These designs would have been very hard to realize without the advancements made in another field being: Computational Mechanics. The next Section explores structural analysis techniques used for curved surface structures.



1.3 Structural Analysis of Concrete Curved Surface Structures

As the developments in Computer Aided Geometrical Design opened doors to new shapes for designers to explore, engineers were facing the challenge of how to analyse these shapes. Parallel to the developments in CAGD the first important steps towards a new structural analysis method had already been made: the finite element method (FEM). As was the case with CAGD this method became successful through the rise of the computer, and the advancements in the computing industry directly influenced the progress made in the field of finite element analysis (FEM Analysis).

Although the underlying 'matrix theory of structural analysis' was already developed in the 1940's, the term 'finite element' was first coined by Clough in his paper on plane stress analysis techniques for the second ASCE Conference of Electronic Computation in 1960 (Clough et al., 1999). 'Finite' refers to the finite number of degrees of freedom of the discretized model. By the early 1970s FEM Analysis was applied to a wide variety of engineering problems. But it wasn't until the development of strong graphical pre- and post-processors in the 1980s that the technique became adopted by a wide range of engineers working in various disciplines. The trend was backed by the rise of microcomputers, including workstations and desktop computers. The main advantages of the finite element method (Barton et al., 2000) are summed up as:

- The ability to deal with complex geometry
- The applicability to a wide range of engineering problems
- The ability to handle complex restraints
- The ability to handle complex loading

Nowadays FEM Analysis is an important part of the engineer's tool kit and is widely available, but its success comes with a risk. Increased size of the models and limited knowledge on the underlying logic, can give a false sense of certainty in terms of presented results. It is necessary to stipulate that the Finite Element Method produces approximated solutions and has inherent errors (Demlow, 2002). Therefore should be used primarily as an analysis tool to gain insight into the structural behaviour of complex structures, and as an indication of required reinforcement quantities in curved concrete structures.

'FEM analysis software' is used as the generic term for a group of software applications based on the finite element method. Within the scope of this thesis InfoCAD (InfoGraph GmbH, 2010) will be part of the Reinforcement Toolbox. Like most FEM Analysis software it incorporates a Pre-processor, Processor, and Post-processor. The Pre-processor includes the possibility of automated meshing. A well-defined mesh is critical in retrieving proper analysis results. Elements with small inner angles or sudden transitions in element size can introduce inaccuracies, which increase the approximation error.

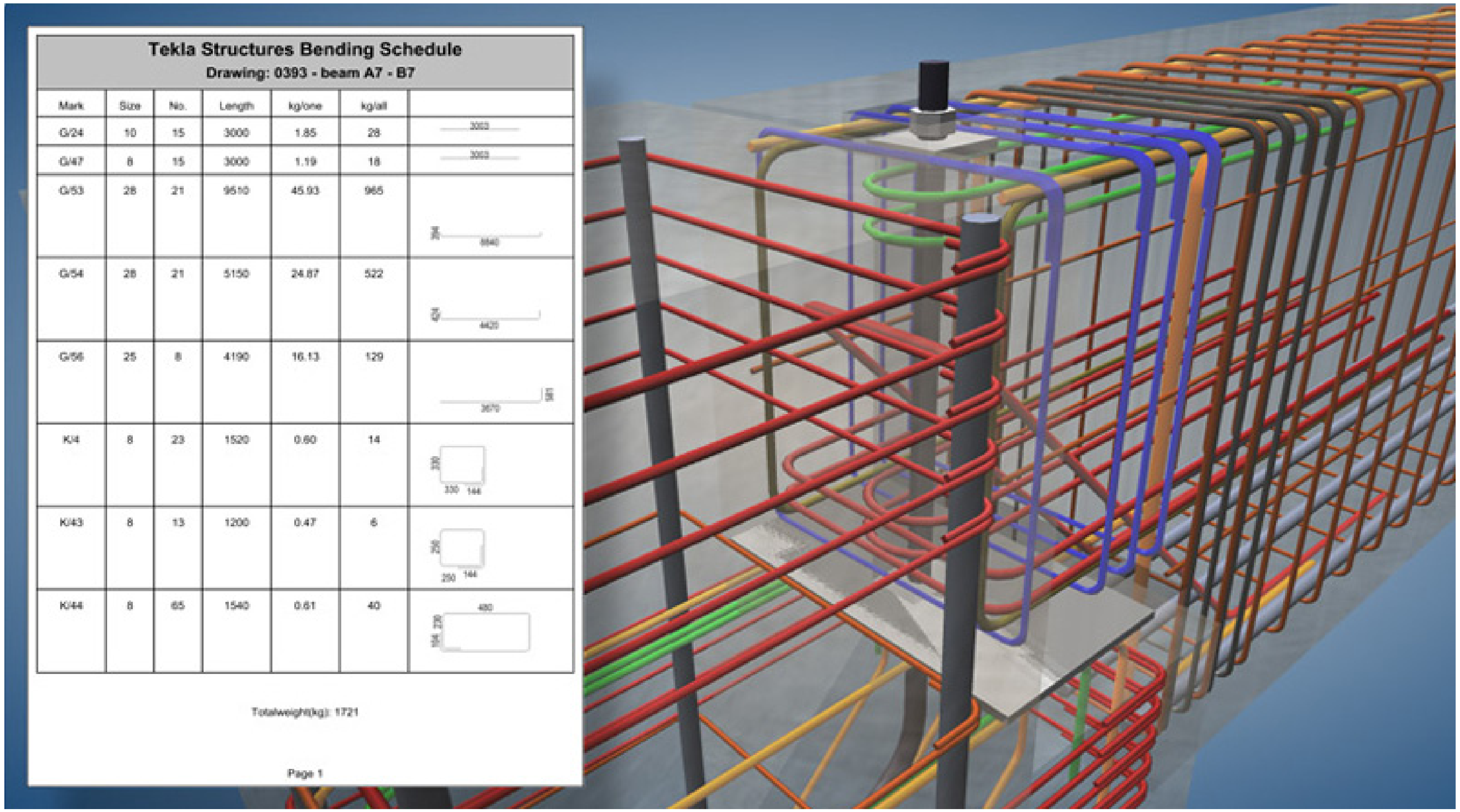
This thesis revolves around reinforcement of concrete curved surface structures. The composite nature of this material significantly adds to the complexity of the finite element analysis as the elements have to model nonlinear orthotropic behaviour. More information on InfoCAD and its underlying principles can be found in Section 2.2.

1.4 Curved Surface Structures and the Applicability of BIM Software

Within this thesis Building Information Modelling (BIM) is considered to be the process of generating and managing a digital model of a building's components and systems throughout its life cycle. A BIM model can be considered as being the container for all relevant information necessary for this process. The objects contained in the model are meant to simulate real-world objects and usually combine dimensional, material and metadata. BIM models are detailed 3D representations of the actual building and its parts, including the reinforcement.

> *"The advantages of working in 3D: since the drawing is generated from a central three-dimensional model, the plan views, elevations and sections are interdependent."* (Corke, 2003)

There are several practical reasons for designing reinforcement in 3D, which all aim at optimizing the reinforcement process. Compared to 2D drawings, 3D drawings are easier to understand and convey information in a less ambiguous way. Professionals in the



Tekla Structures Bending Schedule
Drawing: 0393 - beam A7 - B7

Mark	Size	No.	Length	kg/one	kg/all
G/24	10	15	3000	1.85	28
G/47	8	15	3000	1.19	18
G/53	28	21	9510	45.93	965
G/54	28	21	5150	24.87	522
G/56	25	8	4190	16.13	129
K/4	8	23	1520	0.60	14
K/43	8	13	1200	0.47	6
K/44	8	65	1540	0.61	40

Totalweight(kg): 1721

Page 1

Figure 1.3
Impression of digital reinforcement components (image courtesy of Tekla Structures).

industry identify the need for 3D reinforcement modelling in order to improve the quality of deliverables and increase the structural engineer's practical knowledge on reinforcement (Wapperom, 2006).

Current BIM-software supports the creation of smart building models. Several large BIM software packages like Autodesk Revit, Nemetschek Allplan, and Tekla Structures incorporate Reinforcement extensions. They offer functionality to create reinforcement models for standard concrete elements. A centralized 3D reinforcement model holds all the necessary information from which relevant sections and elevations can be extracted. These software packages all rely on the concept of parametric reinforcement components, for standard structural elements. This implies a group of objects (rebar's) being treated as a single object, which can be easily modelled and adjusted. Closed 3D solids composed of multiple surfaces define the boundaries of the concrete element. Standard elements comprise beams, columns, slabs and other common construction elements. A single reinforcement object includes all relevant types of reinforcement like links, stirrups, hooks and longitudinal rebar. Figure 1.3 shows an example of two reinforcement objects (beam and column) coming together. This way of modelling is called object oriented modelling.

Although object oriented modelling of reinforcement proves a powerful concept in case of geometrically noncomplex structures, the reinforcement extensions of current BIM packages show poor interoperability with NURBS curves and surfaces. Research into the ability to model reinforcement for double curved elements reveals several issues.

Importing NURBS curves and surfaces introduces a large degree of inaccuracy. When setting up BIM models for curved surface structures the interchange between the architectural model and the BIM software becomes crucial. A reinforcement model based on imported NURBS geometry proves to be useless due to the introduced inaccuracies. Furthermore current BIM software is incapable of creating properly defined reinforcement models for geometrically complex curved surface structures, see Figure 1.4.

Figure 1.4
Reinforcement Modelling
BIM-Software comparisons.

	Extension	Producer	Supports BIM file formats	Clash detection	Supports object oriented general arrangements	Supports double curved geometry	Parametric geometry definition	FEA interoperability for complex geomteries
Allplan 2011 Engineering		Nemetschek	yes	yes	yes	yes*	no	no
Revit Structure	Reinforcement	Autodesk	yes	yes	yes	no	no	no
Tekla Structures	Reinforced Concrete Detailing	Tekla Corporation	yes	yes	yes	no	no	no

*Only small amounts of curvature

The fact that BIM software is not yet able to properly deal with geometrically complex concrete structures makes that they cannot benefit from the advancements of object oriented reinforcement modelling. Due to their complex geometry curved surface structures could benefit hugely from 3D reinforcement modelling. These structures need different strategies in order to create digital reinforcement models.

1.5 Problem Statement

Over the past few decenniums advancements in Computer Aided Geometrical Design (CAGD) and Finite Element Method Analysis have had a significant effect on building design. They offered architects and engineers tools to digitally represent and analyse curved surface structures. In case of concrete structures this lead to three specific challenges with respect to the design and production of reinforcement.

The first challenge of reinforcement design for curved surface structures is representation. Straightforward reinforcement configurations, for instance beams and slabs, can easily be communicated through a limited number of sections and elevations. This doesn't hold for curved surface structures, as regular 2D representation is often inadequate to transfer the full complexity. The second challenge is the link between structural analysis and geometrical design of the reinforcement. Unlike straightforward reinforcement configurations the effects of the reinforcement design on the stress distribution are more difficult to predict. The third challenge is linking the reinforcement design to production facilities.

Reinforcement design usually takes place in a late stage of the design process. This is inherently linked to the high amount of detailed information necessary to carry it out. The increased geometrical complexity of a structure directly leads to a higher complexity of the associated reinforcement. Potential areas of conflict are identified on the basis of insight and practical knowledge by experienced engineers. When it comes to reinforcing curved surface structures this experience is often lacking. This lack of experience coupled to the inherent difficulty of representation of complex geometry can lead to inefficiency and uncertainties in a late stage of the design process. While 3D CAD modelling software allows for representation and FEM Analysis software allows for the analysis of complex concrete structures there is no connection between the two types of applications.

The implementation of digital models in the design process has caused a shift, from 2D to 3D, which has important implications for the engineer. Reinforcement extensions of current BIM packages prove to be incapable of properly dealing with curved surfaces, often represented through NURBS curves and surfaces. The absence of proper reinforcement tools for complex curved geometries renders the structural engineer less effective in designing reinforcement for curved surface structures. This leads to the following problem statement:

The appropriate tools to help the structural engineer effectively design reinforcement for curved surface structures do not exist. This leads to inefficiency and uncertainties in a late stage of the reinforcement process.

1.6 Research Objective

Previous sections have shown that the engineer lacks the appropriate tools to effectively design reinforcement for curved surfaces structures. For this reason one of the challenging design and production aspects of this type of structures, being the reinforcement, carries high risks and uncertainties deep into the design- and construction process. The absence of tools can lead to missing out on design potential through ill-informed decisions.
Reinforcement is subject to many different constraints. It is relatively easy to keep account of these constraints when dealing with straightforward, orthogonal elements. When the geometrical complexity increases, however, overview can be quickly lost. Computational design combines the ability of structuring large quantities of data in a logical way, with the creativity of the human brain. This makes computational design a problem solving strategy capable of dealing with the issue of reinforcement in curved surface structures.

Successful tool development starts with a thorough understanding of the design process in which the tool needs to be embedded. Research into the associated stakeholders, design aspects and methodology helps developing a solid computational strategy, or concept, which covers the entire scope of the problem. The main objective of this thesis reads as follows:

To design a computational strategy which supports the design and production enhancement of reinforcement in curved surface structures taking into account the aspects of geometrical control, structural analysis and production.

From a user's perspective the translation of the concept into a working application is most interesting. In order to make proper reinforcement designs the engineer needs to be able to control the various design aspects through a user friendly interface. Therefore the concept will be developed into a toolbox which enables structural engineers to easily model and assess reinforcement for a given concrete curved surface structure. The toolbox should be easily extendable by adding more components or extending the functionality of existing ones. The toolbox should provide for a proof of concept by incorporating the key aspects of the computational strategy for reinforcement design. The second objective therefore is:

To develop a toolbox which enables structural engineers to model reinforcement for concrete curved surface structures, in a virtual 3D environment.

Reinforcement bars supplied on coils, ATG Steel, Raamsdonksveer.

2.0 **Design Aspects of Reinforcement in Curved Surface Structures**

This chapter highlights the most important design aspects of concrete curved surface structures from the perspective of the structural engineer. The design process of concrete curved surface structures is exemplified.

Section 2.1 describes the results of a study into the design process of curved surface structures. The three main design aspects are identified. As the Reinforcement Toolbox aims to be part of this design process these aspects will form important input to the development of the reinforcement toolbox. Section 2.2 goes into further detail on these three design aspects. Section 2.3 illustrates a reinforcement design process for complex curved concrete structures, according to practical examples from the Rolex Learning Centre (EPFL).

2.1 The Design Process of Curved Surface Structures

The design process of concrete curved surface structures is characterized by a direct interplay between architectural- and structural design. The expressive nature of the structure plays an important role in the architecture. For a long time designers who took the lead in this type of structures were engineer-designers like Pier Luigi Nervi, Felix Candela, Eduardo Torroja, Antoni Gaudi and Heinz Isler. The recent tendency to favour the architect over the structural engineer as being responsible for creating the geometry of curved surface structures has led to more sculptural shapes.

Although the introduction of digital models seems to have shifted the emphasis in the form finding process more towards aesthetics, the main focal points during the design process have remained the same. It generally starts with finding an appropriate form. Three different approaches can be distinguished, being sculptural (arbitrary), geometric (description through mathematical formulas) or structural (physical analog modelling) (Coenders, 2006). All of them require additional steps in order to transfer the geometrical information to drawings, which form the basis of further design. Finding structural analogies and performing hand calculations helps the engineer understand the structural behaviour, and order of magnitude of the forces that act on the structure. Preliminary dimensioning can be done accordingly. A more detailed study of structural behaviour used to be carried out by performing stress tests on physical models. The manipulability of reinforcement and formwork is either ensured by building one-to-one mock-ups, or by making design alterations during construction. This process is exemplified in Figure 2.1.

Figure 2.1 (Top)
Subsequent design steps for curved surface structures: Form finding; Form definition; Dimensioning; Stress tests; Mock-ups; Construction.

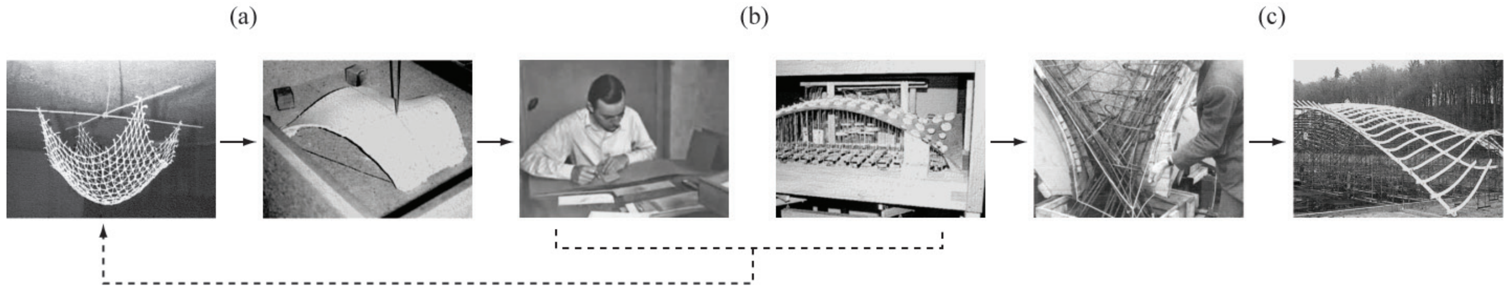
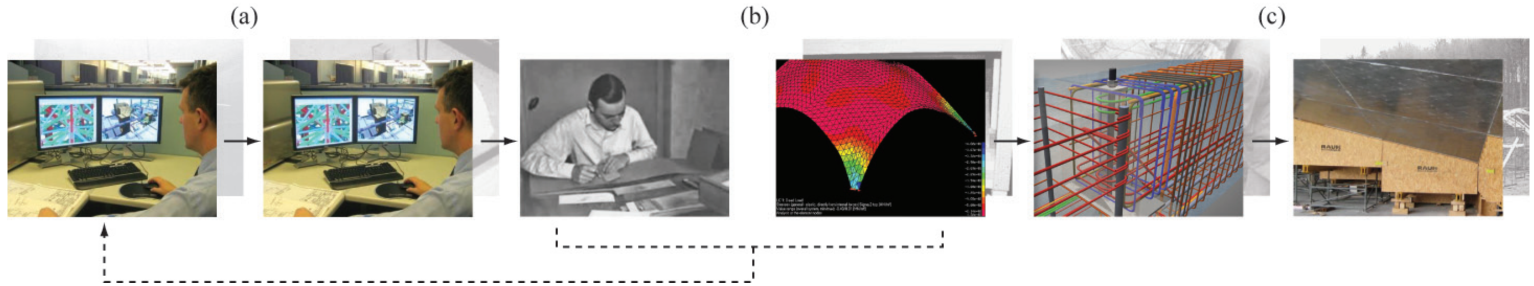


Figure 2.2 (Bottom)
Digital tools replace physical methods in the curved concrete surface design process.



Increased geometrical complexity of a building design shifts the focal points during the design process to the three following design aspects:

a) Geometrical control
b) Structural analysis
c) Production

These are obvious points of attention during regular design processes but become even more demanding when the geometry of the design is of a higher complexity.

The availability of digital models has not changed these fundamental design aspects, but it has changed the tools used to control them, see Figure 2.2. Digital representation of double curved surfaces has largely replaced the physical models. Physical stress tests, although still conducted in specialized laboratories, are now rarely conducted in engineering firms. Instead FEM Analysis software is used to predict structural behaviour. The production process is more and more digitalized by applying BIM. Reinforcement configurations of standard structural elements can now be tested in a virtual environment and linked to production facilities.

The last decades have witnessed a domain shift, from the 'form-finding' engineer to the 'form-creating' architect. This shift in design roles coincides with, and is catalysed by, the emergence of new design tools like advanced 3D CAD software. The structural engineer in the role of advisor needs to be able to quickly adapt to design changes. Proper software tools granting this ability, if not readily available on the market, need to be developed.

The structural engineer has become more reliant on computational tools in the design process. As the geometry is often defined by the architect the role of the structural engineer has changed into that of a highly specialized structural adviser, who has to respond quickly to geometrical changes. The structural engineer has several applications and techniques at his disposal which help him/her to fulfil this role. The next section discusses the three design aspects of reinforcement in curved surface structures.

2.2 Three Design Aspects of Reinforcement in Curved Surface Structures

The three main design aspects of concrete curved surface structures distinguished in the previous Section are geometrical control, structural analysis, and production. They form important input for the design of the Reinforcement Toolbox. All three are directly applicable to the design of the reinforcement and will form the basis for the technical preconditions of the toolbox. The following sections provides for a more detailed description of each design.

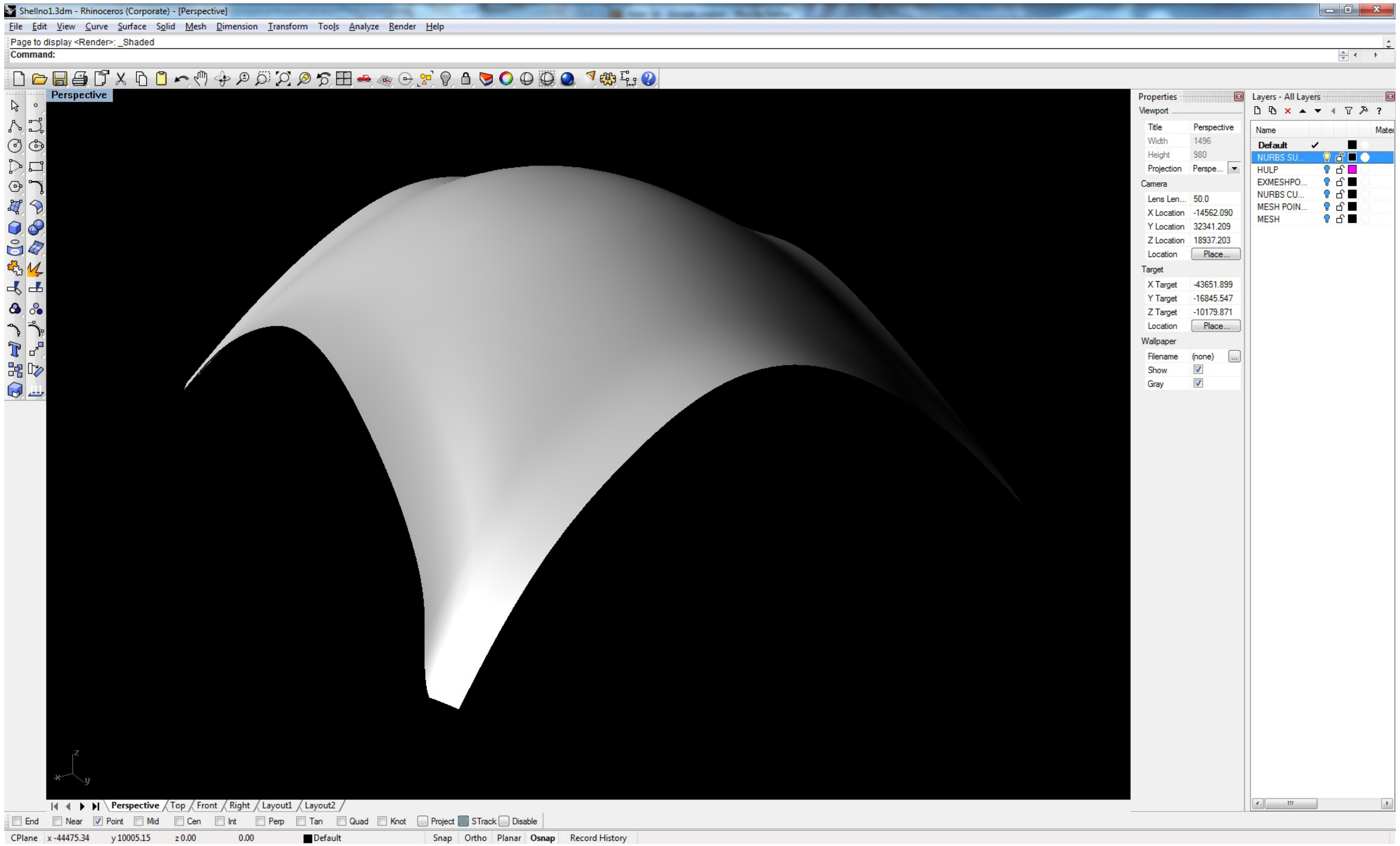
2.2.1 Geometrical Control

Geometrical control plays a vital role in the design of complex geometry structures, and forms the input on which related design processes like structural analysis and production are based. In this thesis geometrical control is referred to as: the ability to unambiguously capture, manipulate and extract geometrical data from a 3 dimensional shape.

Figure 2.3
Smooth surface representation of a curved surface model in Rhino 3D.

Section 1.1 describes the influence advancements in Computer Aided Geometrical Design had on architectural representation of curved surface structures. Advanced 3D CAD packages, like Autodesk Maya and Rhino 3D, have become indispensable design tools. They visualize the high order mathematical relationships which underlie the geometry, and offer graphical tools for manipulation and data extraction. A digital smooth surface model of a typical Isler shell created in Rhino3D using a NURBS surface is presented in Figure 2.3. It exemplifies how modelling tools can help the structural engineer gain control over complex geometries. These tools include operations like basic distance measurement, projections, creating cuts and sections, etc.

Another way of representing complex geometry is through meshes, see Figure 2.4. Meshes produce a coarse surface definition built up of a collection of vertices, edges and faces. The faces are bounded by polygons, and share edges with other faces. Discretisation of curved surfaces into a collection of singular elements offers a way of rationalizing a complex geometry. Section 1.3 has pointed



out the use of meshes in finite element models. Mesh models can help simplify geometrical operations as they rely on less complex mathematical principles compared to free form smooth surfaces. In case of free form concrete structures however, the segmented appearance of meshes is often not desirable in the actual built structure, as architects generally favour smooth fair faced concrete surfaces. This provides for additional challenges during production both in terms of the formwork, as well as the reinforcement.

Successfully deploying a 3D reinforcement model for production purposes relies heavily on dimensional accuracy. When determining the appropriate type of representation on which reinforcement will be based it is important to consider both modelling and production tolerances in order to prevent non-fitting reinforcement bars on site.

Figure 2.4
Mesh representation of a curved surface model in Rhinoceros3D.

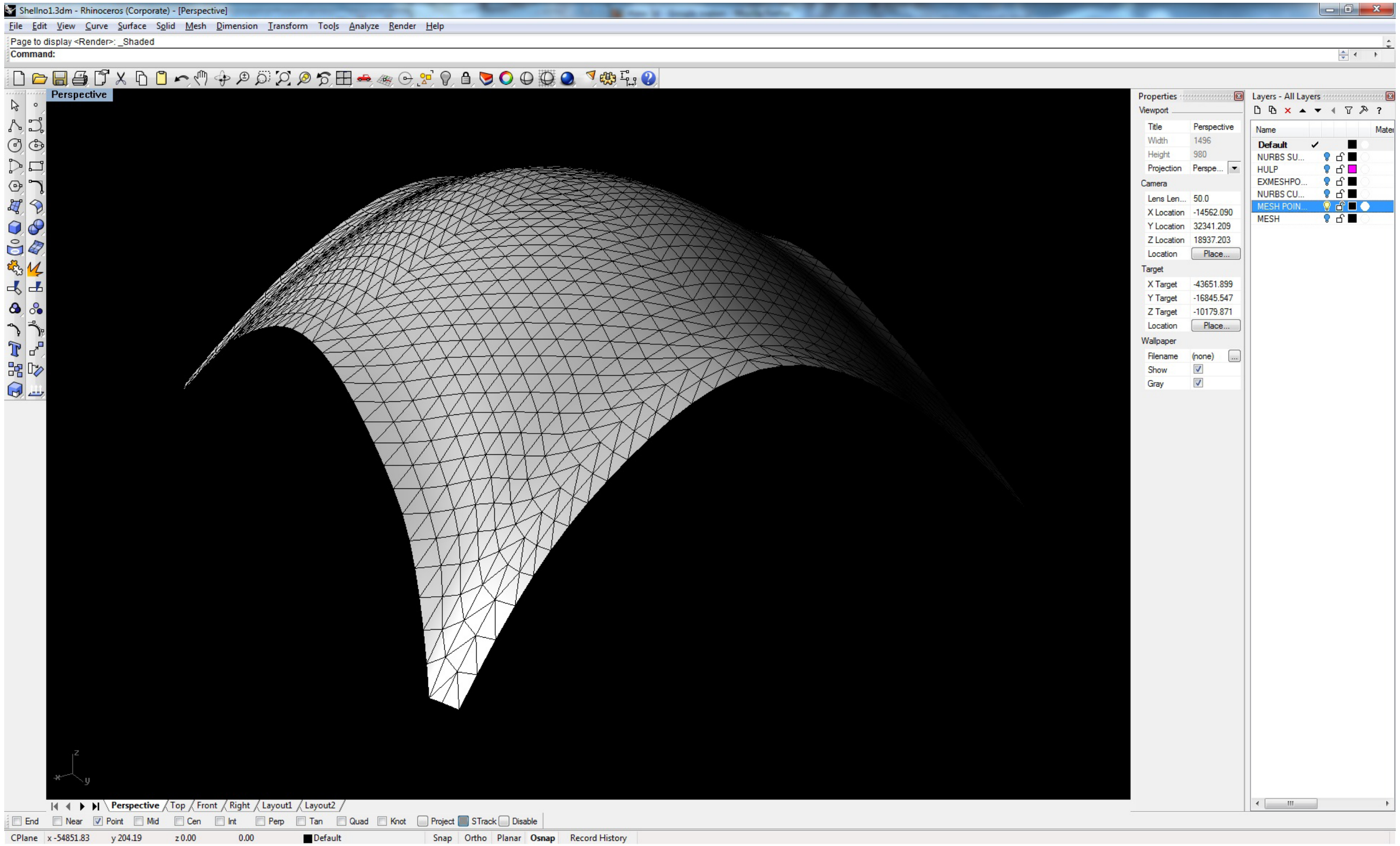
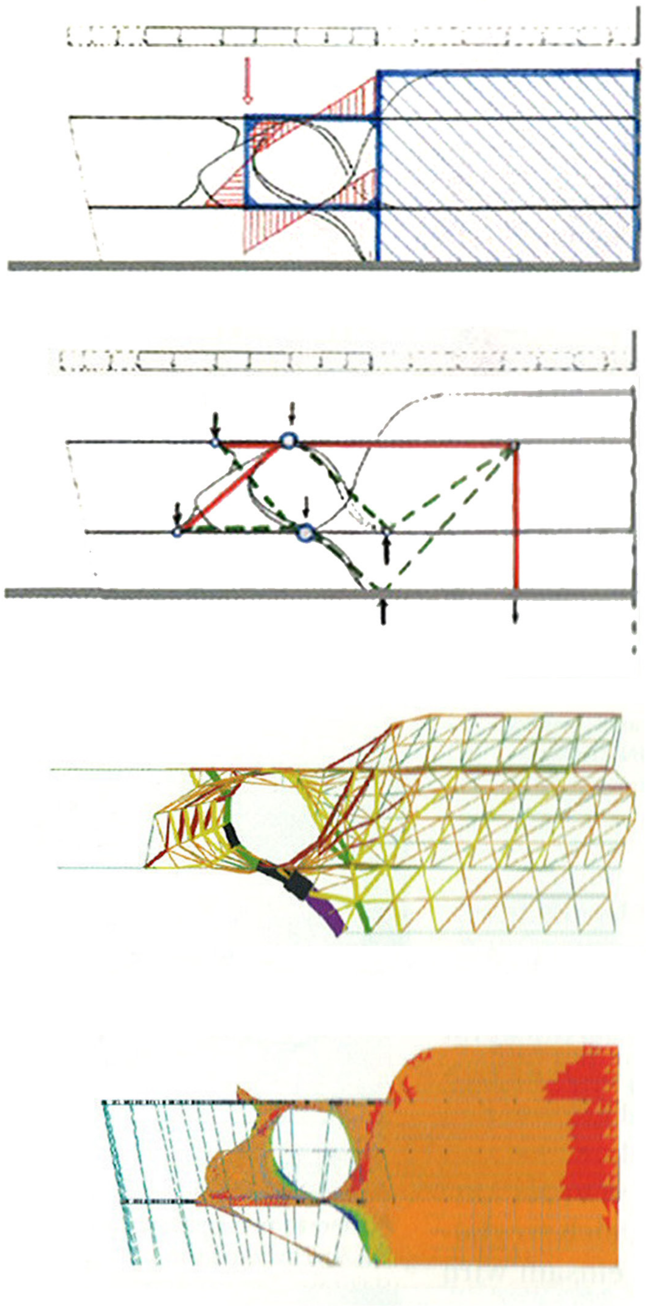


Figure 2.5
Explaining structural behaviour through first principles. Structural analogies to the twisted cantilevering floors of the MUMUTH project.



In order for the structural engineer to assign the correct amounts, position and direction of reinforcement in curved concrete surface structures it is vital to understand the structural behaviour and stress distribution. This is usually accomplished through a combination of structural rationalisation and FEM Analysis. A study into the structural design process of several curved surface structures (Appendix A) shows strong similarities. Control the complex geometry during both the design and realisation stage goes hand in hand with the process of structural analysis.

In a preliminary design stage the structural analysis models are based upon analogies with less complex geometry. One could say that in order to cope with the geometrical complexity of the project, the design is rationalized. Analogies with more familiar situations are applied. In the Darwin Centre, for instance, areas of low curvature are considered as a plane frame problem, and in the MUMUTH project a frame analogy is used to describe the structural behaviour of the twisted cantilevering floors (Mandl, 2008), see Figure 2.5. During later design stages the structural analogies are combined with finite element models.

Through finite element analysis the engineer is able to produce results for even the most complex structures, but these results prove meaningless without proper validation. Results from the finite element analysis, always need to be verified for consistency, for instance by explaining the structural behaviour through first principles.

Predicting the anticipated structural behaviour of concrete curved surface structures is difficult as two different modes of deformations, being membrane- and bending deformation, come together. The approach taken in the design of the MUMUTH project (Figure 2.5) is to combine a frame analogy for bending action approximation, and a strut and tie analogy for pressure and tension. This provides insight into the magnitude of the forces and thus offers the possibility to make preliminary design decisions. The obtained magnitude of forces, using this method, will generally exceed the actual forces as shell action is ignored. Using the reinforcement formulas for a combination of normal force and bending (1) gives a rough estimate of the necessary amount of reinforcement [mm2].

$$(1) \qquad A_{sl} \geq N_d / f_s + M_d / (z \cdot f_s)$$

The value of this estimation depends to a large extent on the validity of the analogy and thus structural understanding of the engineer, and should always be considered a rough first approximation useful in a preliminary design stage.

As stated in Section 1.3, shell behaviour can also be approximated numerically. InfoCAD is used throughout this thesis to exemplify the interaction between the FEM Analysis software and the reinforcement toolbox. For this reason it is important to have knowledge on the underlying principles of Infograph. Element types which can be used for the analysis of shell structures in InfoCad are SH36 (triangular) and SH46 (quadrilateral). Both are planar area elements with six degrees of freedom (ux , uy , uz , φx , φy and φz) for every node, see figure 2.6.

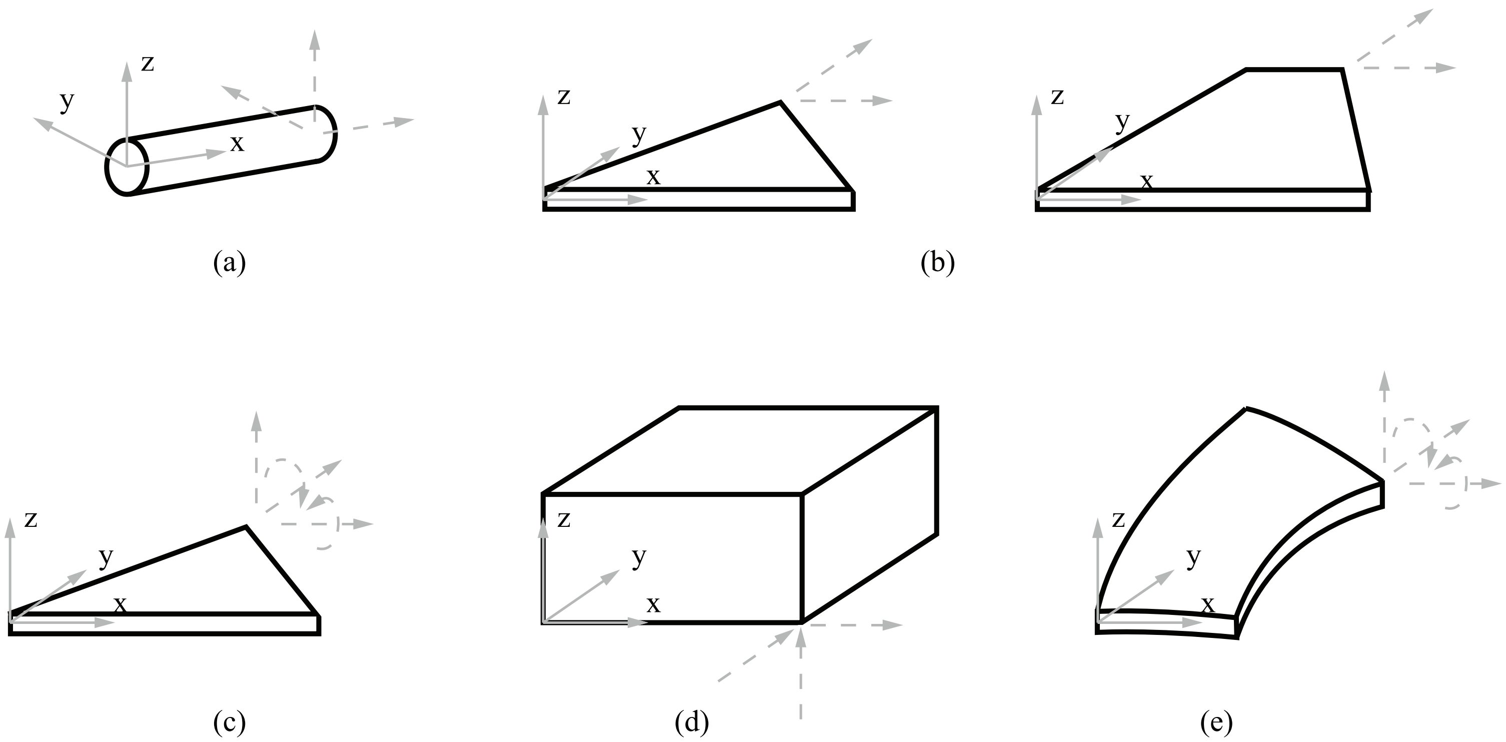
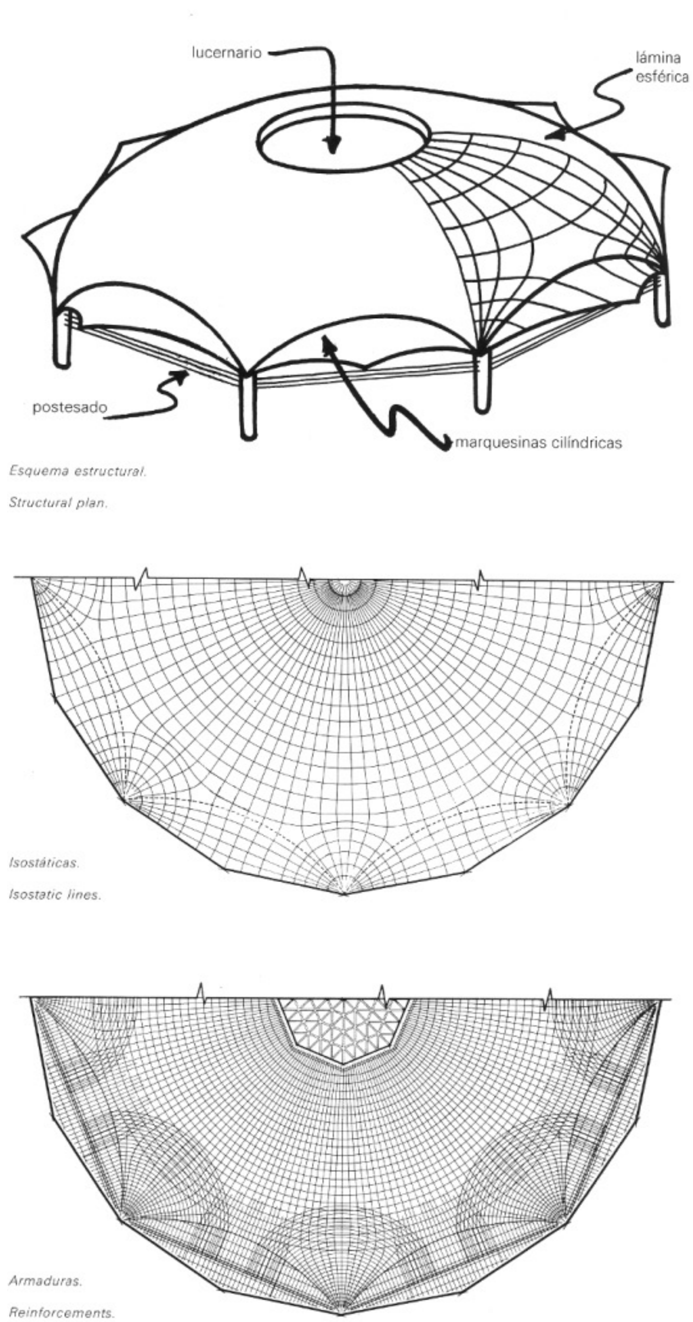


Figure 2.6
Element types for curved shell structures in InfoCAD.

Figure 2.7
Reinforcement follows the isostatic stress lines of the structure.



The standard solver in Infograph solves the system of linear equations directly. Principle stresses can be used to give an indication of the required amount and direction of reinforcement. Reinforcement generally mimics the pattern of isostatic lines, as is exemplified by this drawing of a shell structure by Eduardo Torroja, see Figure 2.7 (Levi, 2003).

In case of a nonlinear system of equations the solution is found using an approximation method (the incremental Newton-Rapson method). A nonlinear analysis is able to take into account geometrical and physical nonlinearities, like second order effects and reinforcement, by using nonlinear orthotropic elements. The amount of reinforcement of the elements can be controlled and by default holds a base reinforcement. Adding reinforcement to a concrete structure affects the principle stress flow, as locally increased stiffness attracts forces. For this reason the reinforcement design process for curved surface structures involves running several nonlinear analyses as reinforcement amounts and directions are adjusted.

Node deformations (ux , uy , uz , φx , φy and φz) are relative to the global coordinate system. Internal forces for area elements are either calculated in the nodes, the centroid or the middle of the edges. Stresses [MN/m²] and strains [‰] are relative to the internal force coordinate system, and are determined at the result locations on the upper and lower element edges. The maximum and minimum principle stresses (σ1 and σ2) in Infograph are displayed in vector format in the centroid of each element. Considering the corresponding principal normal forces fn [kN/m] over a region with width t [m] reinforcement amounts Asl [mm2] can roughly be determined using the following formula:

(2) $A_{sl} \geq (n1_{max} \cdot t) / f_s$

This section has presented analogies and FEM Analysis as the structural design tools available for structural analysis of concrete curved surface structures and related them to specific stages in the structural design process. Insight into this process forms an important input for the Reinforcement Toolbox.

2.2.3 Production

During design stages the structural engineer has to translate structural analysis results into practical reinforcement which complies with the production standards and possibilities. Therefore, the possibilities in terms of reinforcing steel production form a necessary input for the Reinforcement Toolbox. Understanding the production and manipulability of reinforcing steels starts with knowledge on the reinforcement production process. The design process ends with a digital reinforcement model being translated into physical reinforcement through an interface with production facilities. Specialized file formats hold the machine code necessary for translating bending schedules into bent reinforcing bars.

Reinforcement bars are supplied to the fabricators, either on coils or in bundles of straight length of maximum eighteen meters. Coils hold bar diameters up to sixteen millimetres, and weigh two to three tonnes. Reinforcement bars are brought into shapes suitable for fixing into concrete formwork through a subsequent process of cutting and bending, in case of coils preceded by straightening or 'decoiling'.

Straight bars are cut to the required lengths in machines called 'Shear Lines' (Figure 2.8). They are able to cut bars to a minimum length of 600 millimetres. The bending of these cut bars is carried out on so-called 'Power Bending Machines' (Figure 2.9) equipped with either a single- or double headed-bender. The minimum bend radius relates to yielding of the steel, and generally equals two times the bar diameter, a maximum radius is not specified. Using coil instead of straight bars can increase productivity, and reduce material loss. This technique is especially suitable for the production of links through so-called 'Automatic Link Benders' (Figure 2.10).

Figure 2.8 (Top)
Shear Line at ATG Steel Raamsdonksveer.

Figure 2.9 (Bottom)
Power Bending Machine at ATG Steel Raamsdonksveer.

Figure 2.10 (Top)
Automatic Link Bender at ATG Steel Raamsdonksveer.

Figure 2.11 (Bottom)
Use of bending iron at Arnhem Central Station Construction (Image courtesy of Stefan Verkerk, Prorail).

Reinforcement fabricators produce complete prefab reinforcement configurations, as well as pre-bent reinforcing steel for assembly on site. The applied mechanical production techniques produce reinforcement bars which are bent in-plane, and consist of a sequence of either constant or zero curvature segments.

Another way of bringing reinforcement bars into shape is through manipulation on-site. One of the major advantages of manipulation on-site is the direct reference to the formwork, which reduces the risk of errors. The process is however highly labour intensive and therefor costly. Bending reinforcement bar on site is done using mechanical or non-mechanical bending and cutting equipment. A commonly used tool is the bending iron (Figure 2.11). Bar sizes of up to 16 millimetres can be bent this way. The use of pneumatic hand tools can extend this to 24 millimetres. Unlike factory-processed reinforcement bars this technique enables out of plane bending.

Reinforcement bars deflect under own weight. The natural deformed shape depends on the boundary conditions and diameter of the bar. Smaller diameters have less resistance to deformation and will therefore more easily follow a curve. This phenomenon can be described as the natural deflected shape of a reinforcement bar, and allows for easy adaptations to small amounts of curvature, particularly in case of small diameters.

2.3 Reinforcing Curved Concrete Surface Structures, in Practice

The past decade has witnessed the realization of several concrete curved surface structures. Study into how has been dealt with the reinforcement during both design and construction phase provides valuable information, and input for the Toolbox. Appendix A gives an overview on the main design and construction aspects of six concrete curved surface structures (Darwin Centre, 2008; Kakamigahara Crematorium, 2006; Mercedes-Benz Museum, 2006; MUMUTH, 2008; Phaeno Centre, 2005; Rolex Learning Center EPFL, 2009). This section draws conclusions from these case studies and provides insight into the state of the art of design and production of complex reinforcement.

All six case studies rely on on-site reinforcement assembly. Apart from the Darwin Centre (sprayed concrete) they are all cast in-situ. Compared to regular geometry projects their design and construction processes show an increased attention to the reinforcement. A major challenge is the control over reinforcement details.

Roughly two approaches to the reinforcement design can be distinguished from the case studies, the exact definition and the loose definition of reinforcement details. The exact definition of reinforcement strives for control over the exact placement and shape of every individual bar. In this case more effort is allocated to the design process. The loose definition strives to control the principle details, which leaves more space for adaptations on site. In this case more effort is allocated to the construction process. This approach has been employed in the Kakamigahara Crematorium and the Darwin Centre.

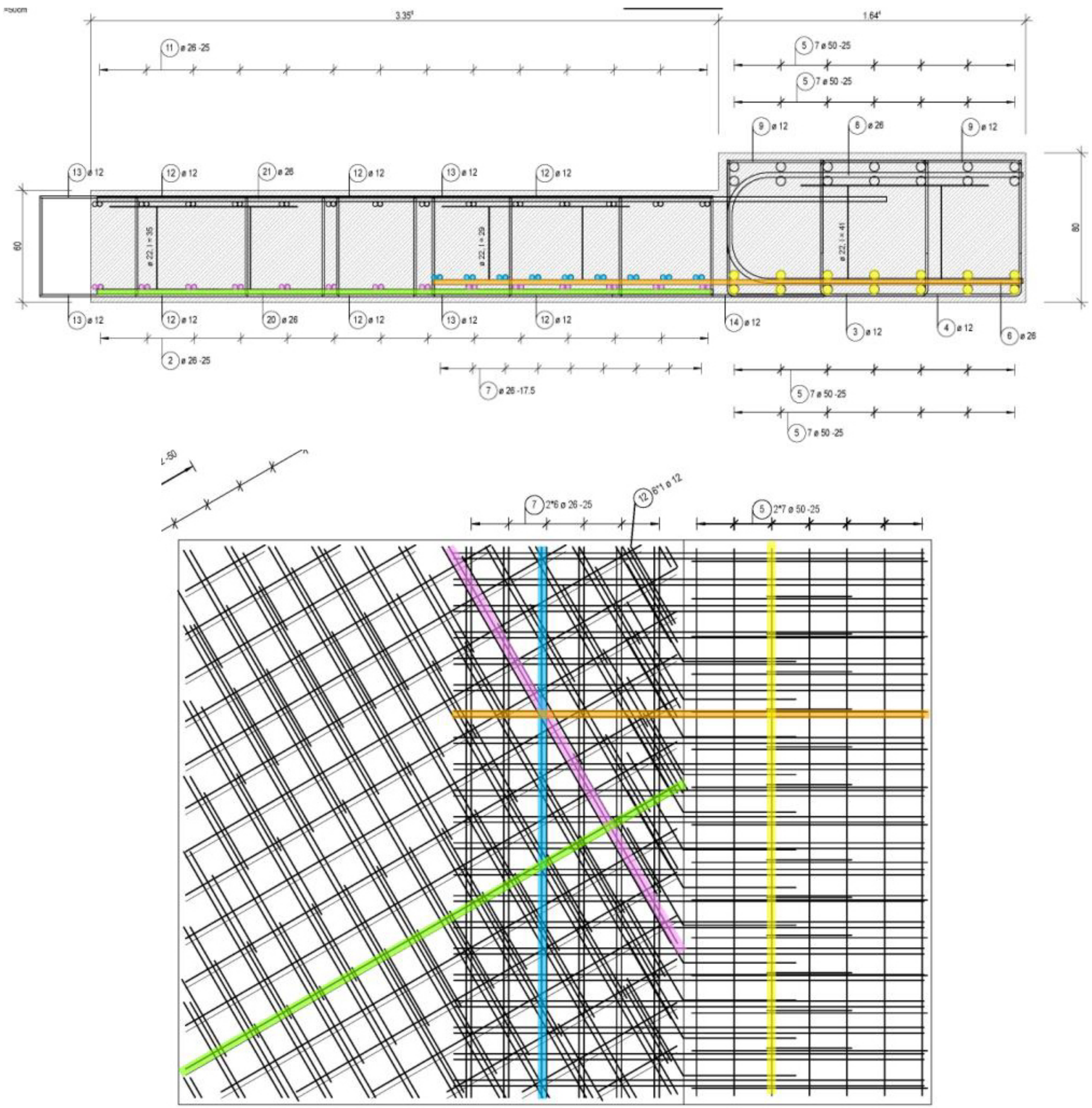
The chosen approach seems related to the overall complexity of the reinforcement and the associated risk in the construction phase. High reinforcement densities and complex bending shapes increase the risk of errors during reinforcement assembly and concrete compaction, this requires more effort during the design phase in order to reduces this risk.

An example of the exact approach is found in the design process of the Rolex Learning Center EPFL. Because of the shallow slope of the structure large bending moments occur. Direct consequence is a relatively high percentage of reinforcement, especially in the arches. Reinforcement bars with diameters up to 50 mm were used. Regions where different reinforcement directions come together were designed using colour codes to distinguish between reinforcement layers (Weilandt, 2009) see Figure 2.12. In addition to the 2D reinforcement drawings, the shell bearings were completely drawn out using 3D CAD software, see Figure 2.13.

> *"This was necessary to assure a right positioning and orientation of the reinforcement bars corbelling outwards the construction joint between slab over the basement and the shells. As the formwork tables of the shells couldn't be placed already before concreting the shell bearings, they couldn't serve as backing for the right orientation."* (Weilandt, 2009)

The most direct way of verifying the quality of a reinforcement detail is through building a mock-up. Both the manipulability of the reinforcement as well as the compacting of the concrete can be physically tested. A drawback is the relatively high costs involved. This technique has been employed in both the Mercedes-Benz Museum as well as the Rolex Learning Center EPFL, see Figure 2.14.

Figure 2.12
Colour coded reinforcement design drawings, the Rolex Learning Centre EPFL.



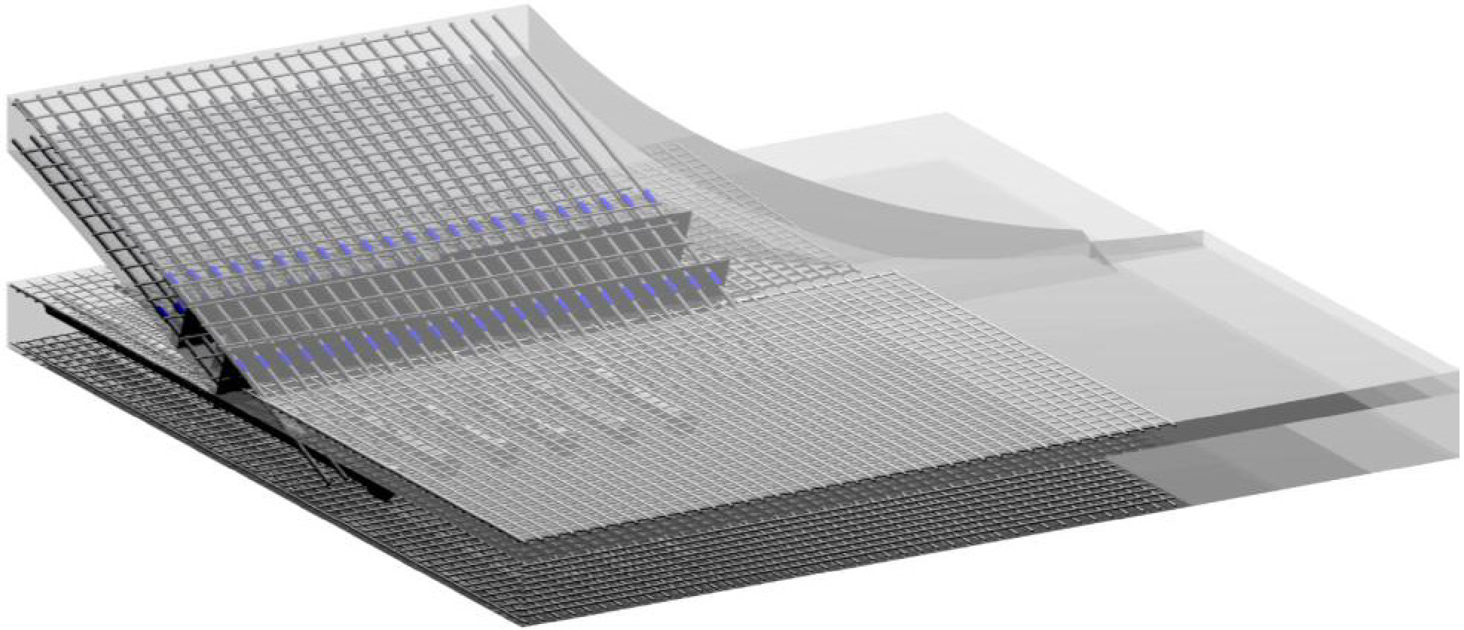


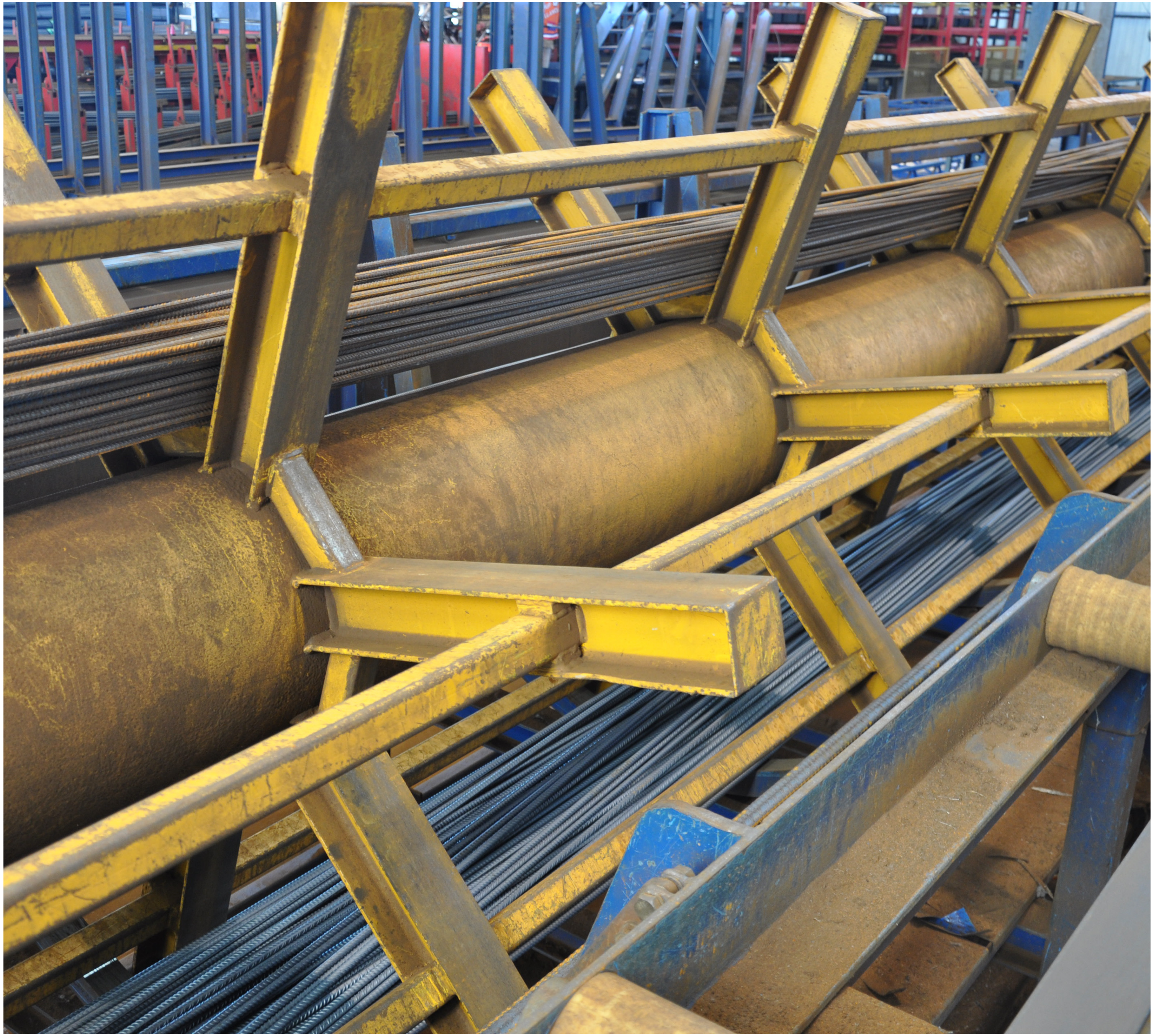
Figure 2.13
3D model of the shell bearings, the Rolex Learning Centre EPFL.

The most direct way of verifying the quality of a reinforcement detail is through building a mock-up. Both the manipulability of the reinforcement as well as the compacting of the concrete can be physically tested. A drawback is the relatively high costs involved. This technique has been employed in both the Mercedes-Benz Museum as well as the Rolex Learning Center EPFL, see Figure 2.14. Areas around the patio edges and landings of the arches are highly congested. To keep risks under control mock ups were made of the most complex areas. Standard reinforcement details were tested, as well as the compacting process.

A major challenge encountered in all of the projects was setting out the reinforcement. The difficulty lies with finding a proper reference. This problem was dealt with in different ways. In case of the Darwin Centre, the floor edges served as a reference on which the reinforcement was set out. In this case it was chosen not to issue detailed drawings per section but to supply a number of principle details which could then be applied according to their location. In all the other projects except for the MUMUTH project, which has a composite construction, reinforcement was set out relative to the formwork. Spacer blocks, or tie bar cones were set out on their exact locations using templates, laser level finders or GPS. The inherent geometrical complexity has had an unmistakable effect on the design and construction process of the case studies. Different strategies and measures have been taken to reduce the risks of construction errors, of which the large mock-ups are most noticeable. Two approaches to reinforcement design have been distinguished, being an exact- and a loose reinforcement definition approach. The complexity of the reinforcement seems interrelated with the chosen design approach.

Figure 2.14
Reinforcement mock-up,
Rolex Learning Center EPFL.

Sorting machine holds various sizes of reinforcement, ATG Steel, Raamsdonksveer.



3.0 **The Reinforcement Process and the Role of the Structural Engineer**

In this thesis the reinforcement process is defined as: the subsequent steps to be taken by the stakeholders in order to realize reinforcement for curved surface geometry which meets the design requirements. The aim is to add value to this process by providing a useful design tool. When developing a design tool, it is important to have a clear vision on the future goals it needs to fulfil and the context against which it is developed.

This Chapter sets out to describe this context by closely examining the reinforcement process. The Sections subsequently describe the stakeholders, documents and document flow associated to the reinforcement process.

3.1 The Stakeholders

The reinforcement process is characterized by close cooperation between design and production industries. Control over the end product, reinforcement for curved surface structures, demands a clear division of responsibilities and agreed communication standards. Reinforcement for curved surface structures is often a one off product, which implies the entire process from design to production has to be repeated for each object.

The stakeholders involved in the reinforcement process can be divided into two groups being internal stakeholders and external stakeholders. The external stakeholders play an important part in setting the preconditions to which the reinforcement process needs to take place. They are either active contributors in the design process like the architect, or passive contributors like legislative institutes and suppliers. The architect provides for the initial curved surface shape which needs to be engineered. If this shape proves to be impossible to reinforce the geometry has to be adopted in accordance with the architect.

The internal stakeholders are the structural engineer (a), the contractor (b) and the fabricator (c), see Figure 3.1. They are directly involved in the design and production process of reinforcement for curved surface structures.

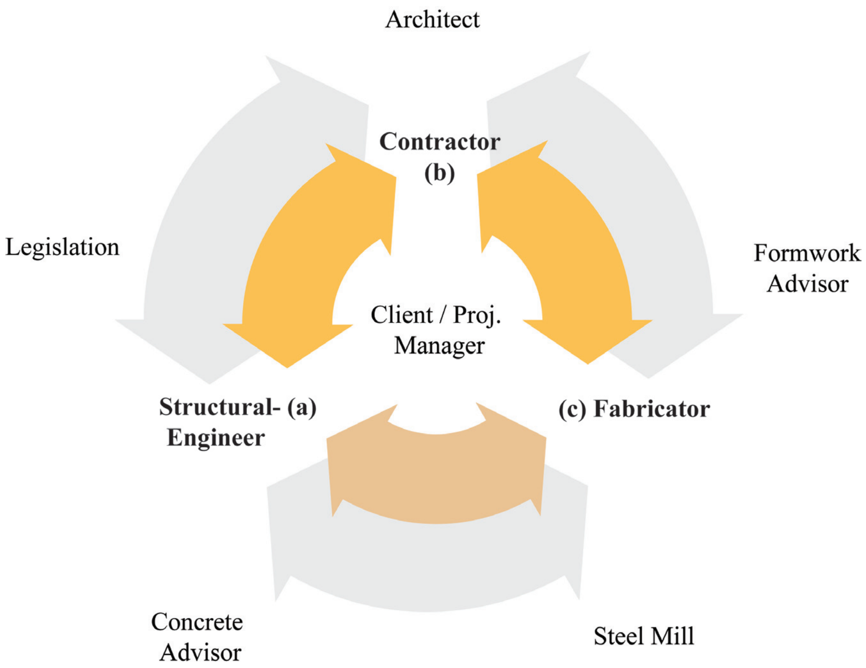
The structural engineer is generally involved from beginning to end, and is responsible for the general positioning and arrangement of the reinforcement in order for the structure to meet the applicable design requirements. Detailed placement drawings are usually produced by in-house CAD detailers in direct contact with the structural engineer. Consultation with the contractor during the design process can improve the practical value of the detailing.

Figure 3.1
Internal and external stakeholders involved in the reinforcement process.

The contractor often advised by concrete- and formwork specialists, coordinates the building process. A project manager coordinates between all the parties involved and instructs the construction supervisors who manages the construction on site, where steelworkers provide for the actual placement of the reinforcement.

A contractor usually subcontracts a fabricator to produce the reinforcement according to a supplied bending schedule. If a bending schedule is not available, fabricators usually have in-house CAD teams with the expertise to assist the drawing-up of bending schedules and using these for quotation and production purposes.

Transfer of reinforcement information during the reinforcement process happens through specialized drawings with specific sign conventions. The corresponding document flow and sign conventions will be discussed in the next Section.



3.2 Reinforcement Documents

This section deals with the documents involved in the reinforcement process. The type of document used to convey reinforcement information depends on the phase in the reinforcement process. Representation of reinforcement in drawings is highly standardized. Drawing conventions are necessary to transfer the complexity of the reinforcement while keeping the drawings comprehensible.

Table 3.1
Reinforcement drawing conventions for reinforcement sketches.

Four types of reinforcement documents are distinguished:

- Reinforcement Sketches
- Structural Drawings
- Placing Drawings
- Bending Schedules

Together they carry the geometrical data involved in the reinforcement process forward. Each one is specifically adapted to a part of the design or production process.

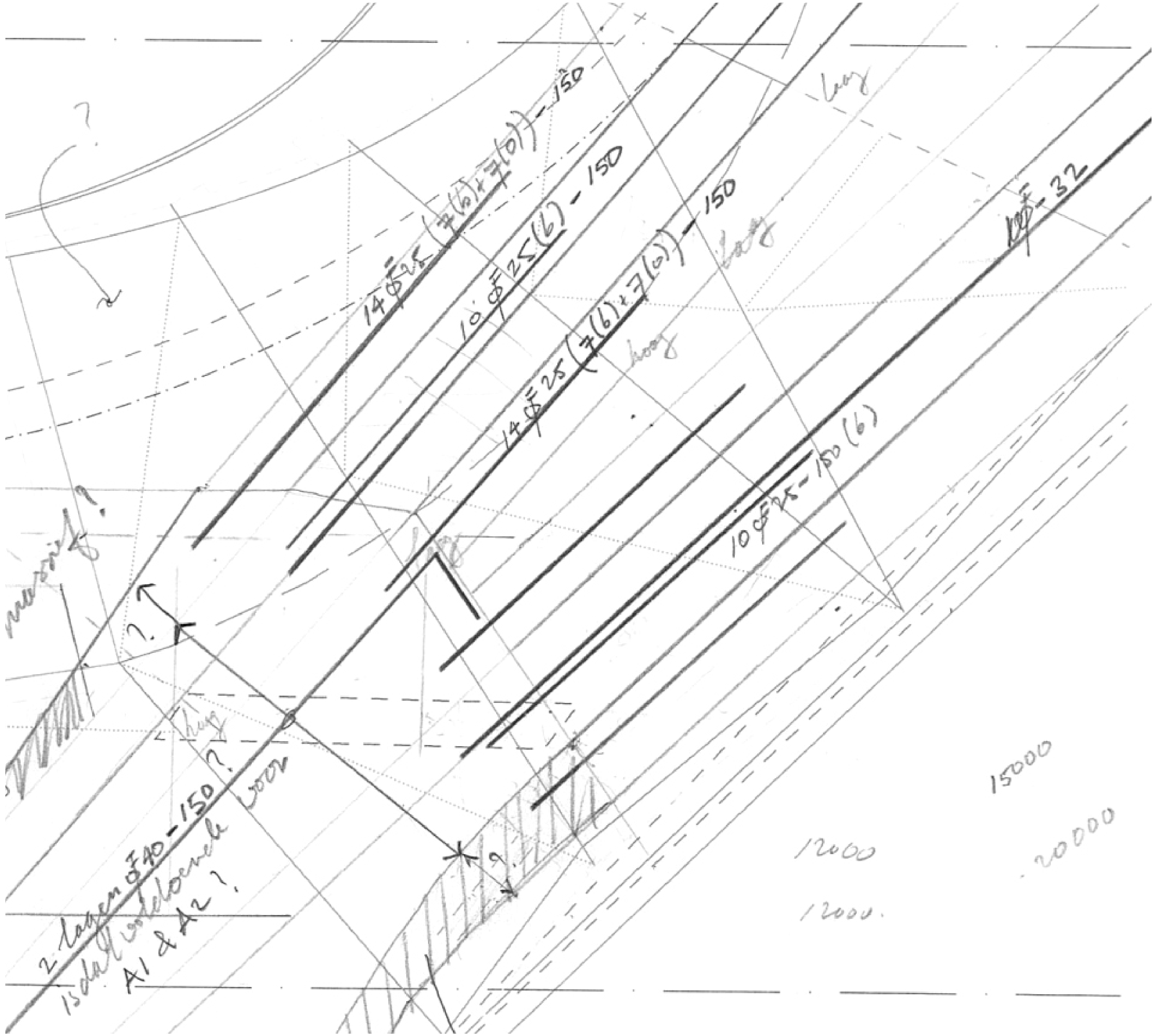
3.2.1 Reinforcement Sketches

Structural engineers use sketches to indicate the amount and distribution of primary reinforcement according to results from the structural analysis. Reinforcement sketches are made alongside the structural analysis to test first assumptions on bar sizes and spacing's. They schematically represent the primary reinforcement, using designated drawing conventions. Another important role of reinforcement sketches is to help the structural engineer communicate the reinforcement concept to the draughtsman. Architectural drawings often serve as underlay to determine the required dimensions of the structural elements or reinforcement zones in case of curved surface structures.

Figure 3.2 shows a typical reinforcement sketch. These sketches are usually depicted in plan, and show the direction, diameter and spacing of reinforcement groups. These are depicted by thick lines accompanied by an annotation containing the amount of bars, the diameter, spacing and a symbol to denote the layer and position of the bar group. Table 3.1 depicts some of the drawing conventions regularly used in reinforcement sketches.

No.	Description	Representation
1	Group of longitudinal reinforcement bars	
2	Rebar group lies in first layer from the bottom	
3	Rebar group lies in third layer from the top	
4	Number of bars	10
5	Bar diameter [mm]	Ø25
6	Bar spacing [mm]	150
7	Position	(t) top, (b) bottom
10 Ø25 - 150(b)		

Figure 3.2
Example of a reinforcement sketch, image courtesy of Arup.



3.2.2 Structural Drawings

Structural drawings are prepared by the engineer and are usually part of the tender documents. These drawings provide all the necessary information to convey the intentions of the structural engineer. He or she has to incorporate the rules stemming from applicable building codes into the design. Structural drawings are complemented with specific details and a set of notes which clarifies the design to the detailer. Based on these drawings, reinforcement detailers prepare placing drawings used for the placement and fabrication of reinforcing steel.

Proper structural drawings contain all necessary information to prepare the placing drawings, like: concrete dimensions, concrete cover, type and location of the reinforcing steel splices, anchorage length, etc. This information is usually conveyed through plans and elevations. Figure 3.3 shows an example of a structural drawing. Some of the primary 2D drawing conventions commonly found in structural drawings are shown in Table 3.2.

Table 3.2
Reinforcement drawing conventions for structural drawings.

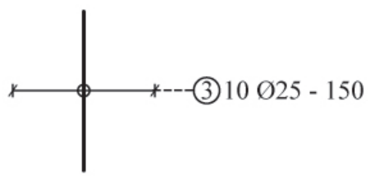
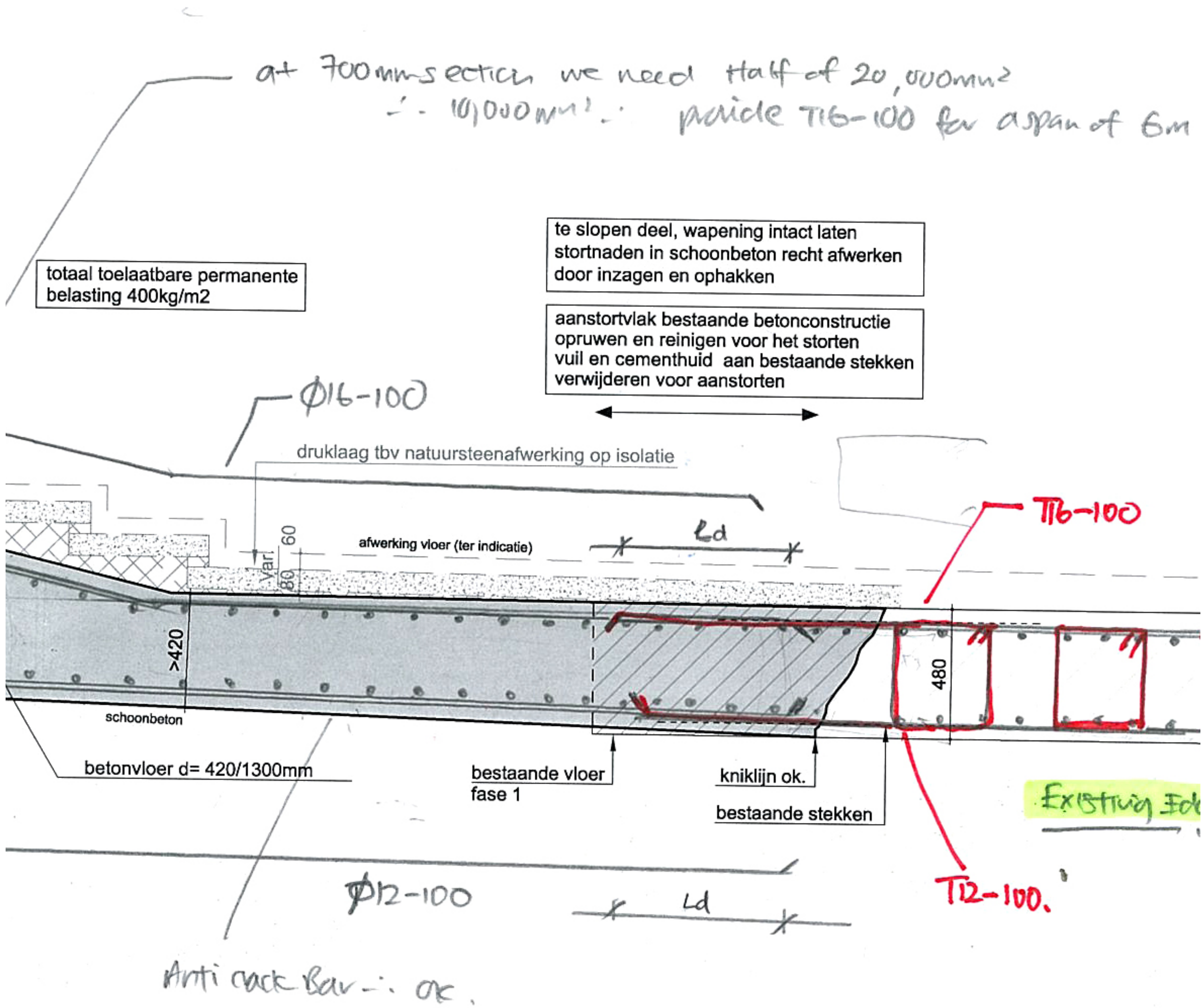
No.	Description	Representation
1	Bar in section	
2	Bar in elevation	
3	Bent reinforcement bar	
4	End indication of reinforcement bars, by using narrow lines with corresponding bar mark.	
5	Bar bent at a right angle away from viewer	
6	Bar bent at a right angle towards viewer	
7	Distribution of bar group marked with a numerical bar mark followed by the amount, diameter and spacing [mm]	

Figure 3.3
Example of a structural drawing in development, image courtesy of Arup.



3.2.3 Placing Drawings

Placing drawings are prepared by a reinforcement detailer, often employed by the fabricator. They comprise plans, elevations, bending schedules and details. Placing drawings are produced in accordance with the structural engineer, who ensures that all the structural principles are correctly implemented. After approval of the placing drawings by the structural engineer, they serve as a basis for the production of the reinforcing steel, and are used on-site to derive the correct placement of bars. Placing drawings show the size, shape, and exact locations of reinforcement in the structure, and are often accompanied by reinforcement details, see Figure 3.4. Figure 3.5 shows an example of a placing drawing.

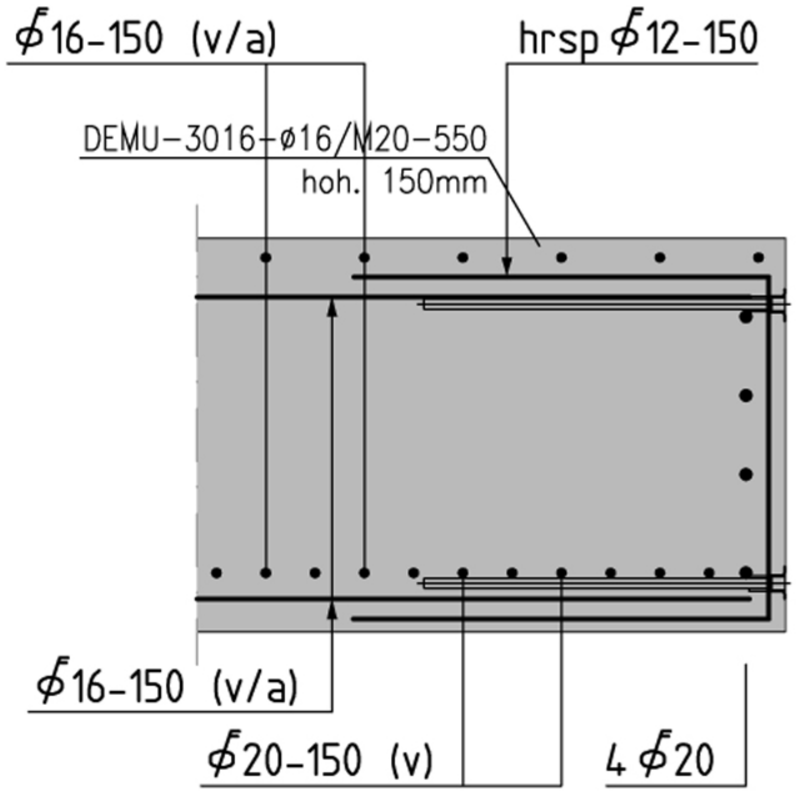
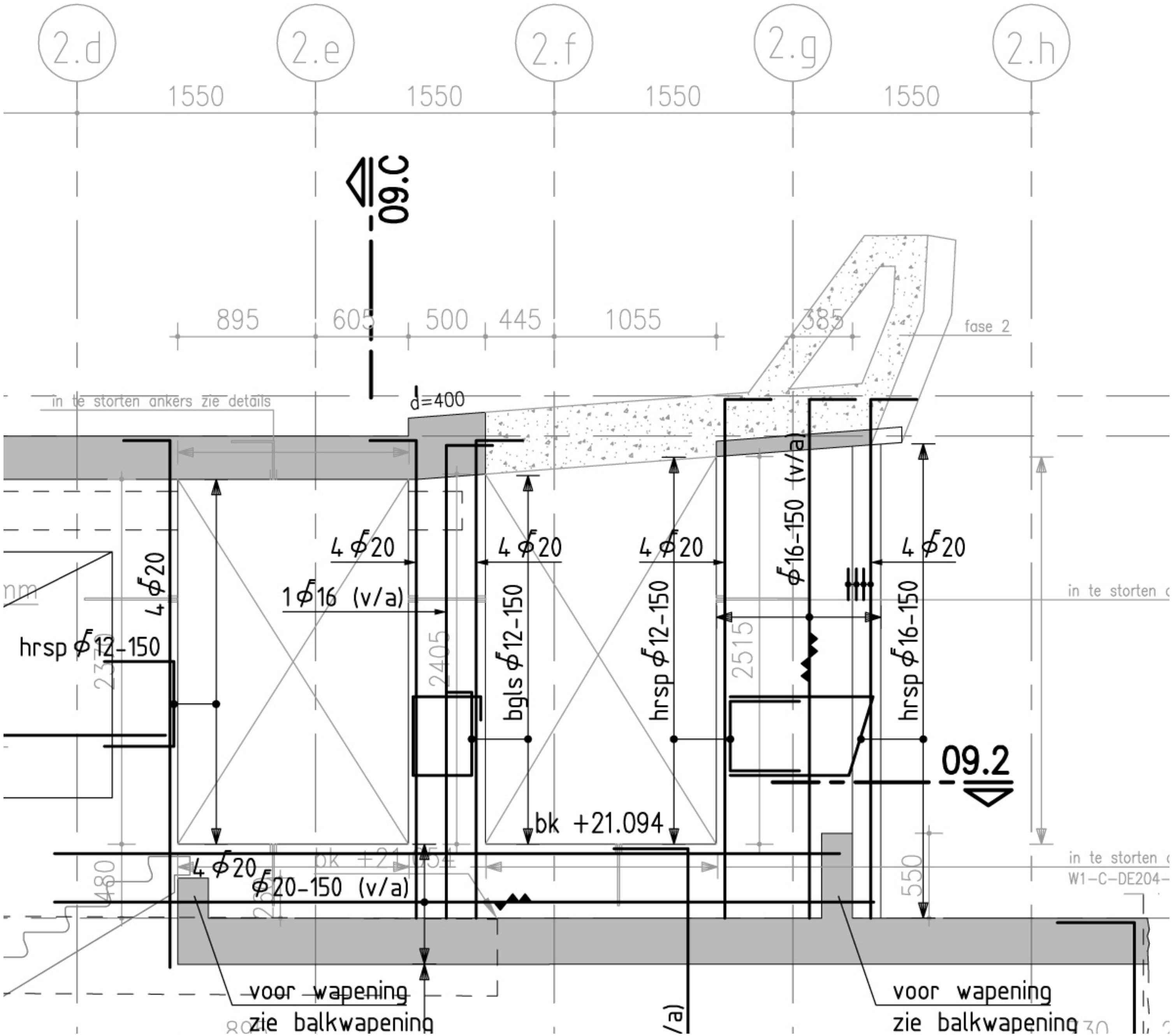


Figure 3.4
Example of a placing drawing detail, image courtesy of Arup.

Figure 3.5
Example of a placing drawing, image courtesy of Arup.

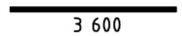
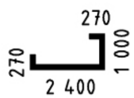
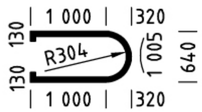
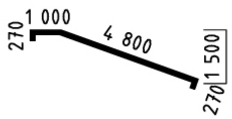
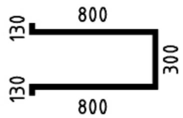
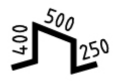
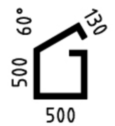


3.2.4 Bending Schedules

A bending schedule is a document prepared by the fabricator, listing the shapes and dimensions of all bars part of the detailers' placing drawings. It helps with quantity and cost approximation and can serve as a digital input to the production machinery. Bar codes refer to the codes found on the placing drawings which allow for easy identification of bar groups on-site.

The shape of bars is communicated through so-called shape codes laid down in the NEN6146. These typical bar bends cover the majority of the practical reinforcement shapes, for bar shapes outside of this scope a customized bar shape can be created. The shape code together with the assigned dimensions determine the shape of a bar group. Figure 3.6 shows an example of a bending schedule, and corresponding bending shapes.

Figure 3.6
Example of a bending schedule
BS EN ISO 3766:2003.

Member	Bar mark	Type of steel	Bar diameter mm	Length of each bar (Method A) m	Number of members	Number of bars in each member	Total number	Total length m	Shape code (Optional)	Bending shape with dimensions	Index
Slab 1	01	BST 500 S	28	3,60	1	10	10	36,00	00		
Slab 2	02	BST 500 S	28	3,94	1	20	20	78,80	11		
Corbel	04	BST 500 S	16	3,27	5	3	15	49,05	13		
Wall	05	BST 500 S	28	6,34	2	4	8	50,72	15		
Beam 1	06	BST 500 S	16	2,16	4	14	56	120,96	21		
Floor slab	14	BST 500 S	20	1,80	1	300	300	540,00		 NOTE 3D representation.	
Support pillar	17	BST 500 S	10	2,26	5	19	95	214,70			

3.3 Document Flow

Formal communication between the stakeholders of the reinforcement process identified in Section 3.1 happens through the exchange of reinforcement documents. The document flow has a clear direction, and holds progressively detailed information pushing towards the production and placement of reinforcement on-site. Studying the document flow provides insight into roles and responsibilities, and possible bottlenecks.

Figure 3.7 shows the document flow associated with the reinforcement process. Dotted lines represent either input from external stakeholders or feedback between internal stakeholders. Closed lines represent direct information transfer in the form of legally binding reinforcement documents. The client usually instructs an engineering firm to produce structural drawings. Considering the design aspects of curved surface structures the structural engineer produces a set of sketches and calculations, which are then developed into a set of 2D structural drawings in consultation with the firms CAD draughtsman. This internal communication loop will reiterate until the desired result is achieved. Structural drawings are passed via the client to the contractor who subcontracts the work to a reinforcement fabricator. Reinforcement detailers, who are either employed by the contractor or the fabricator, produce the bending schedules and placing drawings. The bend rebar are usually delivered on site by the fabricator.

Research into failure costs within the reinforcement process of residential projects by Neijssen identifies some of the commonly encountered problems related to information transfer in the reinforcement process (Neijssen, 2010). Many of these problems involve inaccurate data which causes reinforcement documents to be not fit for use. This can lead to problematic completion due to quality problems. A higher geometrical complexity of projects significantly increases the chance of errors, due to difficulties in communication and plain design mistakes.
Drawings involved in the current reinforcement process, both internal and external, are for the most part 2D plans and elevations. Using 3D reinforcement drawings can greatly improve the communication between stakeholders and thus improve the quality of data involved. This becomes even more relevant when dealing with geometrically complex structures. It asks for an extension of the document flow, incorporating 3D drawings in order to increase the quality of data transferred between stakeholders.

3.4 Vision

The driving force behind this thesis is the conviction that the building industry has to perform better, in order to prevent it to be superseded by other industries. The fundamental challenges which face the building industry are motivated by strong social trends (Coenders, 2011) which demand a smart use of available resources. While the pressure on projects to perform better has significantly increased, the available time and resources to perform extensive design studies has decreased. In other words the building industry has to perform better for less. Exploring innovative computational strategies for design and production enhancement, can contribute to improving the performance of the building industry.

The building industry is unique in a sense that it involves many different stakeholders with many different interests, who contribute to the same end result. Constantly changing partnerships and the production of one-off products seem to counteract the necessary

Figure 3.7
Document flow diagram for the reinforcement process.

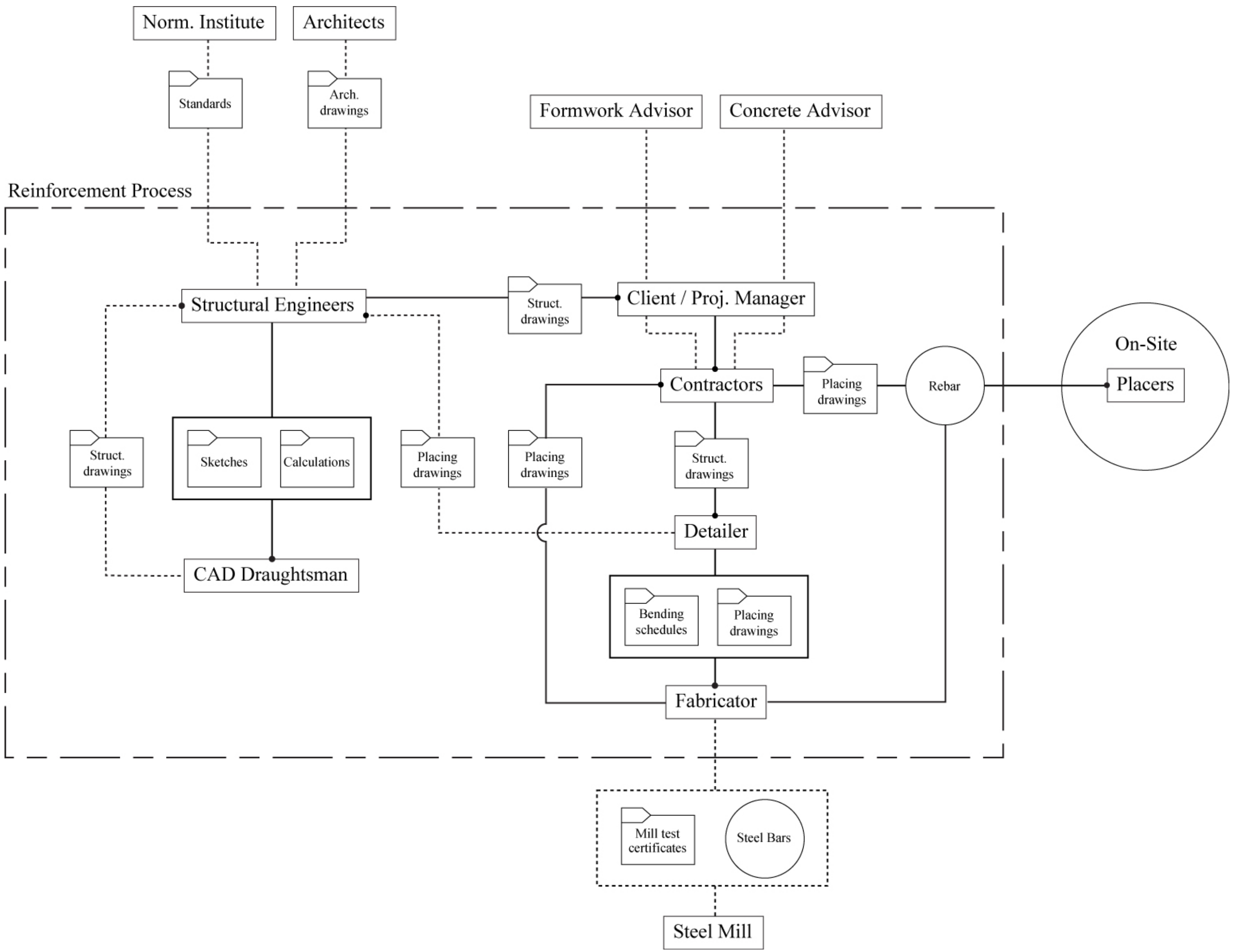


Figure 3.8 caption placed below.

innovation. Compared to other industries the building industry displays a low degree of automation. The chosen strategy of adapting, or downgrading designs to available production technologies and labour skills prevents the industry from moving forward.

Major successes in terms of product innovation in the automotive and aviation industries came from innovative design tools which allowed for new production techniques, see Figure 3.8. Developments in CAGD offered designers the possibility to represent complex geometries. Production technology supporting these shapes soon followed. In the building industry it is usually the other way around: innovation in production techniques leads to new design methods. Exploring a design driven innovation model requires a different mentality in the building industry. Computational design has the potential to aid the building industry in making this change.

Exploring a design driven innovation model requires a different mentality in the building industry. Computational design has the potential to aid the building industry in making this change.

One of the characteristic of the current building industry is the fact that design, engineering and production are distinct disciplines. The document flow diagram of the reinforcement process depicted in Figure 3.6, reflects this. Bringing the disciplines closer together through a computational design tool has multiple advantages:

- A reduced the risk of mistakes due to data loss at the interfaces between stakeholders.
- A more optimized design process, by bringing together the driving design factors, and migrating knowledge of production to earlier design stages.
- The stimulation of new ideas and production techniques as people are forced to look past the boundaries of their own discipline.

The proposed Reinforcement Toolbox aims at blurring the current separation between the draftsman and the structural engineer, and

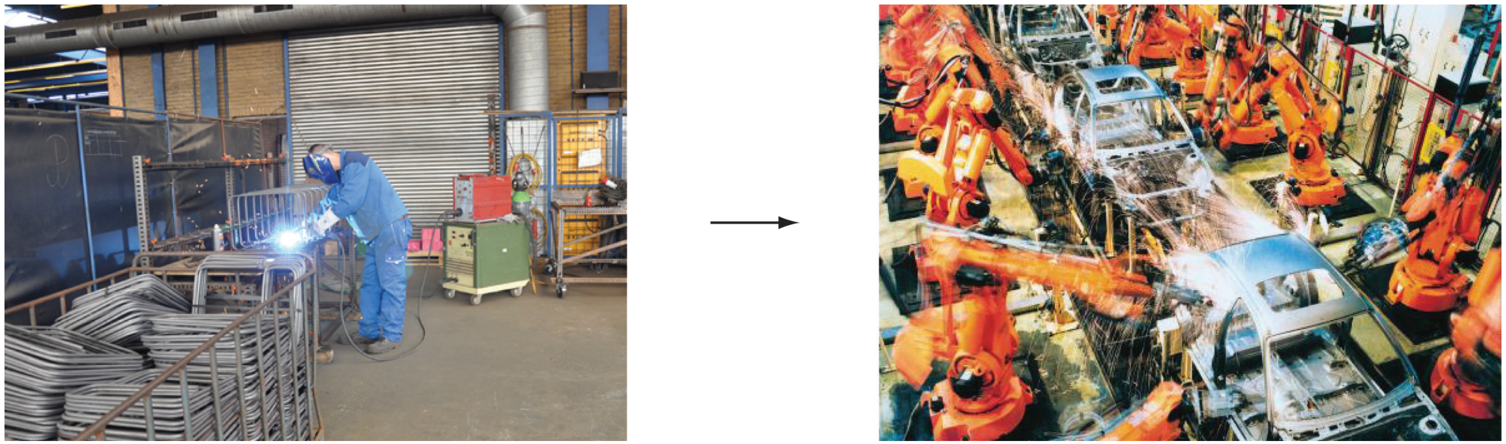


Figure 3.8
Moving away from traditional production techniques in the reinforcement industry.

providing for a more direct relation to production techniques. Curved surface structures are well suited for such a test case since the necessity of an integrated approach is even more important. Some appealing examples of Computational Tools for Design and Production Enhancement already exist (Rolvink, 2010), (van de Straat, 2011). The Reinforcement Toolbox aims at providing structural engineers with a tool which helps them design complex reinforcement in curved surface structures. Computational design tools can lead to more optimized designs and might even stimulate production industries to develop smarter and more efficient ways of producing these designs, see Figure 3.9.

The Reinforcement Toolbox will primarily be designed for the structural engineer involved in the design of reinforcement. It sets out to help remove the current split between draftsman and engineer by offering a design environment which offers the possibility to simultaneously model and verify reinforcement in curved surface structures. In addition it should serve as a lubricant which improves the communication between the structural engineer – contractor, and the structural engineer – detailer/fabricator. Figure 3.10 shows the envisioned role of the Reinforcement Toolbox placed in the reinforcement process document flow diagram.

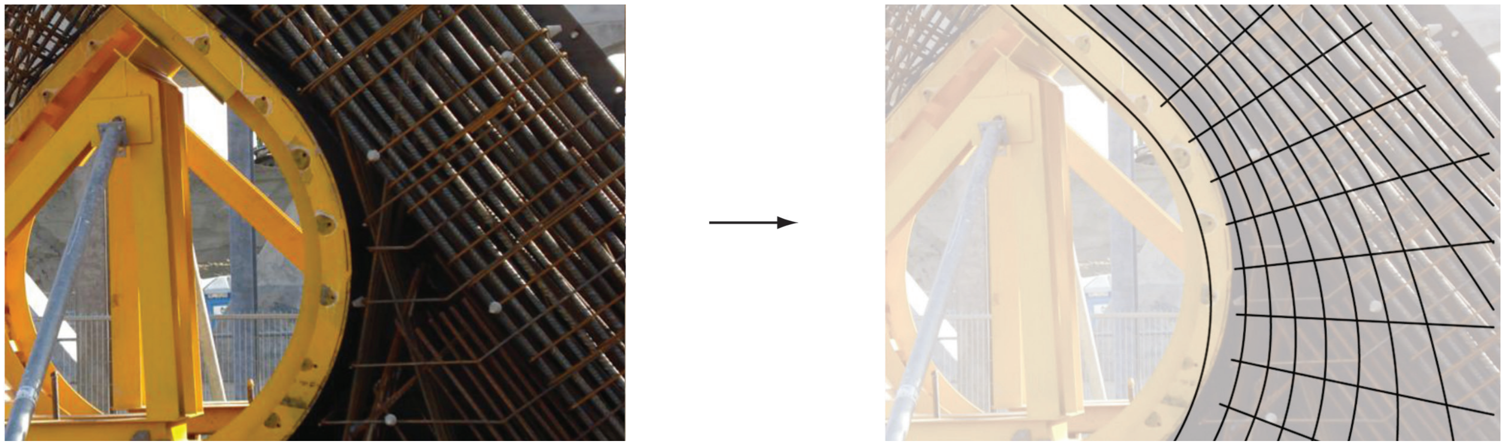
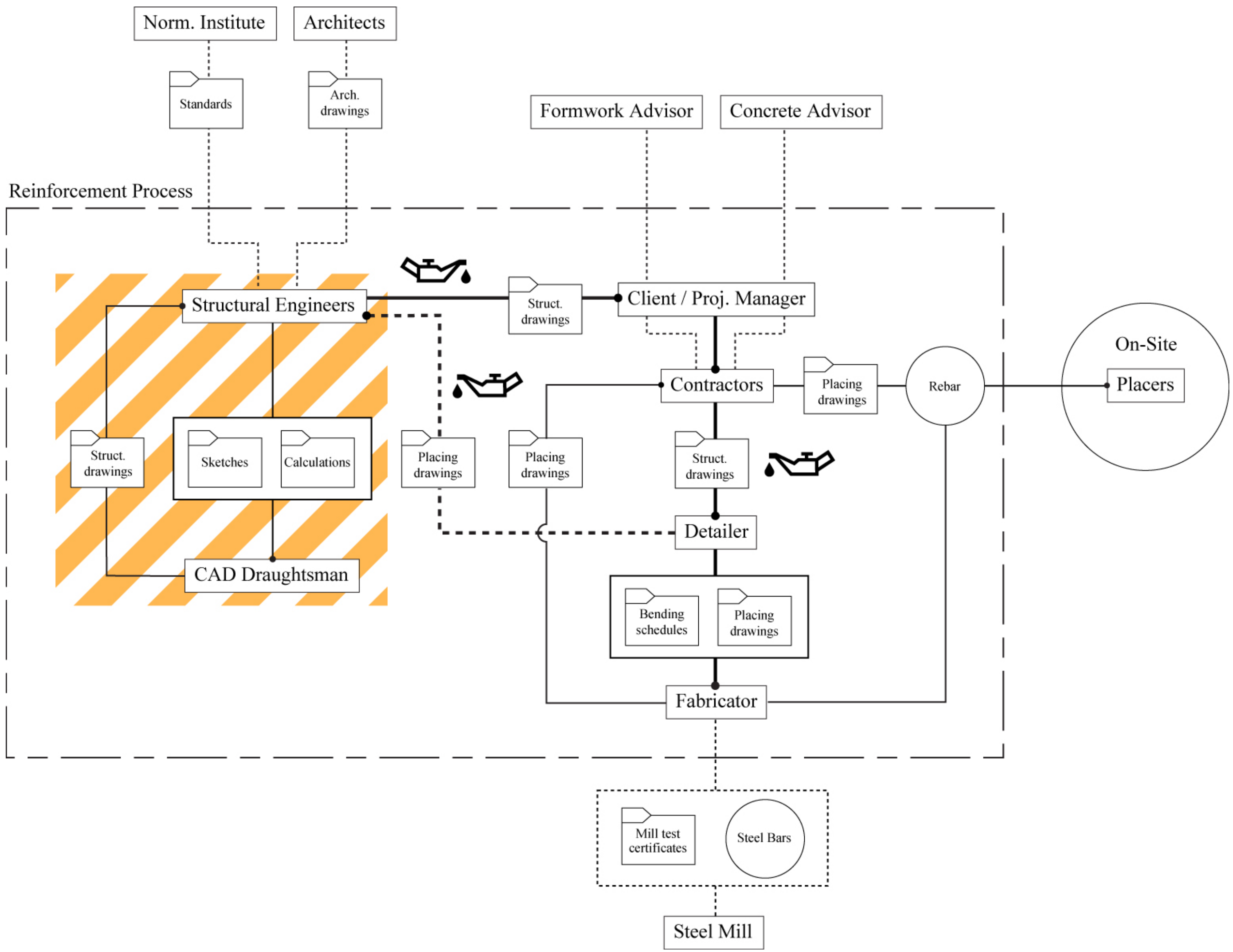


Figure 3.9
New design tools might lead to new reinforcement production techniques.

Figure 3.10
Envisioned role of the Reinforcement Toolbox, abolishing the division between structural engineer and draftsman and improving the communications between stakeholders.



PART II **COMPUTATIONAL STRATEGY AND TOOLBOX DESIGN**

Reinforcement bars of equal size awaiting further processing, ATG Steel, Raamsdonksveer.

4.0 **A Computational Design Strategy for Reinforcement in Curved Surface Structures**

Computational strategies for design and production play a growing role in enhancing the building industry, especially in the realization of complex designs. Applying computational tool development as a problem solving strategy for practical engineering challenges is a growing trend. This trend is already brought into practice by innovative engineering firms who actively apply custom build tools to help solve structural design challenges. An appealing example is the parametric tool used in the design of formwork panels for the EPFL Learning Centre developed by the engineering firm DesignToProduction, see Figure 4.1.

Sections 4.1 and 4.2 describe the development of a computational strategy which enhances the design and production of reinforcement in curved surface structures. The strategy is based on the three important design aspects of reinforcement being geometrical control, structural analysis, and production. The strategy is developed for the reinforcement process, and envisioned to become part of this process. The vision for the improvement of the reinforcement process for curved surfaces structures has been presented in Section 3.4. The developed computational strategy sets out to realize this vision. Sections 4.3 to 4.5 go into detail on the various sub-concepts contained in the strategy. Subsequently the SolidModel, FEM Analysis Visualization, and Rebar DNA are discussed.

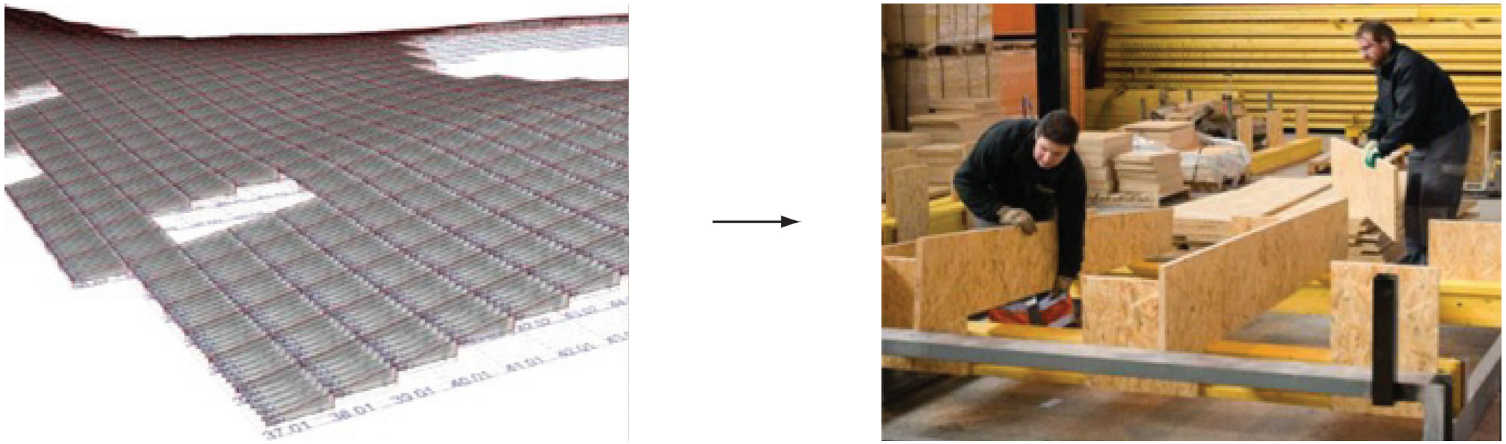


Figure 4.1
Computational strategy helped to optimize the design and production of formwork panels in the EPFL Learning Center in Lausanne (courtesy of DesignToProduction).

4.1 Development of a Strategy for the Reinforcement Process.

Study into the evolution of the design process of curved surface structures in Section 2.1 has revealed a shift to the digital domain. The commonly deployed tools in this process, like advanced CAD modelling-, BIM- and FEM Analysis software, are separately deployed during the course of the reinforcement process. They often show poor interoperability, and more importantly are often not adequately equipped to deal with curved surface structures. This corresponds to the problem statement which states that the appropriate tools to help the structural engineer effectively design reinforcement for curved surface structures do not exist.

A strategy, which proposes a methodology for design of reinforcement in curved surface structures, has been developed. This strategy, which is described in more detail in Section 4.2, forms important input for the development of the Reinforcement Toolbox. The vision, described in Section 3.4, aims at bringing the disciplines involved in the reinforcement process closer together. The strategy answers this part of the vision by combining the mono-functional design tools in a multi-functional 3D design environment, see Figure 4.2. This approach offers several advantages, most notably:

- Increased ease of use
- Elimination of conversion errors
- Instant feedback of results

Bringing together the design tools for reinforcement in curved surface structures in a single 3D modelling environment is an important step towards a more optimized design process. However, not all conventional tools are yet applicable to curved surface structures. The three concepts within the computational design strategy help to overcome this deficiency.

The computational strategy includes all necessary steps of raising an architectural curved surface model to production level in terms of reinforcement. Three important design aspects of curved surface structures distilled in Chapter 2 form the main pillars on which the strategy is based. They are ‘Geometrical Control’, ‘Structural Analysis’ and ‘Production and Manipulability’. These aspects have been translated into three concepts which help to control these design aspects: the SolidModel, FEM Analysis visualization and Rebar DNA. They are addressed in more detail in Sections 4.3 to 4.5.

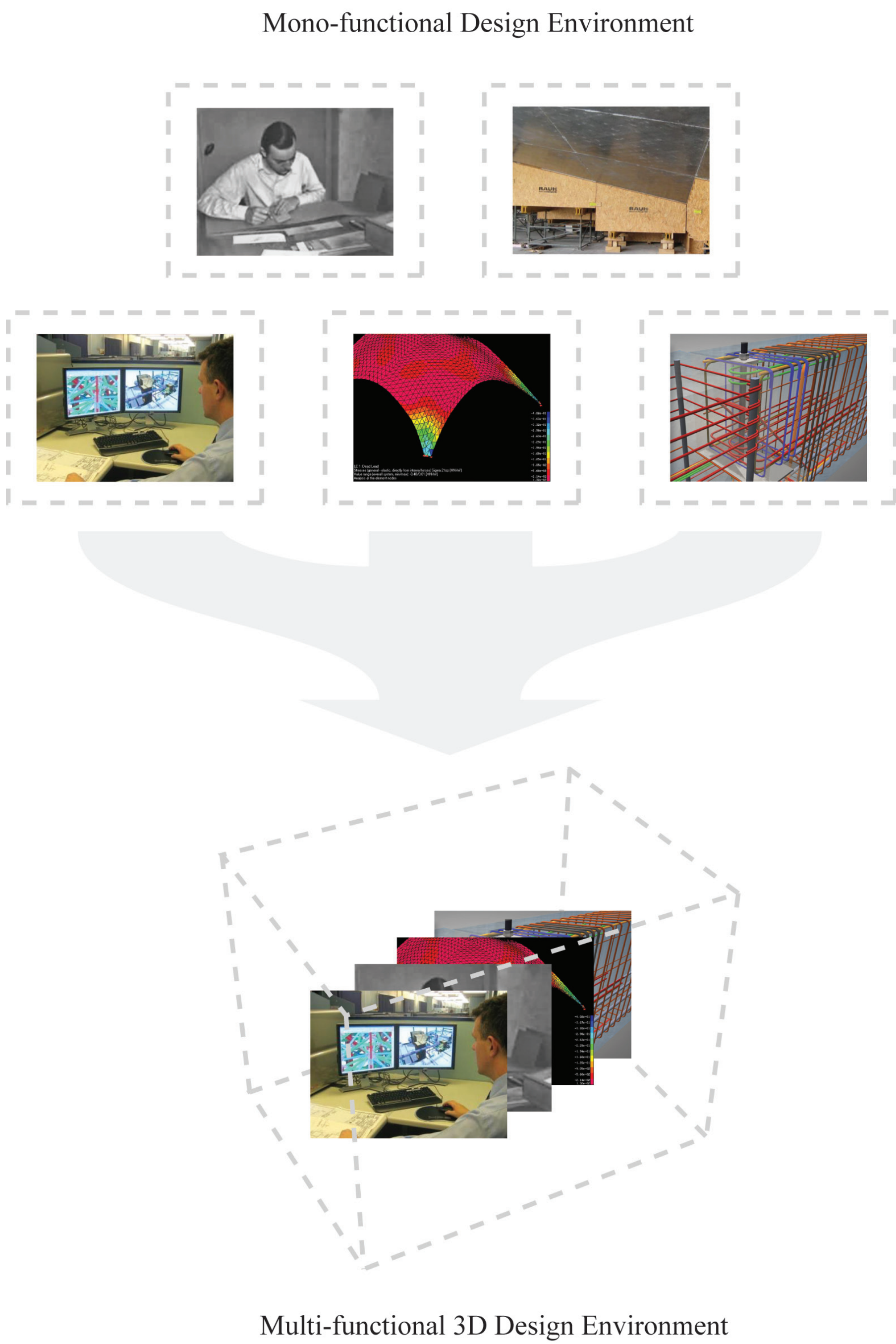
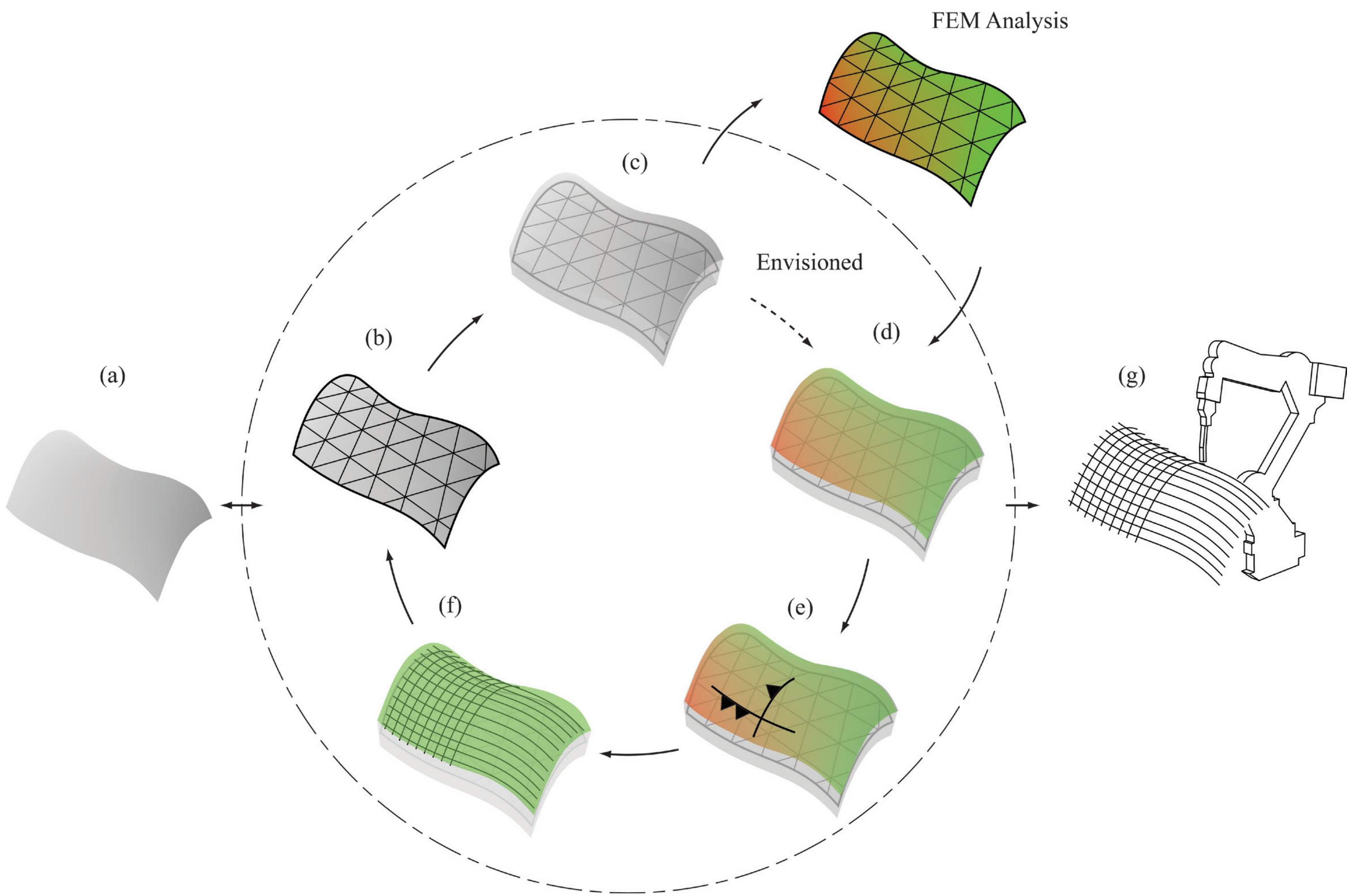


Figure 4.2
Important part of the computational design strategy is to bring together the separate tools used in the reinforcement process into one multi-functional 3D Design environment.

Figure 4.3
Subsequent steps of the computational strategy: (a) Input of a curved surface (b) Surface rationalisation (c) Creation of the SolidModel (d) Visualization of FEM Analysis results (e) Allocation of reinforcement (f) Reinforcement model (g) Production.

4.2 A Computational Design Strategy for Reinforcement in Curved Surface Structures.

The computational design strategy is based on research into the reinforcement process for curved surface structures, presented in Part I of the report. The main preconditions for the strategy come from the three important design aspects of curved surface structures, 'Geometrical Control', 'Structural Analysis' and 'Production and Manipulability'. Figure 4.3 illustrates the computational strategy. It reflects the cyclical character of the reinforcement design process which it supports. The letters in the diagram refer to the various



aspects of the strategy which are described in more detail below.
Starting point of the process is a 3D CAD (curved surface) model of the structure (a), commonly supplied by the architect. Basing the engineering model directly on the architectural model can give advantages in terms coordination, and can improve communication between the two parties, as both are working from the same geometrical starting points.

In order to gain geometric control over the widest possible range of different geometries, the design strategy proposes surface rationalization. Surface rationalisation (b) through meshing is a proven technique which helps to gain control over the geometry of curved surfaces (Pottmann, 2007). The triangle mesh serves as a basis to the SolidModel and can also be used as a calculation mesh for the finite element model. This offers the possibility of bringing the architectural- (3D CAD model) and the structural geometry (FEM analysis model) closer together.

The SolidModel can be considered as the digital representation of the concrete volume in which the reinforcement will be modelled (c). From the SolidModel a FEM mesh can be extracted, which offers the advantage of being able to directly project FEM Analysis results on the SolidModel (d). Section 4.3 goes into more detail on the specifics of the SolidModel.

The visualisation of principle stresses and required amount of reinforcing steel in a single modelling environment in combination with reinforcement modelling functionality hands the structural engineer a powerful tool for the allocation of reinforcement (e). The digital reinforcement model (f) shows the actual reinforcement model and gives feedback on possible clashes.

Providing for a direct link between the reinforcement model and the production facilities (g) finalizes the computational design strategy. It optimizes the document flow between the structural engineer and the fabricator, and hints at the possible production automation of complex reinforcement.

The computational strategy presented in this section proposes a way of progressing reinforcement for curved surface structures from design to production. Currently, the actual finite element analysis is placed outside of this process. This implies a breach in the workflow of the structural engineer. A direct link between the reinforcement model and the analysis tools in a singular environment offers the structural engineer the possibility to quickly research the structural implications of a reinforcement model, and is seen as a future step in the development of the Reinforcement Toolbox. The envisioned strategy aims at incorporating structural analysis methods within the Toolbox, and thus provides for a direct link between reinforcement-, analysis- and production models.

4.3 The SolidModel

Geometrical Control is the first pillar of the computational design strategy. Section 2.2.1 demonstrates its relevance to the design of reinforcement in curved surface structures. Geometrical Control starts with a geometrical definition of the structure in which the reinforcement will be modelled. This volumetric representation is complemented by qualitative requirements associated with the concrete structure, like the concrete grade, the exposure class, fire resistance, etc. Together they form a framework to which the reinforcement can be modelled. This framework is called the SolidModel. The main functions of the SolidModel are:

- Provide a geometric framework for reinforcement bar positioning
- Contain and display FEM Analysis results
- Detect (intersecting) reinforcement bars
- Hold the qualitative requirements associated with the concrete structure

A curved surface CAD model, mostly supplied by the architect, serves as initial input to the computational design strategy (see Figure 4.3). Two definitions can be distinguished, a single surface or double surface definition (see Figure 4.4). In case of the latter the thickness of the structure is defined by the distance between the two surfaces. In case of a single surface definition the structural engineer is assumed to be free to define the thickness. The two different inputs require slightly different approaches in creating the SolidModel.

Figure 4.4
(a) Single surface definition, the thickness of the structure needs to be defined. (b) Double surface definition, the thickness of the structure is fully defined.

The 'SolidModel' serves as the geometrical framework against which reinforcement is modelled. It consists of a sequence of interrelated 'Solids' and associated methods which allow for control over reinforcement bar groups. These methods include point in polygon methods, line surface intersections and other vector math operations. An important added function of the SolidModel is the possibility to extract centre mesh models which can serve as geometrical input to FEM Analysis software.

The previous section has introduced curved surface rationalisation through meshing as a first step in the computational strategy. This fundamental step in the strategy enables to break down the most complex curved surface description into a series of interrelated elements. There are two main reasons for using a mesh as basis for the SolidModel:

- The fact that it consists of simple geometric elements makes it easier to control
- It matches the structure of finite element models, which allows for the transfer of FEM analysis results

Most FEM Analysis and CAD modelling software have extensive meshing capabilities. The Reinforcement Toolbox relies on this functionality for the rationalisation of curved surfaces, and uses the resulting mesh elements as input, see Figure 4.5.

When using this mesh as a basis for the SolidModel, a uniform topology needs to be constructed. The MeshTopology holds the structure and interrelations of the mesh elements. This implies running through the vertices, edges and faces and establishing their interrelations. This ensures that at the basis of any SolidModel lies a uniform structure.

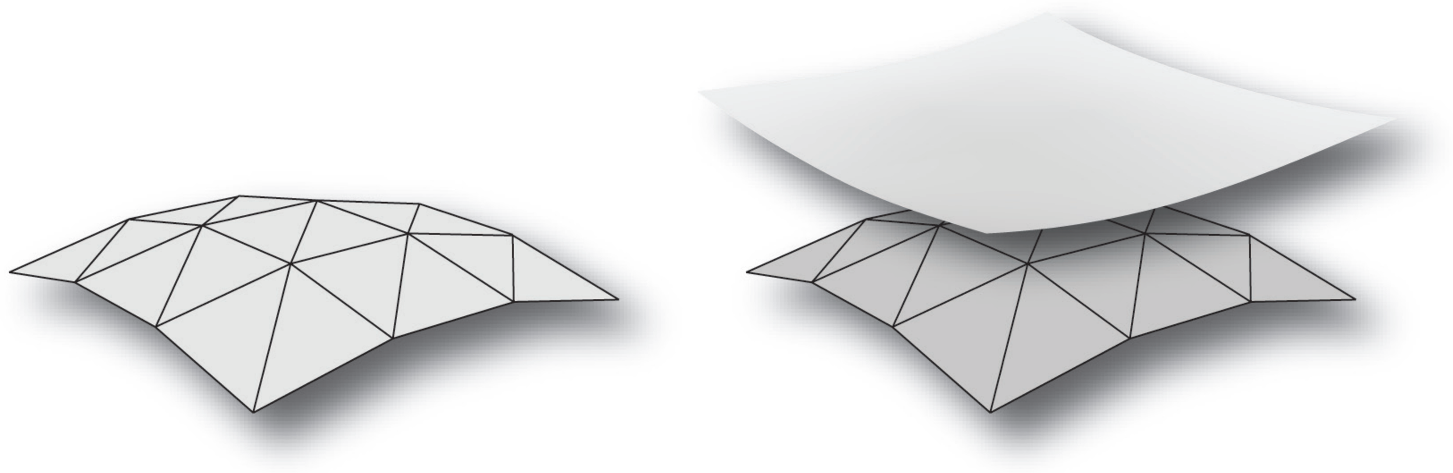


Figure 4.5
First step in the creation of the SolidModel: Curved surface rationalisation resulting in a triangle MeshTopology.

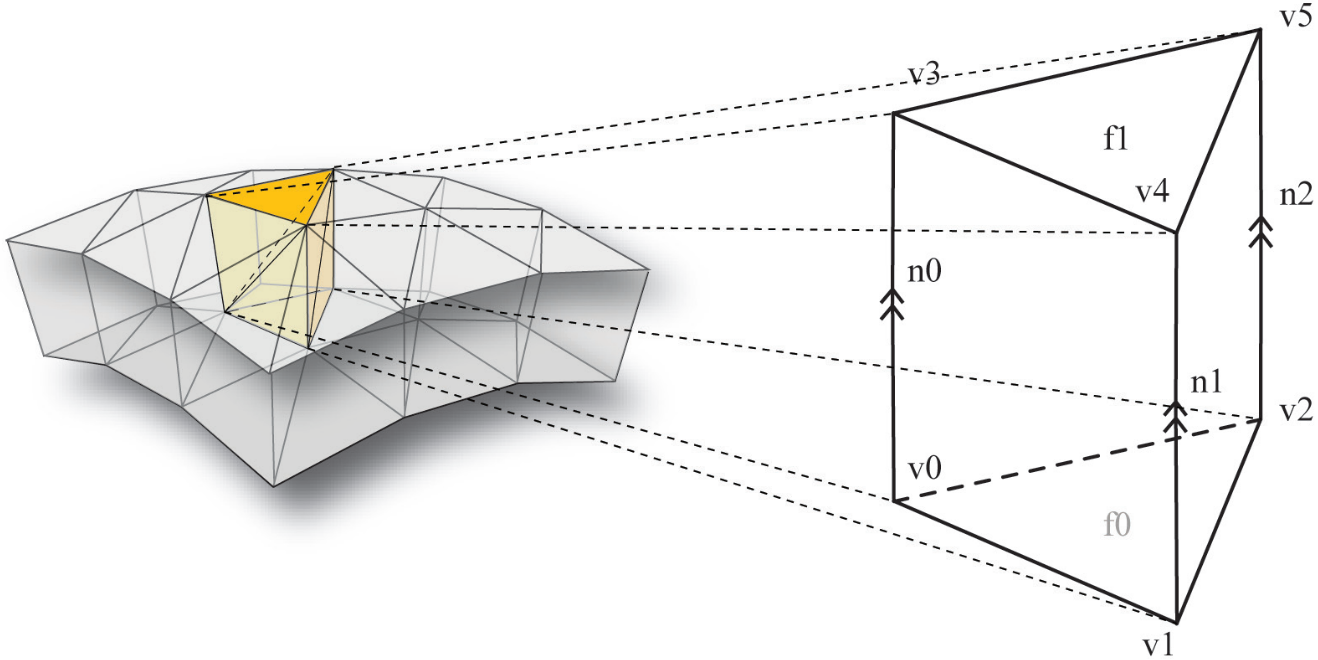
Figure 4.6
The structure of a Solid, built up out of multiple triangles, includes a bottom (f0) and top face (f1) and six vertices (v0 t/m v5) and three offset vectors (n0 t/m n2).

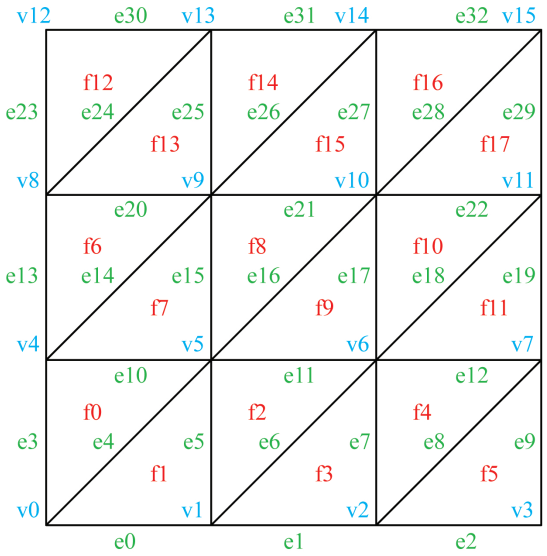
How the elements of the mesh are structured effects how they can be used further along the way. One needs to distinguish between implicit- and explicit mesh representations. The difference lies in the fact that the explicit mesh representation contains direct references to adjacent elements while the implicit mesh representation relies on additional computational methods to retrieve this information.

The building blocks of the SolidModel are so-called ‘Solids’. A Solid is a volumetric element built up out of triangles; its structure is depicted in Figure 4.6. The starting point for creating these Solids is the constructed mesh topology and corresponding offset vectors at the vertices. Each Solid contains a top and a bottom face which indicate the local boundaries of the concrete volume.

The SolidModel lies at the basis of operations which require lots of processing power. For this reason the SolidModel relies on an explicit mesh definition in which the number of explicit relationships between the elements is maximized. The increase in storage size of the model is amply compensated by the decreased amount of required numerical operations, for instance in order to retrieve neighbouring mesh elements.

The information contained in the MeshTopology is structured according to the Winged-edge mesh representation (‘Polygon mesh’, Wikipedia, The Free Encyclopedia). This particular representation contains a high degree of explicit information on all of the elements, which effectively means that each element carries information on its neighbours. Figure 4.7 shows the topology of a mesh





f0	f1 f7
f1	f0 f2
f2	f1 f3 f9
f3	f2 f4
f4	f3 f11 f5
f5	f4
f6	f7 f13
f7	f0 f6 f8
f8	f7 f9 f15
f9	f2 f8 f10
f10	f9 f11 f17
f11	f4 f10
f12	f13
f13	f6 f12 f14
f14	f13 f15
f15	f8 f14 f16
f16	f15 f17
f17	f10 f16

e0	v0 v1	f1	e4 e3 e1 e5
e1	v1 v2	f3	e6 e0 e2 e7
e2	v2 v3	f5	e8 e1 e9 e9
e3	v0 v4	f0	e0 e4 e10 e13
e4	v0 v5	f0 f1	e3 e0 e5 e10
e5	v1 v5	f1 f2	e0 e6 e11 e4
e6	v1 v6	f2 f3	e5 e1 e7 e11
e7	v2 v6	f3 f4	e1 e8 e12 e6
e8	v2 v7	f4 f5	e7 e2 e9 e12
e9	v3 v7	f5	e2 e2 e19 e8
e10	v4 v5	f0 f7	e14 e3 e4 e15
e11	v5 v6	f2 f9	e16 e5 e6 e17
e12	v6 v7	f4 f11	e18 e7 e8 e19
e13	v4 v8	f6	e3 e14 e20 e23
e14	v4 v9	f6 f7	e13 e10 e15 e20
e15	v5 v9	f7 f8	e10 e16 e21 e14
e16	v5 v10	f8 f9	e15 e11 e17 e21
e17	v6 v10	f9 f10	e11 e18 e22 e16
e18	v6 v11	f10 f11	e17 e12 e19 e22
e19	v7 v11	f11	e12 e9 e29 e18
e20	v8 v9	f6 f13	e24 e13 e14 e25
e21	v9 v10	f8 f15	e26 e15 e16 e27
e22	v10 v11	f10 f17	e28 e17 e18 e29
e23	v8 v12	f12	e13 e24 e30 e30
e24	v8 v13	f12 f13	e23 e20 e25 e30
e25	v9 v13	f13 f14	e20 e26 e31 e24
e26	v9 v14	f14 f15	e25 e21 e27 e31
e27	v10 v14	f15 f16	e21 e28 e32 e26
e28	v10 v15	f16 f17	e27 e22 e29 e32
e29	v11 v15	f17	e19 e22 e32 e28
e30	v12 v13	f12	e23 e23 e24 e31
e31	v13 v14	f14	e30 e25 e26 e32
e32	v14 v15	f16	e31 e27 e28 e29

v0	f0 f1	e0 e4 e3
v1	f1 f2 f3	e0 e5 e6 e1
v2	f3 f4 f5	e1 e7 e8 e2
v3	f5	e2 e9
v4	f0 f6 f7	e13 e14 e10
v5	f0 f1 f2 f9 f8 f7	e4 e10 e15 e16 e11 e5
v6	f2 f3 f4 f11 f10 f9	e6 e11 e17 e18 e12 e7
v7	f4 f5 f11	e8 e12 e19 e9
v8	f6 f13 f12	e13 e23 e24 e20
v9	f6 f7 f8 f15 f14 f13	e14 e20 e25 e26 e21 e15
v10	f8 f9 f10 f17 f16 f15	e16 e21 e27 e28 e22 e17
v11	f10 f11 f17	e18 e22 e29 e19
v12	f12	e23 e30
v13	f12 f13 f14	e24 e30 e31 e25
v14	f14 f15 f16	e26 e31 e32 e27
v15	f16 f17	e28 e31 e29

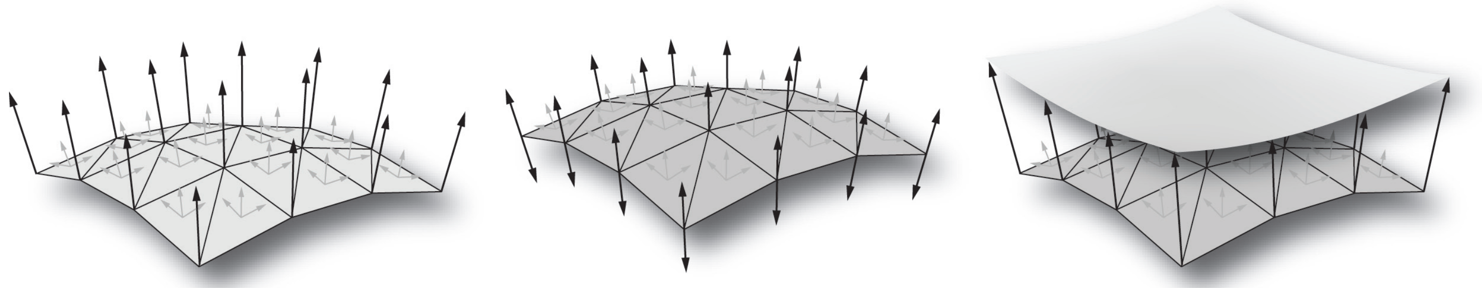
Figure 4.7
Winged-edge mesh topology of a 3x3 triangle mesh.

structured according to the Winged-edge mesh representation.
With the MeshTopology in place additional explicit information can be added to the elements, like local coordinate systems and the averaged normal vectors over the adjacent faces at the vertices. The latter are used to determine the offset direction of the vertices. Different methods for creating the actual offset which defines the concrete volume can be conceived, for the first version of the Reinforcement Toolbox it is chosen to implement the following three methods. Figure 4.8 graphically shows the three possible options for creating a SolidModel:

a) A one-directional offset relative to a reference mesh, defines a SolidModel with a predefined numerical thickness.
b) A bi-directional offset relative to a reference mesh, defines a SolidModel with a predefined numerical thickness.
c) A one-directional or bi-directional offset relative to a reference mesh defines the volume between two referencesurfaces.

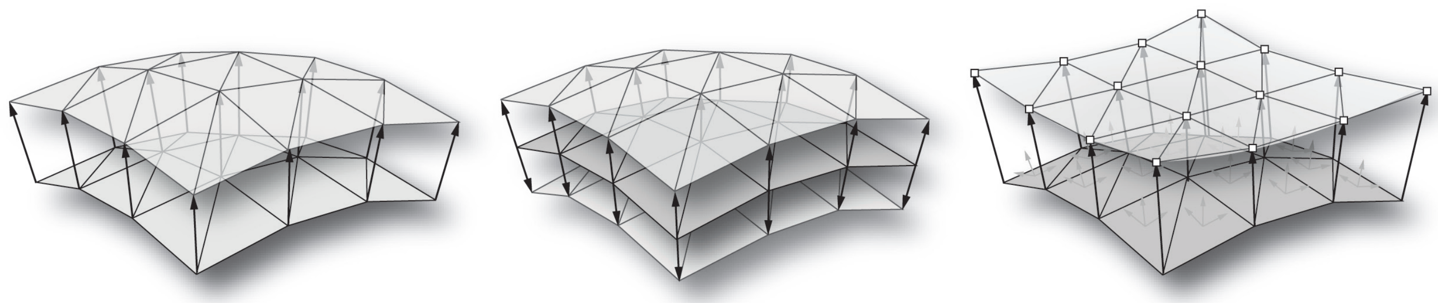
Figure 4.8 (Top)
Second step in the creation of the SolidModel: Establishing the mesh topology and creating the average normal vectors at the vertices.

Figure 4.9 (Bottom)
Size of the offset vectors is either defined through a constant (a) and (c) or by finding the intersections of the averaged normal vectors with the offset surfaces (b).



(a) (b) (c)

These three approaches allow for a SolidModel to be based on either a single surface or double surface definition. In both cases the direction of the offset vectors is determined by taking the average normal vector of connected mesh faces at the vertices. The size of the offset vector is either set as a constant or determined by extruding the vectors to the offset surfaces see Figure 4.9. A center mesh can be extracted from every SolidModel which can then serve as the base geometry for FEM Analysis models.



(a) (b) (c)

4.4 FEM Analysis Visualisation

The Reinforcement Toolbox offers the possibility to design reinforcement based on geometry and practical knowledge. Most structural engineers however will simultaneously want to consult the FEM analysis results, to validate their assumptions. The concept of FEM analysis visualization presented in this section offers the possibility to check the analysis results in the same environment the reinforcement is modelled. This offers the advantage of being able to simultaneously check both geometry and analysis results in the same 3D modelling environment.

The SolidModel presented in the previous section can be considered to be the infrastructure against which reinforcement bars are positioned. In order to complement this infrastructure with the complementary signs on where and how reinforcement is to be placed, the SolidModel holds qualitative information on reinforcement amounts and directions. Section 2.2.2 covers some of the structural analysis of curved concrete structures and discusses the most common approach to obtaining the stress distribution in this type of structures: FEM Analysis. FEM Analysis results, lend themselves well to numerical interpretation, a quality which is used in the computational strategy.

Before FEM analysis results can be used within the Reinforcement Toolbox the relevant information needs to be transferred from the analysis software and projected on the correct elements of the SolidModel. This Section explains which information is used and how it is visualized.

Infograph, the FEM Analysis software deployed to test the toolbox on, derives the necessary reinforcement percentages ωo for each element based on the design moments found in the elastic FEM Analysis. It does so in accordance to rules in the assigned standard (EN1992-1-1 and EN1992-1-2), and bases on the ω-table (TGB). The minimum- (ωomin) and maximum reinforcement (ωomax) percentages are determined within the Reinforcement Toolbox according to the assigned reinforcement steel and concrete quality.

Infograph calculates bending and shear reinforcement [cm2/m] for each area element according to the governing load case:

- asx1.Layer (bending reinforcement, top layer in the x-direction) [cm2/m]
- asy1.Layer (bending reinforcement, top layer in the y-direction) [cm2/m]
- asx2.Layer (bending reinforcement, bottom layer in the x-direction) [cm2/m]
- asy2.Layer (bending reinforcement, bottom layer in the y-direction) [cm2/m]

The local reinforcement coordinate system describes the orientation of the area reinforcement for each element. The concept of FEM analysis visualization is that it provides reinforcement designers with feedback on the amount and direction of reinforcement which has to be modelled in order to meet the design requirements. Colour coding of the center face of each solid reflects the amount of rebar which has to be added to the Solids, see Figure 4.10. The lower limit is set to the minimum reinforcement percentage; the upper limit is set to the maximum amount of reinforcement.

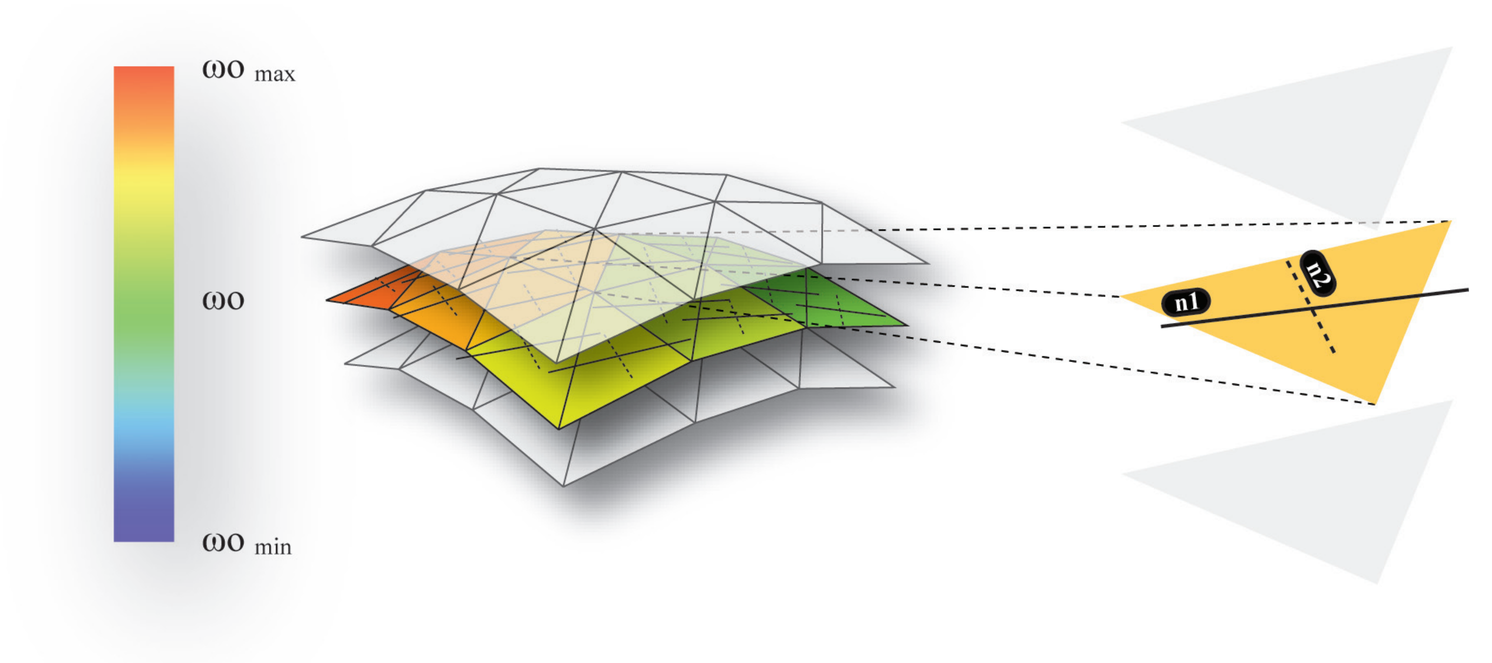


Figure 4.10
Colour coded reinforcement percentage on center faces according to FEM Analysis results. Principle forces n1 and n2 are displayed in vector format on the centroid of each center surface.

Solids contain the information derived from Infograph on the amount and direction of reinforcement in their top and bottom layers [cm2/m]. The amount of reinforcement actually traversing the element can be compared to calculated reinforcement amount belonging to the element, and the colour of the element is adapted based on the designed reinforcement. This provides users with visual feedback on the necessity of adding extra reinforcement in certain areas.

4.5 Rebar DNA and the Arc Spline Algorithm

An important starting point for this thesis is the close link to production of reinforcement. The current production capabilities within the reinforcement industry as described in Section 2.2.3. These practical restrictions serve as important input for the concept for describing the possible bending shapes in the Reinforcement Toolbox. This is not yet implemented in the first version of the Reinforcement Toolbox but will be incorporated in future versions.

A distinction has been made between mechanically and manually processed reinforcing bars, and their limitations in terms of possible bending shapes have been described. Mechanically processed reinforcing bars are assumed to be bent in-plane and consist of a sequence of segments with zero or constant curvature. Manually processed reinforcing bars can be bent out of plane, up to a diameter of 16mm. The bending shape is not of constant curvature but follows the deformation of a clamped bar under an imposed load (maximum 0,25kN at the end of the bar) or its own weight (natural bending shape). When considering a reinforcement bar as a sequence of connected segments it is assumed that a segment is either processed mechanically or manually.

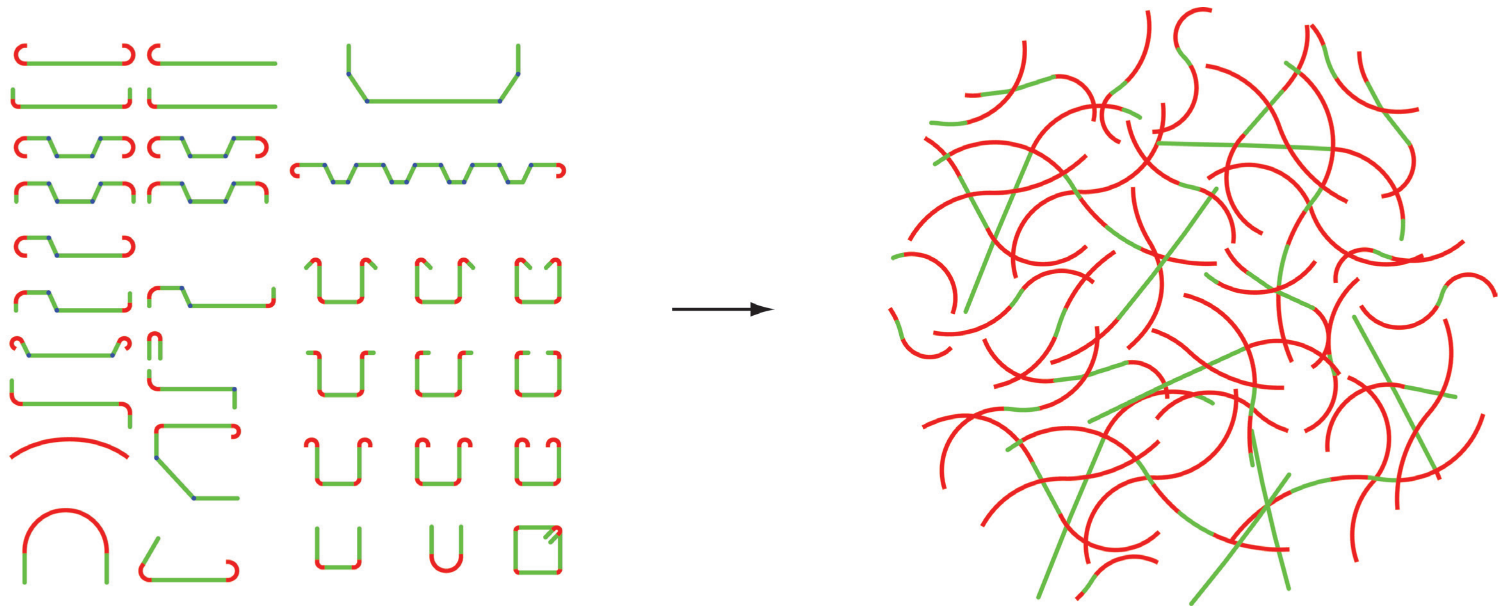


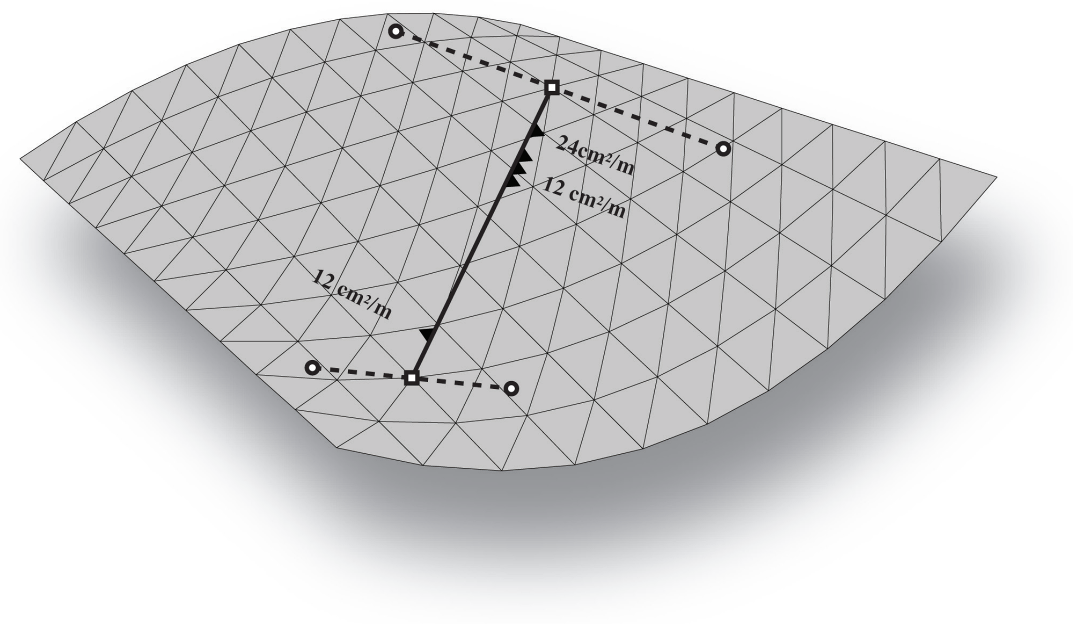
Figure 4.11
The concept of Rebar DNA, the combination of the three conventional reinforcement deformation typologies leads to an infinite amount of bending shapes suitable for curved surface structures.

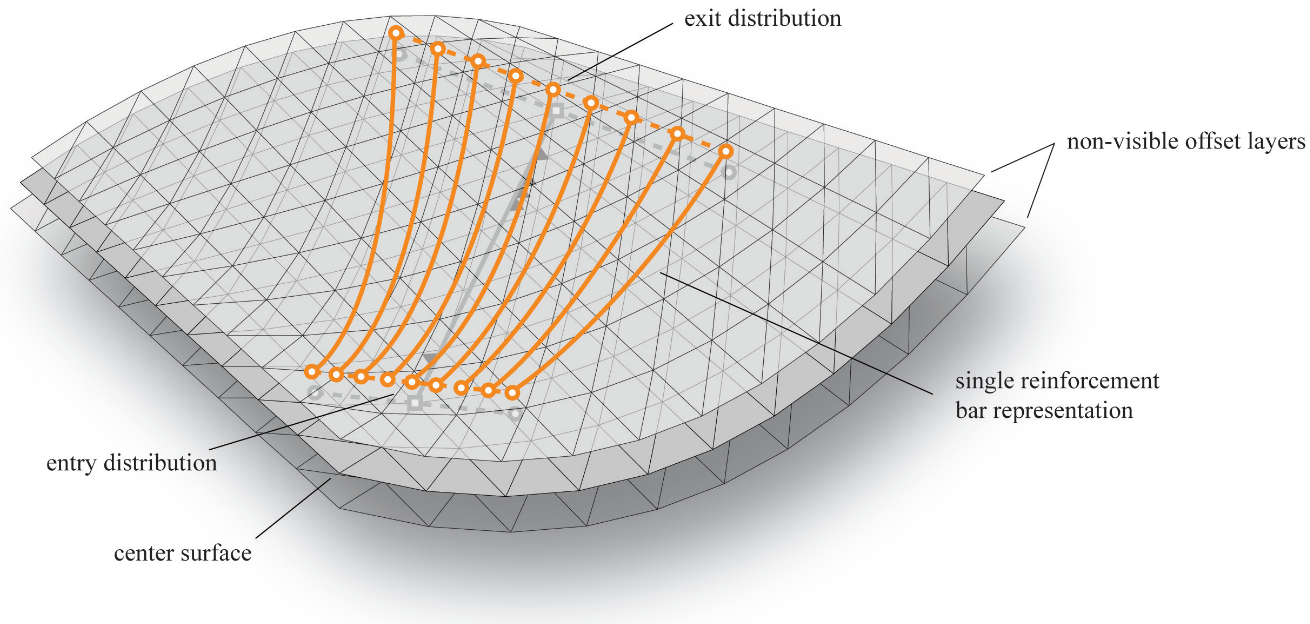
The assumptions have been developed into a concept called ‘Rebar DNA’ which can be described as the combination of the three possible deformation typologies which together form the geometric building blocks of reinforcing bars within the Reinforcement Toolbox: the combination of these building blocks leads to an infinite amount of possible bending shapes, which go beyond the standard reinforcement bending shapes found in bending schedules, see Figure 4.11. This concept provides for the necessary freedom when reinforcing reinforcement in curved surface structures while maintaining a direct relationship to the production and manipulability of reinforcement.
Reinforcement allocation is done according to so called reinforcing paths. These linear segmented paths are placed relative to the center surface of the SolidModel, using its nodes and edges as anchor points. A reinforcement path holds quantitative information and assigns direction to a reinforcement group. The group follows the direction of the path within the boundaries of the solid model, and distributes itself according to the assigned quantity. Display of the reinforcement paths follow the 2D drawing conventions shown in Section 3.2. This leads to reinforcement paths similar to the one depicted in Figure 4.12, which holds the amount of steel, direction and width of the distribution area of the reinforcement.

The maximum distance between the outermost and innermost reinforcing bar belonging to the reinforcement group can be assigned at the end nodes of the reinforcement path. The spacing of the bars is determined according to the amount of steel and diameter of the bars. The SolidModel holds information on the required offset layers in which the reinforcement needs to be placed. Offset layers are created relative to the center surface of each Solid in the SolidModel and comply with the rules of the Eurocode 2.

Figure 4.12 (Top)
A typical reinforcement path, placed on the center surface of a SolidModel, holds information on layer distribution, direction and quantity of a reinforcement bar group.

Figure 4.13 (Bottom)
Entry and exit distribution points, and segmented reinforcement bar representations.





The required amount of reinforcement can either be determined from FEM analysis results or entered manually. The result is an evenly spaced entry- and exit distribution placed in the correct layer, see Figure 4.13. In order to create the individual reinforcement bar representation the so-called entry and exit points are connected. This is done by using cutting planes between corresponding reinforcement points, which intersect the center faces of the SolidModel. By using a plane intersection method the criterion of in-plane bending is automatically met. The method benefits from the ordered SolidModel MeshTopology, which prevents the need to check each mesh face for a possible intersection. This would considerably slow down calculation.

The resulting segmented lines represent the center of reinforcing bars are sufficient for first design purposes. However, as kinks can cause local stress accumulations in the concrete they are undesirable from the perspective of force distribution. Special bar bending machines are capable of bending a reinforcement bar into a sequence of arc segments with different curvature, see Figure 4.14. The concept of Rebar DNA is employed to transform the kinked lines into G1 continuous reinforcement bar representations.

RebarDNA consists of a collection of segments with zero or constant curvature. A curve with the exact same properties is called an arc spline. The building blocks of arc splines are so called bi-arcs. In the past years many papers have been published on curve fitting techniques with bi-arcs (Yang et al., 1996) (Piegl et al., 2002). A bi-arc consists of two smoothly connected circular arcs, A0 and A1 with an identical tangent direction at the connecting point, that interpolate two end points and two end tangents. An important aspect of a bi-arc is its continuity of tangency, so called G1 continuity. From two end points and associated tangents, a family of bi-arcs can be derived which matches a set of given constraints.

Figure 4.14
Bar bending machine, double bender, bends a rebar into a sequence of circular arcs and line segments.

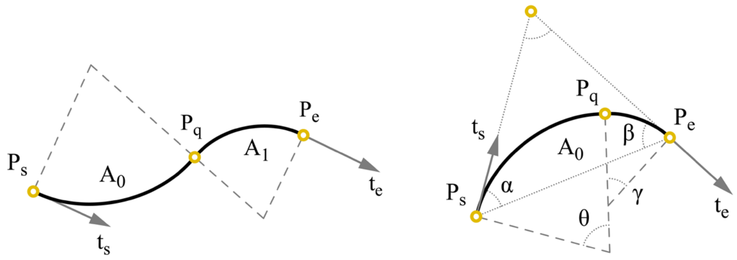


Figure 4.15
An S-shaped bi-arc and a C-shaped bi-arc, and their geometrical relations.

Figure 4.16
Results from the evolutionary arc spline algorithm proposed by Song et al. 2009.

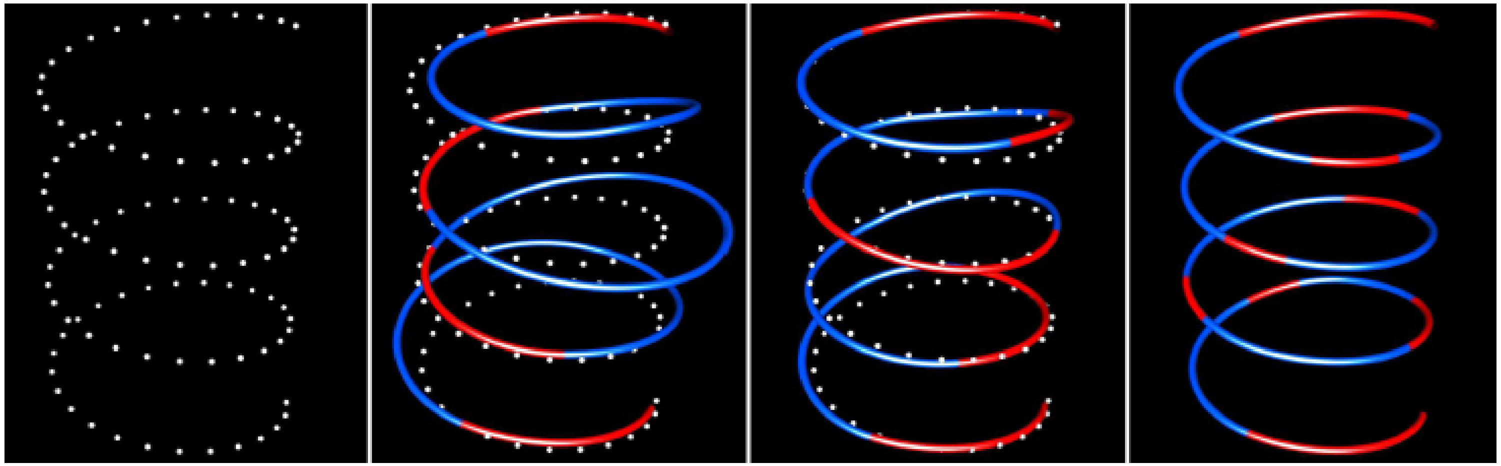
There are two types of bi-arcs, S-shaped bi-arcs and C-shaped bi-arcs, see Figure 4.15. Line segments and single circular arcs are special cases of bi-arcs. The special shapes of biarcs can be identified according to the different relationships between the tangent angles α and β. From figure 3, the following relationship can be obtained:

$$\alpha + \beta = \theta + \gamma$$

Generally three cases can be distinguished:

1) $\alpha = \beta = 0$ the biarc is a line segment.
2) $\alpha = \beta \neq 0$ the biarc is a single circular arc.
3) $\alpha \neq 0$ and $\beta \neq 0$ the general case of a biarc.

They correspond to the geometrical building blocks or ´Rebar DNA´ of reinforcing bars. Creating a sequence of bi-arcs according to a discrete point set is called curve fitting. A continuous arc spline is fitted to the segmented reinforcing bar representation, by using an arc spline algorithm. Anchor points of the segmented curve serve as discrete point set. Various papers describe arc spline approximation based on 2D- and 3D point data. They use various computational methods for constructing the arc spline curves. Piegl (ibidem) describes an arc spline algorithm which uses a specific formulation of bi-arcs especially suited to approximate NURBS curves. Song



proposes a non-linear optimization method for approximating 3D point data by an arc spline curve based on evolutionary algorithm (Song et al., 2009), see Figure 4.16.

The technique which fits best is the method proposed by Yang and Du which uses techniques from optimization theory to approximate discrete point data with arc splines. What makes it especially well suited is the fact that it offers the possibility of assigning a maximum approximation error which is not allowed to supersede a given tolerance. This offers geometrical control, an important aspect of reinforcement modelling. The algorithm iterates until the boundary conditions are met within the desired approximation error. Computation time can be significant, especially when dealing with a large number of control points and small approximation errors. In order not to impede the reinforcement modelling process by introducing large computation times, the arc spline algorithm will be implemented in the Reinforcement Toolbox as a post processing component.

This Section presented a concept which offers the possibility to assign reinforcement in the appropriate offset layer. Using a method based on the arc spline algorithm it is possible to construct a sequence of rebar segments, so called Rebar DNA, within a given tolerance. This process ensures that the final result satisfies the constraints of production and manipulability.

Reinforcement bending machine, ATG Steel, Raamsdonksveer.

5.0 **The Reinforcement Toolbox Design**

Figure 5.1
General workflow for software development. Subsequent phases: determining the constraints and requirements, design and implementation.

The main goals of this thesis, presented in Section 1.6, are the development of a computational strategy for the design and production enhancement of reinforcement in curved surface concrete structures and the deliverance of a proof of concept: the Reinforcement Toolbox. This chapter presents the design of Toolbox based on the developed strategy, as described in Chapter four.

The Chapter is structured according to the general workflow for software development (SehlHorst, 2006) as depicted in Figure 5.1. Section 5.1 describes three use cases from the perspective of the Structural Engineer, the envisioned primary user of the Toolbox. These use cases help to define the functional requirements of the Reinforcement Toolbox, covered in Section 5.2. The non-functional requirements and constraints are addressed in Section 5.3. Section 5.4, 5.5 and Section 5.6 subsequently explain the system architecture, and provide for a detailed description of the various components, and their workings.

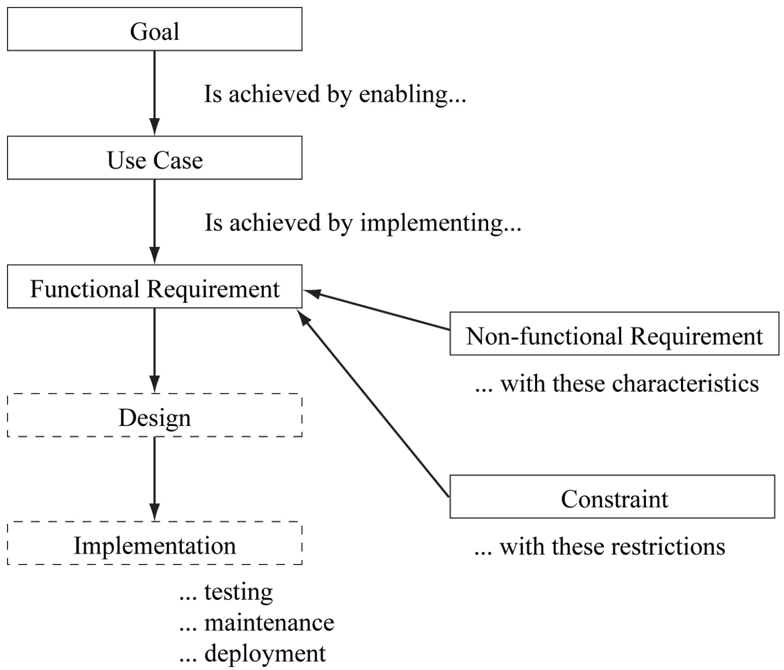


Table 5.1
Use Case 1: Create the Solid-Model of a curved surface structure.

5.1 Use Cases

Use cases help to identify different scenarios in which a software application is likely to be used. They describe the steps or actions between a user (or "actor") and a software system which leads the user towards something useful. ('Use case', Wikipedia: The Free Encyclopedia). The internal stakeholders of the reinforcement process: the contractor; fabricator and the structural engineer, identified in Section 3.1, are all envisioned future users of the reinforcement toolbox but, the main functionality is developed around the structural engineer. Three important use cases, which evolve around this primary actor, have been identified:

- Create the SolidModel of a curved surface structure.
- Create a parametric reinforcement model.
- Add functionality to the toolbox.

Although this list is not exhaustive, it provides a good insight into how the Reinforcement Toolbox can be used. These use cases are presented graphically through so-called use case diagrams, and in tabular form according to the use case template proposed by Derek Coleman (Coleman, 1998). The functional- and non-functional requirements referred to in these tables are described in Sections 5.2 and 5.3.

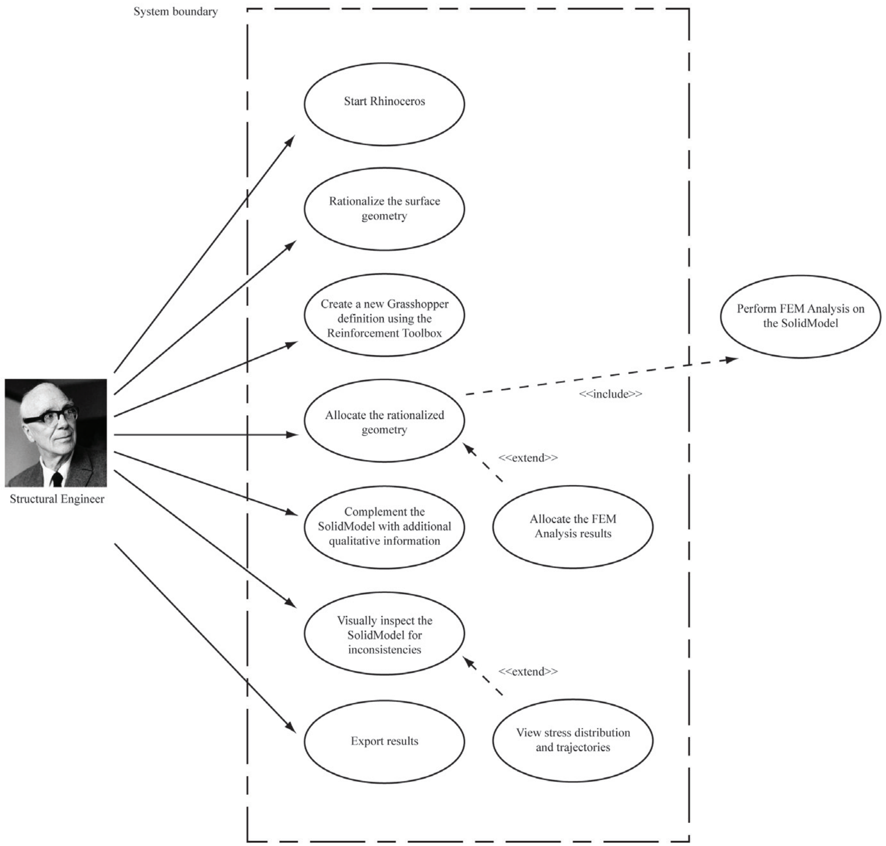
5.1.1 Use Case 1: Create the SolidModel of a curved surface structure

In order to create a SolidModel as described in Section 4.2, the actor has to perform several actions using both the functionality contained in the Toolbox and the standard functionality within Rhinoceros. Table 5.1 presents the use case in tabular form, Figure 5.2 displays it graphically.

Use Case name and identifier:	UC-1 Create a SolidModel for a curved surface structure, based on a double surface definition, and export the resulting geometry to the FEM Analysis software of choice.
Description:	*'After receiving a 3D curved surface CAD model from the architect the structural engineer wants to create a SolidModel to serve as a basis for his FEM Analysis- and reinforcement model. To realize this, he/she starts Rhinoceros3D, opens the curved surface model and creates a triangular mesh based on one of the reference surfaces using the standard mesh functionality contained in Rhinoceros3D and Grasshopper. Bearing in mind the interface with FEM Analysis software, the structural engineer adapts the size and shape of the mesh elements if necessary.* *After this first step of surface rationalisation the appropriate components of the Reinforcement Toolbox are dragged and dropped on the Grasshopper canvas, and the newly created mesh, together with the reference surfaces are assigned to the appropriate inputs. Missing information like the relevant building standard and concrete properties is added to the definition, after which the SolidModel is generated. The structural engineer visually inspects the SolidModel for inconsistencies and exports the resulting center mesh including thickness information to InfoCAD.'*

Actors:	Structural Engineer (primary actor), CAD draftsman
Assumptions:	The actor has knowledge on surface rationalization in Rhinoceros3D and knowledge on FEM Analysis models.
Steps:	1) Start Rhinoceros. 2) Rationalize the surface geometry. 3) Open the Grasshopper plugin, drag and drop the relevant Reinforcement Toolbox component onto the canvas. 4) Allocate the rationalized geometry and the reference surfaces. 5) Complement the SolidModel with additional qualitative information. 6) Visually inspect the SolidModel. 7) Export the results to the FEM Analysis software.
Variations:	Instead of using Rhinoceros3D for surface rationalization, the geometry can also be imported directly from the FEM Analysis software.
Functional Require-ments:	FR-4; FR-7; FR-9; FR-12; FR-14; FR-15
Non-Functional Require-ments:	NFR-2
Issues:	The surface rationalisation, or meshing, relies on functionality outside the Toolbox. Incorporating it in the Toolbox would entail an increased number of ways to define a SolidModel, increase accuracy of the model, and give actors more freedom in thickness allocation.

Figure 5.2
Use Case diagram 1: Create the SolidModel of a curved surface structure.



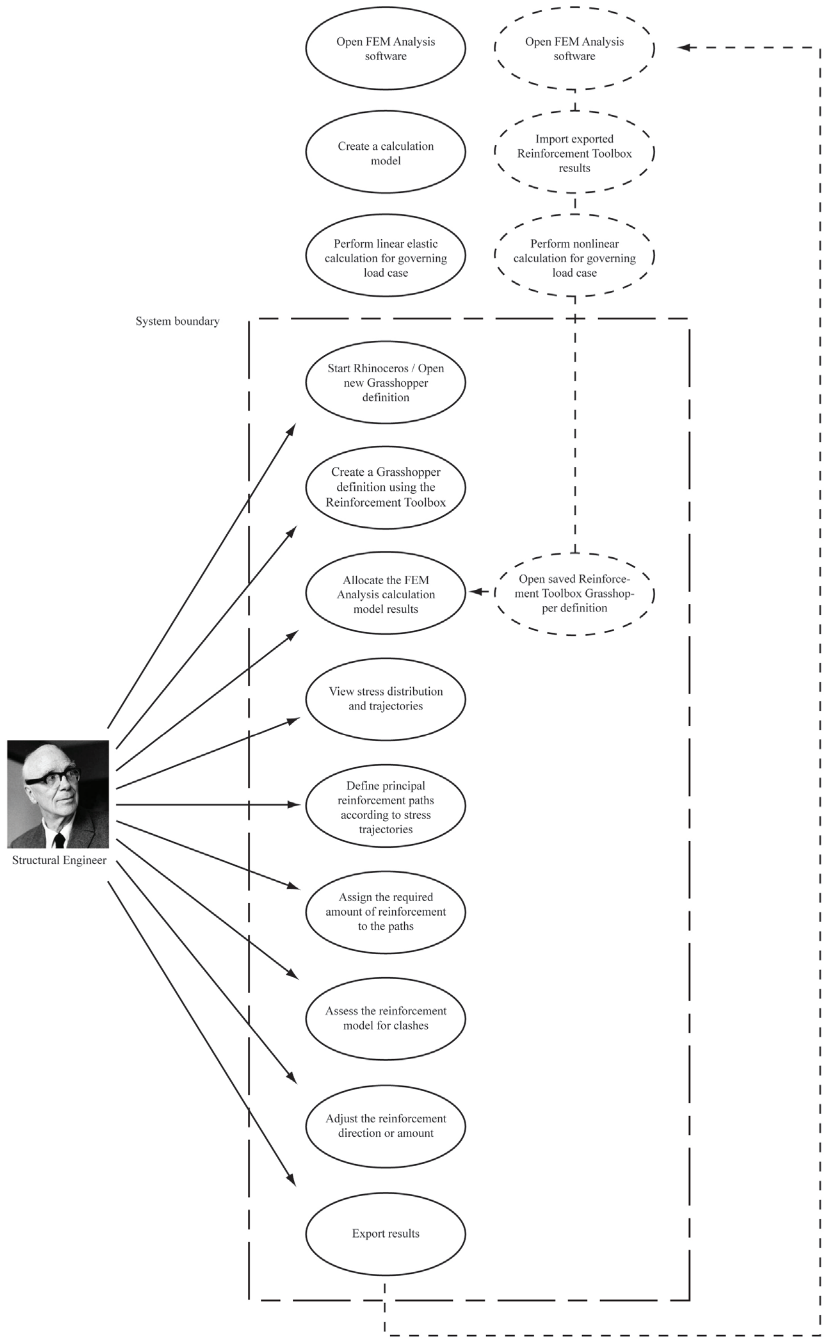
5.1.2 Use Case 2: Create a parametric reinforcement model

In order to visualise structural analysis results using the Reinforcement Toolbox, the SolidModel needs to be based on the FEM Analysis model. Geometry as well as the resulting stress and reinforcement distribution are imported and fed back to the actors. The reinforcement model is compared to the reinforcement quantities coming from the finite element analysis and results are fed back to the actors. Table 5.2 presents the use case in tabular form, Figure 5.3 displays it graphically.

Use Case name and identifier:	UC-2 Create a parametric reinforcement model for a curved surface structure.
Description:	*'After creating a SolidModel using the Reinforcement Toolbox, the structural engineer exports the geometrical information to the FEM Analysis software of choice. Based on the imported geometry he or she creates a calculation model. The results are fed back into the Reinforcement Toolbox.* *The structural engineer interprets the results from the analysis and uses the components in the Reinforcement Toolbox to model the reinforcement. When a sufficiently accurate reinforcement model is designed the results, including reinforcement quantities and directions, are exported to the FEM Analysis software where a nonlinear elastic analysis is performed.'*
Actors:	Structural Engineer (primary actor), CAD draftsman
Assumptions:	The actor has access to the FEM Analysis model of the structure under consideration. The actor has a basic understanding on the use of Rhino and Grasshopper, and knowledge on reinforcement modelling.
Steps:	1) Start Rhinoceros / Open new Grasshopper definition. 2) Open the InfoCAD input component. 3) Allocate the FEM Analysis results. 4) View stress distribution and trajectories in Rhinoceros3D. 5) Define principal reinforcement paths according to stress trajectories. 6) Assign the required amount of reinforcement to the paths. 7) Assess the reinforcement model for clashes. 8) Adjust the reinforcement direction or amount. 9) Export the results to InfoCAD.
Variations:	Apart from basing the SolidModel on FEM Analysis results, the actor can input any type of meshed surface into the SolidModel plugin.
Functional Requirements:	FR-1; FR-2; FR-3; FR-4; FR-7; FR-12; FR-13
Non-Functional Requirements:	NFR-2
Issues:	The FEM Analysis which now takes place outside the system is envisioned to become part of the Reinforcement Toolbox. This will improve the workflow of reinforcement design in curved surface structures.

Table 5.2
Use Case 2: Create a SolidModel for a curved surface structure.

Figure 5.3
Use Case diagram 2: Create a parametric reinforcement model for a curved surface structure.



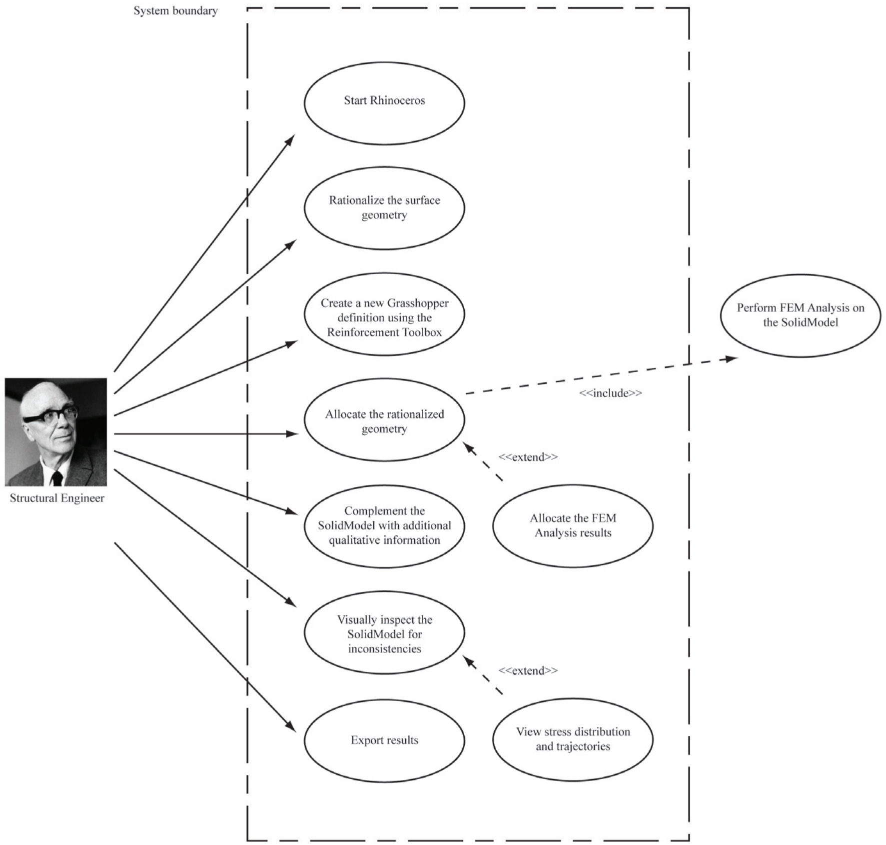
5.1.3 Use Case 3: Extent or modify the functionality of the Reinforcement Toolbox

In order to adapt and extent the Toolbox, the structural engineer has to cooperate with a computational designer. The structural engineer determines the additional functional requirements and the computational designer implements them. Table 5.3 presents the use case in tabular form, Figure 5.4 displays it graphically.

Table 5.3
Use Case 3: Extent or modify the functionality of the Reinforcement Toolbox.

Use Case name and identifier:	UC-3 Extent or modify the functionality of the Reinforcement Toolbox.
Description:	*'After working with the Reinforcement Toolbox, the structural engineer feels limited in terms of possibilities. Together with a computational designer with knowledge on the Toolbox options for adaptations are discussed. The structural engineer provides for the technical details which will be implemented by the computational designer.'*
Actors:	Structural Engineer (primary actor), Computational Designer
Assumptions:	The computational designer has the necessary software and dependencies installed which allow him/her to make adaptations in the programming code of the Reinforcement Toolbox.
Steps:	1) Determine a gap in the current functionality of the Reinforcement Toolbox. 2) Provide for the functional requirements in order to fill this gap. 3) Modify the existing Reinforcement Toolbox. 4) Research a new Reinforcement Toolbox module. 5) Implement a new Reinforcement Toolbox module. 6) Validate new Reinforcement Toolbox module.
Variations:	Structural engineers with computational design skills can extend the functionality of the toolbox without the interference of a computational designer.
Functional Requirements:	Not applicable.
Non-Functional Requirements:	NFR-20
Issues:	Updates in supporting software packages might lead to necessary toolbox updates.

Figure 5.4
Use Case diagram 3: Extent or modify the functionality of the toolbox.



5.2 Functional Requirements

The functional requirements capture the intended behaviour of the Reinforcement Toolbox. The research described in Part I of this thesis help determine these requirements. The requirements form input for the design stage of the Reinforcement Toolbox by providing information concerning the use and purpose of the system.

The computational strategy, described in Chapter four, sets out the envisioned workflow for reinforcement design in curved surface structures. The Reinforcement Toolbox supports this workflow. The first phase in the development of the Toolbox, the proof of concept, focuses on establishing the baseline functionality. This implies that not all functional requirements presented below will be incorporated in the first version of the Toolbox. However in order for the computational strategy to be of use outside of this thesis it is important to consider as many relevant requirements as possible in an early stage.
Functional requirements emerging from the computational strategy form an important input for the development of the architecture

of the Reinforcement Toolbox. However its design is not only based on the functional requirements belonging to the initial proof of concept, but go beyond this and consider requirements of future releases. Future releases are accommodated through architectural qualities like extensibility and flexibility. These specific qualities of the Toolbox are specified in non-functional requirements, see Table 5.2.

Table 5.4 presents the functional requirements which the Reinforcement Toolbox will have to meet. Reference is made to the research section from which the requirement originates. Requirements which will be implemented in the proof of concept are denoted by the addition 'IMP'.

Table 5.4
The functional requirements which serve as input to the Reinforcement Toolbox.

Identifier	Requirement	IMP	Section
FR-1	The system supports principle stress visualization in the structure.	X	2.2.2
FR-2	The system supports clash detection.		2.2.1
FR-3	The system supports parametric reinforcement definitions.	X	2.1
FR-4	The system supports interoperability with FEM Analysis software.	X	2.1
FR-5	The system supports user notification on reinforcement which does not comply with the Eurocode 2.	X	2.2.3
FR-6	The system supports interoperability with BIM software.		1.4
FR-7	The system supports 3D visualization of reinforcement.	X	3.2
FR-8	The system supports 2D drawing extraction.		3.3
FR-9	The system supports interoperability with CAD software.		3.3
FR-10	The system supports reinforcement quantity extraction.	X	1.4
FR-11	The system supports concrete quantity extraction.	X	1.4
FR-12	The system supports required reinforcement quantity estimation according to FEM Analysis results.	X	2.2.2
FR-13	The system supports the use of 2D reinforcement drawing conventions in a 3D modelling environment.	X	3.2
FR-14	The system supports curved surface rationalization.		2.2.1
FR-15	The system supports variable thickness allocation.		2.2.1
FR-16	The system supports linear finite element analysis for elastic solids.		2.2.2
FR-17	The system supports nonlinear finite element analysis.		2.2.2
FR-18	The system supports a realistic constitutive model for reinforced concrete material behavior.		2.2.2

Table 5.5
The non-functional requirements and constraints for the reinforcement toolbox.

5.3 Non-Functional Requirements and Constraints

Non-functional requirements and constraints affect the architecture of the Reinforcement Toolbox. They define the qualities which the system has to meet, and set the constraints. The plan for implementation non-functional requirements is reflected in the system architecture. Non-functional requirements can be divided into two main categories, execution qualities and evolution qualities. The latter refers primarily to the degree of future adaptability of the system. A constraint is a restriction to the degree of freedom in which a solution can be provided. In case of the Reinforcement Toolbox they mainly apply to operating- and platform to which the toolbox is developed.

As the Reinforcement Toolbox relies on highly complex geometrical operations and visualisation it will not developed as a stand-alone application but will be built on top of a specialized 3D modelling environment. The Reinforcement Toolbox will use Rhinoceros3D for visual output and feedback of results to its users, and plugs into the parametric framework of Grasshopper, a graphical algorithm editor for Rhino. Table 5.5 lists the non-functional requirements and constraints of the Reinforcement Toolbox.

Identifier	Technical Requirements and Constraints	Section
NFR-1	The system shall be easily adaptable and extendable.	3.4
NFR-2	The system shall have response times which do not impede the natural workflow of the user.	
C-1	The system shall be based on the .NET framework 3.5.	
C-2	The system shall be developed using the C# programming language.	
C-3	The system shall be developed using Visual Studio 2008.	
C-4	The system shall use the RhinoCommon software development kit.	
C-5	The system shall be developed for Rhino version 4.0 SR9.	
C-6	The system shall be developed for Grasshopper version 0.8.	

5.4 System Architecture

The system architecture of the Reinforcement Toolbox has been developed with strong attention to the multifaceted design process of reinforcement in curved surface structures, and enables users to perform various operations at their own discretion (see Use Case 2). It builds on existing platforms by creating custom components.

RhinoCommon is a .NET plug-in SDK that can be used across all Rhino platforms. It enables developers to extend Rhino's functionality by creating Rhino plug-ins. Grasshopper in its turn is a .NET plugin for Rhino, and additions to Grasshopper can be written in the VB, Python or C# programming languages. The custom Grasshopper components in the Reinforcement Toolbox are written in C#. The Reinforcement Toolbox consists of a collection of custom Grasshopper components each providing for a demarcated portion of the functionality, Figure 5.5. They are linked together through custom parameters of which the content can be controlled by the developer. The power of embedding the Toolbox in the parametric Grasshopper framework, as an overlay on existing systems, is

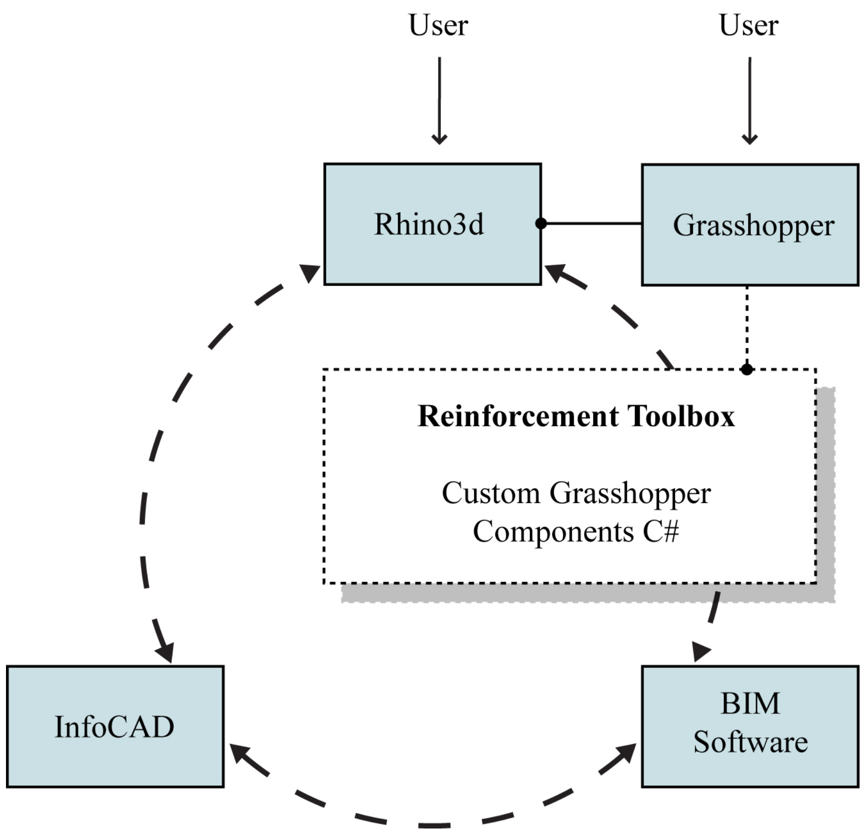
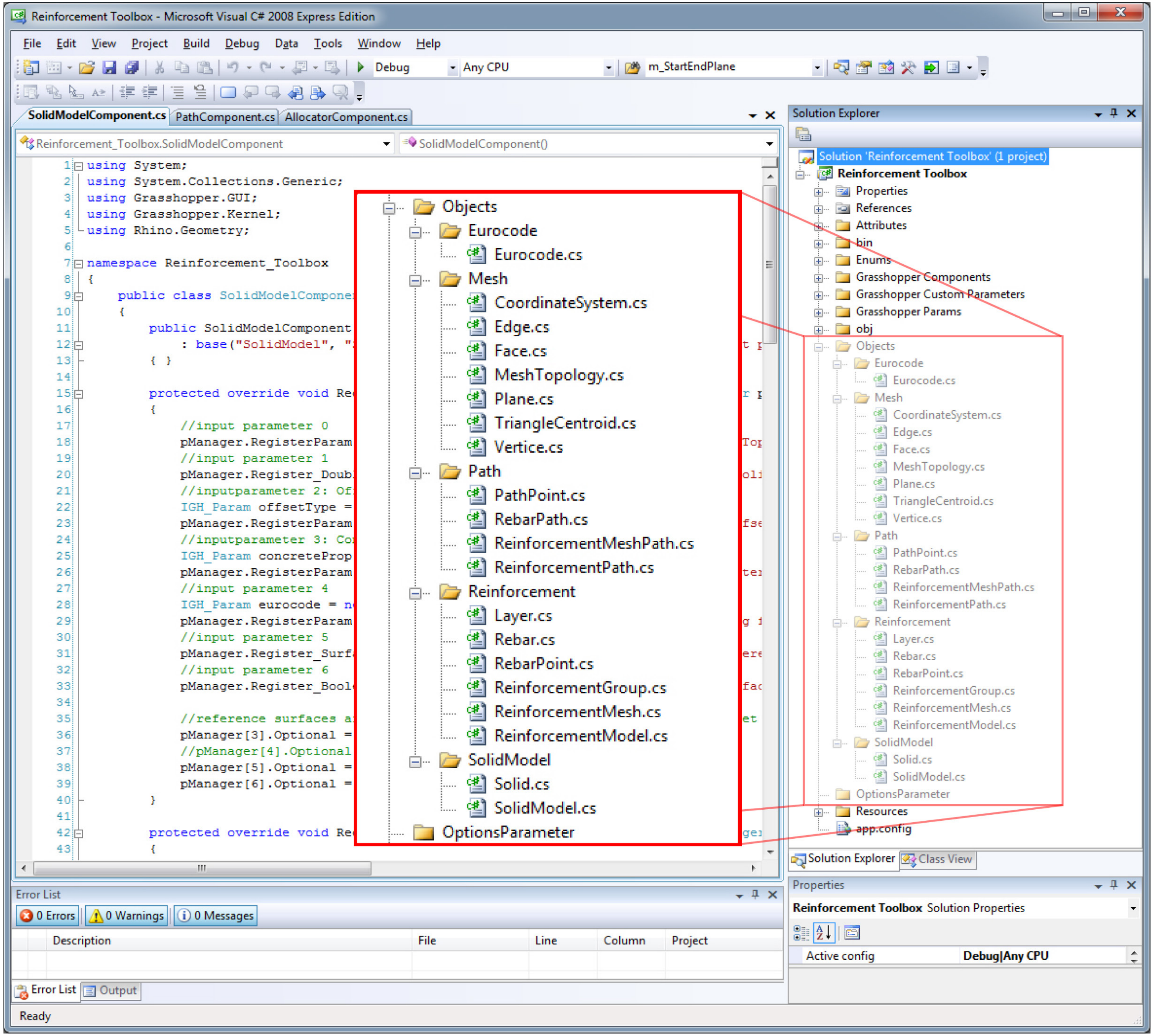


Figure 5.5
The Reinforcement Toolbox functions as an interacting overlay on top of existing systems.

that it can be easily extended by adding new components. The Reinforcement Toolbox facilitates the interface between these existing systems. The Reinforcement Toolbox refers to several libraries, of which the RhinoCommon.dll and Grasshopper.dll are the most obvious. Other libraries include MathNet.Iridium.dll (Rüegg, 2008) for mathematical operations, and the octc.dll (Kam, 2008) for octree data structure operations.

The Reinforcement Toolbox has been developed using Microsoft Visual Studio 2008 and written in C#. In accordance to the possibilities offered by this object oriented programming language, the Reinforcement Toolbox uses a collection of custom objects which can be considered the building blocks of the Toolbox. Figure 5.XX shows the developer environment with an enlargement of the created objects. The objects are categorized in five categories: 'Eurocode', 'Mesh', 'Path', 'Reinforcement' and SolidModel. For the concepts underlying these structures, refer to Chapter four. Section 5.6 refers to these objects when explaining the workings of the Toolbox through key components.

Figure 5.6
The developer environment of Microsoft Visual Studio C# with an enlargement showing the objects used in the Reinforcement Toolbox.



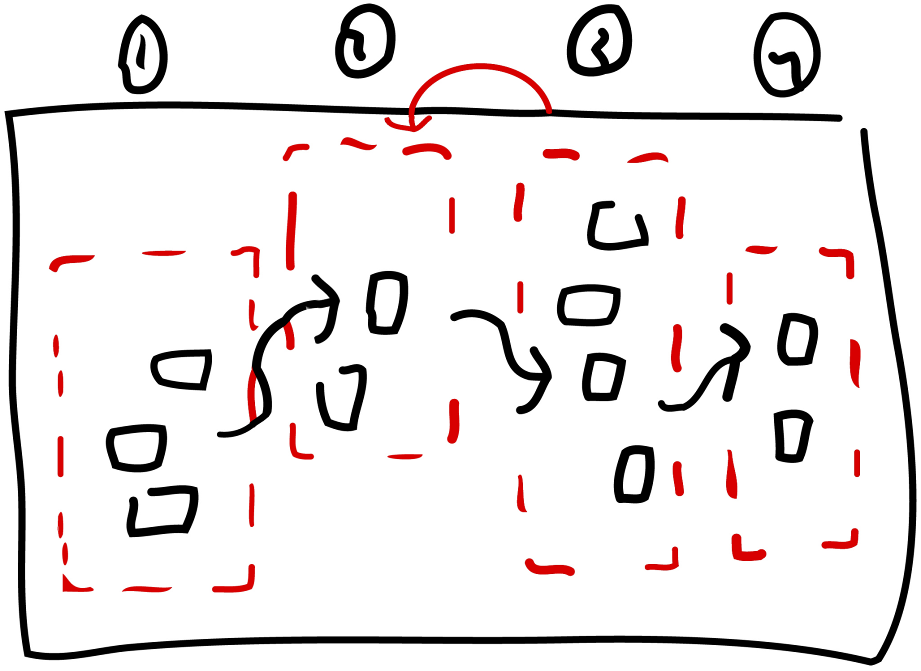


Figure 5.7
Sketch showing the interrelations between the four sub categories of the Reinforcement Toolbox: 1) Conditions; 2) Geometry; 3) Reinforcement; 4) Post-processing.

5.5 Custom Grasshopper Components

This section describes the custom Grasshopper components which form the Reinforcement Toolbox and accommodate the computational design strategy. The majority of components presented in the tables below are implemented in the first version of the Reinforcement Toolbox. These components are indicated by the addition IMP.
The open structure of Grasshopper enables developers to create custom components and custom parameters which plug into the parametric environment. This offers the possibility to tailor them to specific tasks and control their content. The first version of the toolbox contains around twenty components. They have been added to a new Grasshopper category called 'Reinforcement Toolbox'. The Toolbox can easily be extended by adding more components or extending the functionality of existing ones. Together they offer users the possibility to research specific reinforcement design solutions within the assigned boundary conditions. The main tasks of the components are discussed below, together with their in- and output parameters. The Reinforcement Toolbox components are categorized according to the following sub-categories:

1) Conditions
2) Geometry
3) Reinforcement
4) Post-Processing

The scheme in Figure 5.7 shows the hierarchy of a Reinforcement Toolbox configuration. The hierarchy is constructed in such a way that the most elementary factors of reinforcement detailing, the conditions and geometry, form the first elements in the configuration. The reinforcement and post-processing are defined at the end of the workflow. For the first version of the Reinforcement Toolbox several components have been developed. Together they offer the necessary functionality for a structural engineer or CAD draftsman to design longitudinal reinforcement groups and reinforcement meshes for curved surface structures. The content of the sub categories, the associated components, and their input parameters are explained below.

Conditions

Table 5.6 contains the components which hold the qualitative information which affects the detailing of reinforcement. This includes national building codes and concrete quality.

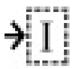
Table 5.6 (Top)
The components belonging to the 'Conditions' sub category of the Reinforcement Toolbox.

Icon	Component	Functionality	In- Output
	Building Code (**IMP**)	Hold the relevant information concerning reinforcement detailing stemming from the relevant building code. The qualitative information of the concrete structure is registered here.	**Input**: Qualitative information (option parameter) **Output**: Building Code (code parameter)
	ConcProp (**IMP**)	Set the properties of the concrete which affect the reinforcement detailing, like the concrete grade, the aggregate size and the fire exposure class.	**Input**: Properties (option parameter) **Output**: ConProp (conprop parameter)

Geometry

Table 5.7 contains the components which deal with the geometrical description of the concrete structure, culminating in the so called SolidModel. Functionality includes creating meshes based on NURBS surfaces, determining mesh topologies of existing meshes and variable thickness definition.

Table 5.7 (Bottom)
The components belonging to the 'Geometry' sub category of the Reinforcement Toolbox.

Icon	Component	Functionality	In- Output
	Building Code (**IMP**)	Hold the relevant information concerning reinforcement detailing stemming from the relevant building code. The qualitative information of the concrete structure is registered here.	**Input**: Qualitative information (option parameter) **Output**: Building Code (code parameter)
	ConcProp (**IMP**)	Set the properties of the concrete which affect the reinforcement detailing, like the concrete grade, the aggregate size and the fire exposure class.	**Input**: Properties (option parameter) **Output**: ConProp (conprop parameter)

	SolidModel (**IMP**)	Create a SolidModel from an input mesh and assigned thickness method. The Solid-Model represents the boundary surface of the concrete volume.	**Input**: Mesh (mesh parameter) Boundary Surfaces (Rhino surface) SolidModel Refiner (solidmodel refiner) FEM input (fem input parameter) Patches (patch parameter) Thickness (double) Building Code (code parameter) Path (path parameter) Rebar (rebar parameter) **Output**: SolidModel (solidmodel parameter) Reinforcement (reinforcement parameter)
	SolidModel Refiner	Refine the SolidModel by subdividing Sol-ids in order to reach greater accuracy with respect to the base geometry.	**Input**: Max. deviation from surface (double) **Output**: SolidModel Refiner (solidmodel refiner parameter)
		Create a Delaunay triangle mesh of an input surface, which can be any of the defined surface types within Rhino.	**Input**: Surface (Rhino surface) Patches (patch parameter) Refiner (mesh refiner parameter) **Output**: Mesh (mesh parameter)
		Refine the created mesh by comparing the triangles' inner angles, minimum edge size and deviation from the input surface.	**Input**: Max. edge length (integer) Min. inner angle (double) Max. deviation from surface (double) **Output**: Refiner (refiner parameter)

Reinforcement

Table 5.8 contains different types of reinforcing bar and reinforcement paths. These can be applied to the SolidModel in order to cre-ate a reinforcement model.

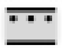
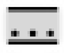
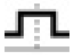
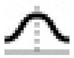
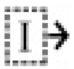
Icon	Component	Functionality	In- Output
	Rebar (**IMP**)	Assign a group of longitudinal rebar to a SolidModel with respect to the minimal offset dictated by the building code, production and direction / quantity of the designated path.	**Input**: Path (path parameter) Production (production parameter) Stirrup (stirrup parameter) **Output**: Rebar (rebar parameter)
	Stirrup	Assign a group of stirrups to a group of rebar.	**Input**: Production standard (option parameter) **Output**: Stirrup (stirrup parameter)
	Net (**IMP**)	Assign a rebar net to a SolidModel with respect to the minimal offset dictated by the building code, production and direction / quantity of the designated path.	**Input**: Path (path parameter) Production (production parameter) **Output**: Net (net parameter)
	Path (**IMP**)	Assign quantitative information and direction to a group of longitudinal rebar. The group of rebar follows this direction within the boundaries of the solid model.	**Input**: Anchor points (Rhino point) Amount (double) **Output**: Path (path parameter)
	NetPath (**IMP**)	Assign quantitative information and direction to a reinforcement mesh. The reinforcement mesh follows this direction within the boundaries of the solid model.	**Input**: Anchor points (Rhino point) Amount (double) **Output**: MeshPath (path parameter)
	Layer (**IMP**)	Assign the cover and diameter of a reinforcement group.	**Input**: Cover (double) Diameter (double) **Output**: Layer (layer parameter)
	TopLayer (**IMP**)	Collect the top layers of a reinforcement group.	**Input**: Layer (layer parameter) **Output**: Layer (List<layer parameter>)

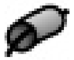
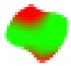
Table 5.8
The components belonging to the 'Reinforcement' sub category of the Reinforcement Toolbox.

Table 5.9
The components belonging to the 'Post-Processing' sub category of the Reinforcement Toolbox.

	BotLayer (**IMP**)	Collect the bottom layers of a reinforcement group.	**Input**: Layer (layer parameter) **Output**: Layer (List<layer parameter>)
	Allocator (**IMP**)	Allocates the reinforcement bars to the correct layers in the SolidModel.	**Input**: Reinforcement groups (reinforcement group parameter) **Output**: ReinforcementModel (reinforcementmodel parameter)
	AnalogDist	Create an analog distribution of reinforcement bars along a reinforcement path.	**Input**: Width (double) ValueA (double) ValueB (double) **Output**: AnalogDistribution (distribution parameter)
	GaussianDist	Create a gaussian distribution of reinforcement bars along a reinforcement path.	**Input**: ValueA (double) ValueB (double) **Output**: GaussianDistribution (distribution parameter)

Post-Processing
Table 5.9 contains the components which require a lot of processing power.

Icon	Component	Functionality	In- Output
	Bender	Create actual bending shapes ready for production.	**Input**: ReinforcementModel (reinforcementmodel parameter) **Output**: Rebars (rebar parameter)
	FEM Analysis Export	Write geometrical and reinforcement information to a FEM model.	**Input**: ReinforcementModel (reinforcementmodel parameter) **Output**: FEM output (fem output parameter)

	Pipe (**IMP**)	Draw the pipes along the rebars.	**Input**: ReinforcementModel (reinforcementmodel param-eter) **Output**: Pipes (Rhino breps)
	Clash Detection	Finds clashes in the reinforcement model and noti-fies the user.	**Input**: ReinforcementModel (reinforcementmodel param-eter) **Output**: Clashes (Rhino breps)
	Evaluate Rein-forcement	Check the reinforcement against the analysis results from the FEM Analysis software.	**Input**: Mesh (Rhino mesh) **Output**: Mesh (Rhino mesh)

More information on how the Reinforcement Toolbox is to be used can be found in Appendix B: ‘The Reinforcement Toolbox Manual’. It includes examples of Toolbox configurations and an explanation on how to operate the components.

Figure 5.8 (Continues on next page)
The workings of the Toolbox explained according to three key components, (a) the SolidModel component, (b) the Path component and (c) the Allocator component.

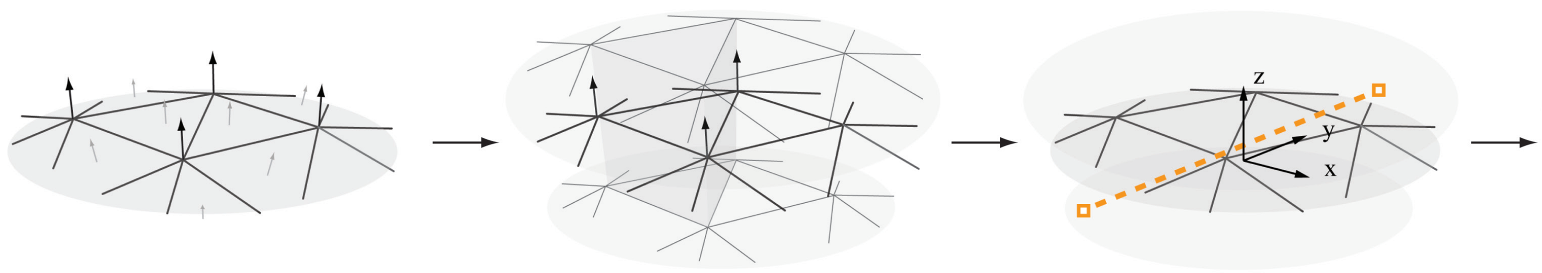
5.6 How the Toolbox Works

This Section explains how the Reinforcement Toolbox works according to three key components. These components lie at the heart of each reinforcement model created with the Toolbox, and are vital to understanding its workings. The three key components are the SolidModel component, the Path component and the Allocator component. Figure 5.8 gives a step by step explanation of how reinforcement is created.

The first two steps are dominated by the SolidModel component (a). In a first step the averaged vectors are created in the vertices of the reference mesh, this done by adding the normal vectors of the adjacent faces. This information is necessary for the second step: creating the Solids. The structure of a Solid consists of a bottom and top face, six vertices and three offset vectors (the averaged vectors in the vertices). Each reference mesh face has a pointer to the associated Solid. This is used in a later stage when the reinforcement is allocated. Together the Solids form the SolidModel, which contains the associated MeshTopology.

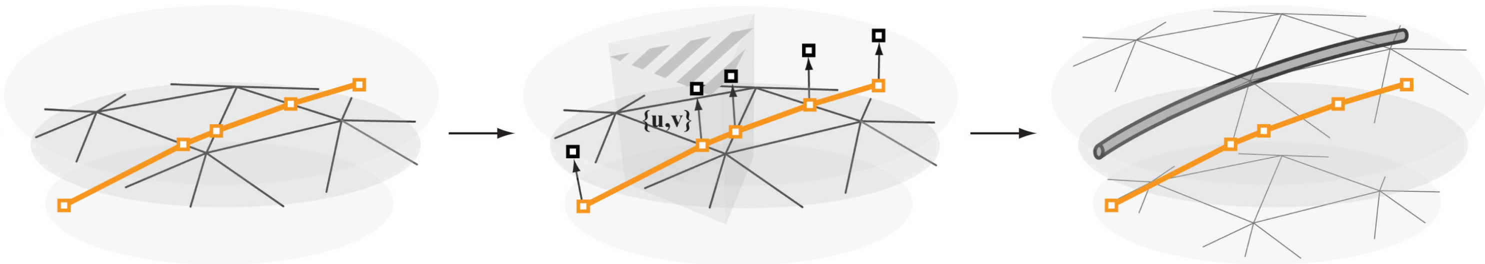
The third and fourth steps are governed by the Path component (b). The start- and endpoints are assigned by the user, together a definition of the coordinate system (relative to the global x,y-plane or relative to the averaged start and end face), the y-axis of the Path's coordinate system aligns with the straight line between the start- and endpoints. In the fourth step the so-called PathPoints are determined through an algorithm which finds the plane edge intersection between the reference mesh edges and the y,z-plane of the coordinate system belonging to the RebarPath.

(a) (b)



The last two steps are dominated by the Allocator component (c) which assigns the PathPoints to the correct offset layer within the SolidModel. Each PathPoint has a pointer to the reference mesh face which contains it, together with the u,v-coordinates which determine its position. The Allocator component uses this information when it creates a RebarPoint: a temporary offset face within the associated Solid is created on which the RebarPoint is plotted. A Rebar object contains multiple of these RebarPoints, together they form the control points for a smooth line which defines the center of the Rebar.

(c)



PART III **APPLICATION, VALIDATION & CONCLUSIONS**

Coil machine used for bending links, ATG Steel, Raamsdonksveer.

6.0 **Application of the Toolbox**

Figure 6.1
Five test cases: (1) Slab geometry, constant thickness; (2) Slab geometry, varying thickness; (3) Single curvature, constant cross-section; (4) Single curvature, varying cross-section; (5) Double curvature, varying cross-section.

This chapter demonstrates the functionality of the Reinforcement Toolbox by applying it to five test cases each with a distinct geometry. They range from straightforward slab geometry to a complex double curved surface structure. Section 6.1 subsequently describes the five test cases, and Section 6.2 draws conclusions.

6.1 Five Test Cases

The Reinforcement Toolbox sets out to assist users throughout the entire Reinforcement Process. It is intended as a design tool which offers freedom to its users. This includes multiple ways of defining the geometry and reinforcement configurations. The five test cases depicted in Figure 6.1, are used to highlight the distinct features of the Reinforcement Toolbox. This provides for a complete picture of its current functionality. All five test cases can be considered as being patches taken from a larger continuous structure, and not (per se) as being stand-alone structural elements.

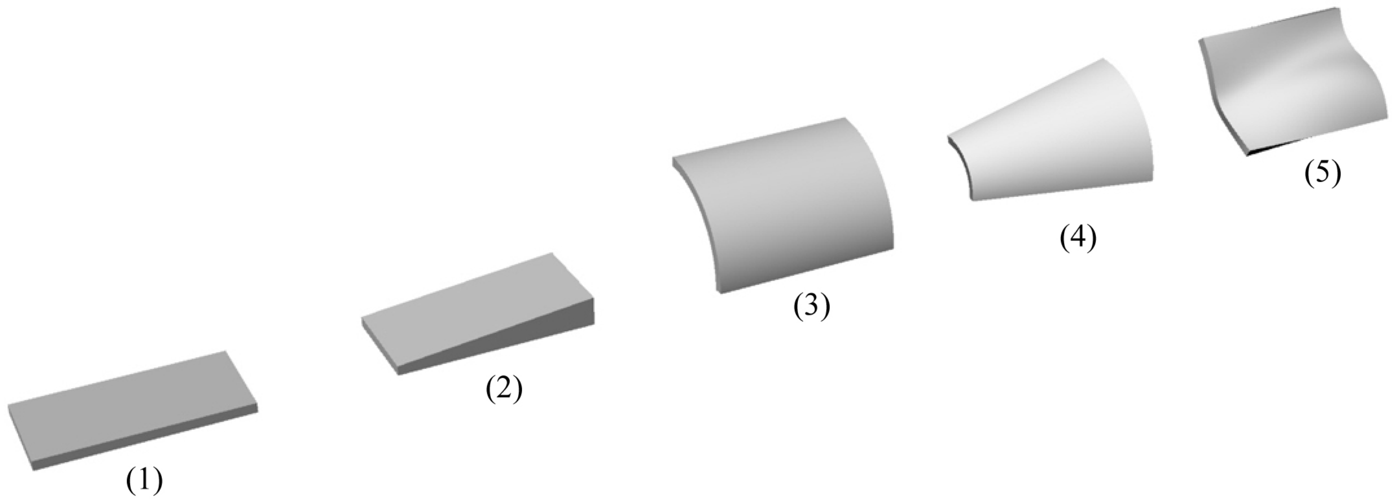


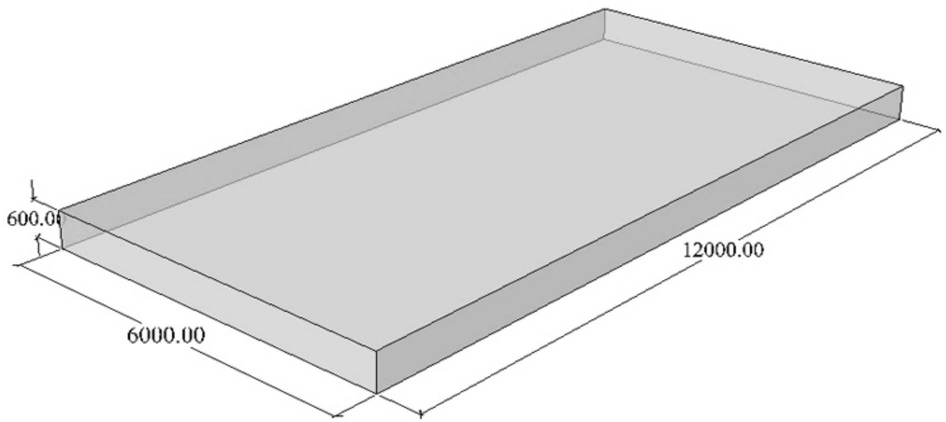
Figure 6.2
Test Case01: Slab geometry with a constant thickness.

Each test case lists the specific features of the toolbox which were addressed to construct the reinforcement model. Test cases (1) and (2) demonstrate that the Reinforcement Toolbox can also be applied on less complex geometry. Case study (1) shows the Toolbox being applied to a slab type with constant thickness. Case study (2) demonstrates the Reinforcement Toolbox ability to deal with structures with a varying thickness. Case studies (3) to (5) represent curved surface structures with increasing complexity. Case study (5) has an irregular double curved geometry which fits one of the main objectives of this thesis: development of a reinforcement design tool for complex curved surface structures.

6.1.1 Test Case01: Slab geometry, constant thickness.

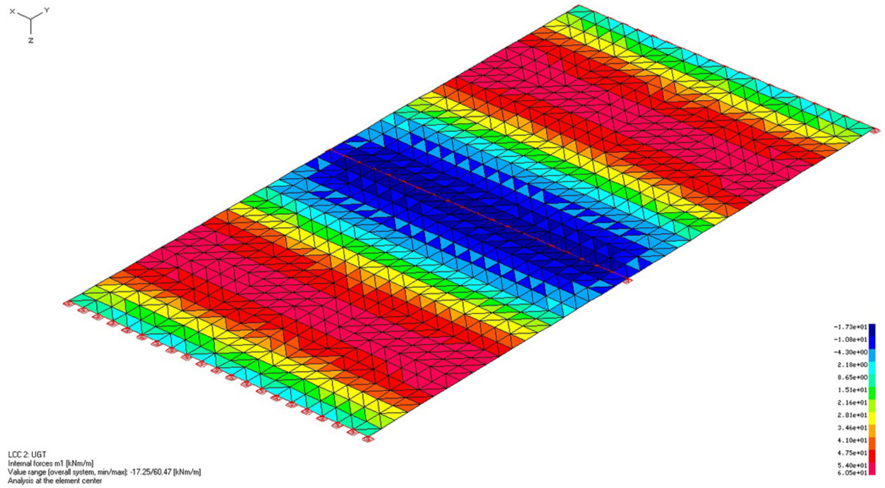
In this test case the Reinforcement Toolbox is applied to a slab type geometry with a constant thickness, see Figure 6.2. A reinforcement model consisting of a top and bottom layer of longitudinal rebars is created. High field moments due to a linear support at midspan constitute grounds for showcasing the possibility of locally adding additional reinforcement to the model. The test case subsequently demonstrates:

- The creation of a SolidModel based on a FEM Analysis model.
- The visualisation of FEM Analysis results from InfoCAD.
- The definition of a reinforcement mesh in a SolidModel.
- The definition of longitudinal reinforcement in a SolidModel.
- The local addition of reinforcement due to high field moments.
- The verification of a reinforcement model in accordance to the Eurocode2



This test case relies on InfoCAD for the initial triangular mesh generation. For the analysis triangular slab elements (PD33) are used. The slab is supported at both ends by hinged line supports (fixed in the z-direction) and at mid-span by a hinged line support (fixed in all directions). Figure 6.3 shows the maximum internal moments in the slab according to a linear elastic analysis performed in InfoCAD for the ULS load case combination (dead load, own weight and live load).

The analysis results including the mesh geometry form the basis for the creation of the SolidModel using the Reinforcement Toolbox. The SolidModel, in accordance with the FEM Analysis model, is created based on a ‘double surface definition’ as described in Section 4.3. Figure 6.4 shows the SolidModel, with analysis results projected on the center mesh.



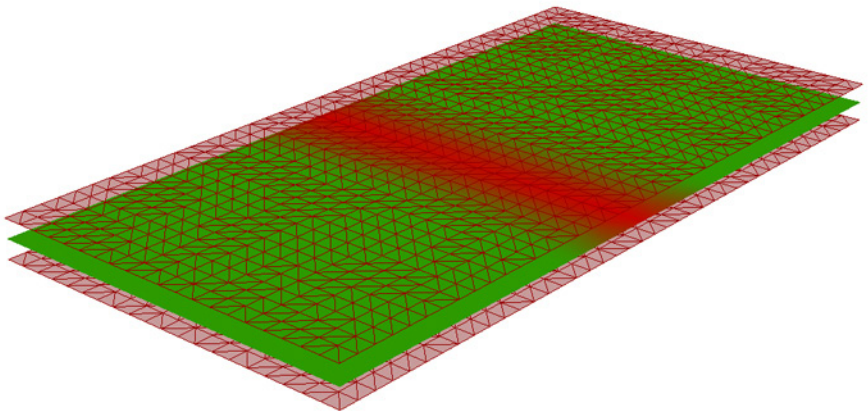
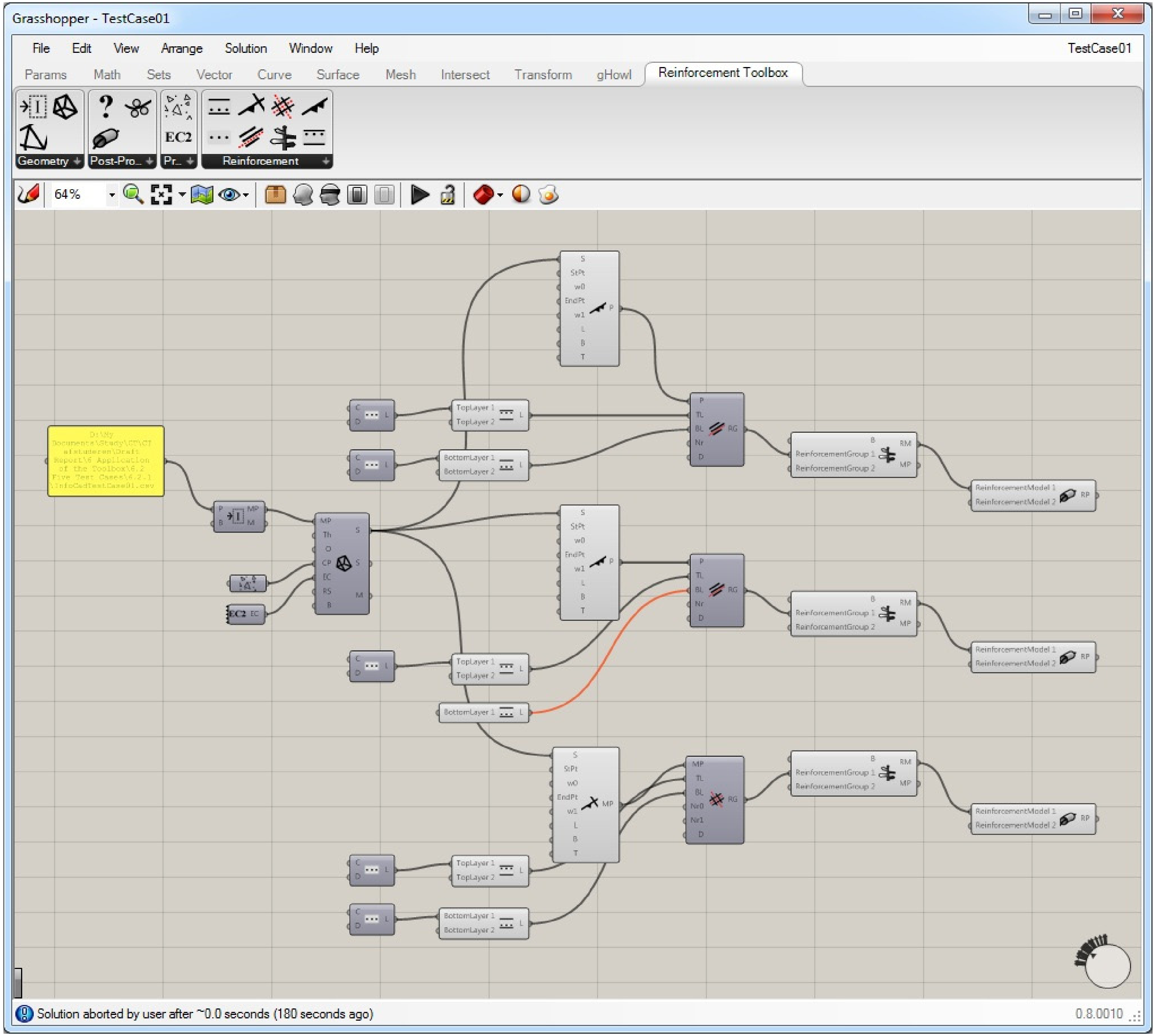


Figure 6.3 (Top)
FEM Analysis results for the slab under the ULS load case combination: visualisation of the maximum principle moments m1 in InfoCAD.

Figure 6.4 (Bottom)
The SolidModel including analysis results projected on the center mesh indicates the necessary amount of reinforcement in the top or bottom layer.

Figure 6.5
The Grasshopper definition belonging to Test Case01.



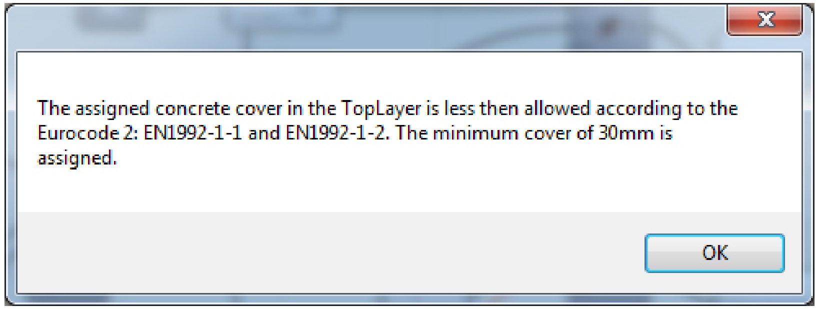


Figure 6.6 (Top)
The Reinforcement Toolbox notifies users when the designed reinforcement model does not comply with the assigned building standard.

Figure 6.7 (Bottom)
The SolidModel belonging to test case01 with the generated reinforcement model.

The Grasshopper definition belonging to the case study is shown in Figure 6.5. Checking reinforcement models against the assigned building standard, in this case the Eurocode2, is part of the functionality of the Reinforcement Toolbox. In case of reinforcement which does not comply with the rules in the building standard the user gets a notification, see Figure 6.6. The created reinforcement model consists of a top and bottom reinforcement mesh complemented with a group of longitudinal reinforcement bars in the top and bottom layer. An extra group of reinforcement bars is assigned to the top layer to take into account the high field moment in the slab, see Figure 6.7. The reinforcement nets have an equal spacing of 150mm, and a diameter of 12mm. The longitudinal reinforcement bars have an equal spacing of 150mm, and a diameter of 16mm.

This test case shows the Reinforcement Toolbox ability to create parametric reinforcement models for structures with straightforward geometry, in this case a slab. It demonstrates the possibility to create reinforcement meshes, and locally add extra reinforcement. Furthermore it demonstrates the interoperability between InfoCAD and the Reinforcement Toolbox, and ability to check reinforcement models for compliance with the building standards.

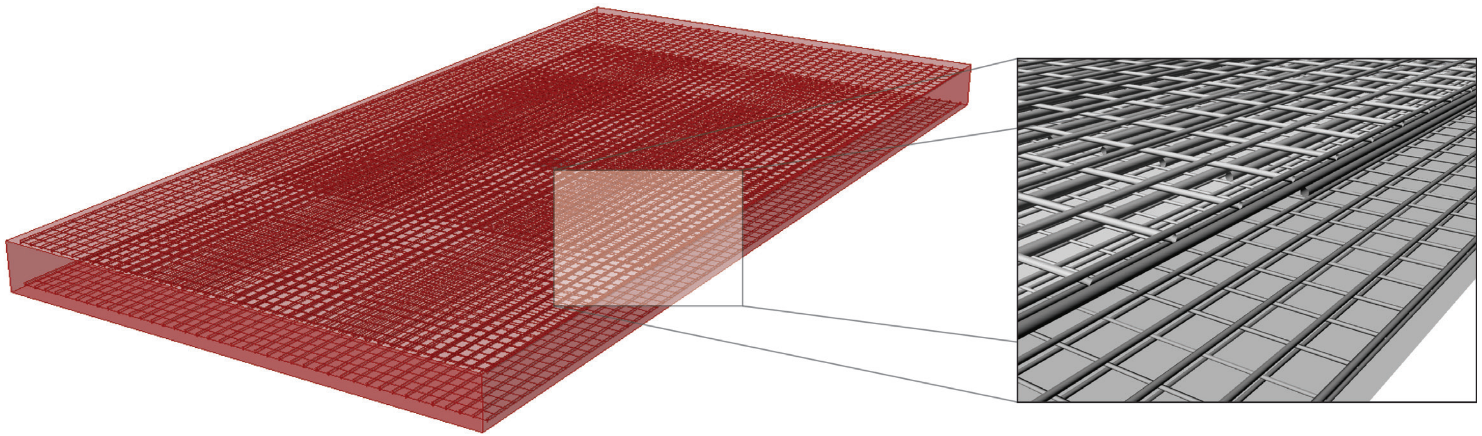


Figure 6.8
Test Case02: Slab geometry with a varying thickness.

6.1.2 Test Case02: Slab geometry, varying thickness.

In this test case the Reinforcement Toolbox is applied to a slab type geometry with a linearily varying thickness, see Figure 6.8. A reinforcement model is created consisting of two top layers and a bottom layer of longitudinal rebars. The test case subsequently demonstrates:

- The creation of a SolidModel based on the ‘double reference surface’ offset option.
- The definition of a center mesh based on the SolidModel.
- The definition of longitudinal reinforcement in a SolidModel with a variable thickness distribution.

The Grasshopper definition belonging to the case study is shown in Figure 6.9. The initial triangular mesh, used as a basis for the SolidModel, is created using Rhinoceros3D. The SolidModel is created based on a ‘double surface definition’. One of the additional functionalities of the SolidModel is the possibility to create accurate center meshes. This can for instance be used for FEM Analysis models which require the center meshes of a volume for the definition of their finite elements. Figure 6.10 shows the center meshes created for this test case; the triangular mesh elements define the center of the SolidModel.

In this test case a group of longitudinal reinforcement bars divided in two top layers and a bottom layer is generated, see Figure 6.11. The reinforcement bars have an equal spacing of 150mm, and diameters of 25mm – 16mm – 16mm (top to bottom). The reinforcement bars follow the planar geometry, which results in straight reinforcement bars. The test case shows the Reinforcement Toolbox ability to create SolidModels for structures of varying thickness. It demonstrates the possibility to create center meshes based on the SolidModel, and shows the possibility to generate parametric reinforcement models.

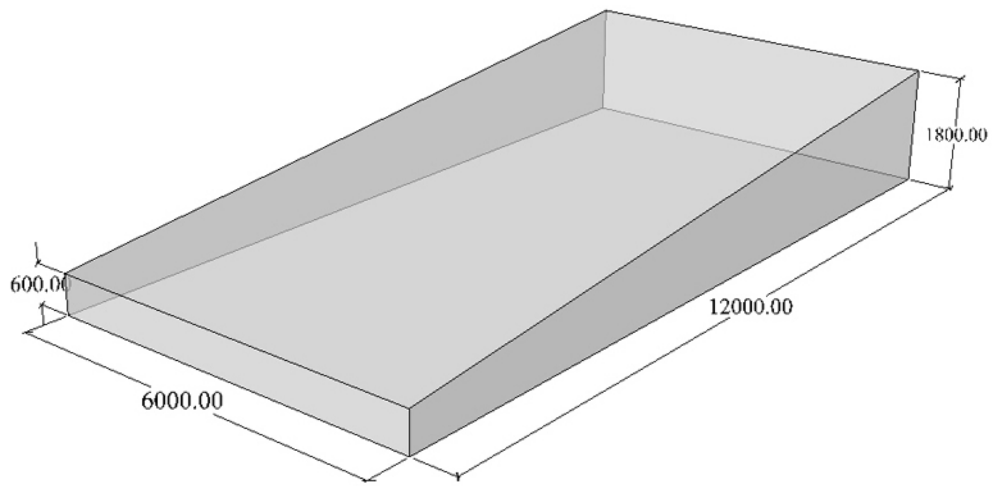


Figure 6.9
The Grasshopper definition belonging to Test Case02.

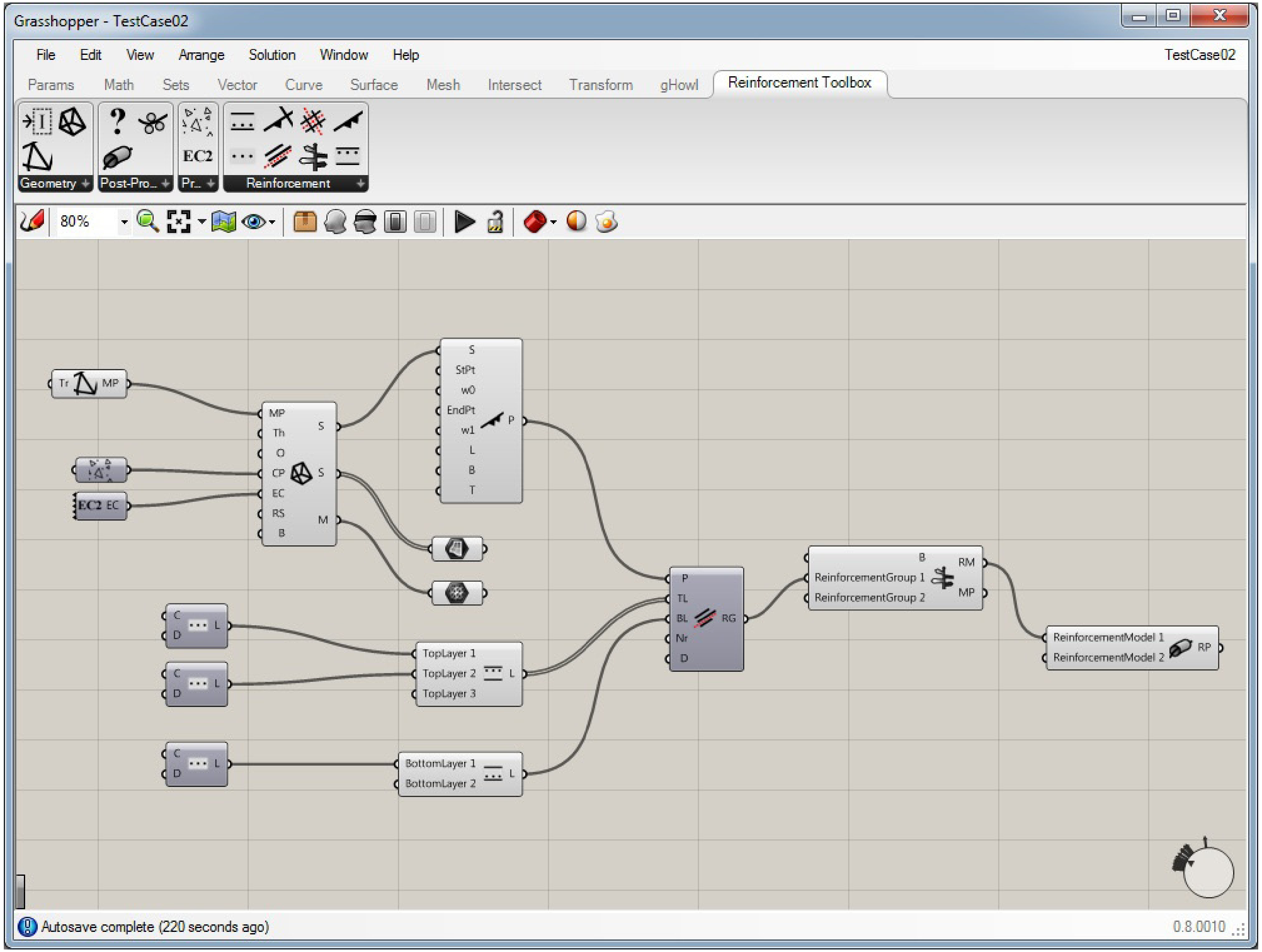
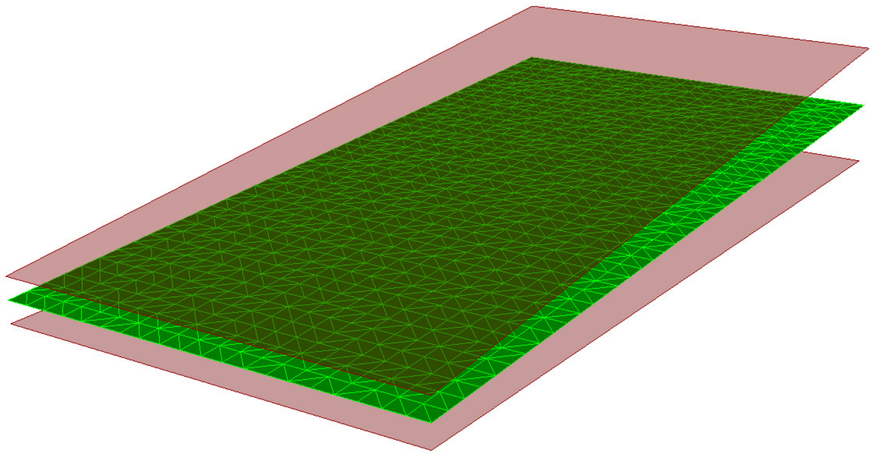
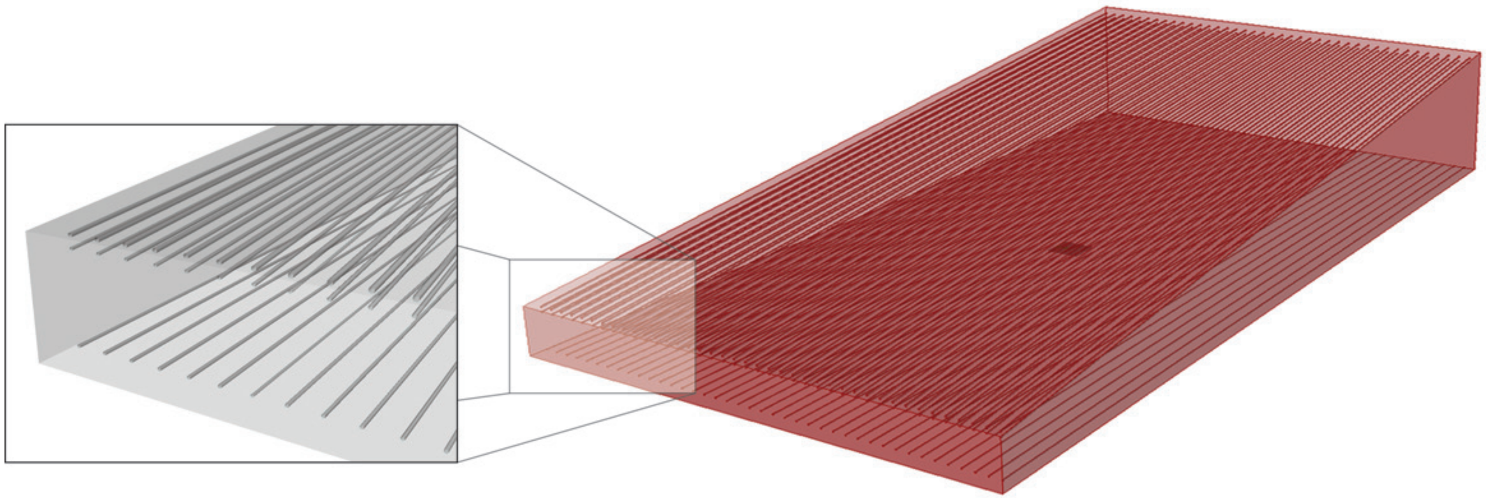


Figure 6.10 (Top)
The SolidModel belonging to Test Case02 including the center meshes (in green).

Figure 6.11 (Bottom)
The SolidModel belonging to test case02 with the generated reinforcement model.





6.1.3 Test Case03: Single curvature, constant cross-section

In this test case the Reinforcement Toolbox is applied to a shell type geometry with a constant cross-section and constant curvature, see Figure 6.12. A reinforcement model consisting of a top and bottom reinforcement mesh is created. The test case subsequently demonstrates:

- The creation of a SolidModel based on a single surface definition.
- The definition of a parametric reinforcement model with curved reinforcement bars.

The Grasshopper definition belonging to the case study is shown in Figure 6.13. The initial triangular reference mesh, used as a basis for the SolidModel, is created in Rhinoceros3D. The SolidModel is created based on a one-directional offset relative to this reference mesh. Figure 6.14 shows the resulting SolidModel, including the reference meshes.

In this test case a top and bottom reinforcement mesh is generated, see Figure 6.15. The reinforcement mesh has a spacing of 150mm, with a bar diameter of 16mm. The reinforcement bars follow the curvature of the structure. The test case demonstrates the Reinforcement Toolbox ability to create a SolidModel for single curved structures. It demonstrates the possibility to create reinforcement meshes based on the SolidModel.

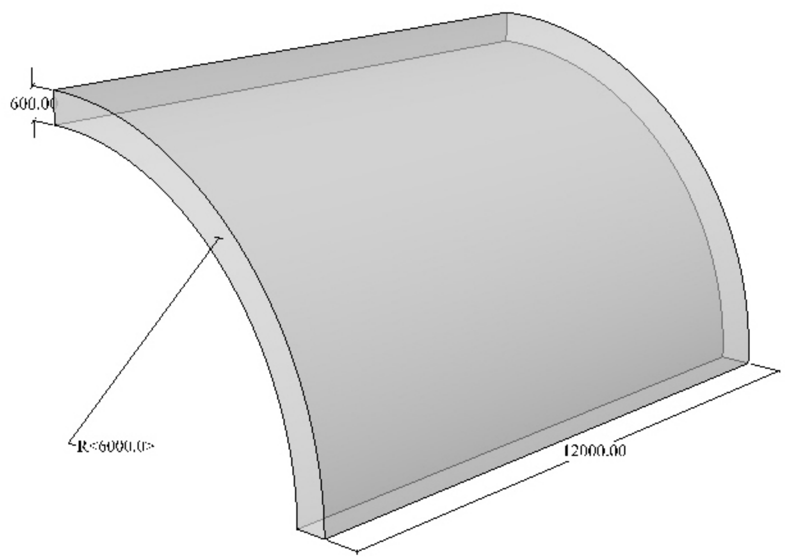
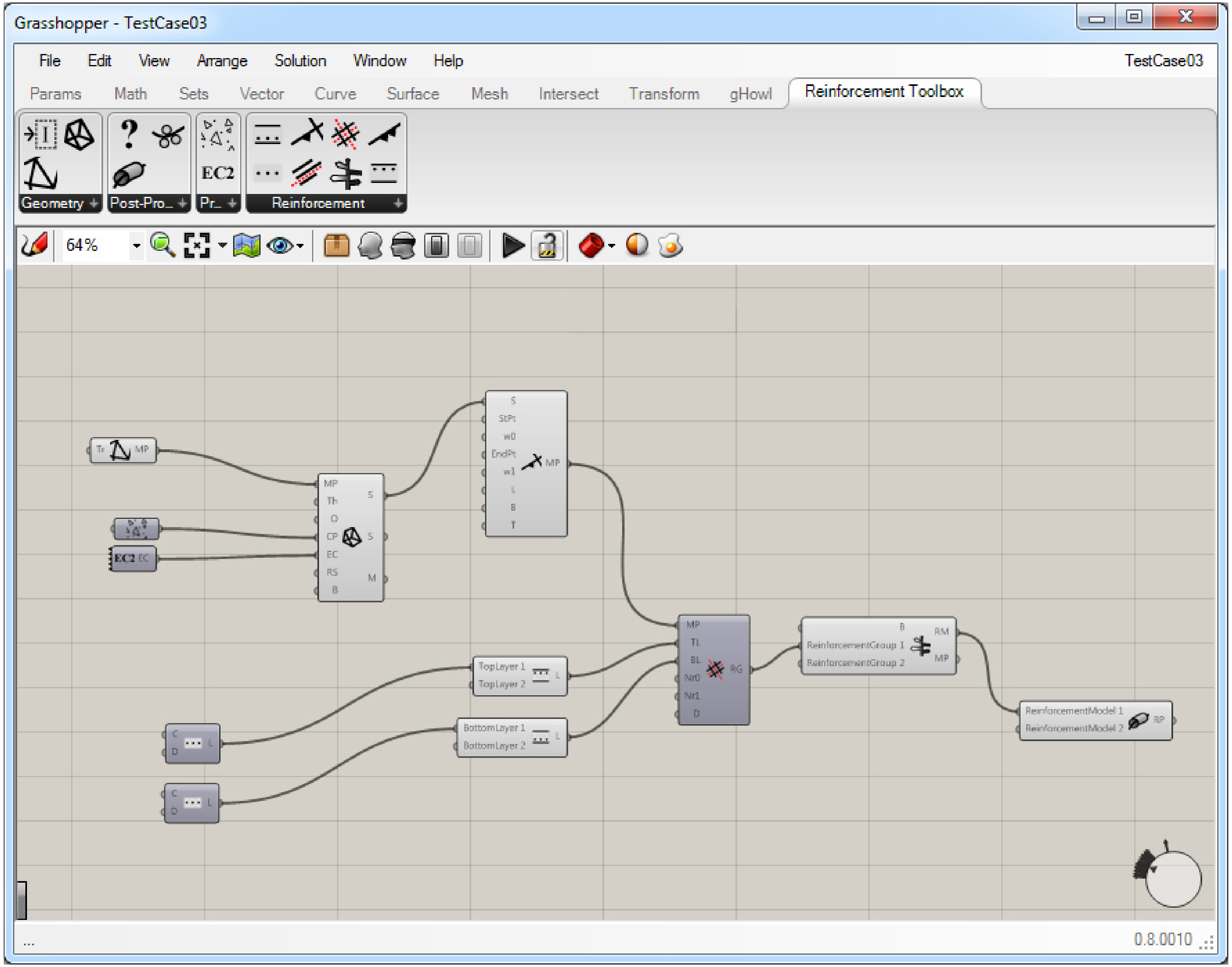


Figure 6.12
Test Case03: Shell geometry with a single curvature.

Figure 6.13
The Grasshopper definition belonging to Test Case03.



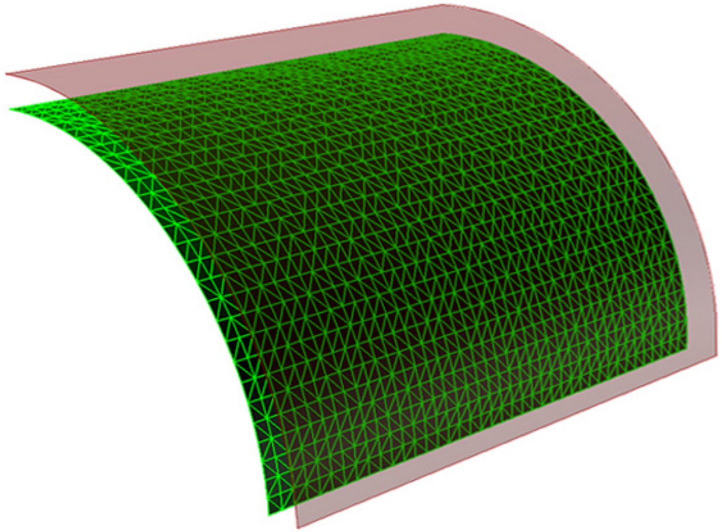
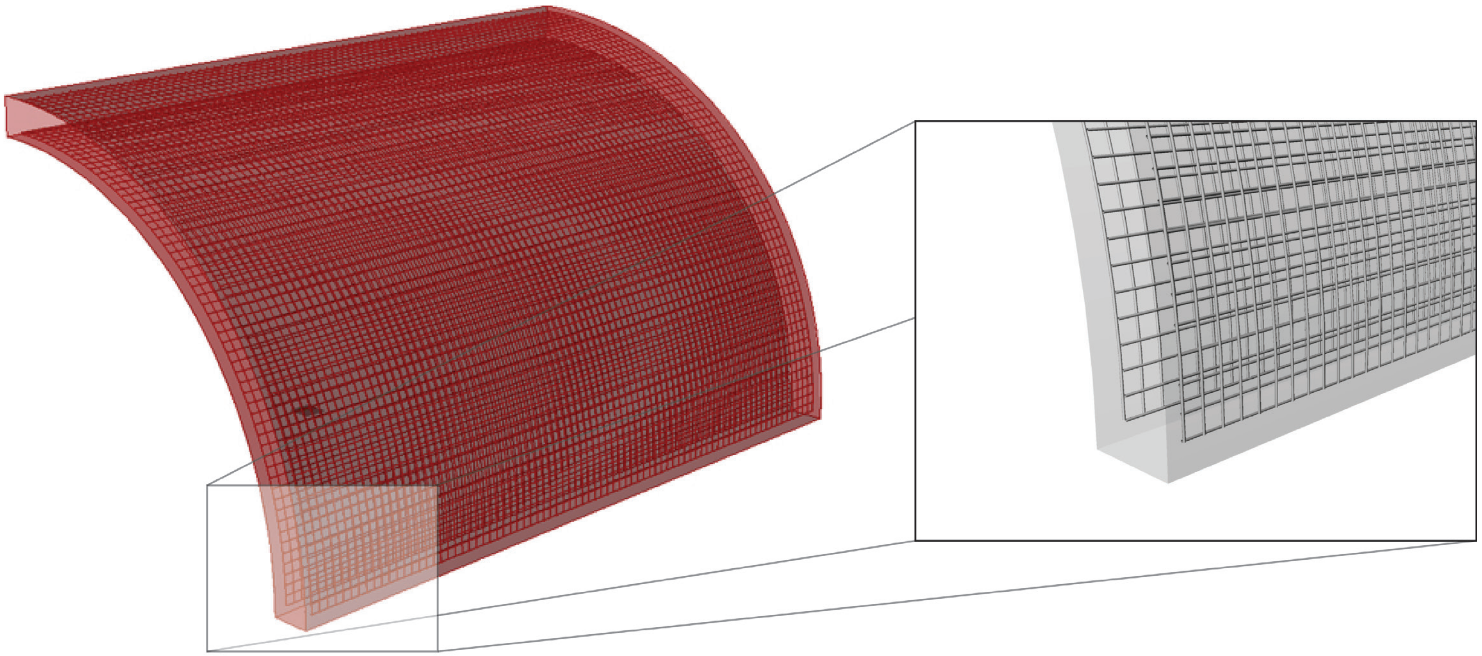


Figure 6.14 (Top)
The SolidModel belonging to Test Case03 including the reference meshes (in green).

Figure 6.15 (Bottom)
The SolidModel belonging to Test Case03 with the generated reinforcement model.



6.1.4 Test Case04: Single curvature, varying cross-section

In this test case the Reinforcement Toolbox is applied to a shell type geometry with a variable cross-section and single curvature, see Figure 16. A reinforcement model with longitudinal reinforcement bars in the transverse direction is created. An extra group of reinforcement placed in an arbitrary direction illustrates the freedom offered to designers using the Toolbox. The test case subsequently demonstrates:

- The creation of a ‘tapered’ group of longitudinal reinforcement bars.
- The creation of a reinforcement group along an arbitrarily placed path on the SolidModel.
- The difference between placing reinforcement bars relative to the global x,y-plane versus placing them relative to the averaged start- and endplane.

The Grasshopper definition belonging to the case study is shown in Figure 6.17. Isolated reinforcement paths can be used to account for existing stress paths or to influence the stress trajectories in the curved surface structure. They can be placed arbitrarily within the SolidModel, see Figure 6.18. Each reinforcement path offers the possibility to define reinforcement bars either relative to the global x,y-plane versus placing them relative to the averaged start- and end plane. Figure 6.19 shows the difference between the two configurations.

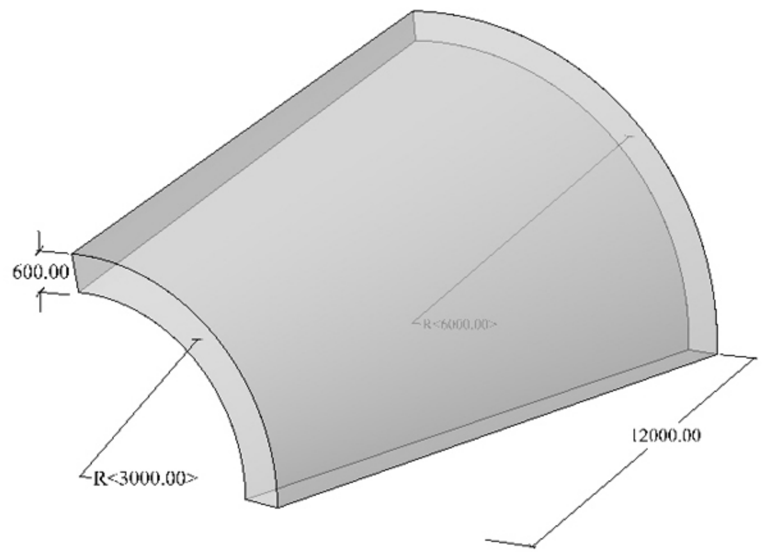


Figure 6.16
Test Case04: Shell geometry with a single curvature and varying cross-section.

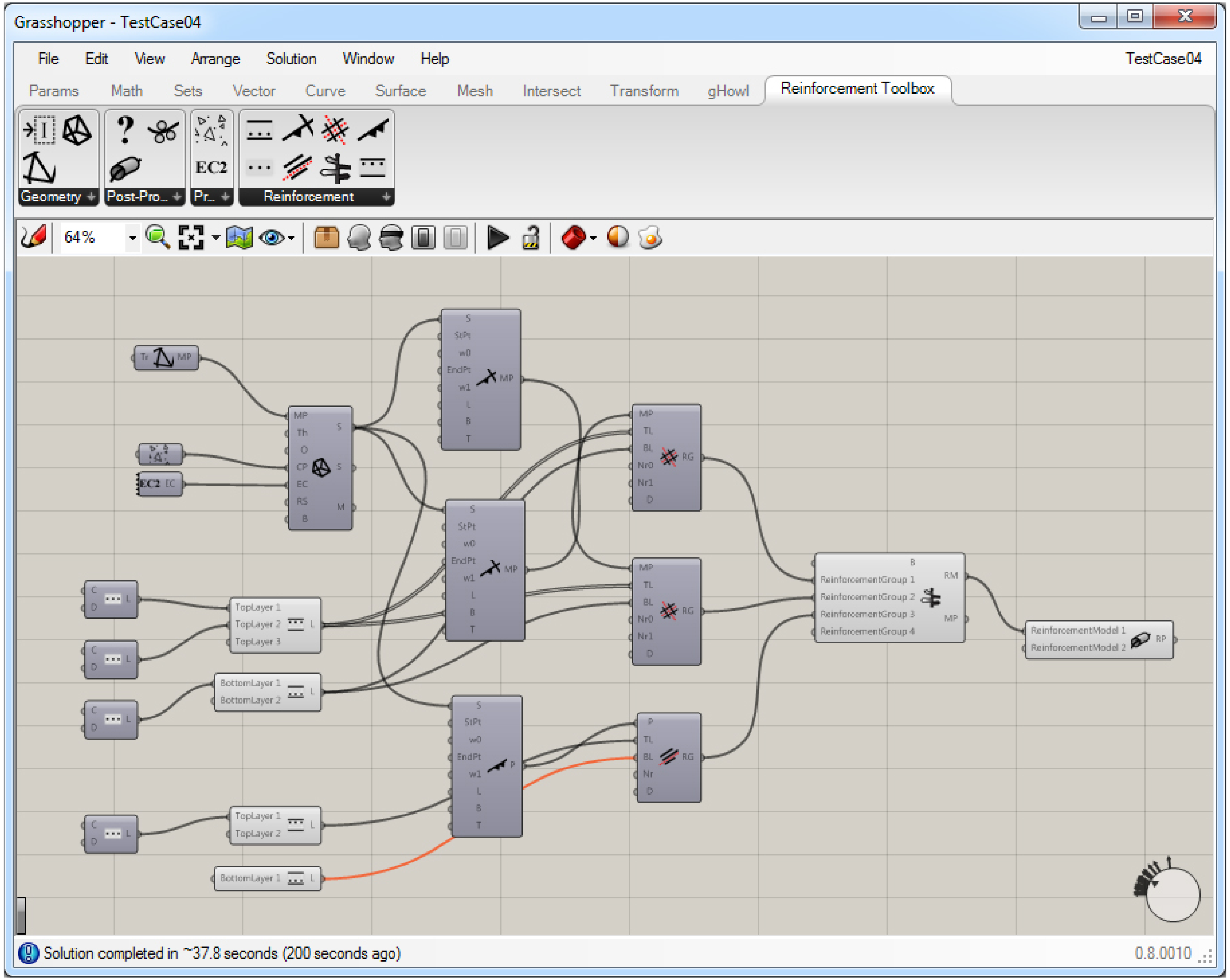
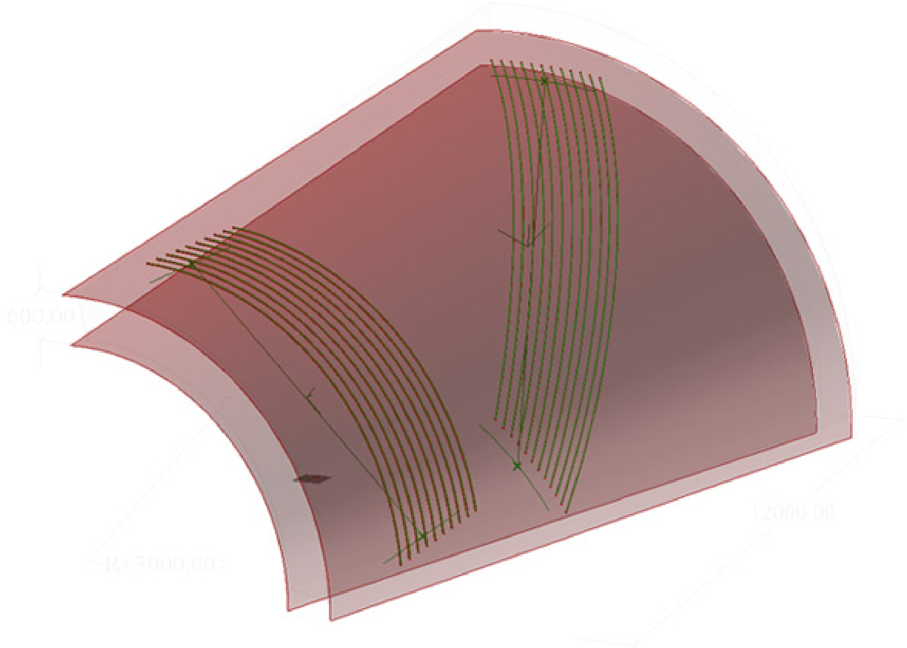
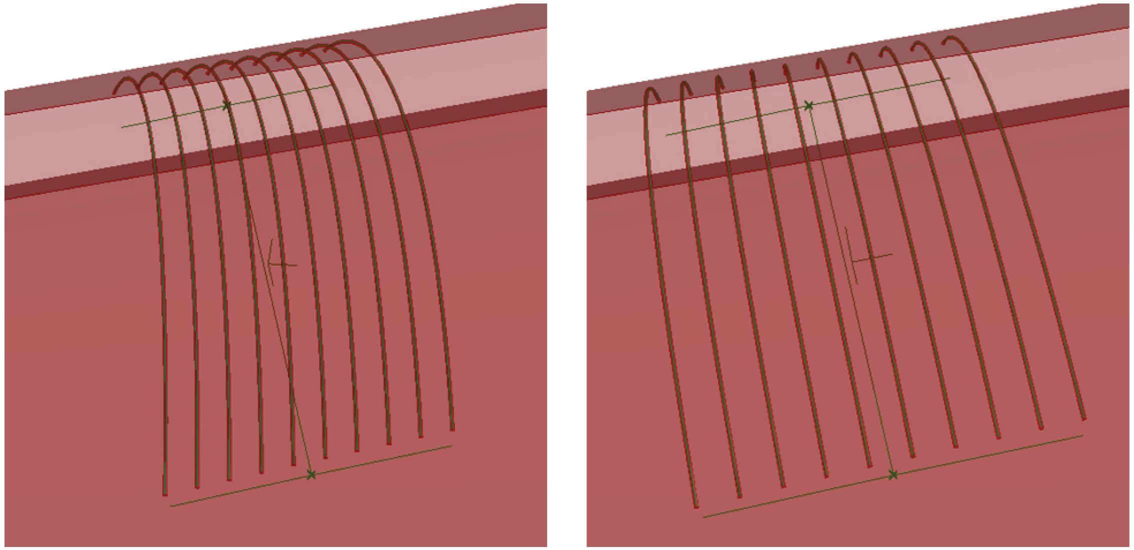


Figure 6.17
The Grasshopper definition belonging to TestCase04.

Figure 6.18 (Top)
The SolidModel belonging to Test Case04 with two arbitrarily placed groups of reinforcement bars.

Figure 6.19 (Bottom)
Two reinforcement group configurations relative to the global x,y-plane (left) and relative to the averaged start- and end plane (right).





In this test case a ‘tapered’ group of longitudinal reinforcement bars is combined with two arbitrarily placed groups of reinforcement bars. It demonstrates the Reinforcement Toolbox ability to generate complex parametric reinforcement models which contains multiple reinforcement groups. Figure 6.20 shows a detail of the reinforcement model in which multiple reinforcement groups with different directions and spacing come together.

Figure 6.20
The SolidModel belonging to Test Case04 with the generated reinforcement model.

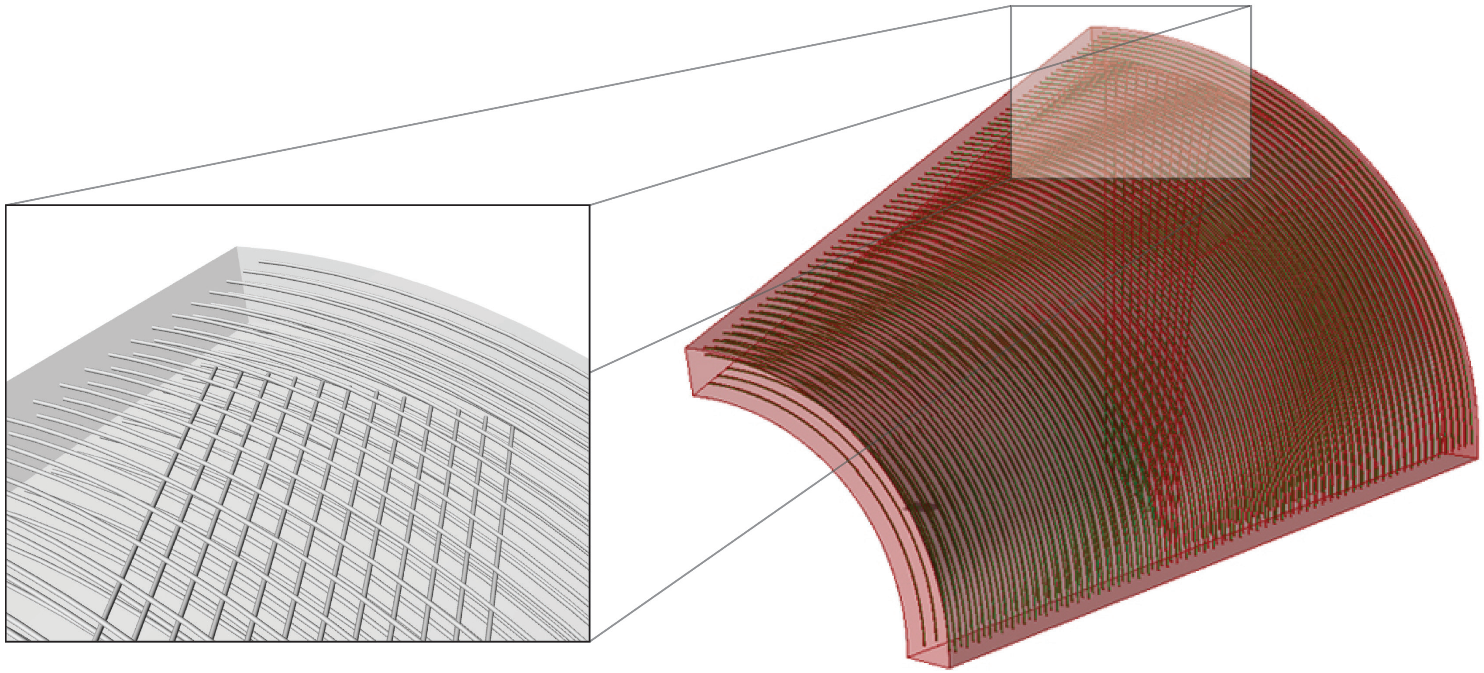


Figure 6.21
Test Case05: Curved surface geometry with a double curvature and varying cross-section.

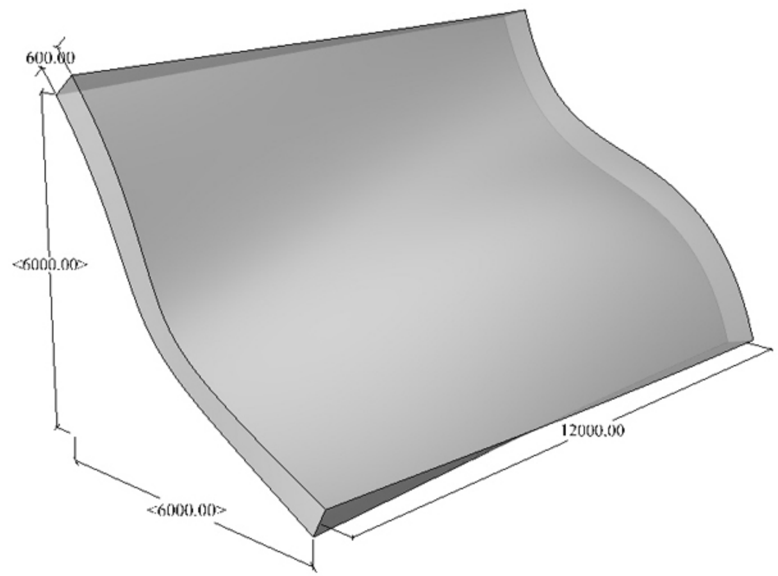
6.1.5 Test Case05: Double curvature, varying cross-section

In this test case the Reinforcement Toolbox is applied to a curved surface geometry with a variable cross-section and double curvature, see Figure 21. A reinforcement model with a top and bottom reinforcement mesh is created. Extra reinforcement groups are placed according the principle stress directions. The test case subsequently demonstrates:

- The creation of reinforcement bars in a double curved geometry.
- The visualisation of principle stress directions.
- The feedback of reinforcement quantities.

The Grasshopper definition belonging to the case study is shown in Figure 6.22. The initial triangular mesh, used as a basis for the SolidModel, is created in Rhinoceros3D. The SolidModel is created based on a ‘double surface definition’. The center mesh which is extracted from the SolidModel forms the geometrical basis to the FEM Analysis model.

For the analysis triangular shell elements (SH36) are used. The slab is supported at both ends by hinged line supports (fixed in the z-direction). Figure 6.23 shows the required amount of reinforcement in the top layer according to a linear elastic analysis performed in InfoCAD for the ULS load case combination (dead load, own weight and live load).



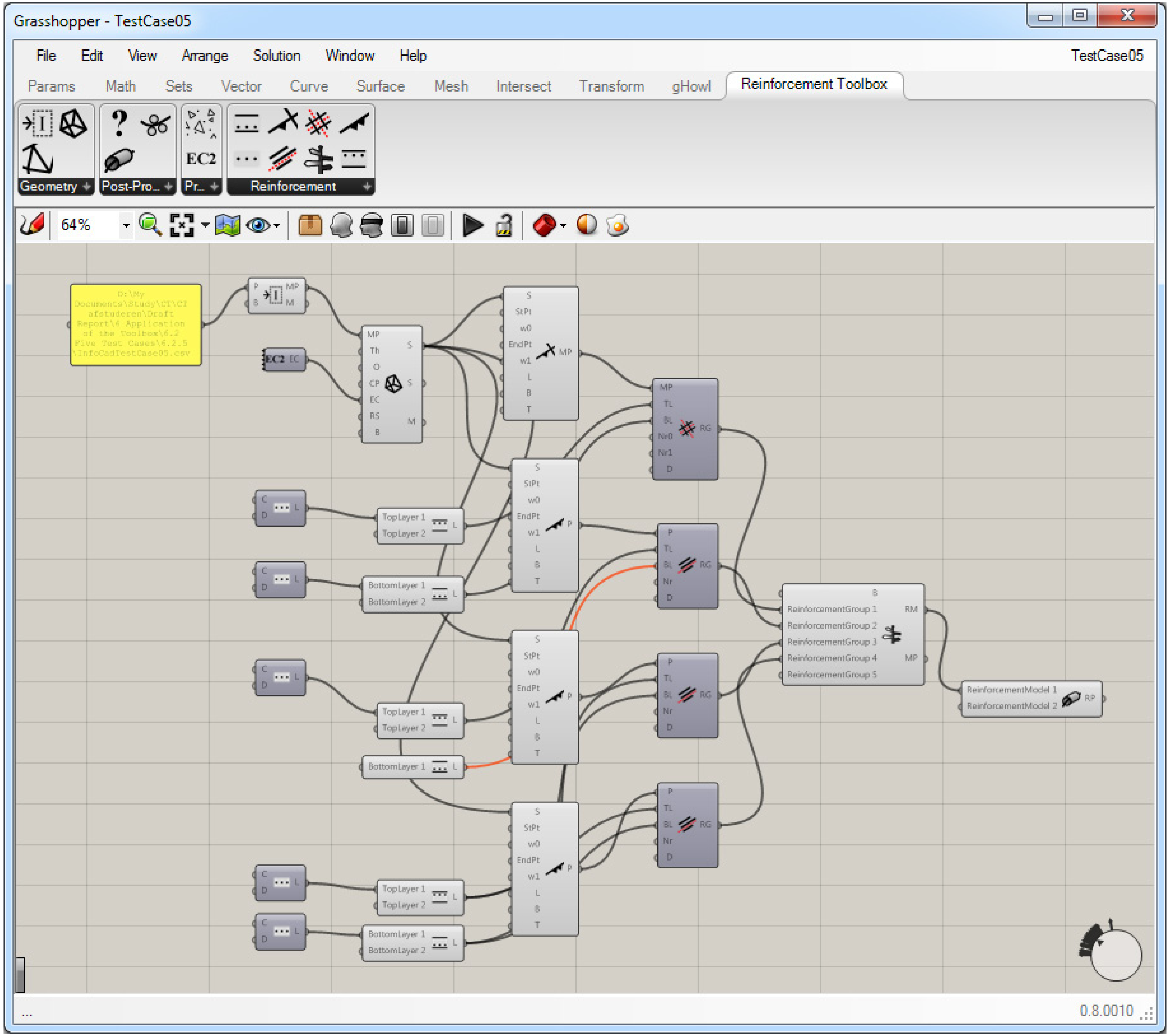
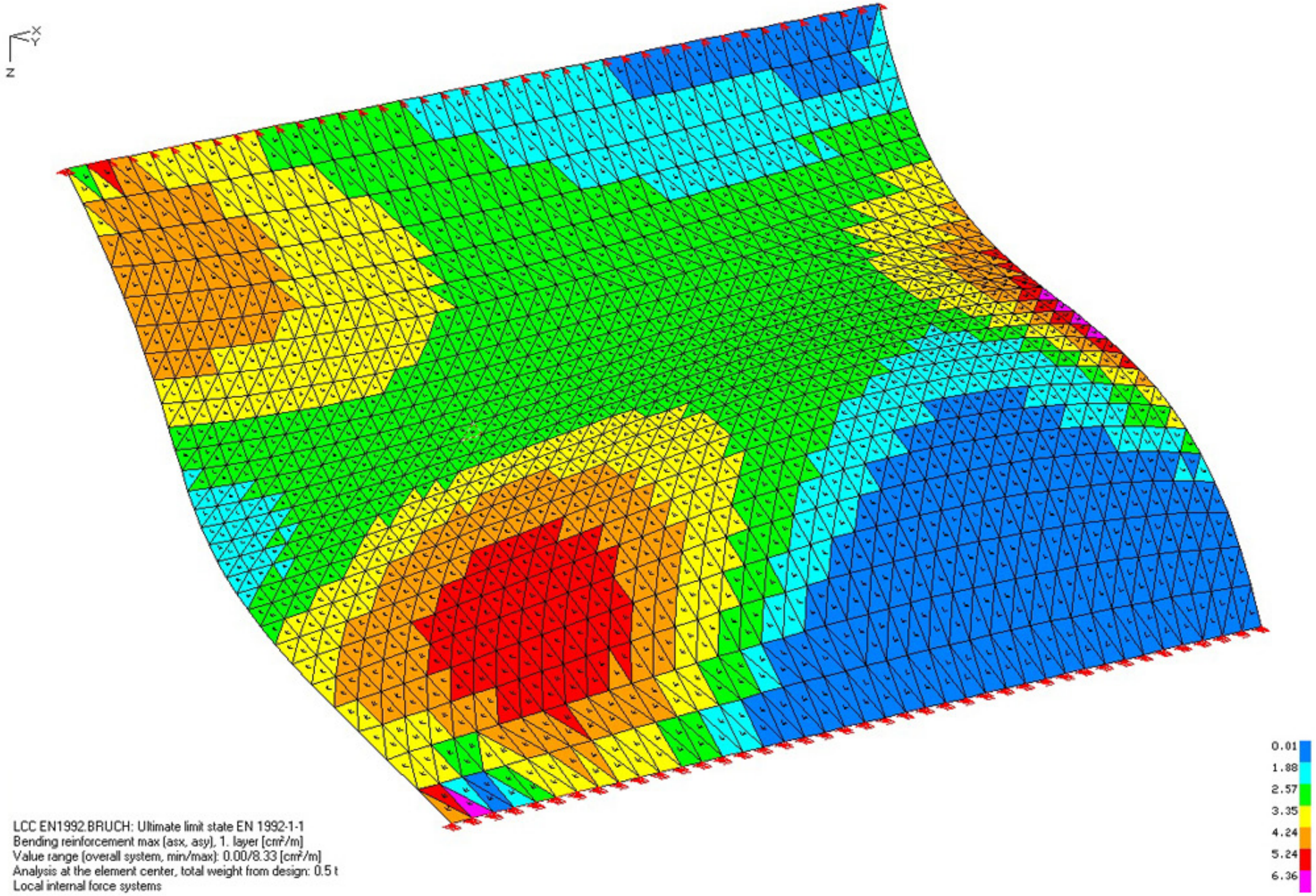


Figure 6.22
The Grasshopper definition belonging to Test Case05.

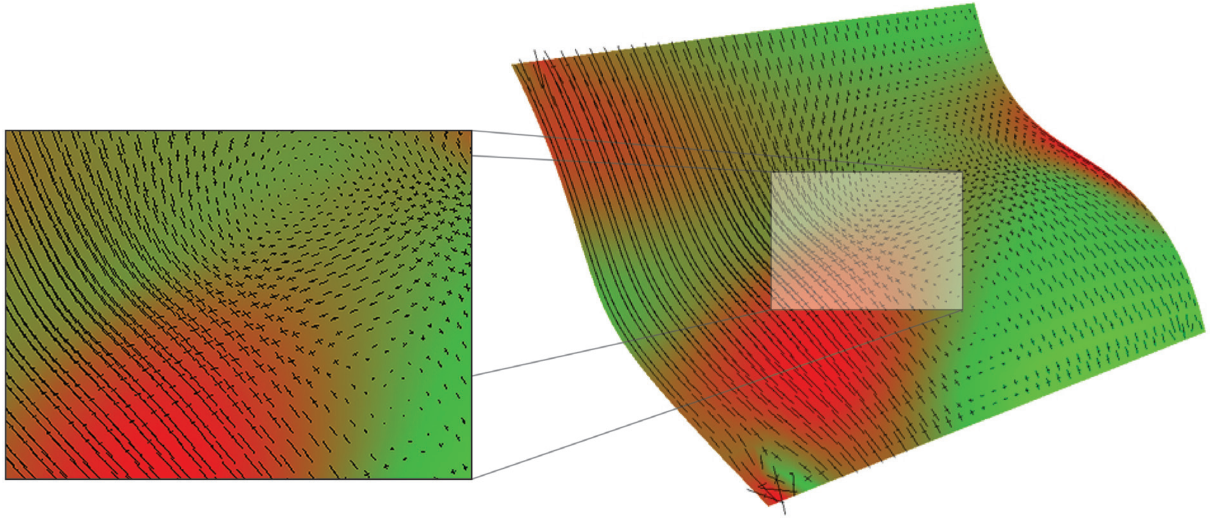
Figure 6.23
The required amount of reinforcement in top layer according to the FEM Analysis performed in InfoCAD.



The results of the FEM Analysis are visualised using the Reinforcement Toolbox, see Figure 6.24. Principle stress trajectories (n1, n2) indicate the flow of forces through the structure. This information, combined with the required amount of reinforcement, assists the user of the Toolbox with the design of reinforcement. The created reinforcement model is compared to the required amount of reinforcement as indicated by InfoCAD, and the results are fed back to the user, see Figure 6.25.

Figure 6.24 (Top)
The Reinforcement Toolbox is used to visualise FEM Analysis results: required amount of reinforcement and principle stresses n1 and n2.

Figure 6.25 (Bottom)
The Reinforcement Toolbox provides feedback on how the modelled reinforcement relates to the required amount as indicated by the FEM Analysis.



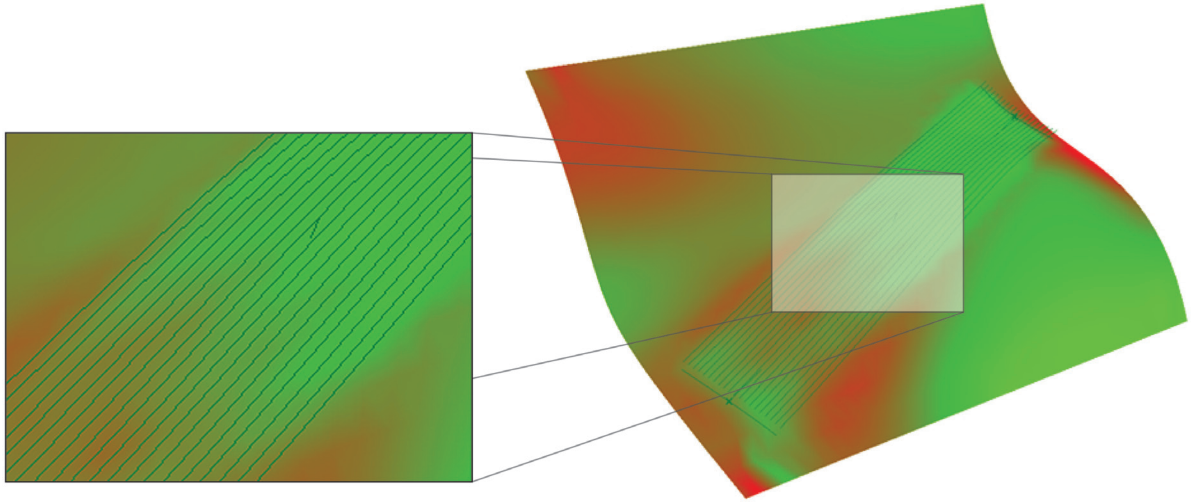
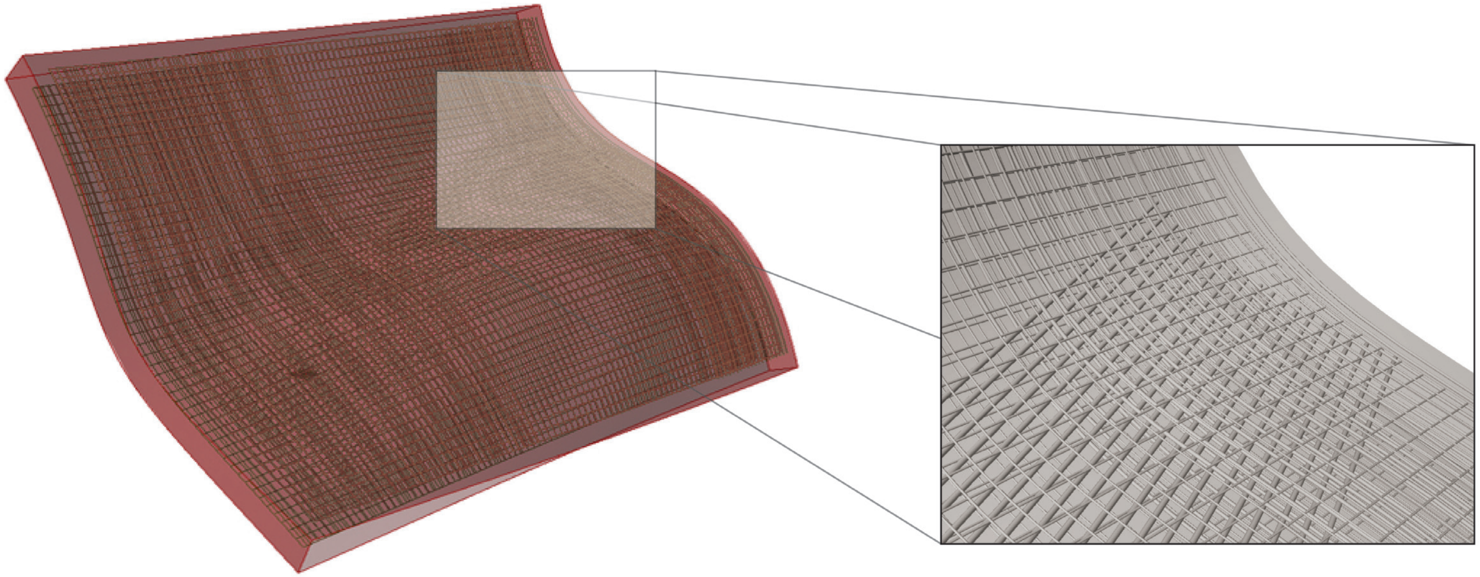


Figure 6.26
The SolidModel belonging to Test Case05 with the generated reinforcement model.

The reinforcement model created consists of a top and bottom reinforcement mesh, see Figure 6.26, together with three groups of longitudinal reinforcement bars. They are placed according to the indicated amount of reinforcement and load paths. This test case demonstrates the Toolbox ability to generate reinforcement for complex curved surface structures.



6.2 Conclusions

The Reinforcement Toolbox has been applied to five different test cases of increasing geometrical complexity. These test cases highlight various aspects of the Reinforcement Toolbox. The concepts described in the second part of this thesis have been developed into a collection of components which together form the Toolbox. By linking these components different configurations can be produced. Each test case has its own specific configuration. This Section concludes on these test cases by summarizing the results.

Several ways of creating a SolidModel have been demonstrated. Depending on the starting points the initial surface rationalization (triangular mesh generation) has been performed within Rhinoceros3D, or InfoCAD. Based on the Input Mesh the three possible approaches for creating a SolidModel (described in Section 4.2) have been demonstrated.

Visualization of FEM Analysis results coming from InfoCAD is demonstrated in Test Case01 and Test Case05. This includes visualization of principle stress directions, and indicated amount of necessary reinforcement. Test Case05 demonstrates the feedback of the generated reinforcement model to the indicated amount of necessary reinforcement.

The definition of reinforcement plays an important part in all five the test cases. They demonstrate the possibility of creating longitudinal reinforcement groups or reinforcement meshes for both curved as well as planar geometry, and address the different methods of positioning reinforcement bars. The Toolbox verifies created reinforcement models in accordance to the assigned building standard; if the reinforcement model doesn't comply the user gets notified.

The five test cases show the versatility of the Reinforcement Toolbox. The fact that it can be applied to both complex as well as non-complex structures makes it a widely applicable design tool. Users can apply the Reinforcement Toolbox at their own discretion within any given stage of the reinforcement process. The parametric reinforcement models are easily adaptable to design changes, which makes them valuable throughout the entire reinforcement process.

Labels used to indicate different Reinforcement groups, ATG Steel, Raamsdonksveer.

7.0 **Discussion**

This Chapter describes the process of application and validation of the Reinforcement Toolbox. Section 7.1 reflects on the research objectives and relates them to the conducted research and development. Section 7.2 describes the validation of two important aspects of the Toolbox: the Mesh Topology and the Reinforcement cover. Section 7.3 points out the current limitations of the Toolbox, and Section 7.4 summarizes the feedback from engineers. Together these Sections provide a picture of the current state of the Reinforcement Toolbox.

7.1 Reflection on Research Objective

The main research objective of this MSc thesis is presented in Section 1.6:

> *'To design a computational strategy which supports the design and production enhancement of reinforcement in curved surface structures taking into account the aspects of geometrical control, structural analysis and production.'*

In order to achieve this objective, research into the reinforcement process of curved surface structures has been conducted. The results are described in Part I of the thesis. Chapter 2 elaborates on the important design aspects of reinforcement in curved surface structures, while Chapter 3 focusses on the process and its stakeholders. This led to the development of the computational strategy for the design and production enhancement of reinforcement in curved surface structures, set out in Chapter 4.

The strategy responds to a number of problems identified in the reinforcement process, such as the use of fragmented design tools and the inability of current reinforcement design tools to deal with complex curved surfaces. Corresponding to the distinguished design aspects, three concepts have been developed: the SolidModel, FEM Analysis visualisation and Rebar DNA. They form the building blocks of the computational strategy which supports the design and production enhancement of reinforcement in curved surface structures. The second objective of this MSc thesis is:

> *'To develop a toolbox which enables structural engineers to model reinforcement for concrete curved surface structures, in a virtual 3D environment.'*

A first version of the Reinforcement Toolbox has been developed. The design of this Toolbox is closely related to the computational strategy, and its associated concepts. It offers structural engineers and other professionals involved in the reinforcement process the possibility to create reinforcement configurations for curved surface structures. Users are free to employ the Toolbox in various stages of the reinforcement process, either to quickly research different reinforcement design alternatives, or use it to build extensive reinforcement models.

7.2 Validation of Results

The mechanism behind the Reinforcement Toolbox consists of a large collection of algorithms which can be invoked in different order. Each algorithm can be regarded as a link in the overall system, whose strength is determined by its weakest link. In order to determine and monitor the strength of the system it is important to validate results.

The process of professional software validation is an extensive process, in some cases even ahead of actual development (Test-Driven Development). The importance of identifying bugs in an early development stage is evident as it saves considerable time and money fixing them compared to later stages (Jones, 2008). It is beyond the scope of this thesis to do extensive unit testing. However during the development process of the Reinforcement Toolbox testing has been applied in various forms by using interactive debuggers, running the application to check its consistency, and creating output files.

> *'Unit tests tell a developer that the code is doing things right; functional tests tell a developer that the code is doing the right things.'* (Canna, 2001)

In order to verify that the Reinforcement Toolbox is doing the right things, it has been tested on two crucial aspects, being the definition of the MeshTopology, which forms the basis of the SolidModel, and the assigned concrete cover which is important for a proper reinforcement definition. More extensive testing of results is desirable and will be recommended in Chapter 8, Conclusions & Recommendations.

7.2.1 MeshTopology Validation

The MeshTopology is the topological structure which lies at the basis of any SolidModel. It establishes the relations between triangular mesh elements in a unified manner so that different meshes can serve as input to the SolidModel. For a further elaboration on its function and structure, refer to Section 4.2. This section elaborates on the mechanism behind the MeshTopology component and discusses its validation.

The MeshTopology component requires users to assign an arbitrary number of triangular mesh elements. These elements are collected in a list which forms the input of the MeshTopology algorithm, see Figure 7.1. Precondition to successful creation of the MeshTopology is that the collected mesh elements are part of a continuous unbroken mesh.

Figure 7.1
The MeshTopology algorithm in pseudo code.

```
public CreateMeshTopology(List<Face> faces)
{
        foreach (face in faces)
        {
                if (the face is not in the List of Faces)
                {
                        Faces.Add(face);

                        //Add the unique Vertices of the face to the List of Vertices
                        foreach (Vertice vertice in face.Vertices)
                        {
                                if (the vertice is not in the List of Vertices)
                                {
                                        vertice.AddAdjacentFace(face);

                                        Vertices.Add(vertice);
                                }
                                else
                                {
                                        Vertices[indexNr].AddAdjacentFace(face);
                                }
                        }

                        //Add the unique Edges of the face to the List of Edges
                        foreach (Edge edge in face.Edges)
                        {
                                if (the edge is not in the List of Edges)
                                {
                                        edge.AddAdjacentFace(face);

                                        Vertices[indexNrStart].AddAdjacentEdge(edge);

                                        Vertices[indexNrEnd].AddAdjacentEdge(edge);

                                        Edges.Add(edge);
                                else
                                {
                                        Edges[indexNr].AddAdjacentFace(face);
                                }
                        }
                }
        }

        //Unify the orientation of all Faces contained in the MeshTopology
        UnifyOrientation();

        //Create the Face normals
        SetFaceNormals();

        //Create the Vertice vectors
        SetVerticeVectors();
}
```

Important aspect of the validation is that it accounts for the random behaviour of users. This random behaviour is simulated using a custom created Grasshopper definition, see Figure 7.2, which randomly selects triangles, each with a random orientation, and adds them to a list. This validation tests whether the orientation or the order in which triangles are supplied affects the validity of the MeshTopology.

Starting point is a 3x3 triangle mesh which, due to the limited amount of elements is fairly easy to verify manually. The resulting output of the MeshTopology component is exported to Excel, using a custom developed ‘MeshTopologyValidation’ component see typical output in Figure 7.3, and checked manually for consistency in terms of element numbering and relations. The direction of the mesh elements is checked in Rhinoceros3D using the ‘Dir’ command which displays the direction of the elements, see Figure 7.4. This method has been applied to twenty randomly generated MeshTopologies, and revealed no inconsistencies. Considering this result it is save to conclude that the MeshTopology component produces a consistent output independent from the order of entering mesh faces, or their individual orientations.

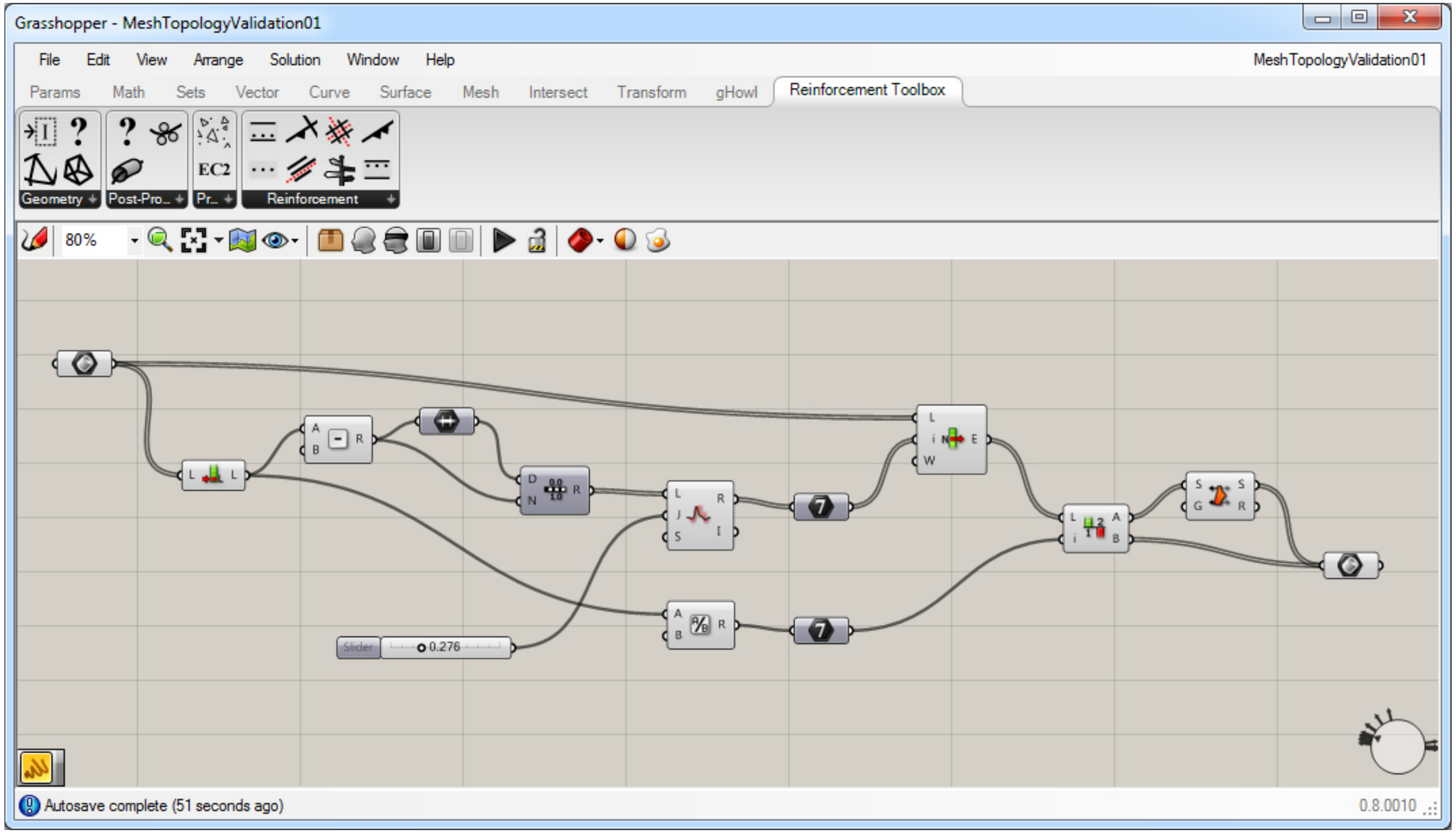
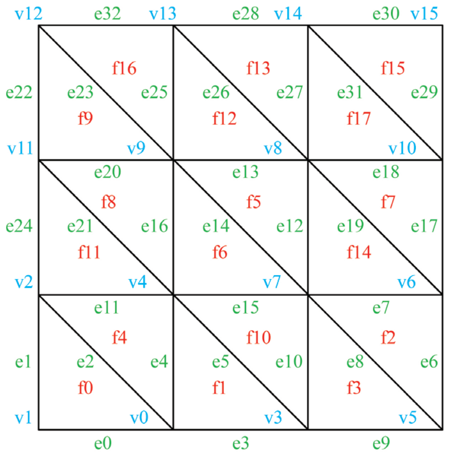


Figure 7.2
Grasshopper definition which randomly shuffles a list of triangles with random orientations.



	X	Y	Z		
v0	150	-450	0	f0, f1, f4	e0, e2, e3, e4
v1	450	-450	0	f0	e0, e1
v2	450	-150	0	f0, f4, f11	e1, e2, e11, e24
v3	-150	-450	0	f1, f3, f10	e3, e5, e9, e10
v4	150	-150	0	f1, f4, f6, f8, f10, f11	e4, e5, e11, e15, e16, e21
v5	-450	-450	0	f2, f3	e6, e8, e9
v6	-450	-150	0	f2, f7, f14	e6, e7, e17, e19
v7	-150	-150	0	f2, f3, f5, f6, f10, f14	e7, e8, e10, e12, e14, e15
v8	-150	150	0	f5, f7, f12, f13, f14, f17	e12, e13, e18, e19, e26, e27
v9	150	150	0	f5, f6, f8, f9, f12, f16	e13, e14, e16, e20, e23, e25
v10	-450	150	0	f7, f15, f17	e17, e18, e29, e31
v11	450	150	0	f8, f9, f11	e20, e21, e22, e24
v12	450	450	0	f9, f16	e22, e23, e32
v13	150	450	0	f12, f13, f16	e25, e26, e28, e32
v14	-150	450	0	f13, f15, f17	e27, e28, e30, e31
v15	-450	450	0	f15	e29, e30

e0	v0, v1	f0
e1	v1, v2	f0
e2	v2, v0	f0, f4
e3	v3, v0	f1
e4	v0, v4	f1, f4
e5	v4, v3	f1, f10
e6	v6, v5	f2
e7	v7, v6	f2, f14
e8	v5, v7	f2, f3
e9	v5, v3	f3
e10	v3, v7	f3, f10
e11	v2, v4	f4, f11
e12	v8, v7	f5, f14
e13	v9, v8	f5, f12
e14	v7, v9	f5, f6
e15	v7, v4	f6, f10
e16	v4, v9	f6, f8
e17	v10, v6	f7
e18	v8, v10	f7, f17
e19	v6, v8	f7, f14
e20	v11, v9	f8, f9
e21	v4, v11	f8, f11
e22	v11, v12	f9
e23	v12, v9	f9, f16
e24	v2, v11	f11
e25	v9, v13	f12, f16
e26	v13, v8	f12, f13
e27	v14, v8	f13, f17
e28	v13, v14	f13
e29	v15, v10	f15
e30	v14, v15	f15
e31	v10, v14	f15, f17
e32	v12, v13	f16

f0	e0, e1, e2	v0, v1, v2
f1	e3, e4, e5	v3, v0, v4
f2	e7, e6, e8	v7, v6, v5
f3	e9, e10, e8	v5, v3, v7
f4	e11, e4, e2	v2, v4, v0
f5	e13, e12, e14	v9, v8, v7
f6	e15, e16, e14	v7, v4, v9
f7	e18, e17, e19	v8, v10, v6
f8	e20 e16, e21	v11, v9, v4
f9	e20, e22, e23	v9, v11, v12
f10	e15, e10, e5	v4, v7, v3
f11	e11, e24, e21	v4, v2, v11
f12	e13, e25, e26	v8, v9, v13
f13	e28, e27, e26	v13, v14, v8
f14	e7, e12, e19	v6, v7, v8
f15	e30, e29, e31	v14, v15, v10
f16	e32, e25, e23	v12, v13, v9
f17	e18, e27, e31	v10, v8, v14

Figure 7.3 (Top)
Typical output of MeshValidationComponent: vertices, edges and faces and their interrelations.

Figure 7.4 (Bottom)
The 'Dir' command in Rhinoceros3D displays the direction of the mesh elements.

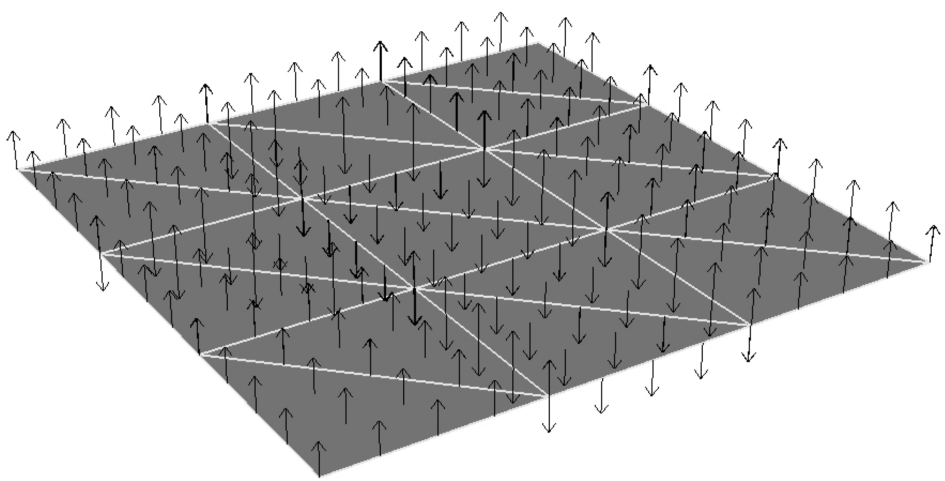


Figure 7.5
The reinforcement model used for cover validation: Ten longitudinal reinforcement bars. The detail shows the Reinforcement curves and reference points of which the distance to the bounding surface is measured.

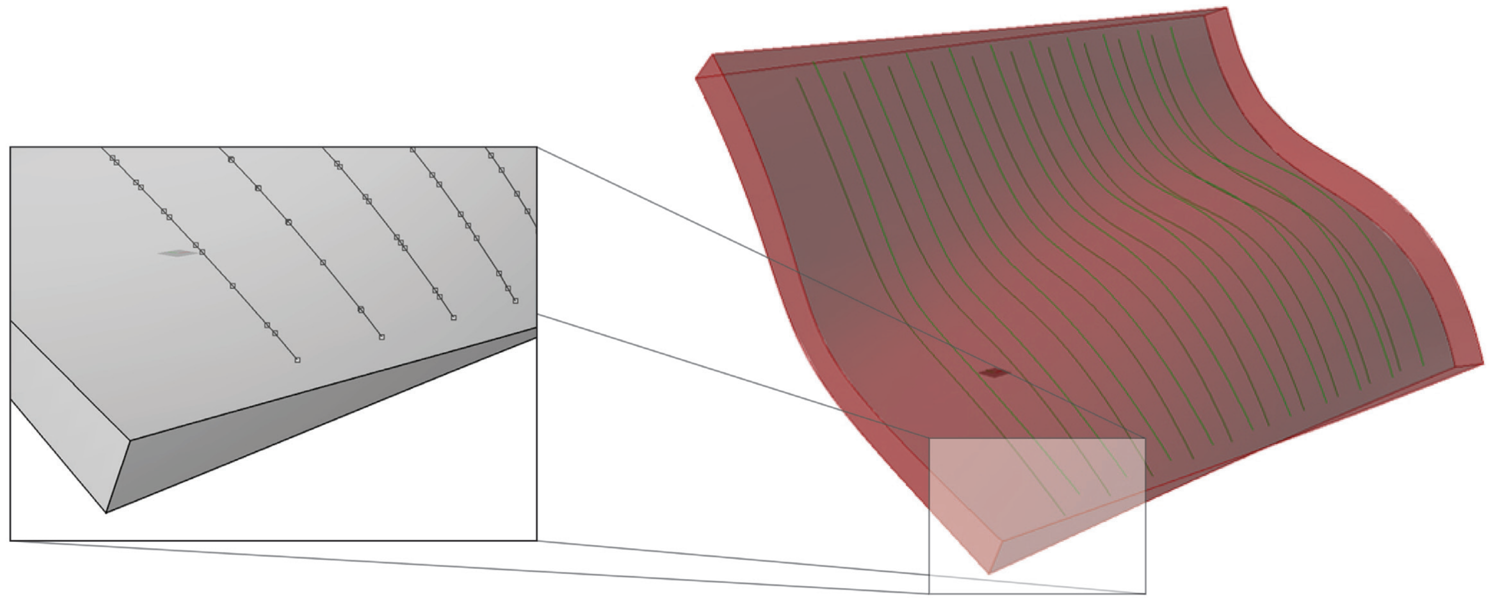
7.2.2 Reinforcement Cover Validation

The reinforcement cover is directly assigned by the user and checked against the minimum cover cmin as prescribed by the Euro Code 2 (EN1992-1-1:2004 table 4.3N). The recommended allowance in design for deviation, Δcdev of 10 mm is maintained (EN1992-1-1:2004 Section 4.4.1.3). The maximum allowed deviation compared to the nominal cover cnom is determined to an absolute deviation of 5mm. The validation of the cover is checked against this threshold.

The Allocator component assigns the individual point data of the segmented reinforcement paths to the appropriate layers in the SolidModel. For a further elaboration on the generation and placement of reinforcement, refer to Section 4.5. Both the cover of the reference points as well as the created reinforcement curves are validated for compliance with the assigned cover.

Higher geometrical complexity is expected to increase the deviations. If the cover stays within the specified tolerances for complex geometry, it is highly likely that it will also hold for less complex geometry. For this reason the geometry of test case 5 is used to validate the cover. A single group of ten longitudinal reinforcement bars is modelled in a top and bottom layer, see Figure 7.5.

The distance of individual points and curves is measured using a straightforward Grasshopper definition, applying the 'ClosestPoint' and 'Distance' components. The resulting output, a list with distances is exported to Excel, see output in Figure 7.6 and Figure 7.7, and automatically checked for compliance with the assigned cover.



Results of the reference point cover validation show an average absolute deviation from the assigned cover of 0.6mm with a maximum of 6.2mm. With 7 out of 560 points exceeding the allowed deviation of 5mm, 1.25% is out of boundaries. Point data from the segmented reinforcement paths serve as the control points of the reinforcement curves. This explains the higher average absolute deviation of 1,6mm and the lower absolute maximum deviation of 5.8mm within the Curve Cover Validation: the method of curve creation levels off extreme values.

Deviations in the Point Cover have two reasons. The first reason is the inaccuracy introduced by the surface rationalisation. A mesh is never hundred per cent accurate in approaching a curved surface. The second reason is the way points are allocated within the Solids. Through different directions in the average vectors at the vertices deviations occur when creating an offset layer. The magnitude of this type of inaccuracy increases with increasing curvature.

Although inaccuracies exist they are of minor scale and magnitude. Furthermore they can be explained. Measurements like mesh refinement can be taken to improve the accuracy of the models.

Figure 7.6
Output of the Point Cover Validation conducted in Excel.

Point CoverValidation.xlsx

	A	B	C	D	E
1	Point Distance BOT	Point Distance TOP	Deviation BOT	Deviation TOP	MaxAbsolute Deviation
2	50,029534	46,925375	0,030	-3,075	3,074625
3	53,093339	49,970674	3,093	-0,029	3,093339
4	51,803813	48,332884	1,804	-1,667	1,803813
5	50,0501	49,950003	0,050	-0,050	0,0501
6	52,006822	48,183147	2,007	-1,817	2,006822
7	50,060684	49,939473	0,061	-0,061	0,060684
8	50,060694	48,105727	0,061	-1,894	1,894273
9	52,143178	49,939711	2,143	-0,060	2,143178
10	52,224768	48,082705	2,225	-1,917	2,224768
11	50,047377	49,952748	0,047	-0,047	0,047377
12	52,181229	48,163179	2,181	-1,837	2,181229
13	50,023414	49,976663	0,023	-0,023	0,023414
14	52,064867	48,287382	2,065	-1,713	2,064867
15	49,98843	50,011634	-0,012	0,012	0,011634
16	49,944625	48,485844	-0,055	-1,514	1,514156
17	51,831738	50,055561	1,832	0,056	1,831738
18	51,501804	48,755829	1,502	-1,244	1,501804
19	49,895008	50,105895	-0,105	0,106	0,105895
20	51,113795	49,07795	1,114	-0,922	1,113795
21	49,843962	50,160637	-0,156	0,161	0,160637
22	50,682424	49,419867	0,682	-0,580	0,682424
23	49,792562	50,214007	-0,207	0,214	0,214007
24	50,773814	49,305734	0,774	-0,694	0,773814
25	49,741003	50,26633	-0,259	0,266	0,26633
26	50,442586	49,592406	0,443	-0,408	0,442586
27	49,694899	50,317763	-0,305	0,318	0,317763
28	50,111209	49,903241	0,111	-0,097	0,111209
29	49,655215	50,358646	-0,345	0,359	0,358646
30	49,756606	50,249641	-0,243	0,250	0,249641
31	49,619526	50,392028	-0,380	0,392	0,392028
32	49,594734	50,628594	-0,405	0,629	0,628594
33	49,38913	50,420141	-0,611	0,420	0,61087
34	49,031783	51,033031	-0,968	1,033	1,033031

	G	H	I
1	Assigned Cover:	50,0	mm
2	Allowed Deviation	5,0	mm
3	MaxAbsolute Deviation BOT:	6,1	mm
4	MaxAbsolute Deviation TOP:	6,2	mm
5	AvAbsolute Deviation BOT:	0,6	mm
6	AvAbsolute Deviation TOP:	0,6	mm
7	Out of boundaries:	7	out of (560)

Sheet1 Sheet2 Sheet3

Figure 7.7
Output of the Curve Cover Validation conducted in Excel.

Curve CoverValidation.xlsx

	A	B	C	D	E
1	Curve Distance BOT	Curve Distance TOP	Deviation BOT	Deviation TOP	MaxAbsolute Deviation
2	48,353686	51,636922	-1,646	1,637	1,646314
3	48,468347	51,538363	-1,532	1,538	1,538363
4	48,963649	51,061534	-1,036	1,062	1,061534
5	48,838527	51,16393	-1,161	1,164	1,16393
6	48,63053	51,401029	-1,369	1,401	1,401029
7	48,819435	51,292833	-1,181	1,293	1,292833
8	49,36362	50,709531	-0,636	0,710	0,709531
9	49,074718	50,856485	-0,925	0,856	0,925282
10	48,912528	51,11362	-1,087	1,114	1,11362
11	49,253917	50,957123	-0,746	0,957	0,957123
12	49,456726	50,493433	-0,543	0,493	0,543274
13	49,197458	50,738096	-0,803	0,738	0,802542
14	49,307698	50,819929	-0,692	0,820	0,819929
15	49,816619	50,456228	-0,183	0,456	0,456228
16	49,419047	50,371565	-0,581	0,372	0,580953
17	49,403083	50,657053	-0,597	0,657	0,657053
18	49,681755	50,516741	-0,318	0,517	0,516741
19	49,488105	50,331859	-0,512	0,332	0,511895
20	49,547533	50,54873	-0,452	0,549	0,54873
21	49,731	50,401403	-0,269	0,401	0,401403
22	49,598693	50,323121	-0,401	0,323	0,401307
23	49,762473	50,392812	-0,238	0,393	0,392812
24	49,715952	50,218922	-0,284	0,219	0,284048
25	49,85819	50,300494	-0,142	0,300	0,300494
26	49,867805	50,136081	-0,132	0,136	0,136081
27	50,000897	50,177467	0,001	0,177	0,177467
28	50,066386	49,991193	0,066	-0,009	0,066386
29	50,136222	50,00357	0,136	0,004	0,136222
30	50,287796	49,825511	0,288	-0,174	0,287796
31	50,298963	49,835239	0,299	-0,165	0,298963
32	50,512288	49,603531	0,512	-0,396	0,512288
33	50,557574	49,769752	0,558	-0,230	0,557574
34	50,72678	49,288514	0,727	-0,711	0,72678

	F	G	H	I
1		Assigned Cover:	50,0	mm
2		Allowed Deviation	5,0	mm
3		MaxAbsolute Deviation BOT:	5,8	mm
4		MaxAbsolute Deviation TOP:	5,8	mm
5		AvAbsolute Deviation BOT:	1,6	mm
6		AvAbsolute Deviation TOP:	1,6	mm
7		Out of boundaries:	4	out of (760)

Sheet1 Sheet2 Sheet3

7.3 Limitations of the Reinforcement Toolbox

The Reinforcement Toolbox has been developed as an initial proof of concept to the computational design strategy. The vision is that it will be developed further into a mature application that can add real value to the reinforcement process. It is important to state that although this first version of the Toolbox takes important steps in attaining this goal, it comes with some limitations.

- The Toolbox is developed for Rhino and Grasshopper. This implies that users need to have these applications installed before they can use the Toolbox. Components are developed using the C # programming language and the .NET framework, future extensions are therefore limited to this language and framework.

- Interoperability with FEM Analysis software is currently limited to one application (InfoCAD). For data transfer between the Toolbox and InfoCAD an Excel sheet is used as an intermediate. This forms a limitation on the ease of use of the Toolbox. Currently a limited amount of analysis results can be transferred, which keeps users from having full access to all the results from InfoCAD within the Toolbox.

- This first version of the Reinforcement Toolbox offers users a limited choice in terms of reinforcement types. Currently groups of longitudinal reinforcement bars and reinforcement meshes can be modelled. This limits users in their freedom to create reinforcement configurations. The amount of detail which can be added to the reinforcement model is limited. This keeps important aspects such as lap length and edge termination from being incorporated in the reinforcement models.

- The Toolbox is capable of creating SolidModels for continuous curved surface structures. When moving into the realm of more discontinuous geometry, like concrete nodes, the options of the Toolbox to create proper SolidModels are still limited. Expanding the SolidModel functionality, in order for it to also incorporate this type of geometry has high priority and would imply a significant increase in applicability.

- Since the structure of the SolidModel often directly relates to the structure of the FEM Analysis model, limitations to the possible shapes of the initial mesh elements in terms of minimum inner angles and size exist.

In general, all the limitations mentioned in this Section, can be considered as reasons for further research. For a more elaborate discussion on this issue, refer to Section 8.3 ‘Future Research and Development’.

7.4 Feedback from Engineers

Important aim of the Reinforcement Toolbox is to offer engineers a valuable and practical tool which can enhance the reinforcement design process of curved surface structures. In order to test this assumption the Toolbox has been consecutively demonstrated to three structural engineers employed in the Arup Amsterdam office. They were asked to give feedback according to the three following questions:

1) *'Is, in your opinion, the Reinforcement Toolbox of added value to the current range of reinforcement tools? For what reason?'*
2) *'Would you consider using the Reinforcement Toolbox when designing reinforcement in curved surface structures? For what reason?'*
3) *'What do you think are the main limitations of the toolbox? Which functionality would you like to see incorporated in future versions?'*

The completed questionnaires are included in Appendix C, 'Feedback from Engineers'. A summary of the main findings and quotations is described below.

'It provides a good tool to visualize a rebar patterns for complex geometries, this helps to gain a better understanding of how actually rebar will look like in complex geometries.'

'The Toolbox is interactive with FEM results of complex systems and, unlike Infograph, able to visualize multiple analysis results in one view. This is helpful when designing reinforcement.'

'The Reinforcement Toolbox makes it easier to quickly design complex reinforcement.'

'The Toolbox currently accounts for surfaces, the more complex nodes are not accounted for. This would significantly increase the Toolbox applicability.'

'Possible export to BIM software / reinforcement detailer would give added value.'

'On screen "fiddling" with the provided rebar is currently not possible; this should be incorporated in future versions.'

'Detailing criteria, such as overlap, hairpins etc. have not been taken into account. This is an important aspect of reinforcement engineering.'

Curved reinforcement, construction of the NSP Arnhem Transfer hall.

8.0 **Conclusions & Recommendations**

This Chapter describes the conclusions related to the conducted research and Reinforcement Toolbox development, described in the previous Chapters. Section 8.1 describes the conclusions related to both the computational strategy as well as the toolbox development. In Section 8.2 recommendations for further research and development are made. These mainly relate to the further development of the Reinforcement Toolbox.

8.1 Conclusions

This MSc thesis has researched the reinforcement process of curved surface structures, and has developed a strategy which aims to improve it. In support of this strategy a Reinforcement Toolbox has been developed. General conclusions related to the research described in this MSc Thesis are:

- Research into the reinforcement process for curved surface structures has revealed the need for new strategies to create digital reinforcement models.

- With engineering tools shifting more and more towards the digital domain, computational tool development has become a viable approach for enhancing the structural design process.

The computational strategy proposes a way of improving the design process of reinforcement in curved surface structures. Three key design aspects have been distinguished: geometrical control, structural analysis, and production. The following conclusions concerning the computational design strategy can be drawn:

- The proposed strategy offers a way of controlling the three design aspects of reinforcement in curved surface structures and embeds them into a cyclical design process.

- Three concepts have been discussed which offer control over the design aspects: the SolidModel, FEM Analysis Visualization, and Rebar DNA. The first two have been developed into working solutions.

- The proposed strategy takes into account the aspect of scalability by providing a modular structure, in terms of the SolidModel, which leaves possibility for further exptension with new modules, opening the way to new and more complex geometries.

The computational strategy forms the main input to the development of the Reinforcement Toolbox. The following conclusions concerning the Toolbox can be drawn:

- A first version of the Reinforcement Toolbox has been developed and tested.

- The Reinforcement Toolbox has been designed considering user friendliness, and freedom of use. The modular setup allows users to combine components at their own discretion allowing for the intended freedom when designing reinforcement.

- The Toolbox supports parametric associative design processes which allows for quick adaptation to design changes.

- Validation of two important aspects of the solid- and reinforcement models created using the Toolbox, the mesh topology and concrete cover, revealed no inconsistencies or large deviations from the allowed tolerances.

- The Reinforcement Toolbox has been demonstrated to a group of structural engineers. They recognize the potential added value the Reinforcement Toolbox can bring to the reinforcement process, especially when its current functionality and scope will be expanded.

8.2 Recommendations for Future Research and Development

Although the research and development have led to some promising results, it needs to be emphasized that this is merely a first step towards a versatile and complete strategy and computational tool for the design of reinforcement in curved surface structures. Further research on this topic is required.

This chapter makes recommendations for possible future research and development of the Reinforcement Toolbox. The topics addressed here are based on interesting paths and possibilities encountered during the research but, due to time constraints, have been left unexplored.

- The interoperability with FEM Analysis software is currently limited to one application, and data transfer takes place through mediation of excel. Optimizing the interoperability between the Reinforcement Toolbox and FEM Analysis software can be topic of further research. The possibility of incorporating a custom developed FEM solver into the Toolbox should also be considered.

- The current range of reinforcement types in the Toolbox is limited. New types of reinforcement like stirrups and hoops should be researched and added to the Toolbox. The modular setup of the Reinforcement Toolbox allows for relative easy addition of extra reinforcement types.

- The amount of detail which can be added to the reinforcement model is limited. Users should be offered the possibility to add detail to the reinforcement model. Practical aspects such as lap length, additional reinforcement and edge termination can increase the practical significance of the Toolbox.

- The current version of the Toolbox is capable of creating SolidModels for continuous curved surface structures. Expanding the possibilities for creating SolidModels to more discontinuous geometry, so-called D-areas, and adapting the Toolbox accordingly would significantly expand its scope.

- More extensive validation of the Toolbox is desirable. Both unit tests and additional functional tests should ensure the overall quality of the Toolbox.

- The Reinforcement Toolbox currently does not recognize the interface between different SolidModels, for this reason reinforcement will not automatically run from one SolidModel into the other. Exploring the possibility of linking multiple SolidModels will extend the possible geometries to which the Toolbox can be applied.

- The computational strategy incorporates a direct link with production facilities. This link has not been researched enough and should be elaborated on. This includes research into exchange formats, and production standards.

- An interesting path for further research is that of automated reinforcement generation. The current functionality of the Toolbox is user driven. Research into options of automatic reinforcement generating through the interpretation of structural analysis results could potentially give rise to optimization of reinforcement models for curved surface structures.

Bibliography

Autodesk (2011). Maya. Retrieved February 12, 2011, from: http://usa.autodesk.com/maya/

Barton, M. et al. (2000). 'Finite Element Primer for Engineers', Academic Service Arizona State University.

Canna, J. (2001), Retrieved November 25, 2011, from: http://www.ibm.com/developerworks/library/j-test/index.html

CEN (2005). Eurocode 2: Design of concrete structures - Part 1-2: General rules - Structural fire design, Technical report, European Committee for Standardization (CEN).

Clough, R. W. et al (1999). 'Early finite element research at Berkeley', Proceedings of 5th US National Conference on Computational Mechanics.

Coenders, J.L.C. (2011). 'NetworkedDesign, next generation infrastructure for computational design', PhD thesis, Delft University of Technology.

Coenders, J.L.C. (2006). 'Structural Design Special Structures', Lecture Notes, Delft University of Technology.

Coleman, D. (1998) 'A Use Case Template: draft for discussion.', Hewlett-Packard Software Initiative, Retrieved October 9, 2011, from: http://www.bredemeyer.com/

Corke, G. (2003). 'Attention to detail', AEC Magazine, 2003-3.

Demlow, A. (2002). 'Numerical Analysis of Differential Equations', Lecture Notes, Cornell University.

Farin, G. (2002). 'CAGD A Practical Guide', Morgan Kaufmann Publishers.

Gehry Technologies (2011). Digital Project. Retrieved February 12, 2011, from: http://www.gehrytechnologies.com/

InfoGraph GmbH (2010). InfoCAD Program System. Retrieved June 22, from: www.infograph.eu/

Jones, C. (2008). 'Applied Software Management', Mc Graw Hill.

Kam, (2008) octc.dll, Retrieved October 27, 2011, from: http://www.codeproject.com/KB/recipes/OctreeSearch.aspx

Levi, F. (2003). 'Eduardo Torroja: from the philosophy of structures to the art and science of building', F. Angeli.

Mandl, P. (2008). 'Freeforms in Composite Constructions; The new House of Music and Music Theatre "MUMUTH" in Graz', Proceedings of Eurosteel 2008.

McNeel (2009). Rhinoceros - Accurate Freeform Modeling for Windows. Retrieved February 12, 2011, from: http://www.en.na.mcneel.com/

McNeel (2010). Grasshopper - Generative Modelling for Rhino. Retrieved June 20, 2010, from: http://www.Grasshopper3D.com/

Neijssen, R. (2010). 'Faalkostenreductie in de wapeningsketen', Master's thesis, University of Twente.

Piegl, L. A. et al. (2002) 'Biarc approximation of NURBS curves.' Computer-Aided Design, 2002-34.

Popescu, C.M. et al (2003). 'Estimating Building Costs', Marcel Dekker inc.

Pottmann, H. et al. (2007), 'Architectural Geometry', Bentley Institute Press.

Rolvink, A. (2010). 'StructuralComponents2.0', Master's thesis, Delft University of Technology.

Rüegg, (2008) MathNet.Iridium.dll, Retrieved June 2, 2011, from: http://www.mathdotnet.com/doc/Default.aspx

SehlHorst, S. (2006) 'Writing Functional Requirements to Support Use Cases.', Retrieved October 9, 2011, from: http://tynerblain.com/blog/2006/02/10/writing-functional-requirements-to-support-use-cases/

Song, X. et al. (2009) 'Circular Spline Fitting Using an Evolution Process.', Paper, University of Science and Technology of China.

van de Straat, R. (2011). 'Parametric Modelling of Architectural Developables', Master's thesis, Delft University of Technology.

Walraven, J.C. (2002). 'College co2051B/co3051B Gewapend Beton', Lecture Notes, Delft University of Technology.

Wapperom, H. (2006) 'Wapenen, Een Vak Apart?', Interview with Joop van Nulland (ATG Steel) and Marcel Linderman (Witteveen + Bos), Cement, 2006-4.

Weilandt, A. et al. (2009) 'Rolex Learning Center in Lausanne: From conceptual design to execution', Proceedings of the International Association for Shell and Spatial Structures (IASS) 2009

Wikipedia, The Free Encyclopedia, 'Concrete' (2011). Retrieved: June 30, 2011, from: http://en.wikipedia.org/wiki/Concrete

Wikipedia, The Free Encyclopedia, 'Polygon mesh' (2011). Retrieved: September 26, 2011, from: http://en.wikipedia.org/wiki/Polygon_mesh

Wikipedia, The Free Encyclopedia, 'Use case' (2011). Retrieved: August 21, 2011, from: http://en.wikipedia.org/wiki/Use_case

Yang, S. N. et al. (1996) 'Numerical methods for approximating digitized curves by piecewise circular arcs.' Computational and Applied Mathematics, 1996-66.

List of Figures

List of Tables

APPENDIX A **CONCRETE CURVED SURFACE STRUCTURES**

Six Case Studies

Darwin Centre, CF Møller Architects
Kakamigahara Crematorium, Toyo Ito
Mercedes-Benz Museum, UN Studio
MUMUTH, UN Studio
Phaeno Centre, Zaha Hadid Architects
Rolex Learning Center EPFL, SANAA

Figure A.1

Darwin Centre, London

A.1 **Darwin Centre**

Project data

Project name:	Darwin Centre (second phase)
Client:	Natural History Museum
Architect:	CF Møller Architects
Structural engineer:	Arup
Contractor:	BAM Construct UK Ltd.
Subcontractor:	Shotcrete
Function:	Museum and Laboratory
Location:	London, Great Brittain
Construction Time:	2006-2008
Project costs:	Approx. 95Mil. Euro

Key figures

Size of construction area:	5.200m²
Gross floor space:	16.000m²
Concrete volume:	900 m³

Brief description

This extension of the Natural History Museum was conceived as a structurally independent concrete blob, enveloped by a light orthogonal glass façade and a transparent EPFE roof. Besides exhibition spaces the extension houses archives and laboratories. The eight story high cocoon houses the high-tech laboratories, and 3.3 km of cabinets.

Construction principle

The cocoon and the atrium are structurally separate. The concrete shell has rigid connections with the floors which are supported by concrete columns and stabilized by a series of reinforced cores and shear walls. With its 30m height and 65m width it is the largest sprayed concrete, curved construction in Europe. The shell is part of the main load bearing structure, able to carry its own weight.

Modelling

The cocoon has a double curved, symmetrical geometry. Its principle lines are based on mathematical equations. The geometry was modelled using the 3D NURBS modelling software Rhinoceros. Initial calculations were made on the basis of analogies. The mid-section of the cocoon has such a small amount off curvature that it can be considered as a plane frame problem. The final geometry including openings was analyzed in Sofistik. In order to come to an adequate mesh model, the Rhino 3D model was imported into AutoCad where it was meshed using the Sofistik Mesh plugin.

Formwork

The method of spraying concrete against a permanent 3mm metal mesh allowed for omitting the otherwise necessary formwork. This introduced a significant cost reduction.

Reinforcement

The floors and columns were cast first. Temporary struts supported the floor's edge. These edges formed the reference to which the reinforcement was set out. Reinforcement bars were attached to the protruding slab edge starter bars and manually forced in the right curvature. The wet concrete was then sprayed against the reinforcement with the metal mesh providing for the necessary backing.

A.2 **Kakamigahara Crematorium**

Project data

Project name:	Meiso no Mori
Client:	Gifu Prefecture
Architect:	Toyo Ito & Associates, Architects
Structural engineer:	Sasaki Structural Consultants
Concrete Contractor:	Toda, Ichikawa & Tentyu
Function:	Crematorium
Location:	Kakamigahara, Japan
Construction Time:	2005-2006

Key figures

Size of construction area:	6.695m²
Gross floor space:	2.265m²
Concrete volume:	800 m³

Brief description

The thin undulating roof seems to float above the site. Slender columns naturally evolve from this plane. A number of marble clad boxes, containing the waiting and valedictory rooms are placed underneath. The volume containing installations for the actual cremation is the only one which touches the roof. This volume also plays an important structural role.

Construction principle

Lateral stability is provided by a structural core which contains the furnace room and associated installations. Twelve columns, varying in length and section, are positioned freely under the roof structure. Their position relative to each other is directly linked to the curved roof geometry. The initial roof geometry as provided by the architect was further optimized through Extended Evolutionary Structural Optimization (EESO).

Figure A.2

Meiso no Mori, Kakamigahara

Modelling

In close collaboration with the structural engineer Sasaki, a set of early calculations were made by hand. Once the boundary conditions like minimum ceiling height were established, the first digital model was made. This model evolved through several hundred evolutionary cycles to its final optimized shape. The data coming from the model was used in the prefabrication of the formwork sections for the columns and capitals.

Formwork

Only the planar formwork sections of the columns were prefabricated, the largest part of the formwork was made on site. It relied heavily on skilled Japanese carpenters for its exact execution. The geometry was controlled precisely through 3.700 checkpoints placed on a grid and continually checked by laser level finders placed on the hill behind the building site.

Reinforcement

The reinforcement was placed relative to the control points, and curved on site. The control points are placed perpendicular to the formwork plane and indicate the thickness of 200 mm. This way the team applying the concrete could control the thickness of the layer. To make pours on the steep sloping roof plane possible a special concrete mixture with a high cement/water ratio was applied. It involved rapid hardening of the concrete.

Figure A.3
Mercedes-Benz Museum,
Stuttgart

A.3 **Mercedes-Benz Museum**

Project data

Project name:	Mercedes-Benz Museum
Client:	Daimler Immobilien GmbH
Architect:	UNStudio
Structural engineer:	Werner Sobek
Co Contractor:	Ed. Züblin AG
	Wolff & Müller GmbH & Co.
Function:	Museum
Location:	Stuttgart, Germany
Construction Time:	2004-2006
Project costs:	Approx. 150 Mil. Euro

Key figures

Size of construction area	53.000m²
Gross floor space	25.000m²
Concrete volume	Approx. 50.000m³
Reinforcement steel	Approx. 3.600t

Brief description

Two ramps spiral down around an eight storey high atrium. The structure is inspired by the mathematical representation of the trefoil knot. Visitors proceed through the museum from top to bottom following one of the two intersecting trajectories. Exhibition and circulation spaces blend together to form a single continuous space, showing the history of the brand.

Construction principle

The main loads are directed through the circulation ramps which, together with the twist elements, transfer the loads to the façade and the central core. Three main cores in the center of the building provide lateral stability. To reduce weight of the floors, steel trusses span between the ramps and the twist girders. Slanted composite columns in the façade plane support the folded edges of the outer skin.

Modelling

Because of the complex geometry, the only efficient way to produce plans and elevations was by extruding them from a 3D computer model. DesignToProduction developed a parametric 3D CAD model which enabled quick adaptation of the 2D drawing in case of changes in the design.

Individual parts like the twists were analyzed using the FE analysis software SOFiSTiK. To make the architectural model suitable for analysis, the contour lines were extracted. A plug in for Rhino called SofiMshb was used to create the meshed surfaces necessary for finite element analysis.

Formwork

The necessary data for the formwork was extracted from the mesh model used for the structural analysis. Projecting the bottom of a twist element on a horizontal plane gives the necessary measurements of the formwork tables. DesignToProduction developed a formwork method build up out of planar boards. Thin plywood panels, cut into the exact dimensions by a CNC milling machine, were then manually forced into the desired shape and attached to the wooden backing.

Reinforcement

The 3D construction model played a very important role in the concrete work. Rebar's could not sufficiently be described in two dimensions because of the distortion which takes place when flattening a 3D curved element onto a 2D plane. A Global Positioning System linked to the 3D construction model helped determine the exact coordinates of the placeholders.

A.4 **MUMUTH**

Project data

Project name:	Haus für Musik und Musiktheater
Client:	University for Art in Graz (KUG)
Architect:	UNStudio
Structural engineer:	Arup London
Concrete Contractor:	Steiner-Bau GesmbH
Function:	Music theatre
Location:	Graz, Austria
Construction Time:	2006-2008
Project costs:	Approx. 22 Mil. Euro

Key figures

Size of construction area	2.800m²
Gross floor space	5.500m²
Concrete volume	3.800 m³
Reinforcement steel	325 t

Brief description

The lead in this building is played by a large spiral which evolves from the concrete walls of the concert hall. A heavy concrete core is contrasted with a light glass and steel mesh façade.

Construction principle

The orthogonal structure of the theatre box is disrupted when its two vertical walls twist and turn to form the first and third floor in the foyer. A load bearing element called the "Twist" cantilevers from the theatre box to support these two floor slabs. This composite element with cast in steel sections carries approximately a third of the total building loads. The main load path runs though the inner edge of the Twist.

Figure A.4

MUMUTH, Graz (Image Courtesy of gabi.weinert)

Modelling
The modelling of the Twist started with finding proper structural analogies. A frame analogy was followed by a strut-and-tie model. These models gave insight into its structural behaviour and allowed for the first rough calculations. The final geometry was assessed using a FE analysis with shell elements.

Formwork
The required high quality fair faced concrete of the Twist only allowed for small formwork tolerances. To achieve this, the formwork was cut out of several large polystyrene elements by a CNC milling machine. These formwork elements where coated with a layer of epoxy to increase strength and smoothness. The absence of concrete ties made a secondary bracing structure necessary. To give support to the polystyrene elements during the pouring of the concrete, a stiff cube was constructed around the Twist. Self-compacting concrete was injected under low pressure through two inlets on the bottom of the structure.

Reinforcement
The Twist is realized as a composite structure, where hollow steel sections work together with the concrete to achieve the necessary strength and rigidity. In between the steel sections polystyrene void formers are used, to decrease the dead load of the Twist while still maintaining a structural efficient section. The concrete cover has a continuous thickness of approximately 150 mm. In this layer regular reinforcement was applied. The steel structure was entirely build up off site, and cut into transportable pieces, which where than reassembled on site.

Figure A.5

Phaeno Centre, Wolfsburg (Image Courtesy of tango56)

A.5 **Phaeno Centre**

Project data

Project name:	Phaeno
Client:	City of Wolfsburg, Neuland Wohnungsbaugesellschaft mbH
Architect:	Zaha Hadid Architects
Structural engineer:	Adams Kara Taylor Engineers
	Ingenieurgruppe Tokarz Frerichs Leipold
Concrete Contractor:	Heitkamp
Function:	Science center
Location:	Wolfsburg, Germany
Construction Time:	2001-2005
Project costs:	79 Mil. Euro

Key figures

Size of construction area:	17.900 m²
Gross floor space:	11.295 m²
Concrete volume:	27 000 m³
Reinforcement steel:	5000 t

Brief description

The Phaeno Science Center is a sculptural building of approximately 153 m long and 80 m wide. The exhibition level is raised 7 m above the ground by ten conical shaped concrete volumes containing several public functions and the entrance. Inside the fluid space of the large exhibition hall invites visitors to wander around.

Construction principle

The concrete cones, together with the raised exhibition slab and façade all work together to form a single structure. Four of the cones continue upwards and, together with the façade, support the steel truss roof structure. All the loads are transferred to the foundations through the concrete cones. Their heavily reinforced cone walls are inclined up to 50º and form a monolith with the concrete floor slab.

Modelling

Each cone has a unique shape and varies in section, both horizontally and vertically. The initial visualization by the architect was done in 3D Studio, and structurally tested using simple wire frame models. This model formed the starting point for a more accurate Finite Element analysis in SOFiSTiK. It also supplied the graphical input in AutoCAD, making an important link between analysis software and 2D representation. For each cone a series of control points were issued by the architect. Control points were located at the tangents of the cone surface and at the edges of the cutting planes. Plan drawings and the unfolded drawings were used as templates on basis of which the reinforcement was organized.

Formwork

The heavy aesthetic demands of the exposed concrete faces involved continuous pours of up to seven meters high. To achieve this, and to avoid laborious compacting, Self-Compacting Concrete was used. The formwork consisted of prefabricated panels build up out of trapezoidal boards. They were erected on site and supported by heavy duty props. The fact that the cones all open out upwards dictated that the outside formwork panels had to be erected first.

Reinforcement

The outside formwork panels act as an orientation plane for the placement of reinforcement. Spacer blocks for the starter bars are accurately placed using templates to identify the correct location. As the pressure of the wet concrete pushed the spacer blocks into the wooden formwork panels causing irregularities to the exposed concrete wall finish, a detail had to be developed on site which enabled the tie bar cones to simultaneously act as spacers.

A.6 **Rolex Learning Center EPFL**

Project data

Project name:	Rolex Learning Center EPFL
Client:	Ecole Polytechnique Fédérale de Lausanne
Architect:	SANAA
Structural engineer:	Bollinger + Grohmann Ingenieure
	Walter Mory Maier Bauingenieure AG
Concrete Contractor:	Losinger Construction AG
Function:	Learning center
Location:	Lausanne, Switzerland
Construction Time:	2005-2009
Project costs:	Approx. 62 Mil. Euro

Key figures

Size of construction area:	88.000m²
Gross floor space:	37.000m²
Concrete volume:	5.400 m³
Reinforcement steel:	2.000t

Brief description

The intention of SANAA was to create an architectural landscape. They designed a continuous single story space which, through a gentle undulation, is subdivided into different zones of use. Large patios form 'intimate public spaces' and enable daylight to enter deep into the building. The large basement level below the ground surface houses all the utilitarian functions.

Construction principle

The floor of the inner space is a continuous concrete slab which lifts itself up from ground level to a maximum height of 5 meters. On top of this a column grid of 9m x 9m is set out on which a light steel roof rests. The roof of the basement level fulfils an important

Figure A.6
EPFL Learning Center, Lausanne (Image Courtesy of carlo. fumarola)

structural function as it takes up the horizontal loads coming from the shells. Arches in between the patios attract most of the loads, and are heavily reinforced.

Modelling

The compromise between architectural and structural requirements led to a construction in which significant deformations had to be accounted for. In terms of modelling, a decision was made to use a 3D model of the cambered geometry alongside the architectural model. From this 3D model the data necessary to produce the formwork tables was extracted via scripting.

Formwork

The automated process of producing the 2.5 m x 2.5 m formwork tables was supervised by the German / Swiss company Design to Production. Every table consisted of two wooden beams on which 7 tapered OSB plates where fixed. Steel scaffolding underneath is used to bring the tables to the exact height. A major advantage of the shallow arches was that no counter-formwork was necessary. Plastic fibres were added to the concrete mixture to improve its behaviour during casting, this way slopes up to 15 % were reached.

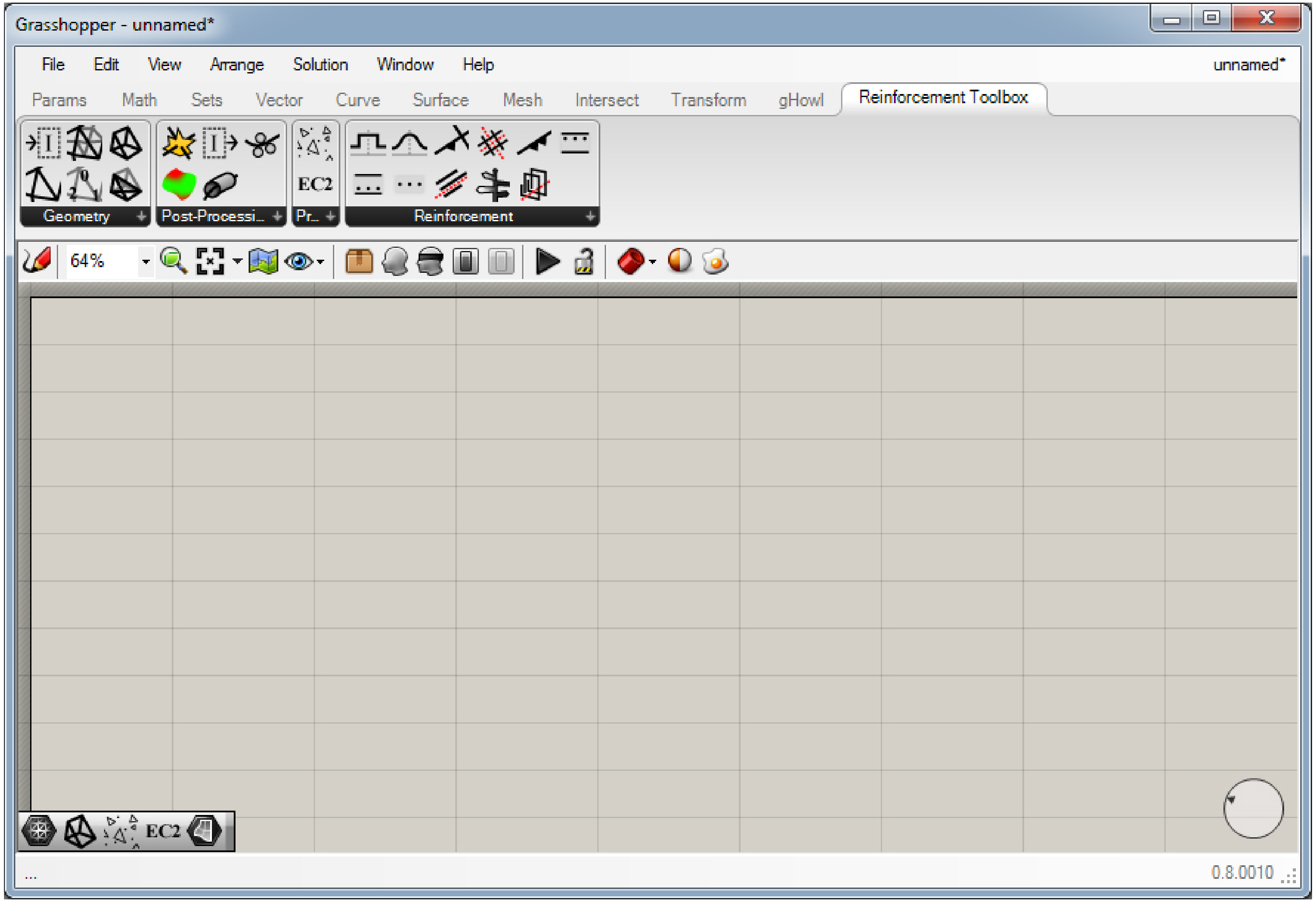
Reinforcement

Because of the low curvature of the arches large bending moments occurred. Direct consequence was a relatively high percentage of reinforcement, especially in the arches. Reinforcement bars with diameters up to 50 mm were used. To prevent spalling of the concrete these large diameter bars where connected by welding joints. Places where arches came together became very congested. To keep risks under control mock ups were made of the most complex nodes. Standard reinforcement details where tested, as well as the compacting process.

APPENDIX B **THE REINFORCEMENT TOOLBOX MANUAL**

This is a step by step user manual on how to subsequently setup a SolidModel definition and a Reinforcement model by using the Reinforcement Toolbox. For this manual Grasshopper version 0.8.0010, and Rhinoceros 3D version 4.0 SR9 are used. Input of the different components and their functionality is explained through screenshots.
Using the '*GrasshopperDeveloperSettings*' command in Rhino the user needs to point to the '*Reinforcement Toolbox*' assembly. When done correctly a new tab in Grasshopper named '*Reinforcement Toolbox*' appears. This tab contains all the components of the Reinforcement Toolbox divided into four categories: '*Geometry*'; '*Post-Processing*'; '*Properties*' and '*Reinforcement*'. Input for the components can be assigned either by right clicking the input parameter and selecting '*set theInputparameter*' or by directly connecting the output of another component by dragging this output to the input.

Figure B.1
Grasshopper canvas and Reinforcement Toolbox icons



B.1 **Different Ways of Creating a SolidModel**

In accordance with Section 4.3, which describes the characteristics of the SolidModel, the Toolbox incorporates three different mechanisms of defining a SolidModel: a Center Surface Definition; a Single Reference Definition and a Double Reference Definition. These mechanisms are subsequently described below according to the geometry of Test Case05 described in Section 6.1.

Center Surface Definition
Starting point is a curved surface representation consisting of triangular mesh elements. This mesh can be constructed using the existing meshing functionality within Grasshopper or Rhinoceros3D. A requirement to the mesh is that it forms a continuous, unbroken sequence of triangular Brep elements.

1.

First step in creating a SolidModel is constructing the MeshTopology. This is done by subsequently dragging the MeshTopology component to the Grasshopper canvas and assigning the collection of Breps to the input, see Figure B.1.

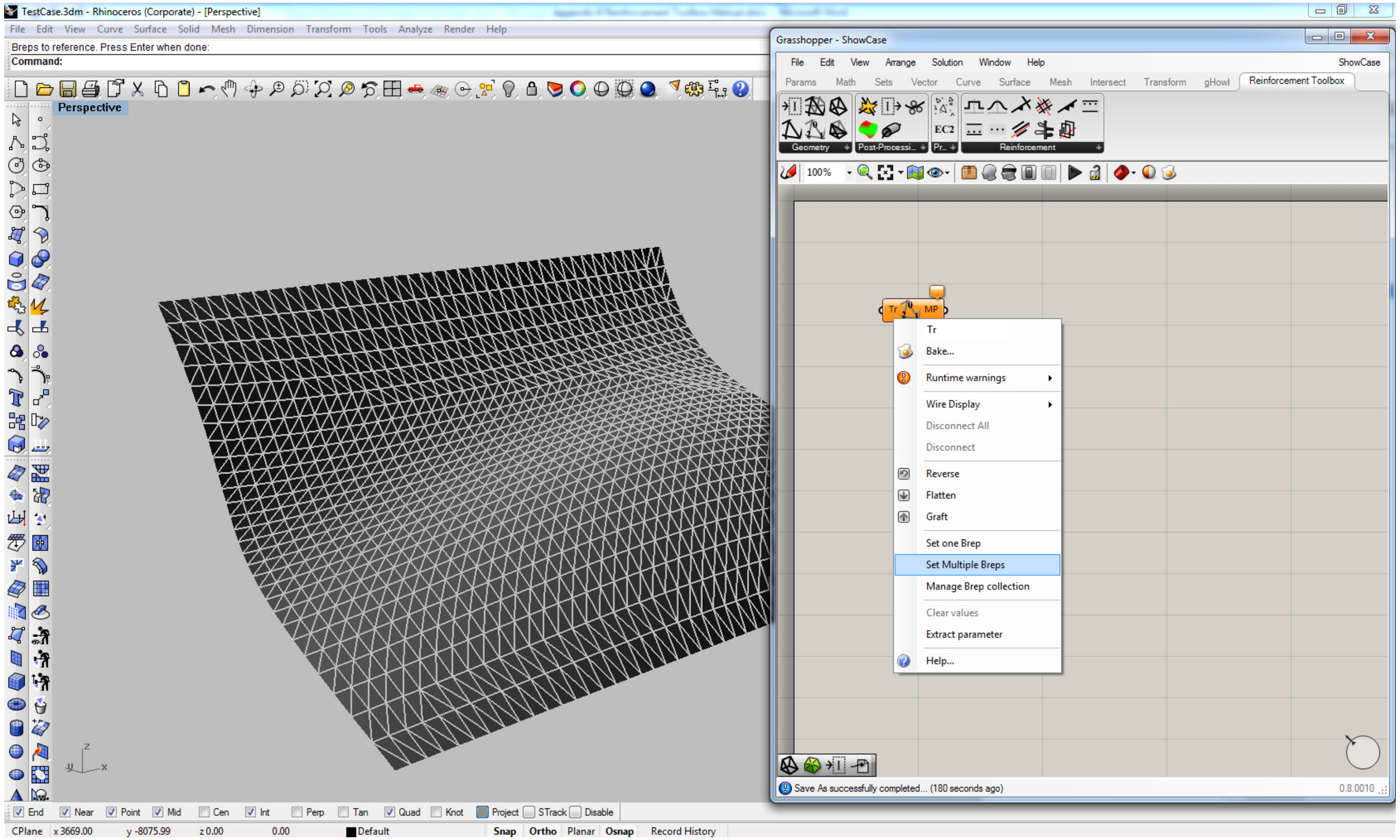


Figure B.2
Step 1: Assigning a collection of Breps to the input of the MeshTopology component.

2.

The second step in creating a SolidModel is linking the created MeshTopology to the first input of the SolidModel component. Together with the other six parameters this component defines the SolidModel. The thickness is entered as a number. In this case the offset type of the SolidModel is set to ‘Center’. The Concrete Properties Parameter which hold the ‘Concrete grade’, ‘Aggregate size’, ‘Exposure class’, and ‘Fire exposure’ forms an input to the SolidModel component, see Figure B.3.

Figure B.3
Step 2: The properties of the concrete are entered in the Concrete Properties Parameter and assigned to the SolidModel.

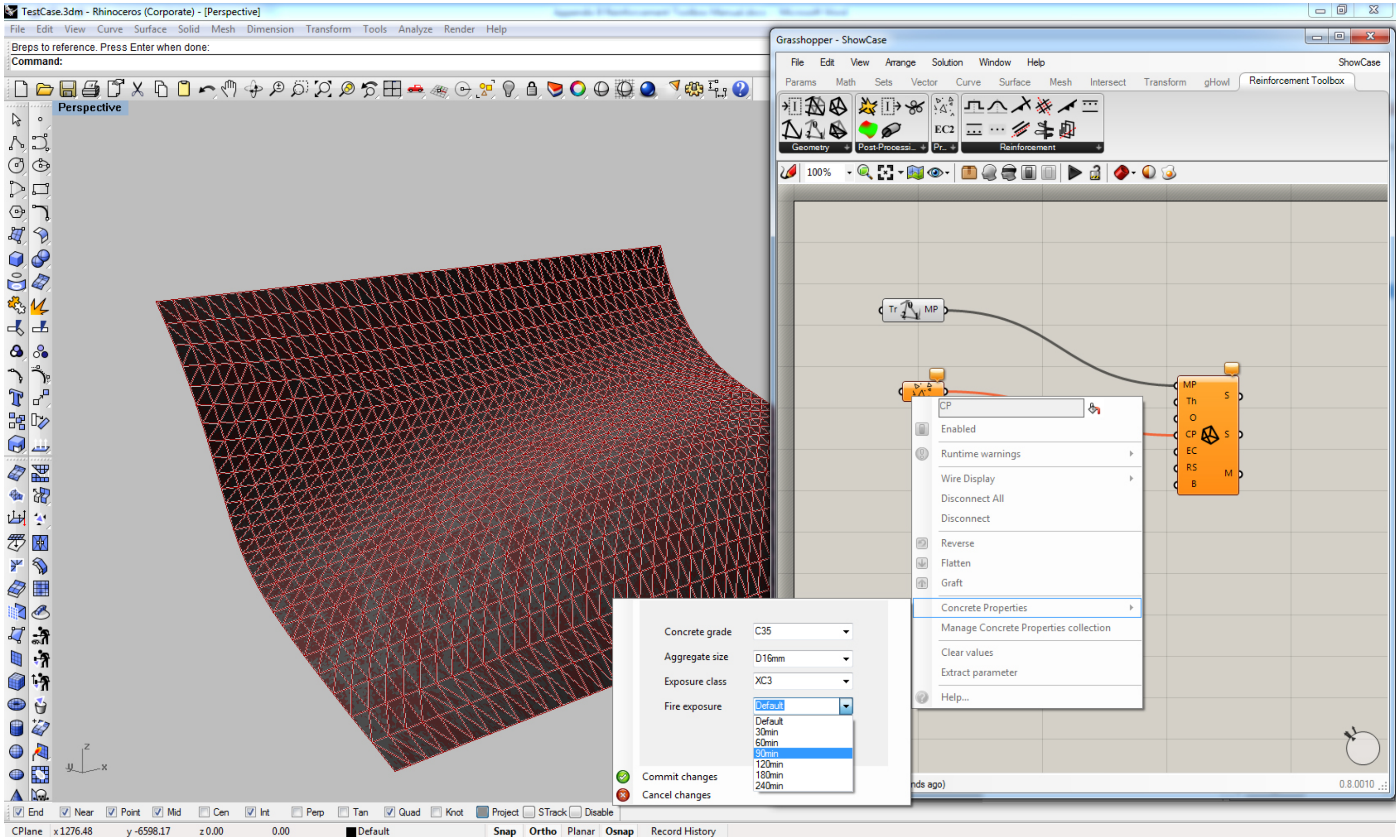
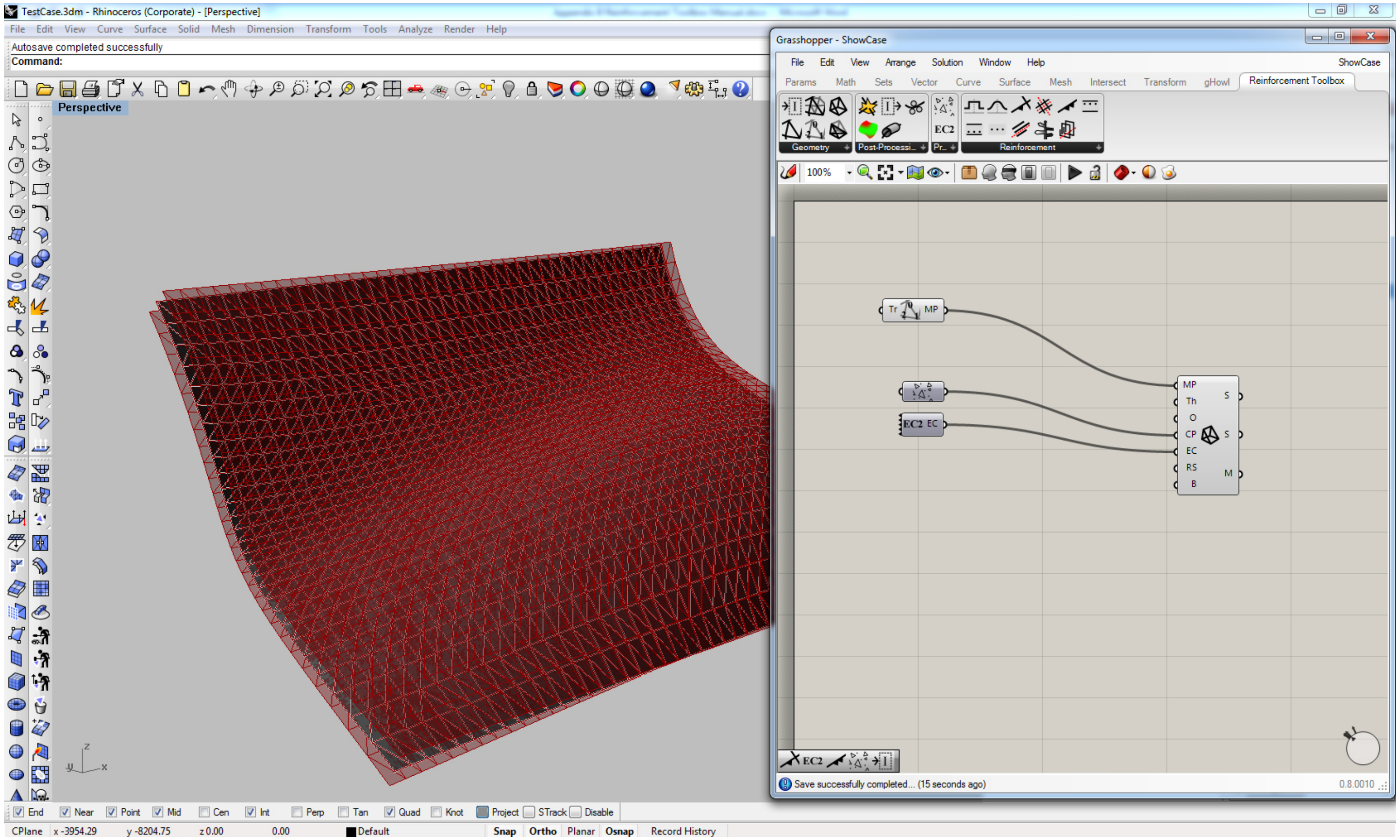


Figure B.4
Step 3: A SolidModel created according to the 'Center' offset type.

3.
The third step involves assigning the associated building code. The Eurocode component completes the input, and a center surface SolidModel definition is created, see Figure B.4.



Single Reference Definition

The creation of a single reference definition follows steps 1 till 3 of a center surface definition, with the exception that the offset type is set to ‘SingleRef’, see Figure B.5.

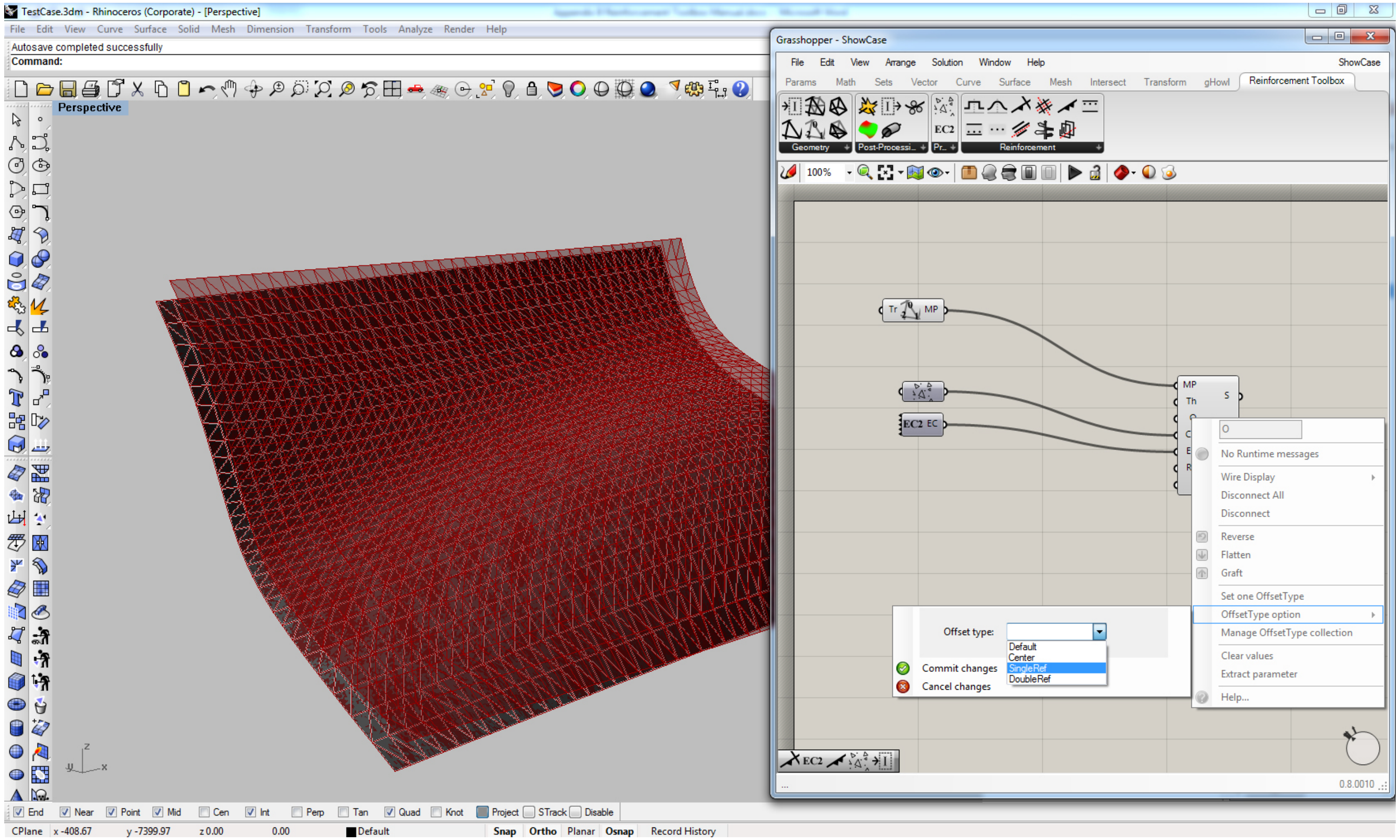


Figure B.4
Step 3: A SolidModel created according to the ‘SingleRef’ offset type.

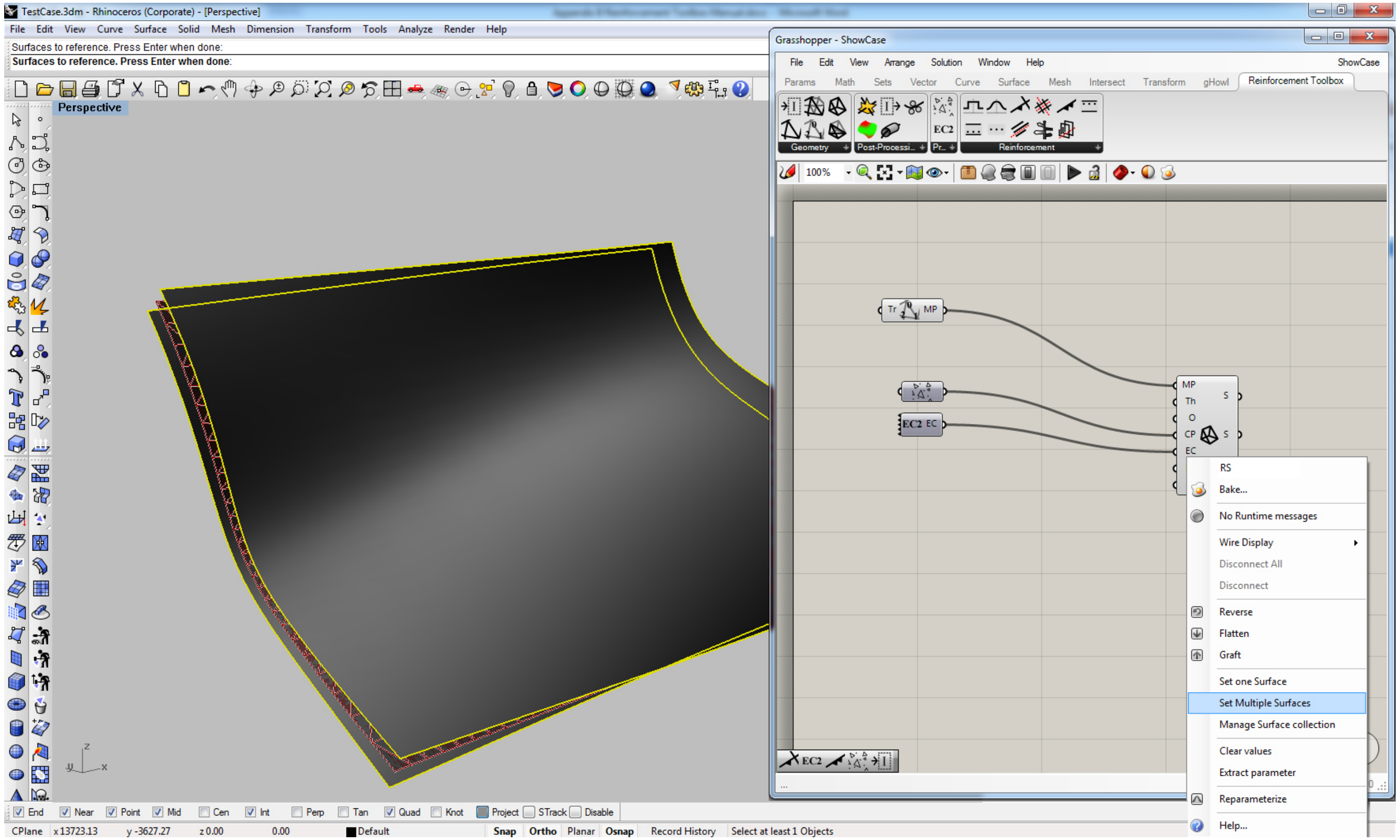
Figure B.5
Step 4: In case of a 'DoubleRef' offset type two reference surfaces are assigned to the SolidModel component.

Double Reference Definition

In case of a double reference definition two reference surfaces define the boundaries of the SolidModel. The creation of a double reference definition follows steps 1 till 3 of a single reference definition, with the exception that the offset type is set to 'DoubleRef'.

4.

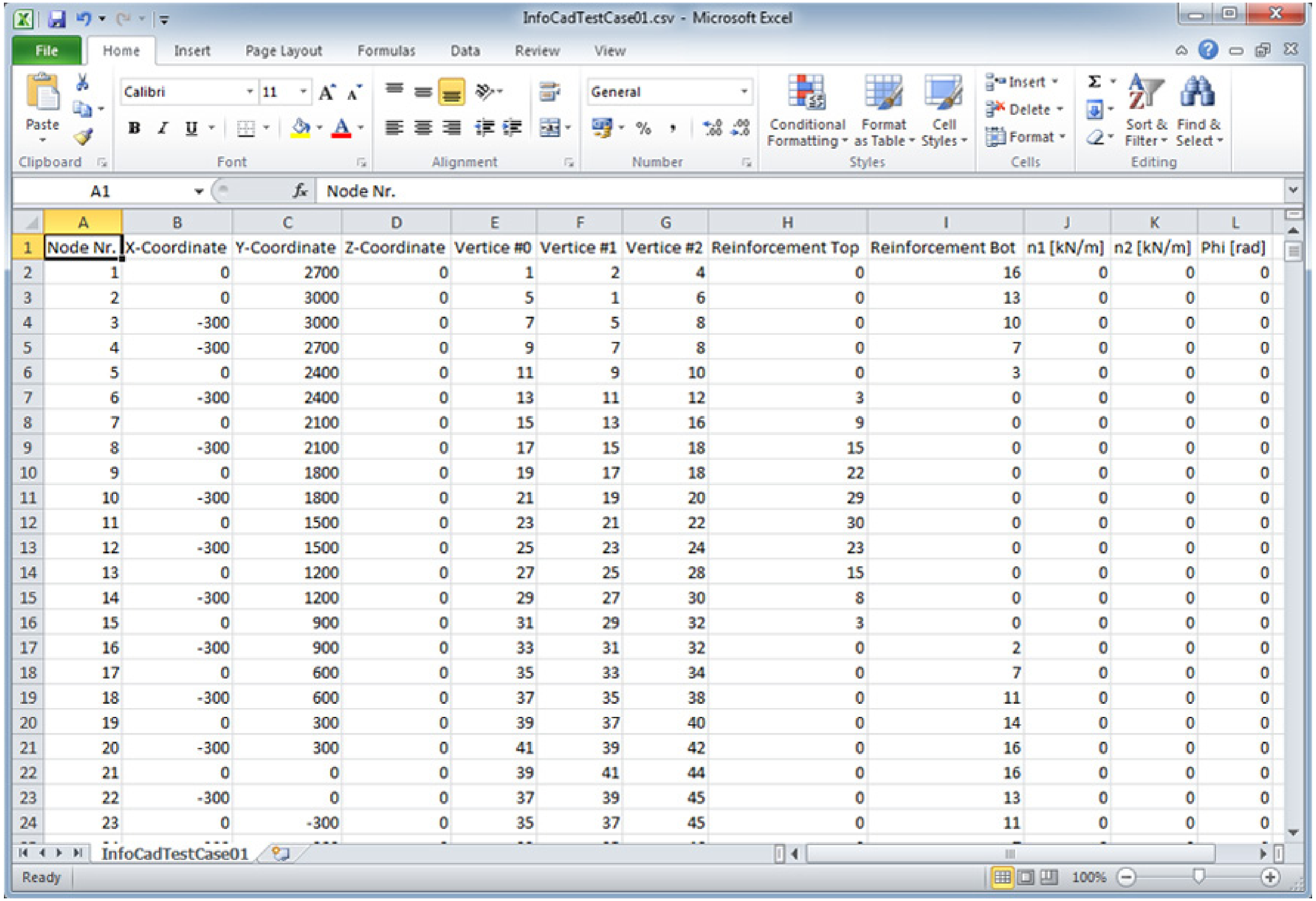
In an additional step the two reference surfaces are assigned to the correct input of the SolidModel component, see Figure B.5. The mesh which serves as an input to the MeshTopology component needs to be in between the two reference surfaces.



Creating a SolidModel from InfoCAD Input

Data from InfoCAD is imported through an Excel spread sheet. A predefined template, of which an example is shown in Figure B.6, holds the columns which need to be populated with the InfoCAD analysis data.

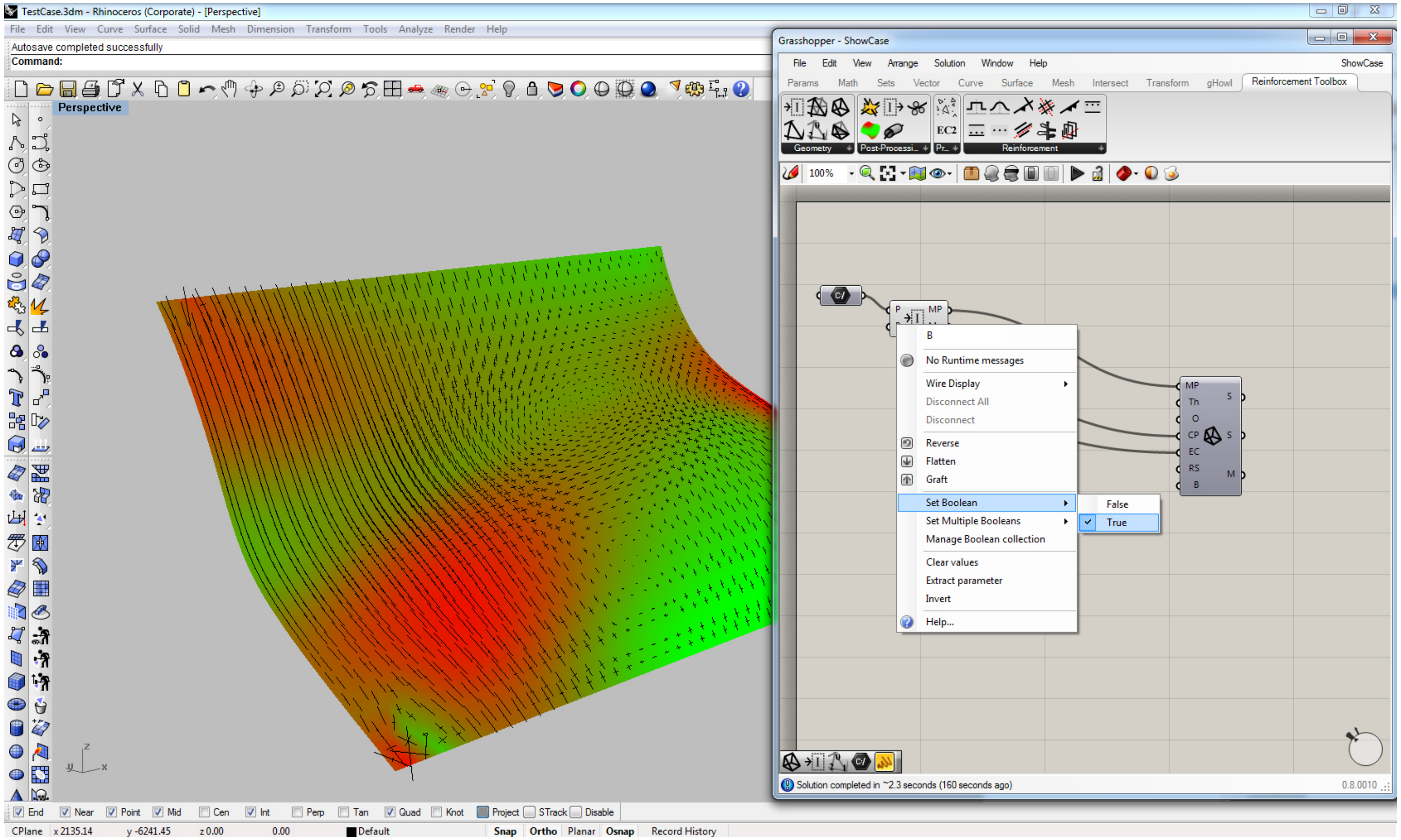
Figure B.6
Excel data sheet template used to import data from InfoCAD.



Node Nr.	X-Coordinate	Y-Coordinate	Z-Coordinate	Vertice #0	Vertice #1	Vertice #2	Reinforcement Top	Reinforcement Bot	n1 [kN/m]	n2 [kN/m]	Phi [rad]
1	0	2700	0	1	2	4	0	16	0	0	0
2	0	3000	0	5	1	6	0	13	0	0	0
3	-300	3000	0	7	5	8	0	10	0	0	0
4	-300	2700	0	9	7	8	0	7	0	0	0
5	0	2400	0	11	9	10	0	3	0	0	0
6	-300	2400	0	13	11	12	3	0	0	0	0
7	0	2100	0	15	13	16	9	0	0	0	0
8	-300	2100	0	17	15	18	15	0	0	0	0
9	0	1800	0	19	17	18	22	0	0	0	0
10	-300	1800	0	21	19	20	29	0	0	0	0
11	0	1500	0	23	21	22	30	0	0	0	0
12	-300	1500	0	25	23	24	23	0	0	0	0
13	0	1200	0	27	25	28	15	0	0	0	0
14	-300	1200	0	29	27	30	8	0	0	0	0
15	0	900	0	31	29	32	3	0	0	0	0
16	-300	900	0	33	31	32	0	2	0	0	0
17	0	600	0	35	33	34	0	7	0	0	0
18	-300	600	0	37	35	38	0	11	0	0	0
19	0	300	0	39	37	40	0	14	0	0	0
20	-300	300	0	41	39	42	0	16	0	0	0
21	0	0	0	39	41	44	0	16	0	0	0
22	-300	0	0	37	39	45	0	13	0	0	0
23	0	-300	0	35	37	45	0	11	0	0	0

Figure B.7
The ‘Draw internal force indicators’ input of the InfoCAD component is set to ‘true’ in order to visualize the principle stress vectors.

The InfoCADInput component requires the file path to the .csv file which contains the InfoCAD data. This component imports both the geometry as well as the analysis results. It automatically creates the MeshTopology which can be progressed into a SolidModel by following steps 2 till 4 described above.
The InfoCADInput component automatically visualizes the required reinforcement amount. In order to visualize the principle stress vectors in the centroid of each element the ‘Draw internal force indicators’ input needs to be set to ‘true’, see Figure B.7.



B.2 **Ways of Defining Reinforcement in a SolidModel**

The Reinforcement Toolbox enables users to define both longitudinal reinforcement groups and reinforcement meshes. The way these are defined is slightly different. This section of the manual exemplifies how both types can be defined and how the resulting reinforcement model can be compared to the analysis results from InfoCAD.

Creating a Longitudinal Reinforcement Group
The direction of a longitudinal reinforcement group is dictated by a corresponding reinforcement path. This path is set relative to the base mesh which is used to construct the MeshTopology. The created SolidModel serves as input to the reinforcement path component.

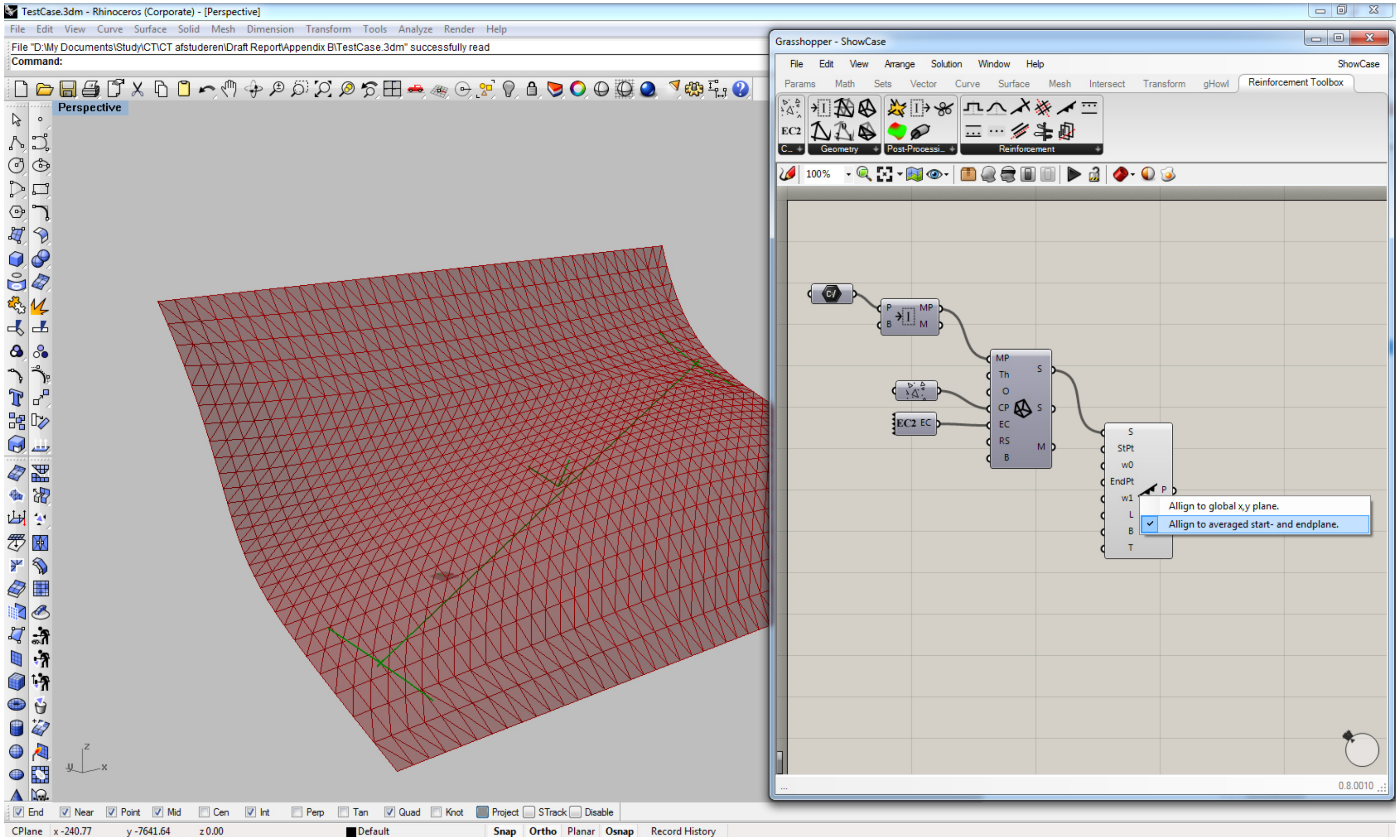
subscription 1
Iquas sunt aliquaspero est et laboriatur, cum ius aspis ut lam quia ipid erum anda pro moluptati del in necti dolum quodipitas nones net la

subscription 2
Iquas sunt aliquaspero est et laboriatur, cum ius aspis ut lam quia ipid erum anda pro moluptati del in necti dolum quodipitas nones net la

subscription 3
Iquas sunt aliquaspero est et laboriatur, cum ius aspis ut lam quia ipid erum anda pro moluptati del in necti dolum quodipitas nones net la

Figure B.8
A base mesh with a longitudinal reinforcement path, the orientation is set to align to the averaged start and end plane of the path on the base mesh.

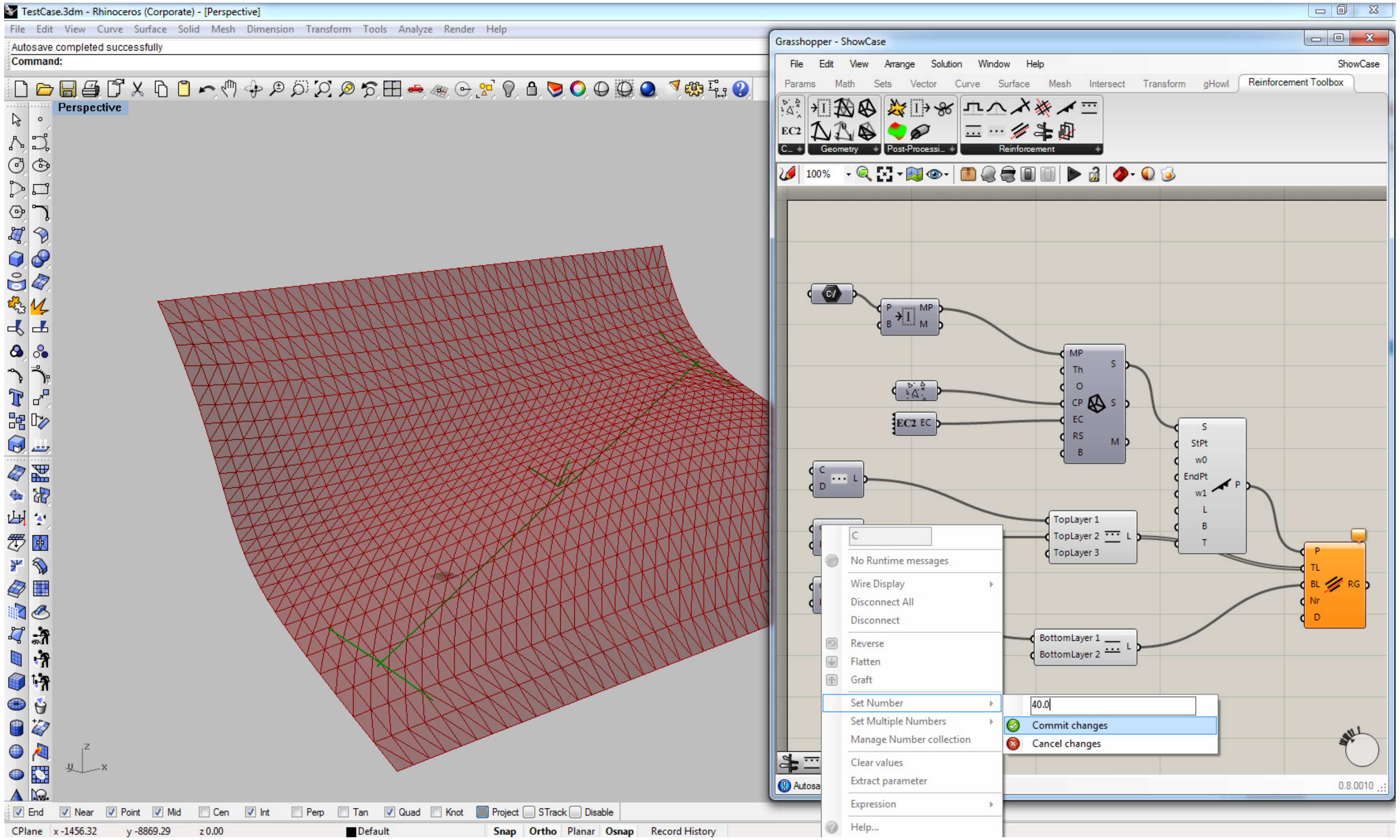
1.
First step in creating a longitudinal reinforcement group is setting out the reinforcement path which determines the direction and width of the reinforcement group. A longitudinal reinforcement path requires a start and endpoint on the base mesh. They can be placed arbitrarily on the edges or vertices of the mesh. The begin and end width is entered in millimetres. By right clicking on the component the orientation of the path can be set align with either the global x,y-plane or the averaged start and end plane of the path on the base mesh, see Figure B.8.



2.

The path serves as primary input for the reinforcement group component. Layer information is entered through the designated layer components, see Figure B.9.

Figure B.9
The top and bottom layer components hold the information on the amount and cover of the reinforcement layers.



3.

In order to allocate the reinforcement to the correct layers within the SolidModel, the reinforcement group is passed to the Allocator component. The optional reinforcement visualization is set to 'true', see Figure B.10.

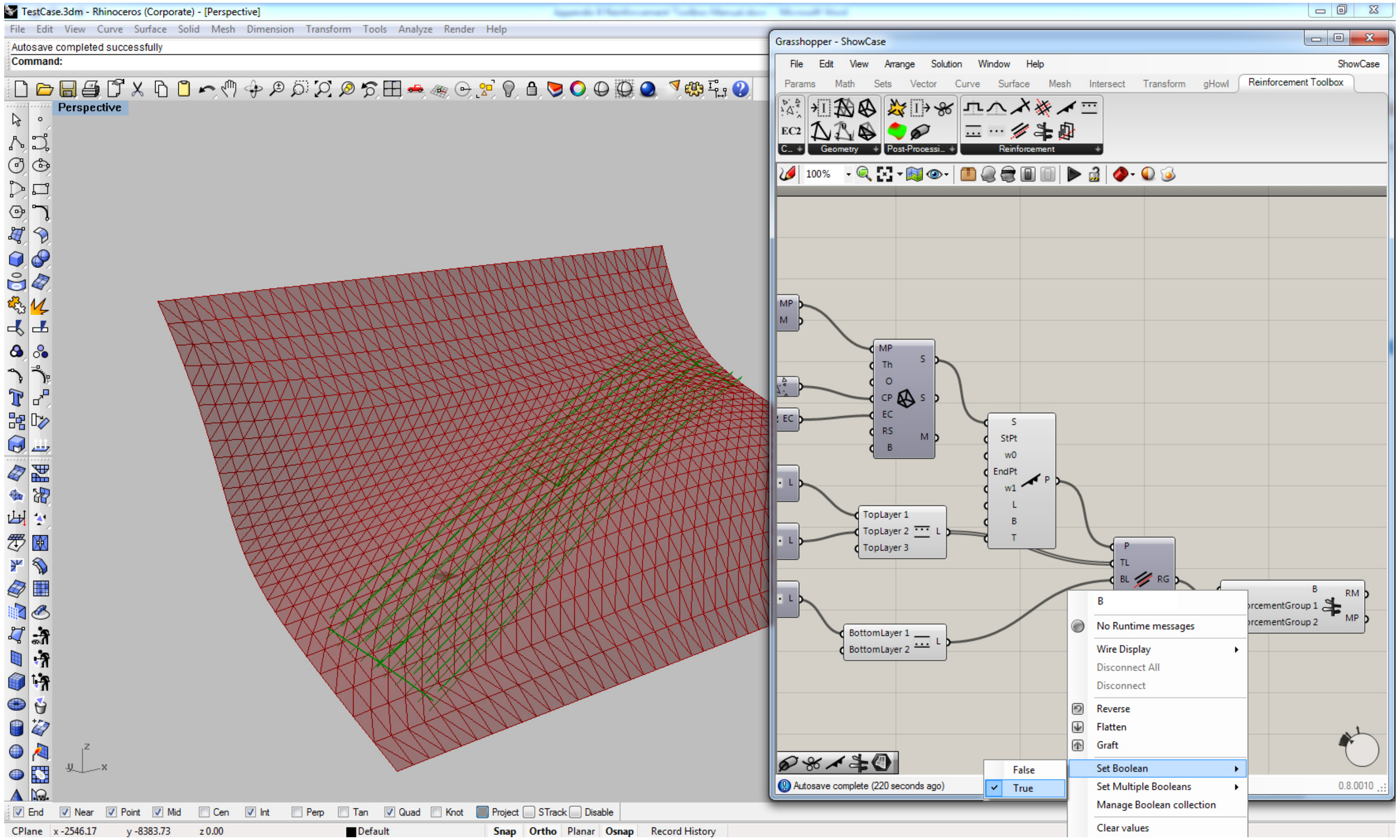


Figure B.10
Reinforcement visualisation in the Allocator component is set to 'true'.

4.

After having created the reinforcement model the profiles of the reinforcement bars can be visualized. The pipe component takes a reinforcement model and creates the reinforcement bar profiles according to the assigned diameter, see Figure B.11.

Figure B.11
The Pipe component draws the profiles of the reinforcement.

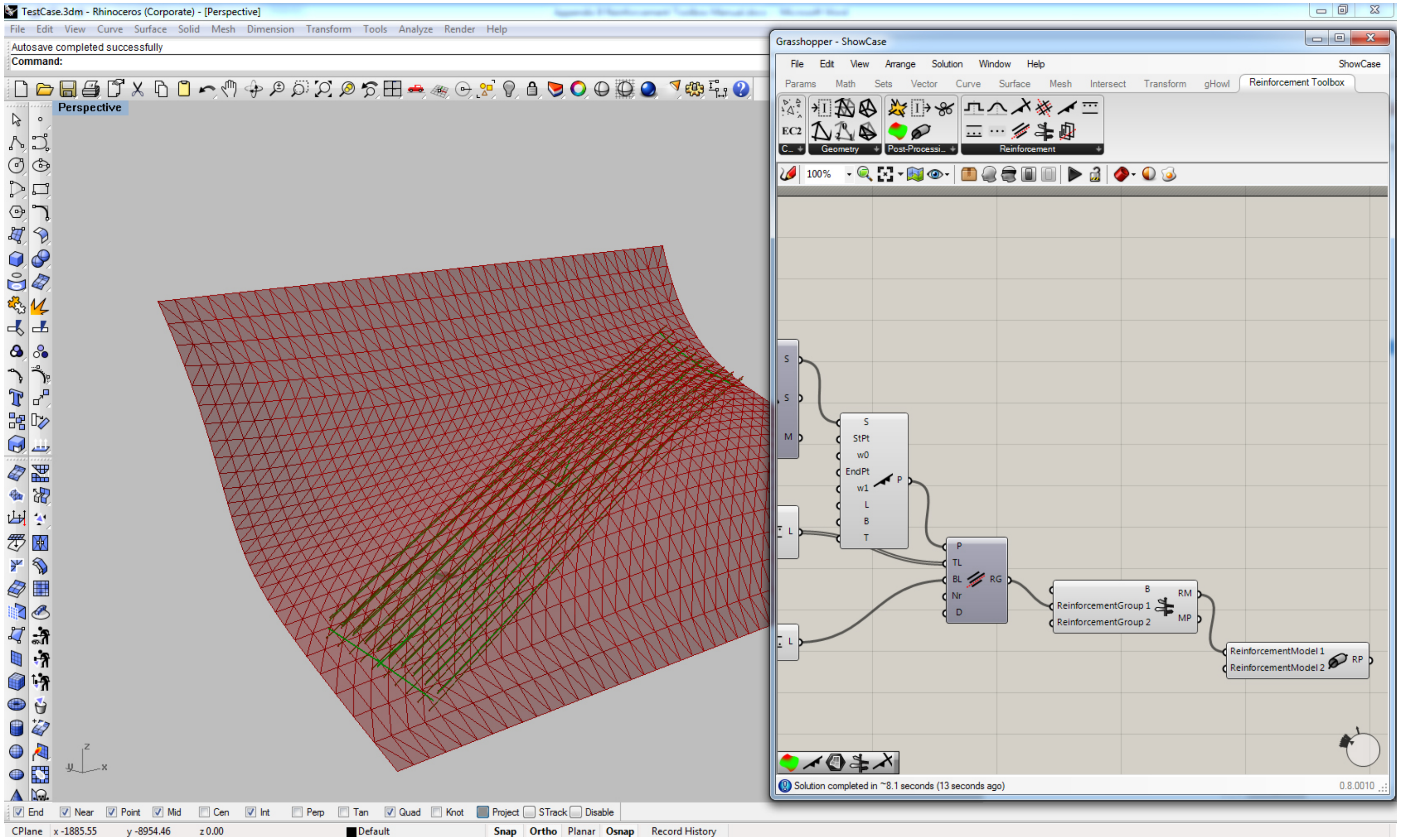
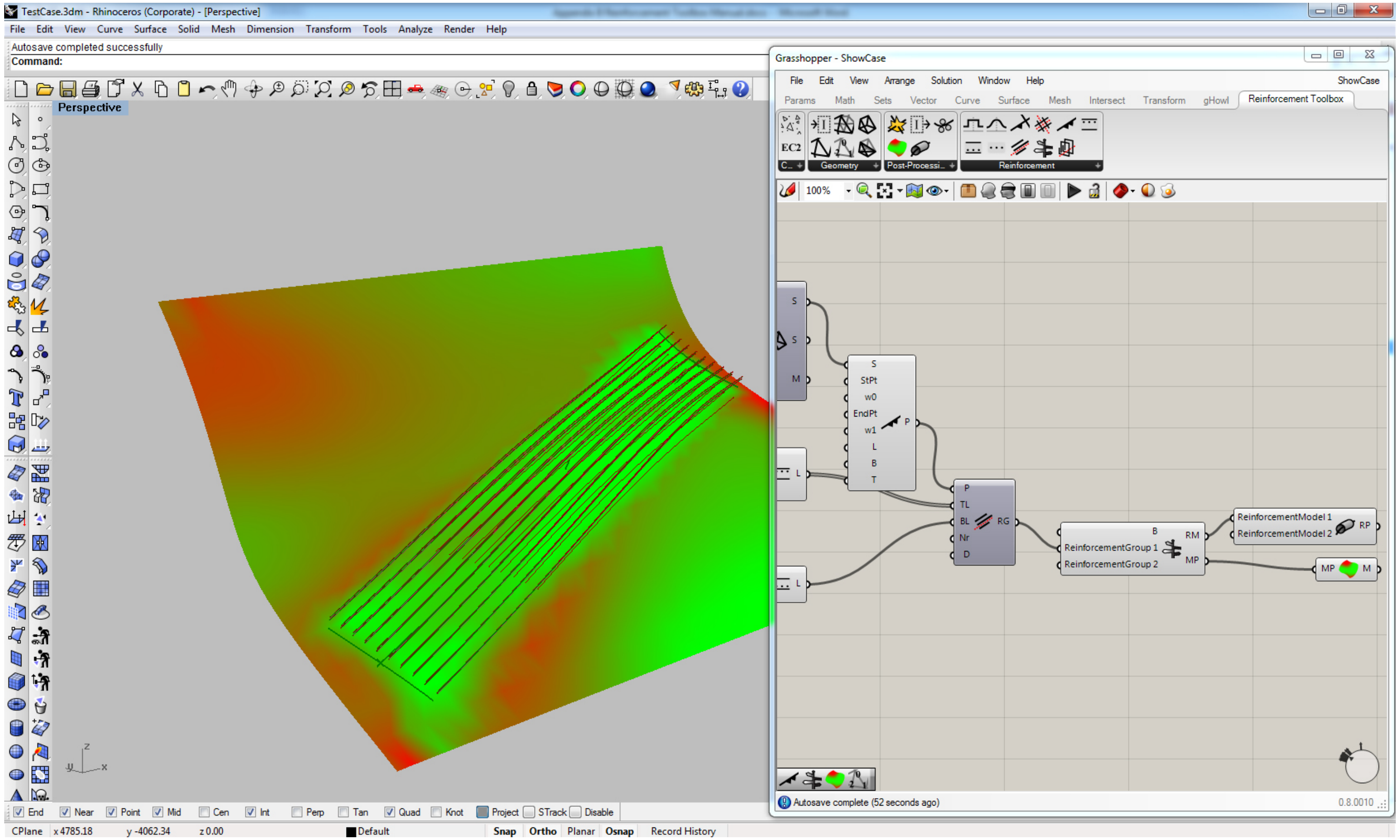


Figure B.12
The ‘Evaluate Reinforcement component’ compares the created reinforcement model against the indicated steel quantities from InfoCAD, and provides visual feedback.

5.
In order to check the created reinforcement model against the quantities indicated by InfoCAD the Reinforcement Toolbox incorporates an Evaluation component. Input is the created reinforcement model, see Figure B.12.



Creating a Reinforcement Mesh Group

The process of creating a Reinforcement mesh group follows the same lines as that of the longitudinal reinforcement group described above. The differences in assigning the mesh path and reinforcement mesh group (step 1 and step 2) are addressed below.

1.

In case of a Reinforcement mesh path the area for which the reinforcement mesh is created is visualized, this is depicted in Figure B.13.

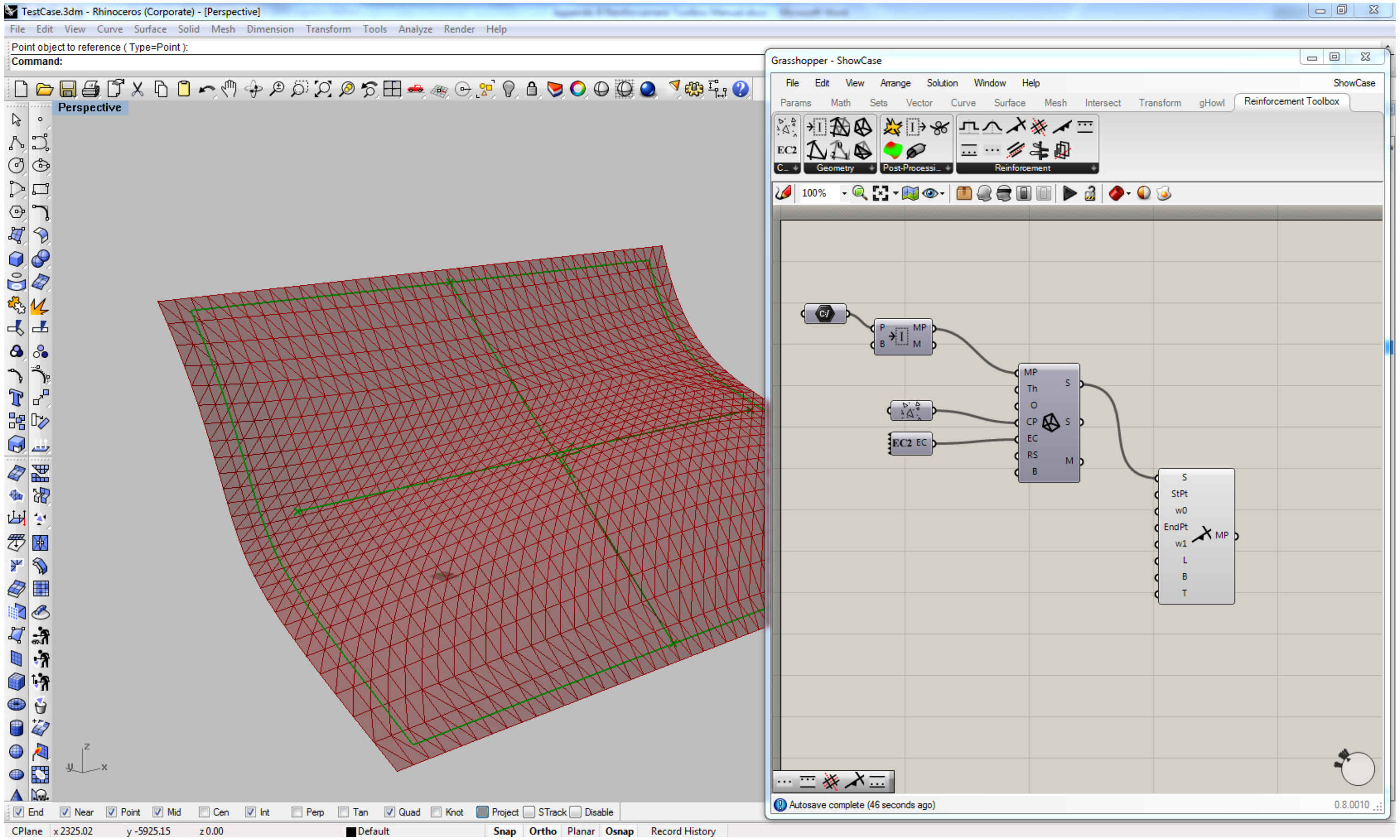
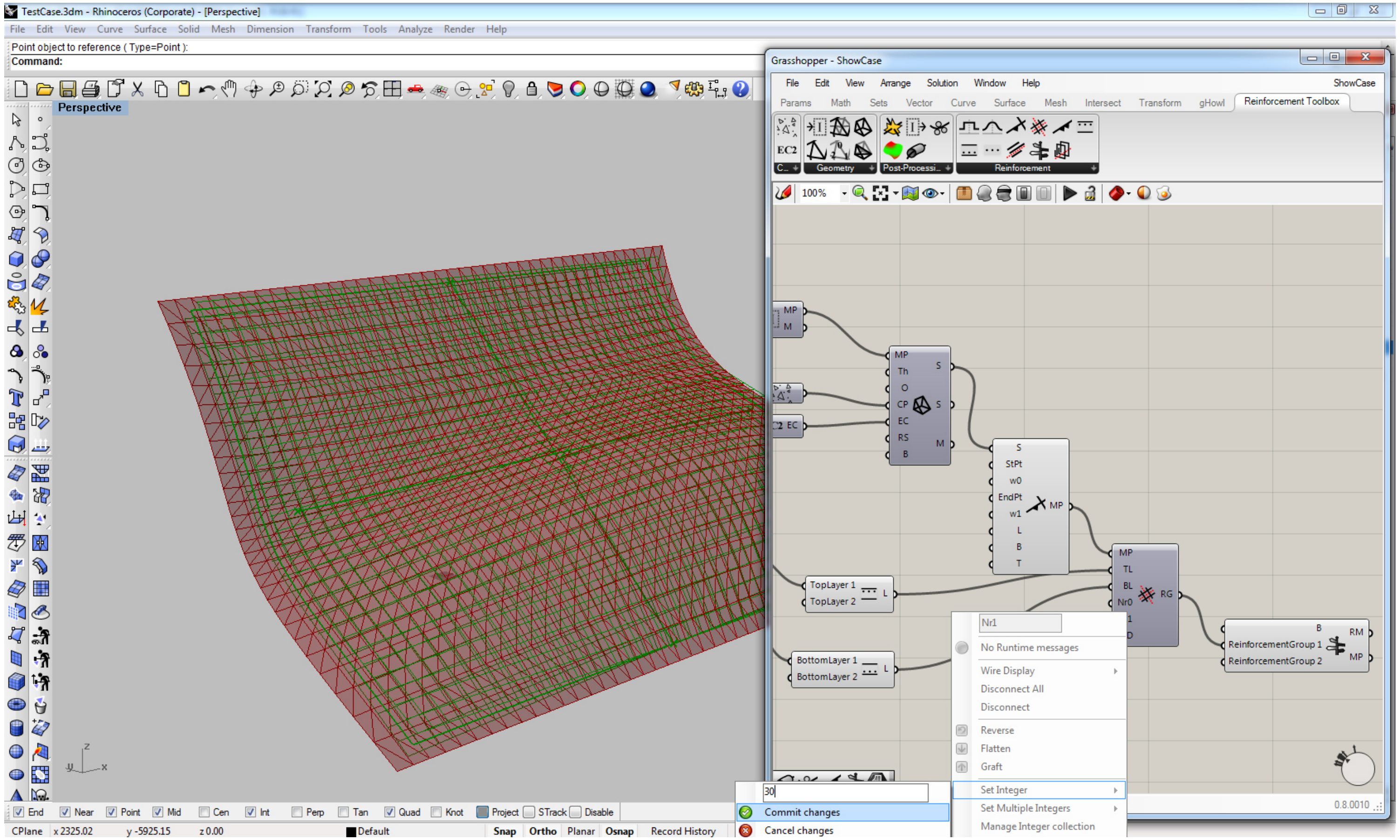


Figure B.13
The Reinforcement mesh path visualization shows the area for which the reinforcement mesh is created.

Figure B.14
The Reinforcement mesh component requires the number of reinforcement bars in two directions.

2.
The reinforcement mesh component requires the number of reinforcement bars set in two directions, see Figure B.14. The reinforcement allocator displays the reinforcement meshes.



APPENDIX C **FEEDBACK FROM ENGINEERS**

Is, in your opinion, the Reinforcement Toolbox of added value to the current range of reinforcement tools? For what reason?

- it provides a good tools to visualise a rebar pattern for complex geometries.
- it is interactive with FEM results of complex systems.

Would you consider using the Reinforcement Toolbox when designing reinforcement in curved surface structures? For what reason?

yes

To gain a better understanding of how actually rebar will look like in complex geometries.

What do you think are the main limitations of the toolbox? Which functionality would you like to see incorporated in future versions?

main limitations:

- detailing criteria such as overlap, hairpins etc not take into account. → engineering required.
- * - output for reinforcement not provided.
  (how will the rhino model of the reinforcement actually be built?)
- * - on screen fiddling with the provided rebar not possible
  " engineering.

* : to be incorporated in future versions.

Succes met het afronden!

Groet Jules.

Is, in your opinion, the Reinforcement Toolbox of added value to the current range of reinforcement tools? For what reason?

DE TOOLBOX MAAKT HET EENVOUDIGER OM RELATIEF SNEL COMPLEXE WAPENINGS PATRONEN TE BEPALEN EN TE VISUALISEREN.

Would you consider using the Reinforcement Toolbox when designing reinforcement in curved surface structures? For what reason?

JA, ZIE REDEN BOVENSTAAND ANTWOORD

What do you think are the main limitations of the toolbox? Which functionality would you like to see incorporated in future versions?

- DE TOOL BESLAAT SLECHTS VLAKKEN, DE ~~[illegible]~~ ZEER COMPLEXE DELEN (DE AANSLUITINGEN) ZIJN (NOG) NIET MOGELIJK.

- EXPORT NAAR EEN BIM ZAL EEN GROTE TOEGEVOEGDE WAARDE HEBBEN
- " " " BUIGCENTRALE " " " " "

Is, in your opinion, the Reinforcement Toolbox of added value to the current range of reinforcement tools? For what reason?

Yes, as a tool it can help enormously in understanding the reinforcement of a difficult surface and it easy to simply model normally time consuming alternatives.

Would you consider using the Reinforcement Toolbox when designing reinforcement in curved surface structures? For what reason?

Yes, to help understanding possible solutions and to assist in presenting it.

What do you think are the main limitations of the toolbox? Which functionality would you like to see incorporated in future versions?

Edges and other disturbances can determine the choice of lay out of the reinforcement. It seems a good approach not to include this in the current tool but should be considered in future versions