SUSTAINABLE TIMBER BRIDGE DESIGN WITH DESIGN-TO-BUILD WORKFLOW INVOLVING HUMAN-ROBOT COLLABORATION

Master Thesis Research

Jun Wen Loo

Class of 2022

MSc in Architecture, Urbanism and Building Sciences (Building Technology)

Technical University of Delft (TU Delft)

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Mentors:
Serdar Asut | Design Informatics, TU Delft
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I would like to thank my parents for providing me with this wonderful opportunity to conduct my masters education abroad, in TU Delft. I cherish this opportunity and I want them to know they deserve my eternal gratitude for they have relentlessly provided me with love, care and support in every manner, shape and form possible.

Furthermore, pursuing higher education in a foreign country amidst a pandemic has been trying and at times isolating. It is not without the support and care of my circle of friends - who has really become my "2nd family" in Delft - that the challenges becomes manageable, relatable and also fun. So thank you for being in my life and making things vibrant amidst the bleakness of the pandemic and academic stress.

This thesis would also be impossible without the patient guidance of my mentors and advisors, their forthrightness and experience has enriched it manifold.

Alas, this is just the beginning of the next chapter of my life, so I am grateful with how far an education in Bouwkunde, TU Delft has brought me. I look forward to build a better world through design!

ABSTRACT

Buiksloterham, situated on the northern banks of the IJ river, is undergoing massive urban redevelopment as it transits from an industrial town to a mix-use development. However the lack of connectivity within the neighbourhood has become an ever more prominent problem for its growing residents and workers. Gemeente Amsterdam has proposed the construction of 7 new bridges in Buiksloterham to improve the local connectivity while staying rooted in circular and sustainable goals laid down in the green masterplan, Groenevisie 2020-2050. As such, the thesis proposes the construction of a novel timber structure embodying the circular vision of design for disassembly, using renewable and bio-based materials. The bridge will also serve as a landmark for the community, symbolizing the potential of timber architecture in the digital era.

Furthermore, as digital technology ushers in the 4th industrial revolution, the growing complexity and inter-dependencies in computational design of structures and buildings is no longer sufficiently represented in static plans (Helm et al., 2017). Since the inception of digital technology into timber fabrication processes in 1980s, it has transformed hand-tools to multi-axis machines, enabled further by parametric models, to produce highly varied components without lost in efficiency (Buri & Weinand, 2013). Despite the high degree of automation in fabrication, the assembly of these structures are still largely manual (Helm et al., 2017), limited by the scale of the components, machines involved and transportation required.

Should the digital information of fabrication and assembly be directly transmitted to the robots and implemented, this would allow for a seamless workflow (Bachmann, 2009) without the intermediary manual process where digital information and assemblage efficiency could be lost. Tapping on the strengths of robotic systems in processing large amount of data, having high level of precision as well as being capable of taking over dirty, dangerous and mundane tasks, this presented the opportunity for integration of Human-Robot Collaboration into the construction system (Reinhardt et al., 2020).

Therefore the focus of this thesis aims to develop meaningful and productive Design-to-Build workflow involving HRC in the construction process of a timber bridge structure in Buiksloterham, Amsterdam.

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Chapter 1:

INTRODUCTION

1.1 SCOPE

Sustainable Timber Bridge Design with Robotic Construction Workflow

This master thesis titled "Sustainable Timber Bridge Design with Design-to-Build Workflow involving Human-Robot Collaboration" is primarily focused on HRC in the design-to-build workflow of bridge design. The thesis falls under two main Chair in TU Delft MSc. Architecture (Building Technology) namely Design Informatics (DI) and Structural Design & Mechanics (SDM). It is mentored by Serdar Asut (DI) and Joris Smits (SDM). External advisors involved in contributing to this thesis includes Cyrus Clark, Lead Designer of Public Space in Gemeente Amsterdam, as well as Laurane Néron, Structural Engineer of Timber Engineering in NEY & PARTNERS WOW.

The Introduction Chapter will provide the main overview of the thesis beginning with an understanding of the Problem Statement which leads to the formulation of specific Research Questions. A Research Methodology outlining the 4 main phase of the thesis progression will be elaborated and concludes with a Design Assignment indicating the intended outcome of the thesis.

1.2 PROBLEM STATEMENT

Lack of Urban Connectivity & a need for effective automated Design-to-Build Robotic Processes

The problem addressed in this thesis stemmed from 2 main areas; firstly the lack of urban connectivity in Buiksloterham and secondly the need for an effective workflow conversion of digital design to a production process involving human-robot collaboration.

Urban Redevelopment of Buiksloterham

With the rapid urban development in the northern bank of the IJ in Amsterdam, its transition from an industrial town to a mix-use development underscores the growing need for better urban connectivity. Buiksloterham, is amongst the many neighbourhood on the northern bank of the IJ undergoing massive developments. The Amsterdam Gemeente (Municipality of Amsterdam) has identified in Bruggen Buiksloterham (Gemeente Amsterdam, 2021a) the need for seven separate bridges to be design and constructed in accordance to the circular vision as laid out in Groenevisie 2020-2050 (Gemeente Amsterdam, 2020b) as well as Circular Buiksloterham (Metabolic et al., 2014). Planned to be built in phases, a tender (Gemeente Amsterdam, 2021) has been recently issued on 7th December 2021 for the design and construction of the first of seven bridges, connecting Asterweg and Grasweg across Tolhuiskanaal Oost.

This site is thus chosen for this thesis project because of the alignment of the municipality's aim for circular construction and materials with the thesis's exploration of timber bridge structures. Furthermore, with a main span of 38m and use as a pedestrian and cyclist bridge, this sets manageable site and functional requirements to design and test a novel timber structure built with robotic processes.

Fig 1.1: Buiksloterham, North Amsterdam, Netherlands.

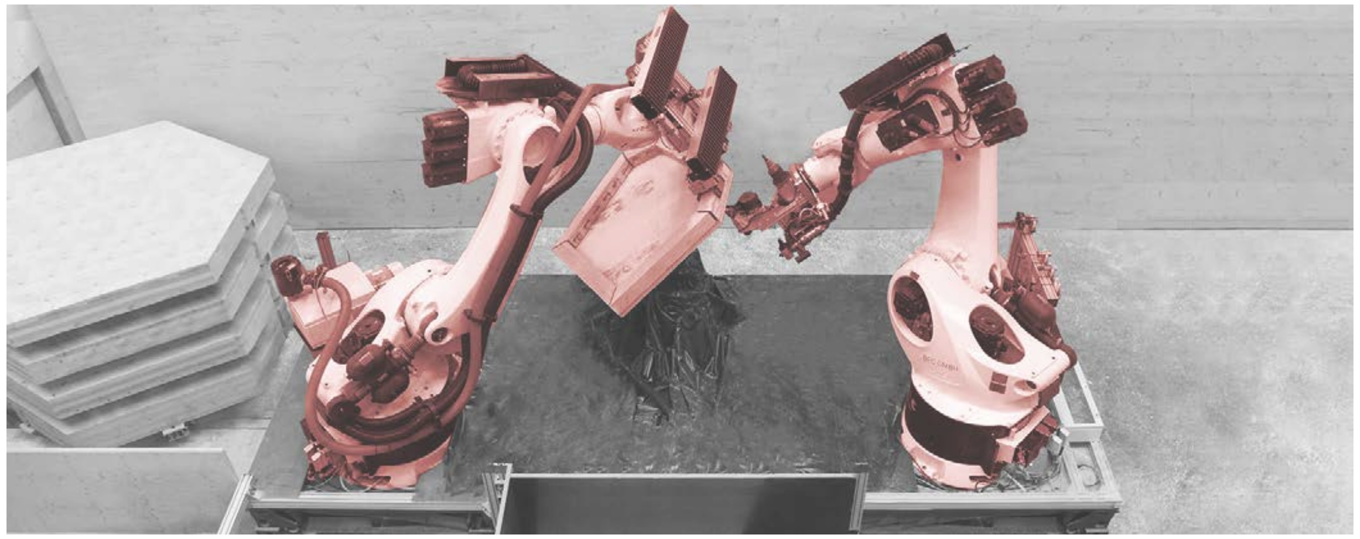

Fig 1.2: Robotic Fabrication & Assembly of timber shell, Buga Pavillion 2019.

A need for effective Human-Robot Collaboration in the Design-to-Build Robotic Process

The second problem stems from the lost of information and efficiency between digital fabrication and its subsequent assembly which is typically manual. The conversion of digital assembly information into analogue plans for the worker to interpret and assemble requires a translation of highly precise information into less precise manual instructions. Furthermore, with the growing complexity and inter-dependencies in computational design of structures and buildings, it is no longer sufficient to represent it in static plans (Helm et al., 2017).

Since the inception of digital technology into timber fabrication processes in 1980s, it has transformed hand-tools to multi-axis machines, enabled further by parametric models, to produce highly varied components without lost in efficiency (Buri & Weinand, 2013). Despite the high degree of automation in fabrication, the assembly of these structures are still largely manual (Helm et al., 2017), limited by the scale of the components, machines involved and transportation required.

Should the digital information of fabrication and assembly be directly transmitted to the robots and implemented, this would allow for a seamless workflow (Bachmann, 2009) without the intermediary manual process where digital information and assemblage efficiency could be lost. Tapping on the strengths of robotic systems in processing large amount of data, having high level of precision as well as being capable of taking over dirty, dangerous and mundane tasks, this presented the opportunity for integration of Human-Robot Collaboration into the construction system (Reinhardt et al., 2020). There has been a prominent rise in development of collaborative robots or CoBots with multimodal interactive capabilities to translate a complex range of human interactions into digital signals in improving multimodal interactions (Andraos, 2015; Dubor et al., 2016; Galin & Mamchenko, 2021; Rossi & Nicholas, 2020). With CoBots developing firms such as Baxter by Rethink Robotics, iiwa by KUKA and YuMi by ABB and research groups from ETH Zurich, ICD Stuttgart, Carnegie Mellon University and MIT pushing the boundaries of HRC, it presents a promising field of exploration to develop a new construction workflow involving HRC.

Thus the focus of this thesis aims to develop meaningful and productive Design-to-Build Workflow involving HRC in the construction process of a timber bridge structure in Buiksloterham, Amsterdam.

1.3 RESEARCH QUESTIONS

Timber bridge design with Design-to-Build workflow involving HRC

Main research question:

How can we develop an architectural design with a design-to-build workflow by integration of human-robot collaboration in the construction of a timber bridge in Buiksloterham, Amsterdam?

Keywords:
bridge design, design-to-build workflow, human-robot collaboration (HRC), timber, buiksloterham

Sub-Research Questions (SRQ):

Site Design & Analysis

SRQ 1:
What are the site conditions and requirements of connecting Buiksloterham and how to design for it?

Structural Design

SRQ 2a:
What are the conventional typologies of timber bridge structures?

SRQ 2b:
What are the novel timber structures involving digital design, fabrication and assembly which has been explored?

Workflow Design

SRQ 3a:
What are the factors influencing the implementation of Human-Robot Interaction/ Collaboration in onsite and offsite building construction?

SRQ 3b:
What are the strengths of humans and robots respectively in the construction process?

SRQ 3c:
What is the design-to-build workflow for the proposed concept design?

SRQ 3d:
How can Human-Robot Collaboration be integrated into the construction workflow?

1.4 DESIGN ASSIGNMENT

Scope & Overview of Thesis Direction

Bridge Design for Buiksloterham's Urban Redevelopment

The design assignment is crafted in conjunction with Amsterdam Gemeente's Masterplan for Buiksloterham, specifically the creation of a bio-based and circular bridge across Tolhuiskanaal connecting Asterweg and Grasweg. The first part of the thesis will address the design and construction of a novel timber bridge structure in accordance to the design brief as outlined in Bruggen Buiksloterham Concept Programma van Eisen – A – Tolhuiskanaal Oost (Gemeente Amsterdam, 2021a) which will be further elaborated in *Section 3.2 Design Brief*.

Design-To-Build Workflow involving Human-Robot Collaboration (HRC)

In addition to the Programme of Requirements provided by Amsterdam Gemeente, another key aspect of the thesis involves the development of a Design-To-Build Workflow involving Human-Robot Collaboration (HRC) for the proposed bridge design. This will address SRQ 3a-d within this thesis. It is key to first establish an understanding into the factors influencing the implementation of HRC into the building construction phase. This provides the knowledge into the state-of-the-art development of HRC integration into the construction process where potential direction can be further explored within this thesis.

The Design-To-Build Workflow of the proposed bridge design will then be developed to identify which stages of construction is suitable for the integration of HRC. A set of evaluation criteria will be used to determine its suitability based on the nature of the tasks and the strengths and limitations of the agents involved in HRC.

With the specific construction processes within the workflow identified for HRC integration, a scaled model of the bridge segment will be developed into a prototype to demonstrate and evaluate the potential of the proposed HRC workflow.

Altogether, this will allow for a comprehensive design proposal fulfilling the requirements of the site while constructed with state-of-the-art robotic construction processes in achieving a novel timber bridge. Specific deliverables and deadlines will be specified in the following *Section 1.5 Research Approach*.

1.5 RESEARCH APPROACH

Timeline & Methodology

Phase:	Deliverables:	Methodology:	Week & Duration:
1 | Research; Site Analysis & Timber Structures	*Sub-Research Qns 1* - Site Introduction, Mapping & User Requirements - Design Brief - Climatic & Environmental Studies	Literature Review Site Mapping Data Analysis	Wk 1 - 10 (10 Wks)
	Sub-Research Qns 2a - Timber Properties - Conventional Timber Structures - Timber Design Strategies	Literature Review Case Studies	
	Sub-Research Qns 2b - Novel Timber Structures State-of-the-art Digital Design & Fabrication in Timber construction	Literature Review Case Studies	
2 | Design Phase; Bridge Design	*Sub-Research Qns 1* - Urban Site Strategy - Architectural Design Explorations & Strategy - Preliminary Structural Calculations - Key Design Details & Visuals	Research by Design Structural Simulations	Wk 6 - 14 (9 Wks)
3 | Design-To-Build Workflow & Analysis	*Sub-Research Qns 3a-d* - Design-To-Build Workflow of Design - Sub-Process for Robotic Prototyping - Computational Workflow (e.g RoboDK, GH) - Material Order	Research by Design Computational Tools Robotic Arm Application	Wk 12 - 18 (7 Wks)
4 | Robotic Construction & Prototyping	*Sub-Research Qns 3a-d* - Prototypical Setup Design - Testing equipment & Prototyping Assembly - Prototype Model of a Bridge segment	Experiment & Testing	Wk 16 - 26 (10 Wks)
5 | Final Consolidation	- Thesis Report - Reflection & Evaluation - Presentation - Models Preparation	Documentation Refinement & Consolidation	Wk 25 - 26, Wk 29 - 30 (4 Wks)
Key Milestones	P1 - Wk 1 (16/11/21) P2 - Wk 11 (26/01/22) P3 - Wk 19 - 20 P4 - Wk 27 - 28	P5 - Wk 31 - 33	

1.6 KEYWORDS & DEFINITIONS

Glossary

Trees, Wood & Timber related definitions

Within this report, wood is used to describe unprocessed logs harvested from trees while timber refers to wood which has been processed into planks, veneers or strands by sawing, planning, peeling, stranding, drying cutting and sorting.

Adsorption

The property of a solid or liquid to attract and hold to its surface a gas, liquid, solute, or suspension.

Desorption

The process of removing an adsorbent from an adsorbate (a substance that is adsorbed).

Moisture Content

Moisture Content (MC) of timber is indicated by u (moisture ratio) and is determined by the ratio of the weight of water in wet material to the weight of the dried wood after drying at 103°C for 24 hours (Swedish Wood, 2016).

$$u = \frac{m_u - m_{dry}}{m_{dry}} \cdot 100$$

Equation 1: MC equation, u = Moisture Ratio, m_u = Mass of Moist Wood, m_{dry} = Mass of Dry Wood

Engineered Timber / Mass Timber / Mass Engineered Timber

Engineered timber refers to engineered wood products with improved structural integrity and can be used for various types of developments such as infrastructure, commercial, residential and institutional buildings (BCA, 2018). Engineered timber is commonly made from softwood and examples of it includes Cross Laminated Timber (CLT), Glue Laminated Timber (glulam) and Laminated Veneer Lumber (LVL).

Conventional Timber structures

Within the scope of this thesis report, conventional timber structures refers to structures constructed primarily from timber or engineered timber which can be well categorized into the well-developed structural typologies such as slab, beam, truss, arch, suspension, cable-stay, rigid frame, monocoque and tube. This was defined to distinguish between the novel timber structures which are derived from the combination of the conventional structural typology or entirely unique typology.

Novel Timber Structures

Within the scope of this thesis report, novel timber structures refers to structures constructed primarily from timber or engineered timber which are a combination of well-developed structural typologies or a structural system which has been rarely developed for a particular application. Typically, these includes pioneering timber structures which makes use of the potential of digital design and fabrication and state-of-the-art construction technology.

Design-to-Build or Design-to-Production Workflow

A workflow which describes the process and parameters involved in converting a design into fabrication, construction and assembly procedures in order to realise a built version of it.

Digital Design and Fabrication

(Definitions below are extracted from TS/ISO 15066:2016)

Human-Robot Collaboration (HRC) / Interaction (HRI)

Human-robot collaboration is defined in TS/ISO 15066:2016, is an operation where a human worker and a purposely designed robot system can perform tasks in a defined collaborative space concurrently during a production operation.

Collaborative Workspace

Space within the operating space where the robot system (including the workpiece) and a human can perform tasks concurrently during production operation.

Collaborative Robots / Cobots

A robot that can (Capable) for use in a collaborative operation.

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Chapter 2:

LITERATURE REVIEW & CASE STUDIES

2.1 WHY TIMBER?

Suitability of timber for environmental, robotic & historical relevance

Timber is the oldest building material of the human civilization (Schweitzer, 2004). Its universal applications from everyday objects to musical and cultural instruments as well as its pivotal role as a building material has largely propagated the development of civilizations and cultures around the globe. Although the usage of timber in our built environment was abruptly dropped by the late 19th and into the 20th century (Kaufmann et al., 2018), there is a resurgence of interests in building with timber, more specifically engineered timber or mass timber in the 21st century. The practice of sustainable forestry formulated by Hans Carl von Carlowitz around 1700s to “not cut more than will regrow” is a pre-cursor to organizations like Forest Stewardship Council (FSC) and Programme for the Endorsement of Forest Certification (PEFC) to regulate and certify timber from sustainably managed forests. This provided a good way to curb the use of timber from illegal logging and deforestation.

Timber as Renewable Resource

Timber is a renewable resource which stores carbon throughout its lifetime. This aligns well with the urgent need to reduce carbon emissions in our built environment to mitigate the impacts of climate change (ARUP, 2019). Furthermore, timber can be cascaded into multiple applications before being incinerated to generate energy (Lugt & Harsta, 2020), as shown in Fig 2.1. This happens while more trees are grown during the same period, thus making it a regenerative material suitable for a circular economy. However, it is noteworthy that the suitability of timber usage depends on the availability of sustainable timber sources in the region, thus it would be superfluous to assume it is appropriate for all regions. As this thesis project is situated in the Netherlands where sustainably managed forestry and timber resources are in close proximity, this makes it a suitable building material to achieve the ambitious goals laid out in Groenevisie 2020-2050 by Gemeente Amsterdam (2020).

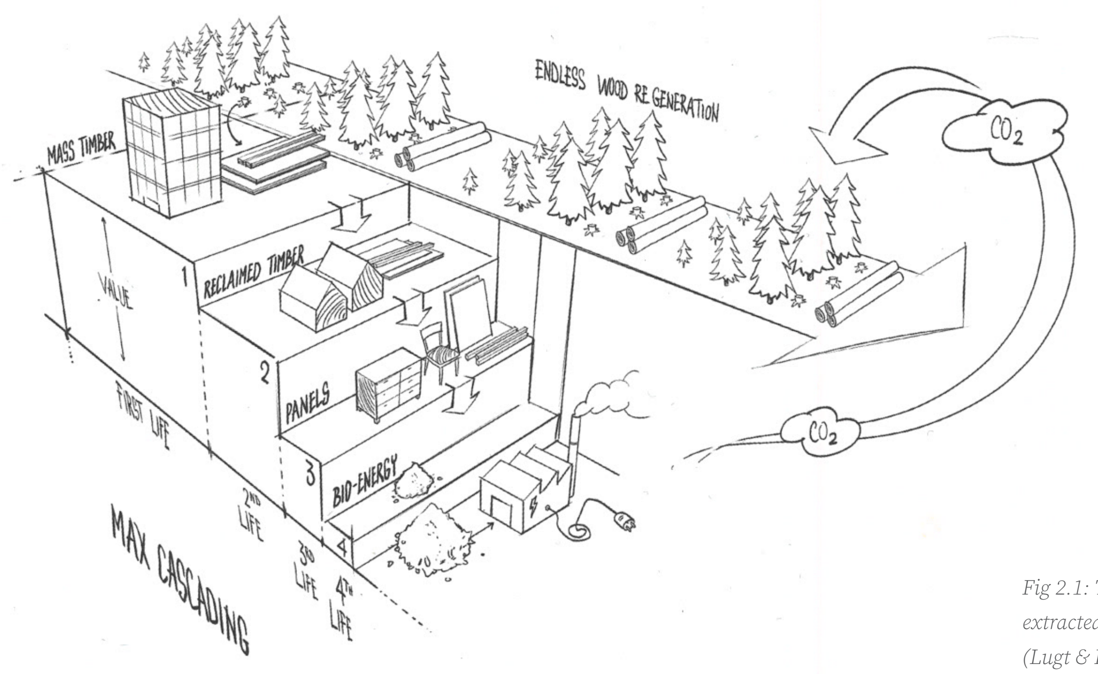


Fig 2.1: Timber cascade diagram, extracted from Tomorrow's Timber (Lugt & Harsta, 2020).

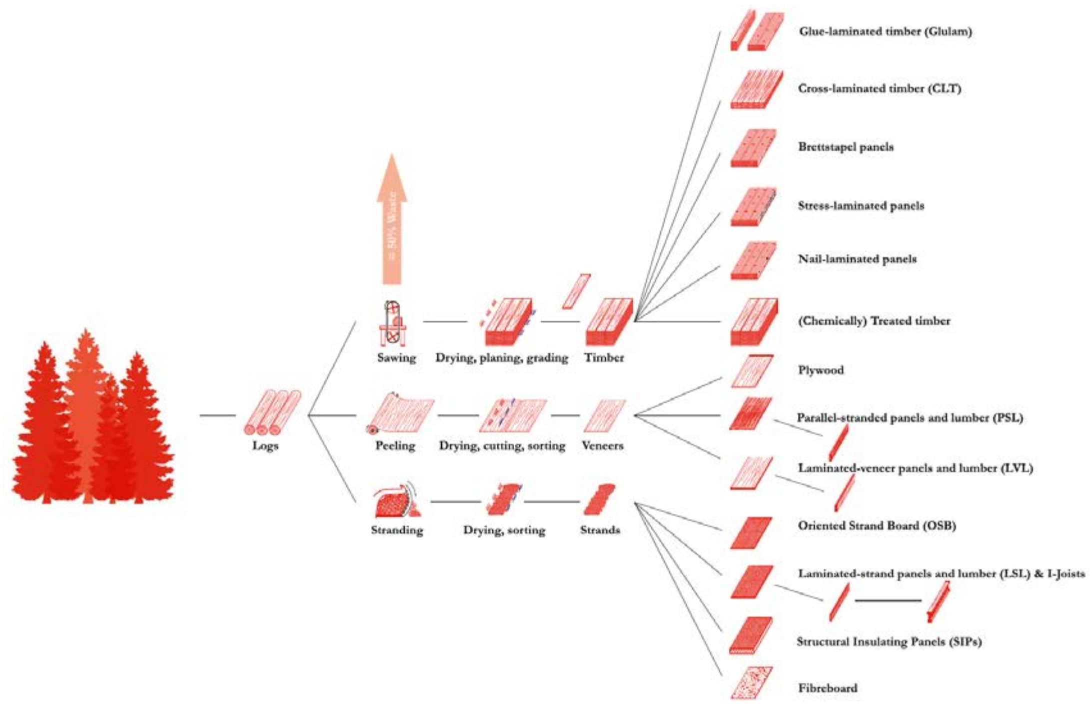


Fig 2.2: Timber processes & products. Extracted from The wood from the trees: The use of timber in construction. (Ramage et al., 2017)

Engineered Timber development

Furthermore, the development of stronger, more homogenous engineered timber in 1990s has made it a viable substitute for building materials with high carbon footprint such as concrete and steel. With 20% higher strength-to-weight ratio than structural steel, four times lighter in mass and almost two times more thermally resistant than concrete (Granta Design Limited, 2009), it is highly suitable in both structural or non-structural applications. A wide range of engineered timber products assembled from timber planks, veneers or strands (Fig 2.2) are produced, differentiated by their strength, fiber orientations and areas of application.

Industry 4.0

As the fourth industrial revolution, Industry 4.0, transforms the building and construction industry beyond automation to mass customization by "digitally controlled production machines and parameterizable design tools" (Buri & Weinand, 2013), the manufacturing process departs from pure automation and having human operators providing "one-time machine setting". Rather, the digital information inherent to a workpiece is directly transmitted to the machine, allowing for a seamless translation of design to manufacturing and construction instructions which are interpreted by machines to produce highly adaptable and individualized components without a lost in efficiency (Willmann et al., 2019).

With current development, digital fabrication systems are able to adapt to the heterogeneity and anisotropic qualities of wood and algorithmically adjust or optimise fabrication processes (Menges et al., 2016), thereby articulating it in the tectonics and constructional logic of the design. The tectonics of timber structures represents how the construction and assembly of it takes an active role in shaping and becoming an integral part of its design (Buri & Weinand, 2013). Thus it is expected that the development of digital fabrication and construction processes will play a pivotal role in defining the expression and possibilities of timber structures moving forward. It is therefore crucial within this thesis to explore how this reciprocal relationship between construction technology and design can be expressed and further developed in the context of a bridge.

2.2 TIMBER MECHANICAL PROPERTIES

Understanding the Compressive, Tensile and Shear Strength of Sawn Timber

An integral part of designing in timber is the understanding that it is an anisotropic material with varying mechanical strength in different directions. This differentiation in strength arise from the biological composition and arrangement of its fibres as shown in Fig 2.3. Simply, wood can be described as a bundle of tubes oriented along the length of the tree. This gives it high compressive and tensile strength parallel to the fibre (Fig 2.4) compared to its significantly low stiffness perpendicular to the fibre.

This influences the design of timber structures as the close alignment of the force flow along the fibre of the timber member is most effective in transferring loads. This is true when anisotropic timber products like sawn timber, glulam, laminated-veneer lumber (LVL) or oriented-strand boa rd (OSB) are used. CLT on the other hand, which is assembled from alternating layers of timber planks oriented in 90 degrees to each other, gives it isotropic properties, effective in transferring loads from all principal directions. Therefore, the types of timber products used will depend on the loading conditions of the design. In this thesis, the choice of timber products will also be influenced by the design principles outlined in *Section 2.3.3 Design for Disassembly*.

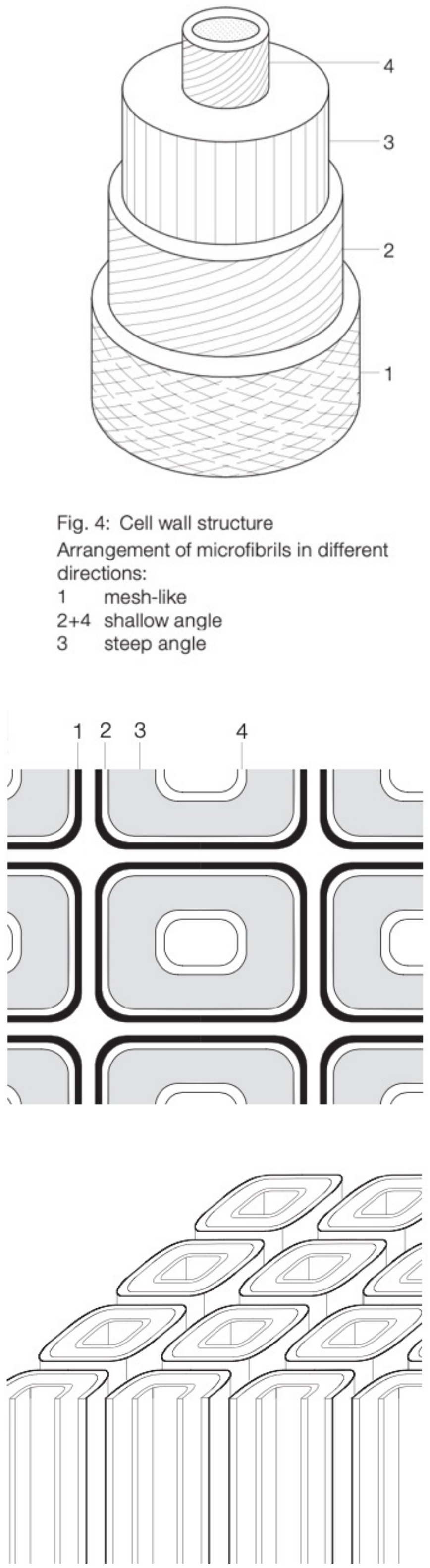


Fig 2.3: Cellular structure and composition of wood. Extracted from Timber Construction Manual (Herzog et al., 2008).

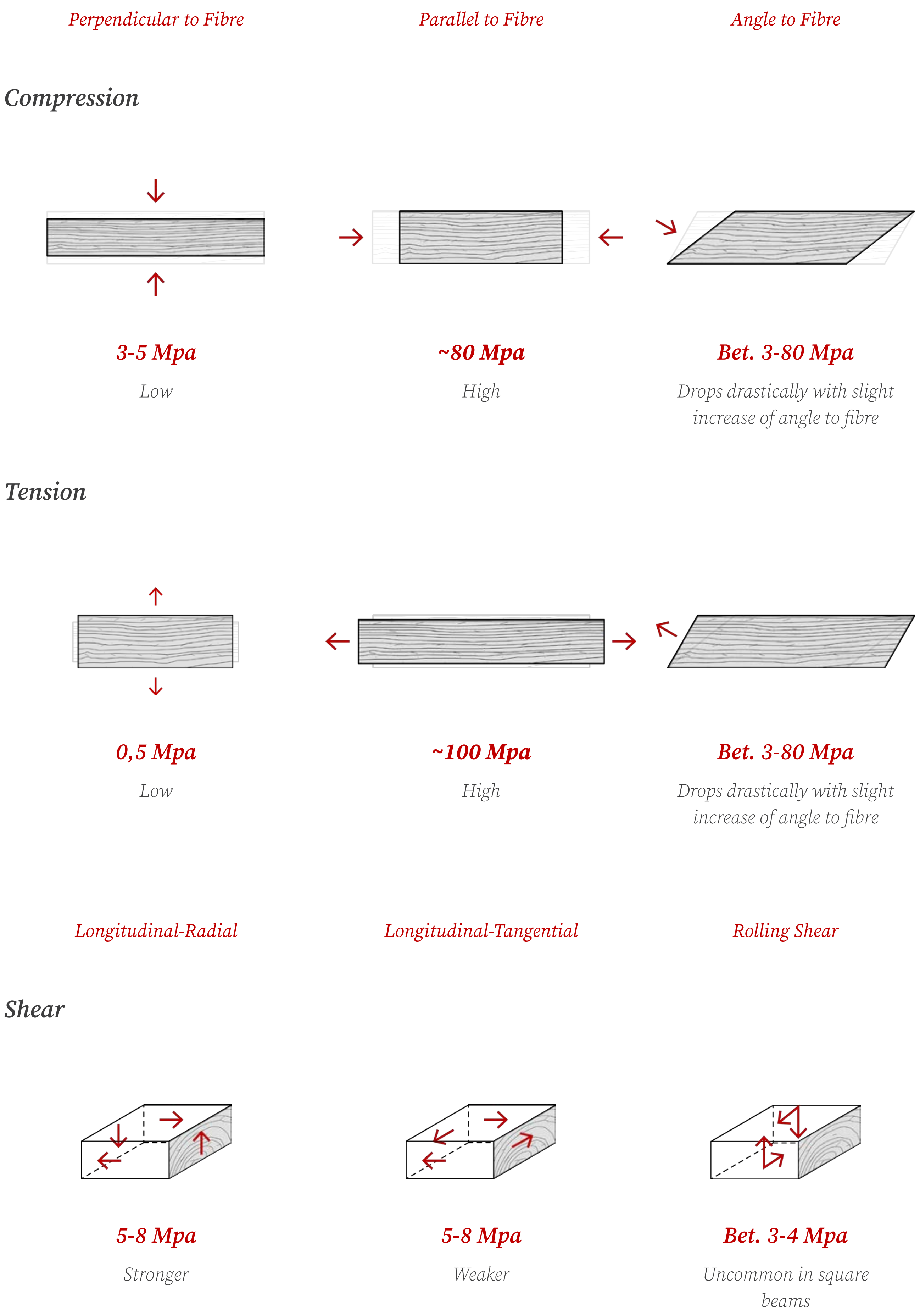


Fig 2.4: An overview of timber's strengths in various directions, with data extracted from Design of Timber structures, Volume 1 (Swedish Wood, 2016).

2.3 TIMBER DESIGN STRATEGIES

Moisture Management, Connections & Supports, Design for Disassembly

2.3.1 | Moisture Management

Timber is a natural material which must be dried before any durable form of applications. Presence of excessive moisture is the pre-requisite for biological degradation by fungi, insects and other organisms. As the rising levels of moisture has direct correlation to declining strength and stiffness of timber (Swedish Wood, 2016), it is stipulated under the European standards that only timber with Moisture Content (MC) less than 20% is allowed for use as structural material (Swedish Standards Institute (SIS), 2017).

Moisture Content (MC) of timber is indicated by u (moisture ratio) and is determined by the ratio of the weight of water in wet material to the weight of the dried wood after drying at 103°C for 24 hours (Swedish Wood, 2016). It can be calculated using Equation 1:

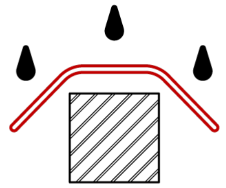
$$u = \frac{m_u - m_{dry}}{m_{dry}} \cdot 100$$

Equation 1: MC equation, u = Moisture Ratio, m_u = Mass of Moist Wood, m_{dry} = Mass of Dry Wood

Equilibrium MC can be achieved when the wood has sufficiently balanced adsorption and desorption to ambient conditions. It will fluctuate with changes in Relative Humidity (RH) and temperature as wood is a hygroscopic material, however when kept below 20%, growth of fungi and its subsequent decay can be prevented (Swedish Wood, 2016).

Prior to assembling a timber structure, it is pertinent to ensure that the MC of the newly installed timber structure is as close to the equilibrium MC at the installed location to prevent splitting and distortion (Wiegand, 2008). After the timber structure is assembled, it will solely rely on the moisture management strategies which are integrated into the design to maintain a stable equilibrium MC. With proper moisture management strategies in place and MC of the timber kept under 20%, insects, fungi, and other dimensional instabilities can be avoided, improving the long term durability of the timber structure.

Therefore during the design phase, sufficient moisture management strategies are required to be integrated into the design of timber structures (Volz, 2008). The strategies are Deflection & Drainage, Ventilation and choosing a Durable Material, ranked in decreasing order of effectiveness. These individual factors will then be further explained with 4 case studies of conventional bridge structures in *2.4 Conventional Timber Structures*.



2.3.1.1 | Deflection & Drainage

A control for moisture ingress into timber structures by re-directing or collecting moisture accumulated on the structure and expelling it away from the structure by means of gravitational flow. This prevents stagnation of water on timber and shedding it before it is adsorbed, which can subsequently increase MC of it. Deflection and drainage strategies is most effective when applied in various scales – from the macro level down to the micro level of joints and individual timber members if it is exposed to weathering (Volz, 2008). For instance in the case of *2.4.2 Case Study 2: Neckartenzlingen Bridge* and *2.4.4 Case Study 4: Centre Pompidou-Metz*, an overhang and canopy membrane respectively is installed as a macro level deflection and steel flashings and larch cladding as micro level deflection strategy in *2.4.1 Case Study 1: Bow River Footbridge* and *2.4.3 Case Study 3: Dunajec Bridge*.

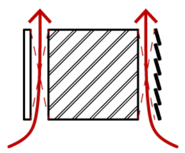
Due to the biological composition of wood, timber is more susceptible to moisture ingress at the end grains – direction parallel to the grain – compared to the longitudinal side – direction perpendicular to grain. Hence it is crucial to pay extra attention to protecting the end grain by means of coverings or coating whenever possible.

Covering & Sloping

- Overhanging eaves
- Weathering boards & strips
- Flashings & drip edges

Isolation

- Elevated from base

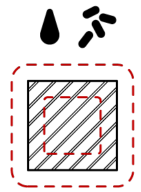


2.3.1.2 | Ventilation

The removal of moisture within the timber structures by air movement and vapour diffusion into the surrounding air. This requires ventilation space for air to enter and leave the structure. This can easily be achieve by introducing air gaps which allows for sufficient ventilation, however the effectiveness of can be limited by the vapour permeability of the timber used, as listed below.

Factors affecting vapour permeability:

- Moisture/vapour barrier coating & installations
- Air gap between exterior cladding & timber structure
- Air gap between timber members



2.3.1.3 | Durable Material

The use of timber species with sufficient tolerance to moisture and biological decay/agents as required in the location of use is key to its long-term durability and lifespan. Timber can be treated thermally or chemically to enhance its resistivity to moisture and biological decay, which are listed below.

Timber Species

- Resistance to moisture ingress (Corsican Pine, Maritime Pine, Norway Spruce, Larch, Oak etc.)
- Resistance to fungal/insect attack (Robinia, Sweet Chestnut, Yew, Oak etc.)

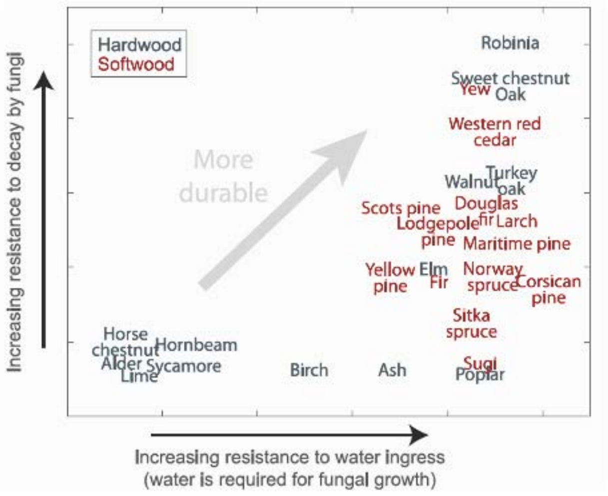


Fig 2.5: Durability of heartwood in Europe, ordered from most (top right corner) to least (bottom left corner) durable. Extracted from The Wood From Trees (Ramage et al., 2017)

Thermal & Chemical Treatment

Thermal Modification | This treatment is most widely adopted whereby timber is heated to 190-220 degrees Celsius and low oxygen level in an industrial autoclave. This changes the biological structure of the timber and leaves lesser hydroxyl groups in it. Consequently, this increases the mass and strength of timber by 80% allowing its durability to reach Class 1-3 in EN350 (Lugt & Harsta, 2020).

Although increasing temperatures and duration could directly increase stiffness and resistivity to moisture, it also makes the timber more brittle and less suitable for structural purposes (Lugt & Harsta, 2020). Hence it is more commonly used as external cladding as opposed to decking. Thermally modified wood in Europe is largely sold under brand name ThermoWood.

Acetylation | It is a chemical modification process whereby low durability softwood reacts with acetic anhydride in a large vacuum pressure autoclave (Lugt & Harsta, 2020). During this process, the hydroxyl groups in the cells are substituted with the acetyl groups, thereby increasing the stability of the timber by making it resistant to bonding with hydroxy groups which can be found in water. This increases the mass and strength of timber by 80% allowing its durability to reach Class 1 in EN350 (Lugt & Harsta, 2020).

Most prominently known as Accoya, acetylation has been developed for over 80 years. Its durability made it possible to construct fully exposed, heavy traffic bridge such as Sneek Bridge by Onix & Achterbosh Architecture (OAK) in Sneek, Netherlands (Fig 2.6). Having a durability of over 80 years, as stipulated by Dutch regulations, the Sneek Bridge has proven to exceed that limit such that two of this bridge was constructed in 2008 and 2010.

Fig 2.6: Sneek bridge, spanning 40m across the A7, with cycling and traffic lanes is capable of withstanding 65 tons of load.

Furfurylation | Similar to Acetylation, Furfurylation involves a chemical reaction to replace the hydroxyl groups of timber with furfuyl groups, which can be abundantly found as an agricultural waste of sugar cane (Lugt & Harsta, 2020). This consequently increases the durability of the timber by 50% to Class 1-2 in EN350 (Lugt & Harsta, 2020). Furfurylated timber is known under brand names such as Kebony and NobelWood. A durability comparison of different types of timber and treatment methods (Fig 2.7) shows that even widely abundant softwood like Scots Pine which when untreated attains only Class 4 in EN 350, could potentially achieve Class 1 in strength after acetylation. This shows the potential of wood treatment in increasing durability of naturally weaker timber species.

Fig 2.7: Durability comparison (EN 350), adapted from Tomorrow's Timber (Lugt & Harsta, 2020).

2.3.2 | Connections & Support Conditions

The design of timber connections are ultimately the most crucial part where tension, compression, shear or bending moments are transferred from one element to another (Herzog et al., 2008). Within DIN 1052, the strength and design of connections contributes largely towards the stiffness of structural systems. The elasticity of a connector corresponds to the types of forces it needs to transfer. There are 3 main types of timber connections namely, Traditional Timber Joints, Dowelled Joints and Glued Joints (Swedish Wood, 2016). Each connection method has different force transfer characteristics which will need to be considered when designing joints between different components.

Connector types based on Force Transfer

Based on Design of Timber Structures, Volume 1 (Swedish Wood, 2016), *Traditional Joints* are connections whereby specific profiles are cut out of the timber members before fitting them together in a specific sequence. *Dowelled Joints* transfer forces through shear using mechanical fasteners arranged at an angle to the direction of the force. It is the most widely used type of connections which includes nails, screws, bolts, dowels and nail plates. *Glued Joints* are the strongest type (Fig 2.8) and can be used to connect structural elements such as LVL, glulam and CLT. Gluing however needs to be done in a controlled environment and hence is unsuitable onsite.

Due to the wide scope of connection types available, the analysis on suitable joints will be conducted through selected case studies collected in *Section 2.4 Conventional Timber Structures*. The selection of suitable joints is also dependent on the principles of Design for Disassembly which will be further elaborated in the next *2.3.3 Design for Disassembly*.

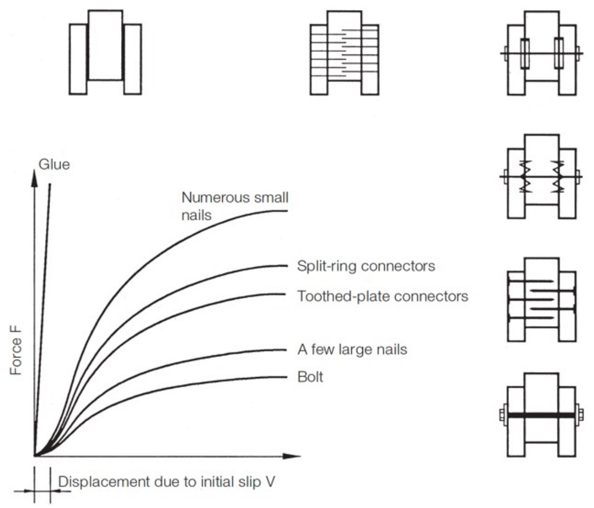


Fig 2.8: Deformation behaviour of Glued v.s Dowelled Joints (Herzog et al., 2008).

2.3.3 | Design for Disassembly

The focus on the principles of Design for Disassembly in the scope of the thesis aligns with the design assignment's requirement of applying the concept of circularity and sustainability into the bridge design. The definition of Design for Disassembly relates to designing products and assemblies which can be easily taken apart and reused or recycled (Moffatt & Russell, 2001). Of the 3 principles of Circularity, Design for Disassembly relates to the second principle of circulating products and materials at their highest value (Ellen MacArthur Foundation, 2019). Since timber is a renewable building material, it goes through the Biological Cycle and can undergo the R-Ladder to increase its circularity within the product chain (Lugt & Harsta, 2020), as shown in Fig 2.10.

According to the Design for deconstruction and reuse of Timber structures – state of the art review (Cristescu et al., 2020), consolidating the Design for Disassembly principles put forth by Crowther (2005), Guy and Ciariboli (2008) and Hradil et al. (2014), it can be summarized that the principles below are critical:

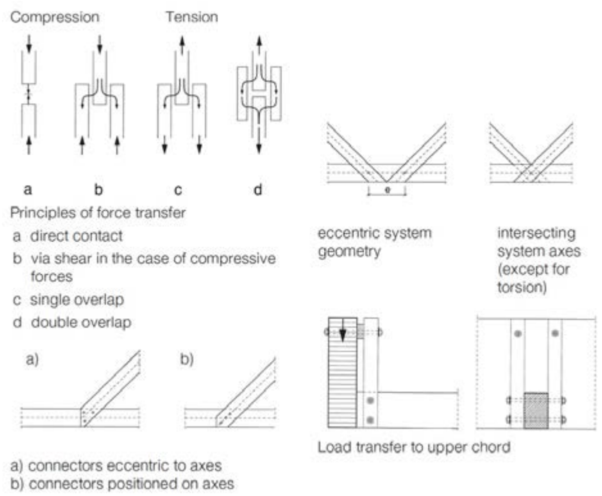


Fig 2.9: Types of connections for various forms of force transfer, extracted from Timber Construction Manual (Herzog et al., 2008).

Ease of disassembly

- Low weights and small sizes for easy dismantling
- Low weights and small sizes for easy dismantling
- Accessibility of joints
- Separability of subcomponents for easy dismantling
- Low susceptibility against damage during disassembly

Reusability (including repurposing of individual structural elements)

- Repetitiveness (number of similar elements)
- Similarity (variation of elements)
- Standardization level (shapes, sizes, elements)
- Low exposure to deterioration processes
- Expected long-term deformations are not significant
- Transportability: remoteness of the building
- Documentation about design and maintenance

These key characteristics will significantly guide the formulation of the bridge design, its structural system as well as the construction and assembly processes.

2.4 CONVENTIONAL TIMBER STRUCTURES

Historical Overview & Case Study Analysis

Wood, being one of the oldest building material in the world has been developed regardless of culture and context (Schweitzer, 2004) into a multitude of forms. Being the predominant building material before the 20th Century, timber structures and buildings were abundant in geographically diverse locations with the availability of forests.

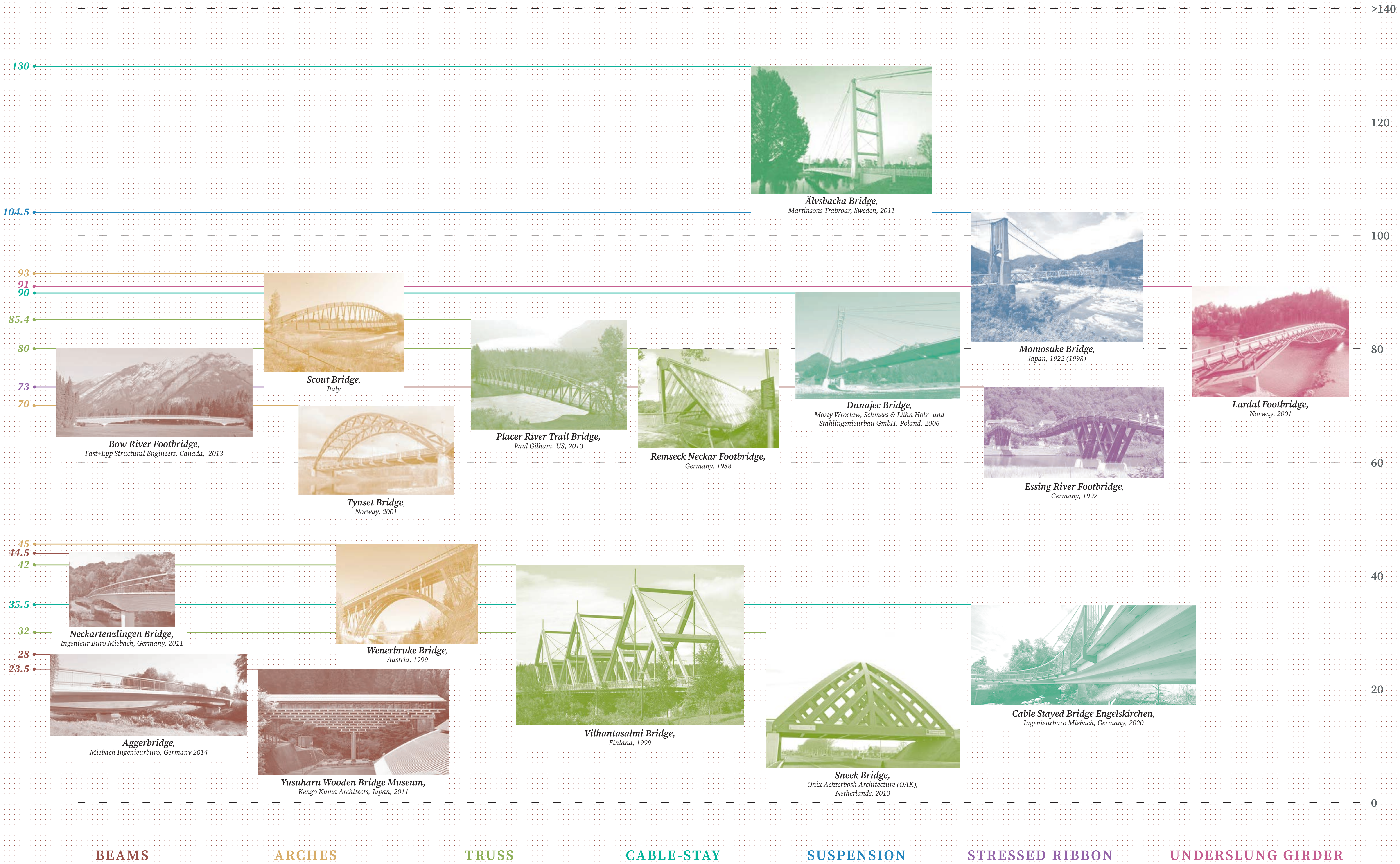
Early timber bridges are largely beam girders and truss bridges, with the oldest currently known bridge dated back to 600BC (Partov et al., 2016). The most popular of which is the Ponte Degli Alpini in Bassano del Grappa by Andrea Palladio (Fig 2.11) while the oldest timber bridge in operation is Kapellbrücke (Chapel Bridge) in Lucerne Switzerland which was built in 1333 (Fig 2.12).

In Asia, the oldest timber bridge, Rulong Bridge in China was constructed in a parallel log arch-beam structure in 1625 and is part of over 3000 "corridor" bridges in the Fujian and Zhejiang Province, exceeding the number of covered bridges in Europe and North America (Knapp et al., 2020). Other vernacular examples of bridges constructed out of wood is most notably the Living Root Bridges (Fig 2.14) in the East Khasi Hills of Meghalaya, where bamboo scaffolding guide roots from trees on riverbanks creates a crossing that grows over time.

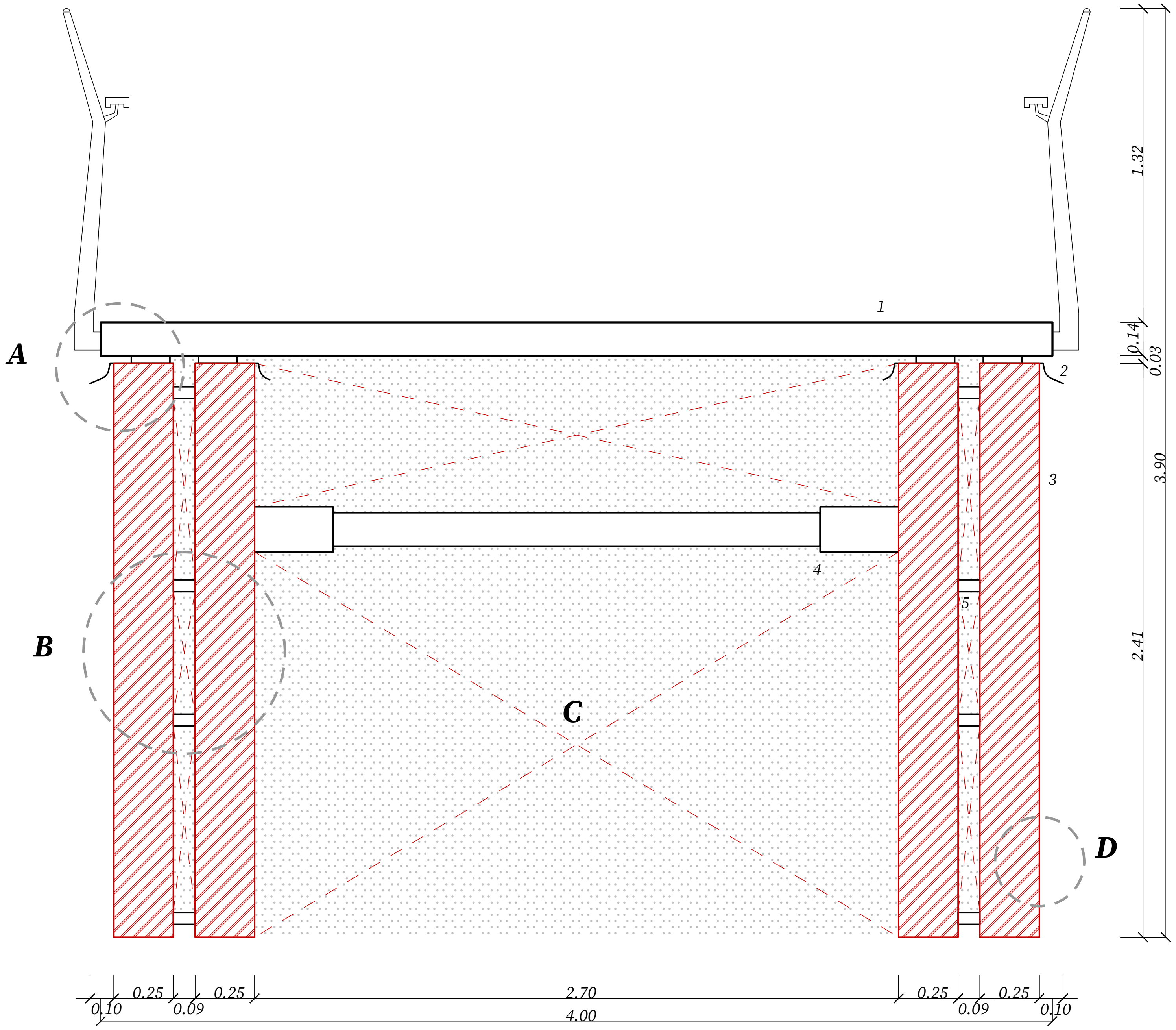
With the advent of cast iron from 1780s, then steel from 1890s and reinforced concrete, timber and stone has largely been replaced as key structural materials for bridge construction. In the late 20th Century, the developments of engineered timber products and stronger timber connections with steel allowed a resurgence of the use of timber as structural members in bridges (Bell, 2008). Thus, this section aims to cover the notable timber bridge of key structural typologies – beams, arch, truss, cable-stay, suspension, underslung and stressed ribbon – as well as the possible span ranges for each typology. Furthermore, selected projects such as the Bow River Footbridge, Neckartenzlingen Bridge, Dunajec Bridge and Centre Pompidou-Metz were taken as case studies to highlight the moisture management strategies involved.

Fig 2.11-14: Top to bottom: Ponte Degli Alpini (Bell, 2008), Kapellbrücke, Rulong Bridge (Knapp et al., 2020), Living Root Bridges.

2.4 | Conventional Timber Structures



2.4.1 | Case Study 1: Bow River Footbridge



Bow River Footbridge Simplified Section | Scale 1:25

Air Exposure
Timber Member

Timber Deck | 1
Galvanised Steel Flashing (100mm from timber face) | 2
Glulam Girders | 3
Steel Diaphragm Truss | 4
Laminated Veneer Lumber (LVL) Blocking | 5

0 0.25 0.75 1.25m

Name:
Bow River Footbridge

Location:
Canada

Structural System:
Beam (no cladding)

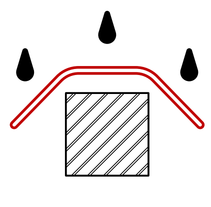
Use Type:
Pedestrian & Cyclist

Span & Width
80m / 4m

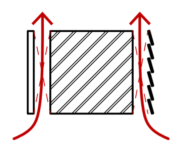
Architect / Engineer:
Ingenieurburo Miebach, Schafferer Holzbau

Year:
2013

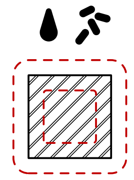
Moisture Management Strategy:



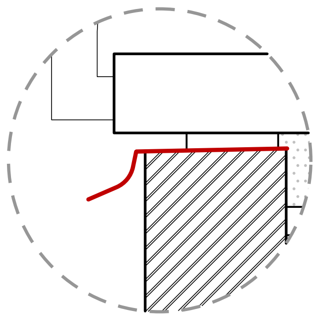
Deflection & Drainage



Ventilation

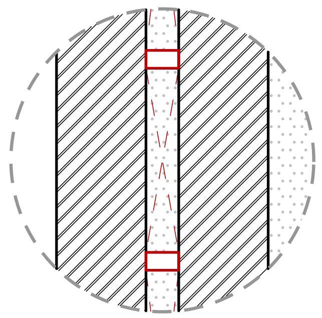


Durable Material



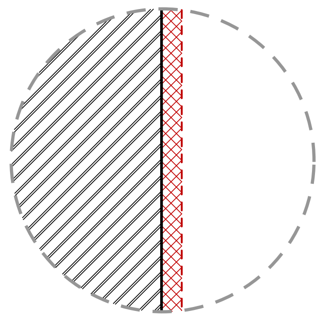
A: Cover
100mm Galvanised Steel Flashings

+ Overhang under Timber Deck



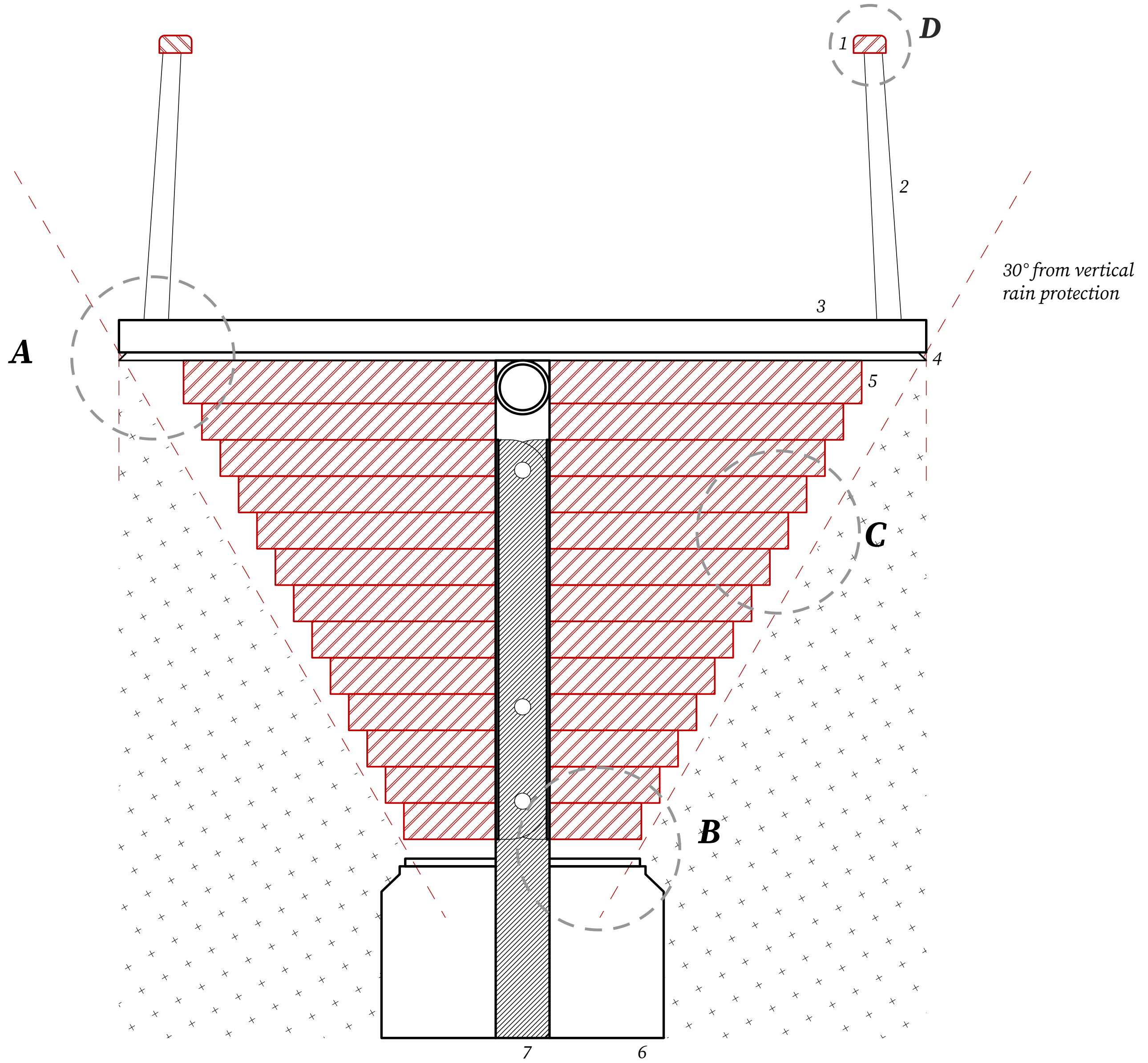
B: Air Gap
LVL Blocking creates air gap within Glulam Beam

C: Air Gap
Spacings between Glulam Girders



D: Coating
Vapour resistance membrane coating + Darker Tint UV Protection

2.4.2 | Case Study 2: Neckartenzlingen Bridge



Neckartenzlingen Bridge Simplified Section | Scale 1:25

Air Exposure
Timber Member
Rain Exposure

Accoya Timber Handrail | 1
Galvanised Steel Railings with Steel Cables | 2
Precast Concrete Deck with Anti-slip | 3
Deck Gutter | 4
Block Laminated Glulam | 5
Concrete Pier | 6
Steel Pillar | 7

0 0.25 0.75 1.25m

Name:
Neckartenzlingen Bridge

Location:
Germany

Structural System:
Hinged Girder / Glulam & Steel

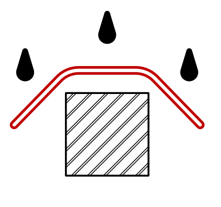
Use Type:
Pedestrian & Cyclist

Span & Width:
44.5m / 3.5m

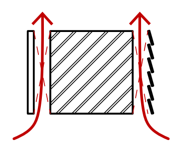
Architect / Engineer:
Ingenieurburo Miebach, Schafferer Holzbau

Year:
2017

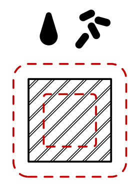
Moisture Management Strategy:



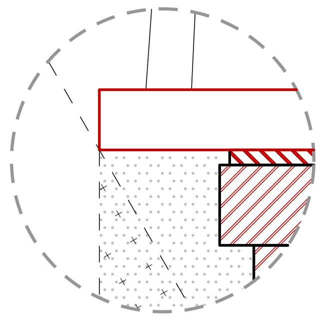
Deflection & Drainage



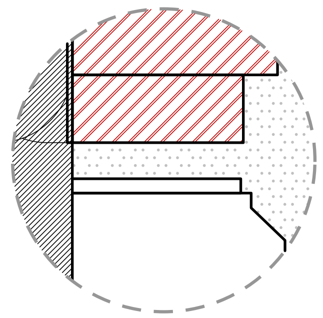
Ventilation



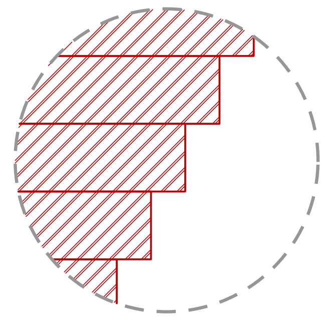
Durable Material



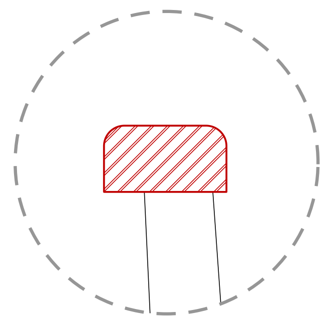
A: Overhang 30° Protection
240mm extended Concrete deck above Glulam, 30° to vertical rain protection (DIN 68800)



B: Isolation & Gap
Exposed Glulam elevated from concrete pier by Steel Connections & Column

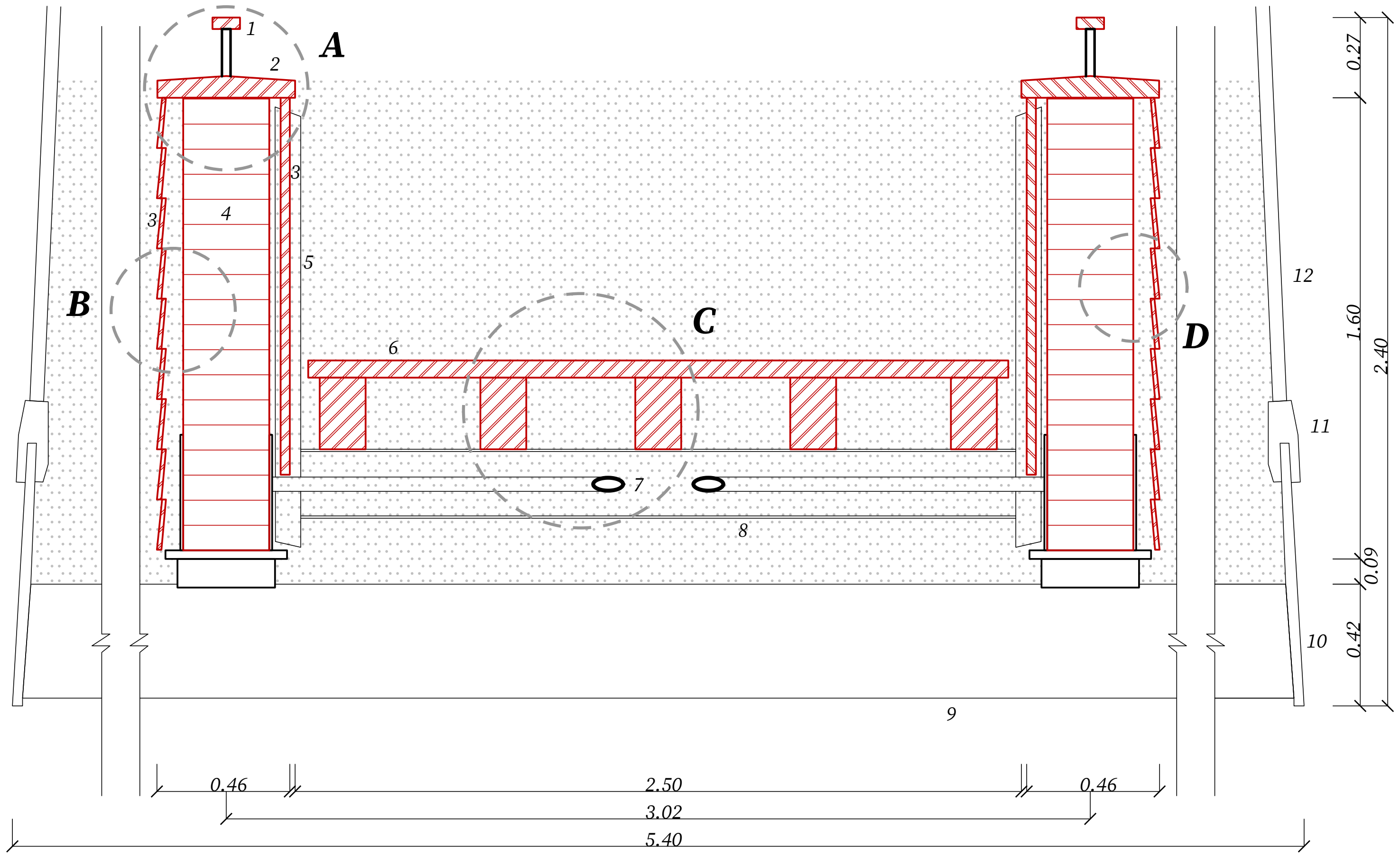


B: Glulam
Block Laminated Glulam



D: Treated Timber
Acetylated Timber (Accoya) Handrail

2.4.3 | Case Study 3: Dunajec Bridge



Dunajec Bridge Simplified Section | Scale 1:25

Timber Handrails | 1
Timber Covering | 2
Larch Wood Boarding | 3
300x1600mm Glulam Girder (Class GL32) | 4
Steel Semi-frame | 5
45mm (t) 2500mm (w) Wooden Deck Pavement | 6
Wind Bracing | 7
Steel Semi-frame | 8
Transverse Steel Tube ø406 mm | 9
Anchorage Plate | 10
Pfeiffer Active Anchorage | 11
Full Locked Cables ø40 & ø28mm | 12

Air Exposure
Timber Member

0 0.25 0.75 1.25m

Name:
Dunajec Bridge

Location:
Poland

Structural System:
Cable-Stay / Glulam & Steel

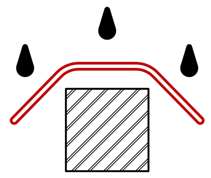
Use Type:
Pedestrian & Cyclist

Span & Width
90m / 3.5m

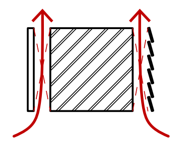
Architect / Engineer:
Mosty Wroclaw Test & Design Office, Schmees & Lühn Holz- und Stahlingenieurbau GmbH

Year:
2006

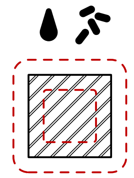
Moisture Management Strategy:



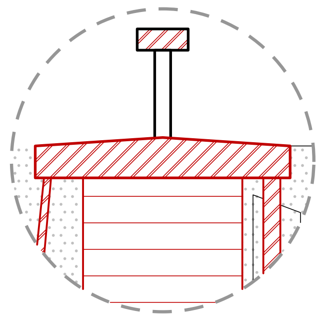
Deflection & Drainage



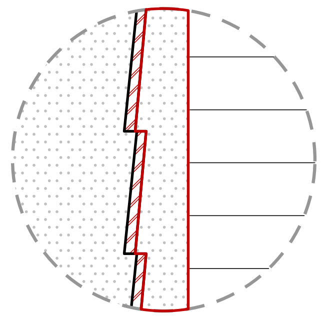
Ventilation



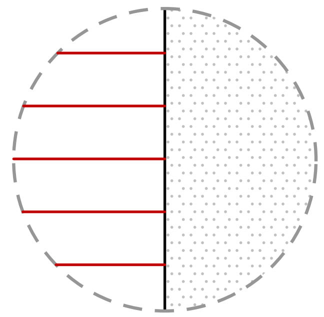
Durable Material



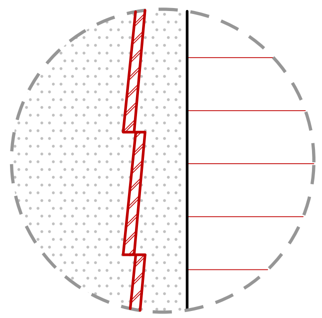
A: Cover
Timber covering on top of GL32 Spruce Glulam



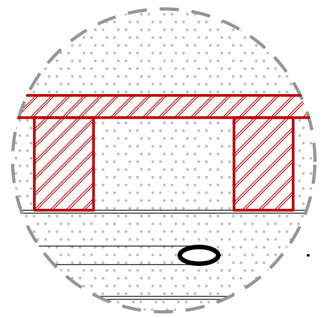
B: Air Gap
Between Larch Wood Boarding & Glulam



D: Glulam
GL32 Spruce Glulam with waterproof glue (PUR)

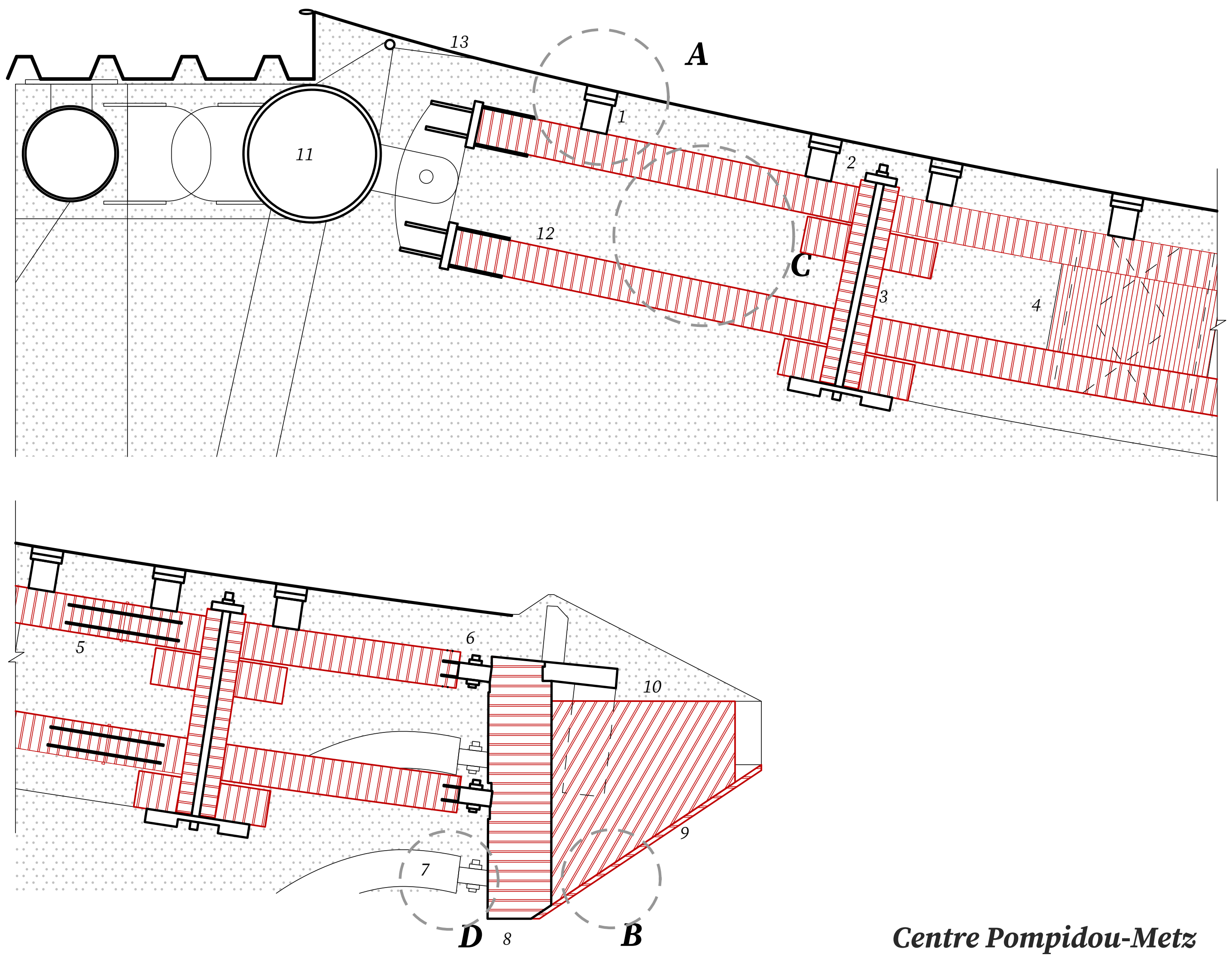


B: External Cladding
Larch Facings on exterior of Glulam



C: Isolation & Gap
Exposed & Isolated Timber Deck & Beams

2.4.4 | Case Study 4: Centre Pompidou-Metz



Centre Pompidou-Metz
Simplified Section | Scale 1:25

5mm Steel membrane support bent to shape | 1
24mm Dia. Threaded Bolt w/ Tension Spring | 2
Hexagonal Laminated Timber Dowels | 3
105/328/615mm Laminated Timber Shear | 4
5mm Slotted Steel connect bet. elements | 5
5mm Slotted Steel Shoe for beam w/ Hinged Connection | 6
2x140/440 laminated softwood double column with larch foot | 7
250/1000mm Laminated Timber Edge Beam | 8
19mm 3-ply Laminated Larch Sheeting | 9
69mm laminated framed timber | 10
Steel Ring Beam | 11
140x440mm Spruce Glulam | 12
Fibre glass & Teflon Membrane (ETFE) | 13

Air Exposure
Timber Member

0 0.25 0.75 1.25m

Name:
Centre Pompidou-Metz

Location:
France

Structural System:
Timber Lattice Grid Shell

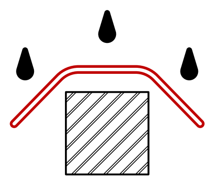
Use Type:
Roof Structure - Museum

Span:
40m

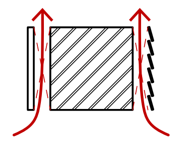
Architect / Engineer:
Shigeru Ban Architects, Jean de Gastines, SJB Kempter Fitze AG

Year:
2010

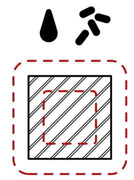
Moisture Management Strategy:



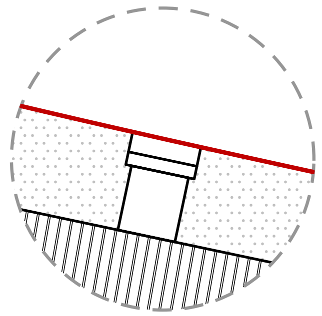
Deflection & Drainage



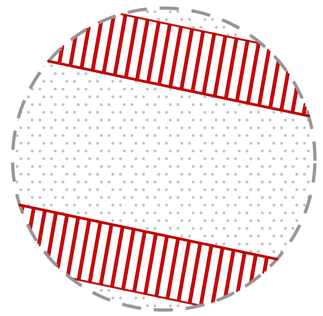
Ventilation



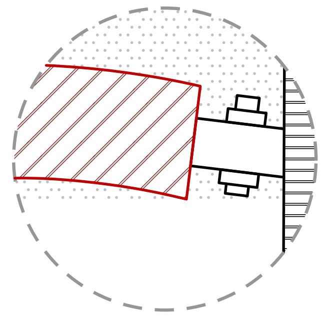
Durable Material



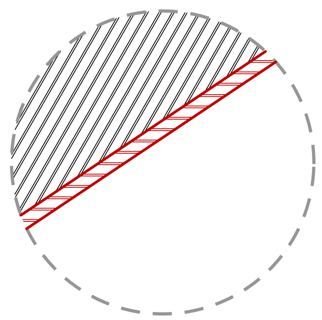
A: Membrane Canopy
ETFE Membrane protects against weather



C: Air Gap
Bet. Timber beams of lattice structure



D: Water Resistivity
Double beam Larchwood as column due to its water resistivity



B: Exterior Cladding
Laminated Larch Sheeting for water-resistivity

2.5 NOVEL TIMBER STRUCTURES

Timber Structures involving Digital Design & Fabrication Processes

2.5.1 | State-of-the-art Digital Design & Fabrication of Timber Structures

This section covers the literature review conducted to establish an understanding of the state-of-the-art timber structures constructed with digital design and fabrication technology, addressing sub-research question 2b. The approach and keywords used in conducting this review can found in *Appendix 7.2 Novel Timber Structures involving Robotics*.

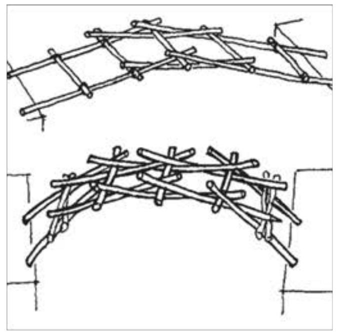
From *Section 2.4 Conventional Timber Structures*, several key timber bridge typologies have been established and its corresponding span ranges mapped. In this section, the literature review collated 26 projects where digital design and fabrication technology has been applied and 21 of them has been represented in Error! Reference source not found.. The inclusion of the projects within the figure is based on a few factors – diversity of scale and design, the number of projects representing a certain typology as well as the maximum spans achieved for each represented typology.

This figure highlights an increasing trend in the development and exploration of timber shell structures, from bending active structures to plate and grid shell, as it represents more than half of the projects collated. For shell structures are highly efficient in spanning spaces, most has been constructed as research pavilions, museum and office building. Amongst shell structures, the grid shell is the most developed, achieving spans of 35 - 50m in several large-scale public buildings like Centre-Pompidou Metz and Metropol Parasol.

There is also an emergence of new structural typologies such as weaved structure, bending active shell and curved plate structure. The first utilizes the elastic bending behaviour of timber plywood to weave and interconnect them with notched joints, strengthening the structure by balancing the bending and tension forces of alternate strips. Bending active shell performs similarly using the malleability of timber plywood either in resisting the bending at joints between each member of the shell in ReciPly Dome or increasing the stiffness of the structure in Bending Bridges. Lastly, curved plate structure takes advantage of the curvature of timber, due to its hydroscopic nature, into creating curved CLT plates.

Due to the novel nature of these structures, they are largely constructed by research institutes from the Institute of Computational Design (ICD) and Institute of Building Structures and Structural Design (ITKE) of the University of Stuttgart, Gramazio Kohler Research (GKR) of ETH Zurich, IBOIS EPFL, Royal Danish Academy (KADK), Vrije Universiteit Brussel (VUB) and TU Delft. Several architecture firms such as Shigeru Ban & Associates, Arch-Union Architects (Phillip Yuan), CEDIM, Jurgen Mayer and Studio RAP has also been involved in developing these novel timber structures.

2.5.2 Reciprocal Frame (RF) Structures



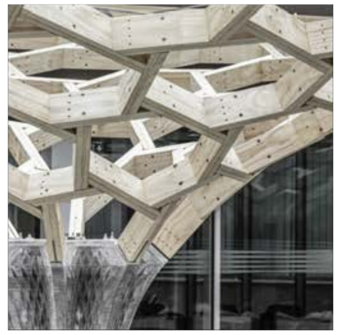
Temporary Bridges
Leonardo da Vinci, 1500s

Zollinger Roof System
Friedrich Zollinger, Early 1940s

Seiwa Exhibition Hall
Kazuhiro Ishii, 1992

Pergola ETH Science City
Udo Thoennissen, 2015

Coeda House
Kengo Kuma, 2017



Future Tree
Gramzio Kohler Research, 2019

Fig 2.16: Selected RFs throughout history and across cultures, images extracted from multiple sources.

2.5.2.1 | Introduction & Precedence

Reciprocal Frames (RFs) describes a structural typology formed by linear flat or inclined elements that supports each other and are arranged in a closed circuit or unit. They are typically used in roof applications and would transfer and direct forces down to a ring beam, columns or supporting. Within an inclined configuration, loads are mainly transferred by combined axial and bending action while in flat assemblies, it is primarily the latter (Popovic Larsen, 2014). Throughout history, this technique has been used widely across cultures in various forms, with the earliest documented form in Leonardo Da Vinci's Temporary Bridges in 1500s, to Seiwa Exhibition Hall (1992) by Kazuhiro Ishii, and recent built projects by Udo Thoennissen (2015), Kengo Kuma (2017) and Gramazio Kohler Research (2019) as consolidated in Fig 2.16.

2.5.2.2 | RF Morphologies and Connections

RF is fundamentally less efficient than grid shell structures, which works primarily in axial action, but has certain advantages. This includes being formed by short members, a large degree of built-in redundancy and having the same joints and members within a symmetrical configuration (Popovic Larsen, 2014).

There are 3 main morphologies of RF, basic RF, multiple RF grids and complex RFs. The elementary form of RF structures is the basic RF as it is a simple closed circuit system where sloping beams transfer forces from one to another by mutually lying on each other. This basic unit when aggregated around its perimeter into a grid structure creating a multiple RF grid structure. A complex RF is created when one or more basic RF is added to the central opening of another basic

2.5 | Novel Timber Structures

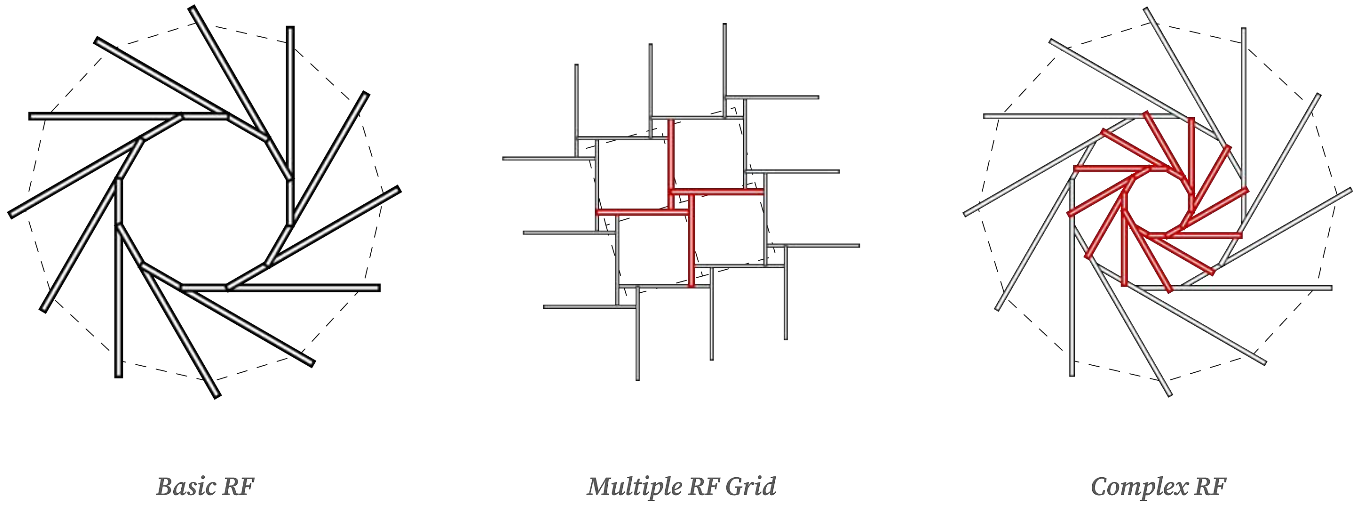


Fig 2.17: 3 Main morphologies of RF structures – Basic RF, Multiple RF Grid, Complex Grid RF, left to right.

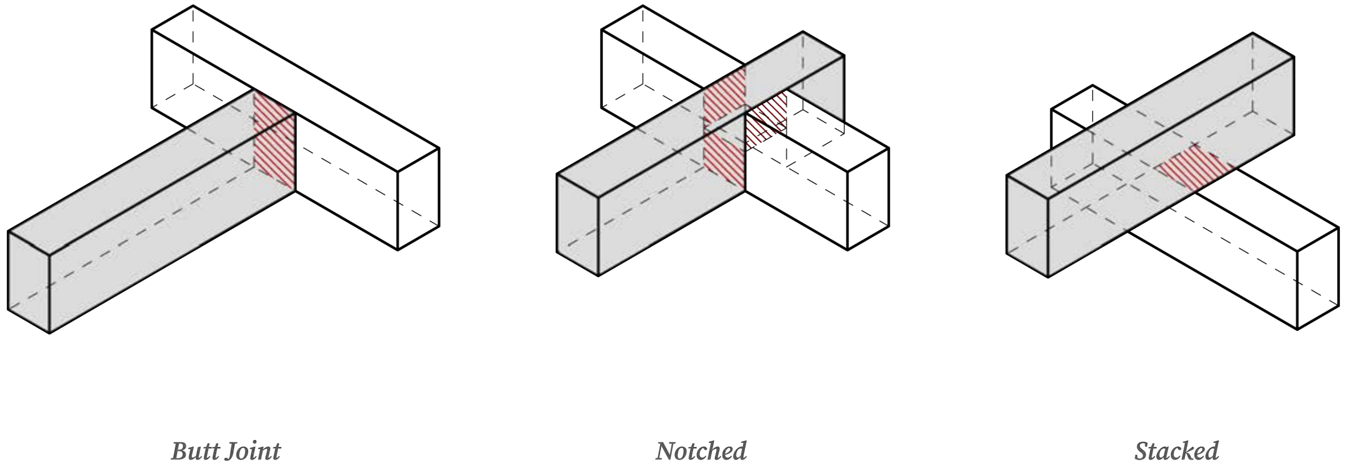


Fig 2.18: Types of connections between individual members of RF structure with red hatch indicating the point of contact for load transfer.

RF instead of its perimeter (Larsen, 2008). These 3 morphologies are illustrated in Fig 2.17.

RF structures consists of joints which involves only two intersecting members, thereby simplifying the design of each joint. The common types of connections between members of a RF structure includes Butt Joint, Notched and Stacked as illustrated in Fig 2.18. Each joint types have varying load transfer characteristics and surface area of contact as highlighted in red hatch. While the Notched joint allows for a stiffer connection compared to others, the location of the notch where highest shear stress is applied is not a desirable one. Hence the cross section of the elements will either need to be increased or the depth of the notched decreased. On the other hand, although the Butt and Stacked joint utilizes the full cross-section of the elements in load transfer, both are less efficient at transferring shear forces. Therefore, each type of connection has individual strengths and weaknesses which will influence the overall structural stability of an RF structure. As the type of connection is not the only factor affecting its stability, geometrical parameters such as internal and external radius, length, inclination and angle of beam are also crucial to designing a RF structure. This however is highly dependent on the type of tessellation and morphology of RF structure and will be further developed and explored in the subsequent *Chapter 3: Site Analysis & Bridge Design*.

"The art of deploying construction technology in such a way that it forms an integral component of the design and actively helps to shape it is what Kenneth Frampton defines as tectonics."

- Weinand, Y & Buri, H.U (2011)

Chapter 3:

SITE ANALYSIS & BRIDGE DESIGN

3.1 SITE INTRODUCTION

Buiksloterham, Amsterdam

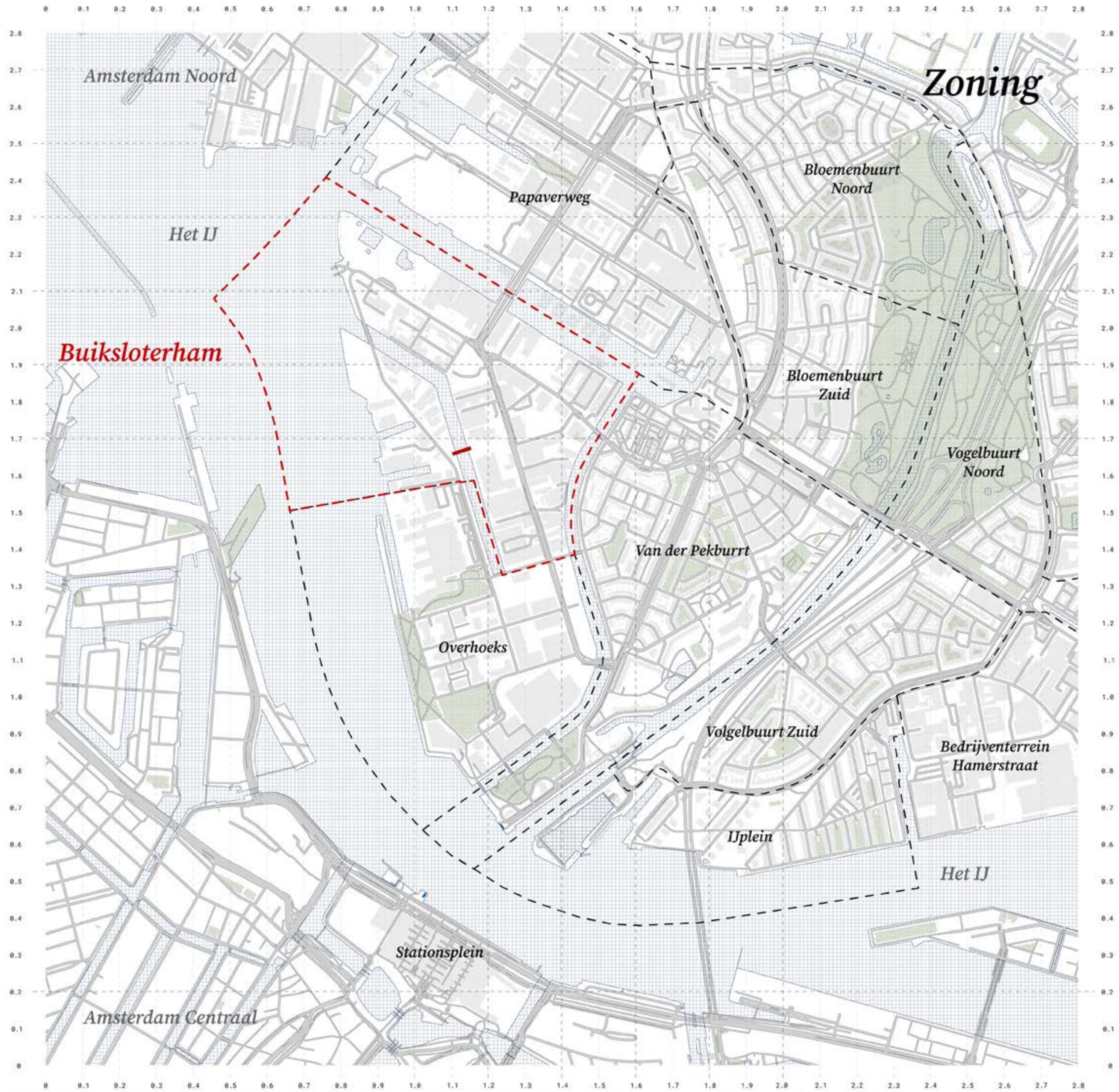


Fig 3.1: Site map of Amsterdam Noord with the site location Buiksloterham labelled in red.

Buiksloterham, is a neighbourhood located in the Northern part of Amsterdam and Het IJ as shown in Fig 3.1. The population of the site in 2021 is 710 (allchartsinfo, 2021) and Amsterdam's population is set to grow by 10.000 per year as outlined in Circulair Buiksloterham (Metabolic et al., 2014). Currently, Overhoeks and Bukisloterham are prime areas for redevelopment as Amsterdam

Fig 3.2: The formation of Buiksloterham between 1660 and 1900, extracted from Circulair Buiksloterham (Metabolic et al., 2014).

city is becoming increasingly dense and these neighbourhoods while being close to the city center holds potential for more public and living space for the burgeoning population. Hence there is an impetus to redevelop the once industrial estate of Buiksloterham to a mix-use neighbourhood (Metabolic et al., 2014) accommodating more residential estates and businesses.

History of Buiksloterham

Before 1660, Buiksloterham did not exist and was part of the IJ ("Den Ham"), as shown in Fig 3.2. Since 1886, a polder was constructed and dredged materials from Amsterdam Center filled up the river banks of Buiksloterdijk, eventually forming Buiksloterham (Metabolic et al., 2014). By the turn of the 20th Century, major industries making use of the proximity to the IJ as water passage started to occupy the site, most notably Bataafsche Petroleum Maatschappij (former Royal Dutch Shell) and Fokker Aviation industry (Metabolic et al., 2014).

During World War One (WWI), municipality housing began to house industrial workers who moved to the city, leading to the formation of the first few neighbourhoods Disteldorp (1918), Asterdorp (1926) and Tuindorp (1927) (Metabolic et al., 2014). Gradually from 1980s onwards, industrial activities began to move away from Buiksloterham

Fig 3.3: Distribution of immobile contaminants between 0-2m of top soil in Buiksloterham due to the dredged materials and past industrial activities, extracted from Circulair Buiksloterham (Metabolic et al., 2014).

as the municipality began redeveloping the area. Most recently, the Investment Memorandum Bukisloterham 2020 (Investeringsnota Buiksloterham 2020) – as formulated by Gemeente Amsterdam (2020b) – has indicated the need to focus on Densification as a mixed urban neighbourhood, a Circular district (Metabolic et al., 2014), Productive district with businesses and manufacturing industries combined with residential estates and lastly an Undivided district from Amsterdam City.

Pollution & Water Safety

Since Buiksloterham was formed from waste dredged material and has housed many heavy industrial activities in the past, more than 80% of its soil is contaminated with immobile contaminants like heavy metals and asbestos (Metabolic et al., 2014). The need for remediation of the soil is urgent in order to make the neighbourhood safe and healthy for further development since about 1-2m of top soil contains around 25-50% of contaminants (Fig 3.3).

Pioneering development such as De Ceuvel (Fig 3.4) has shown that even the polluted wastelands could be remediated into safe and healthy live-work space through phytoremediation – the use of plants to absorb and purify the soils from

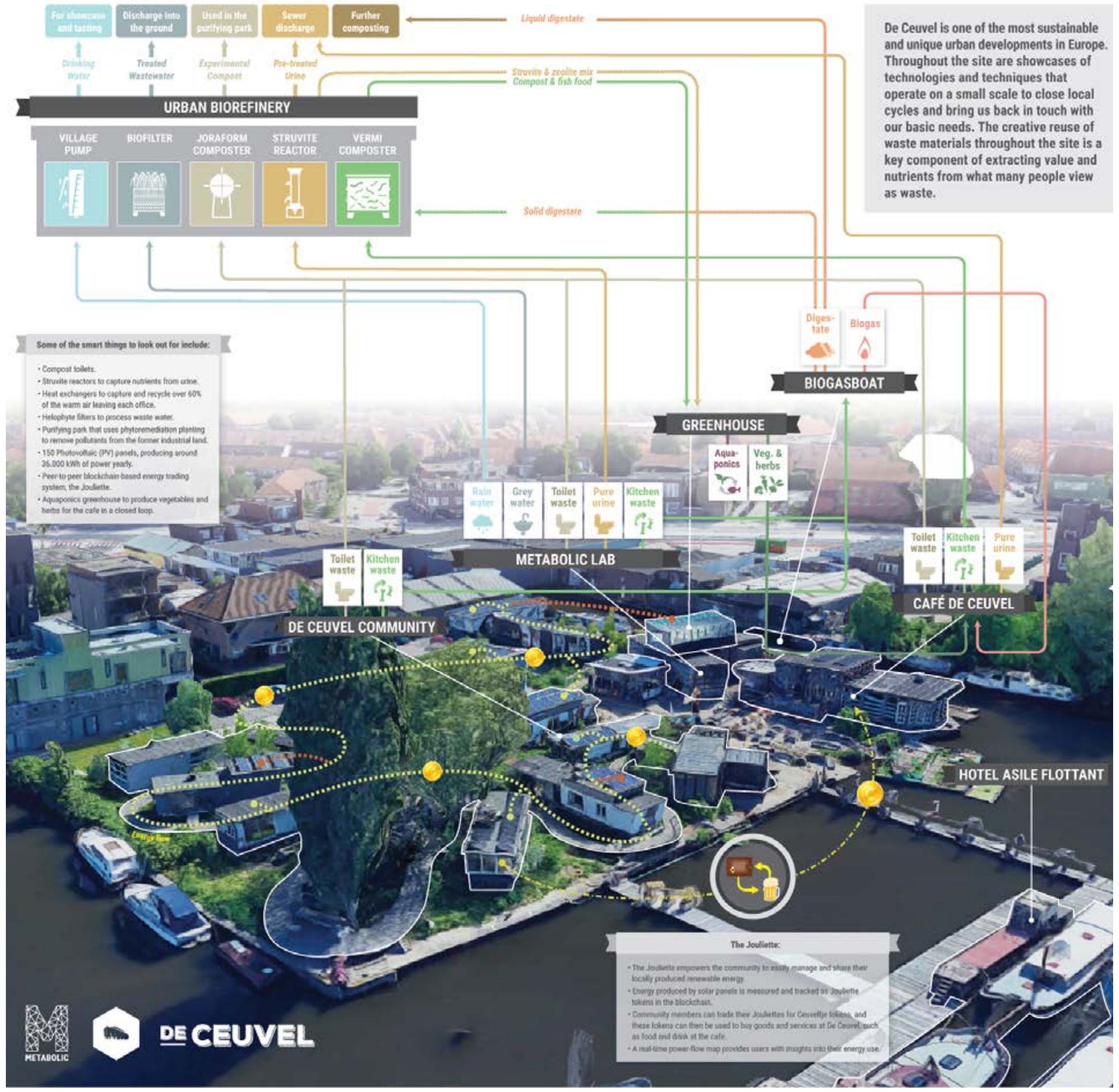


Fig 3.4: Energy flows and green technology used in De Ceuvel, a pioneering redevelopment project aimed at remediating polluted industrial wastelands to a safe, live-work neighbourhood. (Metabolic Lab, 2014)

Fig 3.5: Plant species selected based on their ability for phytoremediation, absorbing the contaminants within the soil and purifying it over time. (Metabolic Lab, 2014)

toxic contaminants – the use of clean sustainable systems for waste and energy as well as upcycled houseboats.
The need for remediation of the soil applies precisely to the bridge site proposed by Gemeente Amsterdam as it is aimed to be developed into a public park space for the local residents. The application of the unique plant species in Fig 3.5 for phytoremediation is key to making these parks safe and healthy for the users of these green spaces and the bridge.

3.2 DESIGN BRIEF

Design Criteria

Programme of Requirements (PoR)

Location: Tolhuiskanaal Oost, btw. Grasweg & Asterweg
Users: Disabled, Pedestrian, Cyclists
Traffic Type: Slow traffic, Local
Bridge Type: Removable, Symmetrical
Urban Integration: 2 parcels of parks on both sides of the bridge to be integrated into the design

Goals:

- Circular Vision – Reusable, Bio-based, Adaptive/ Flexible, in addition to the goals outlined in Circular Buiksloterham (Metabolic et al., 2014) and Groenevisie 2020-2050 (Gemeente Amsterdam, 2020b)
- Visibility and Sightlines along the shore (minimal obstruction)
- Thin, Transparent Bridges
- Open Banks – Abutments separate from quays
- Industrial Heritage of Buiksloterham
- Environmentally aware

Dimensions

Width of Water Passage: 35-38m
Setback from Edge of Tolhuiskanaal: 1.5m on each side
Minimum Width of Free Waterway: 7.2m
Minimum Height of Free Waterway: +2.15 NAP
Bridge Width: 5.8m
Maximum Bridge Slope Gradient: 4%

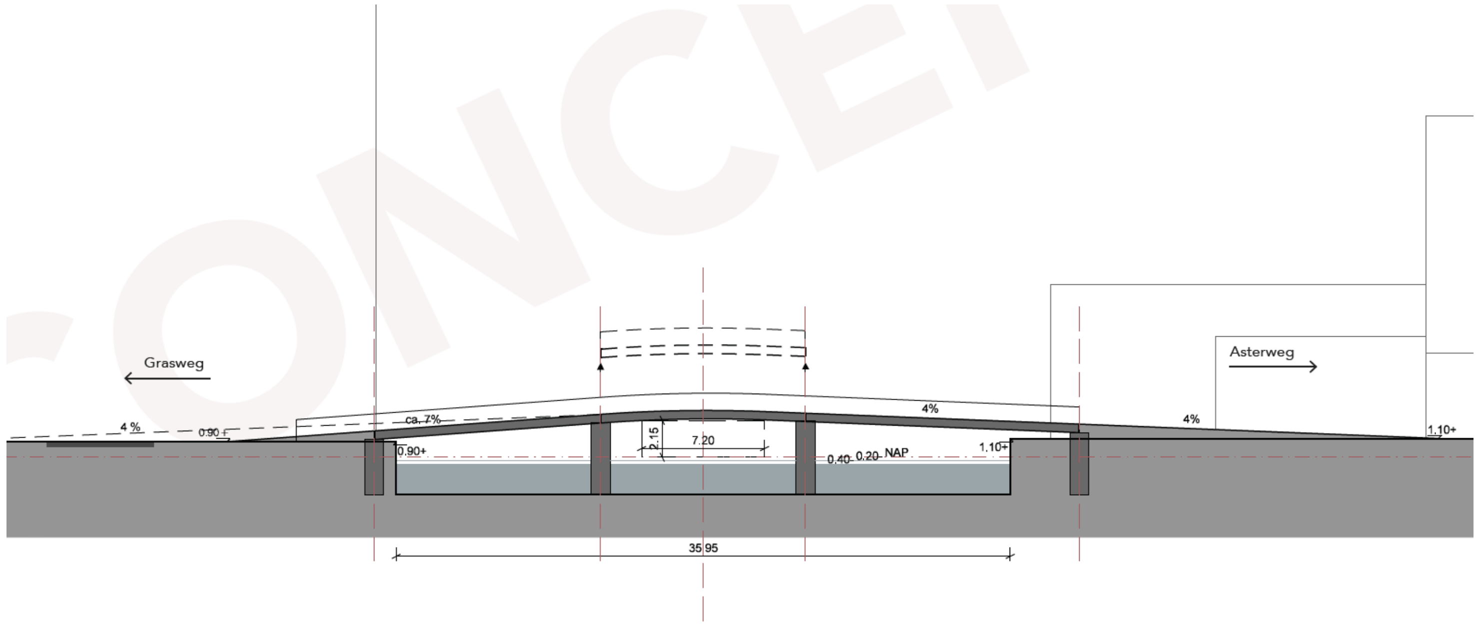


Fig 3.6: Section of conceptual bridge design provided by Gemeente Amsterdam with a bridge span divided into 3 segments and slope grade of 7% for cycling path and 4% for pedestrian path. Minimum free waterway width and height is also indicated.

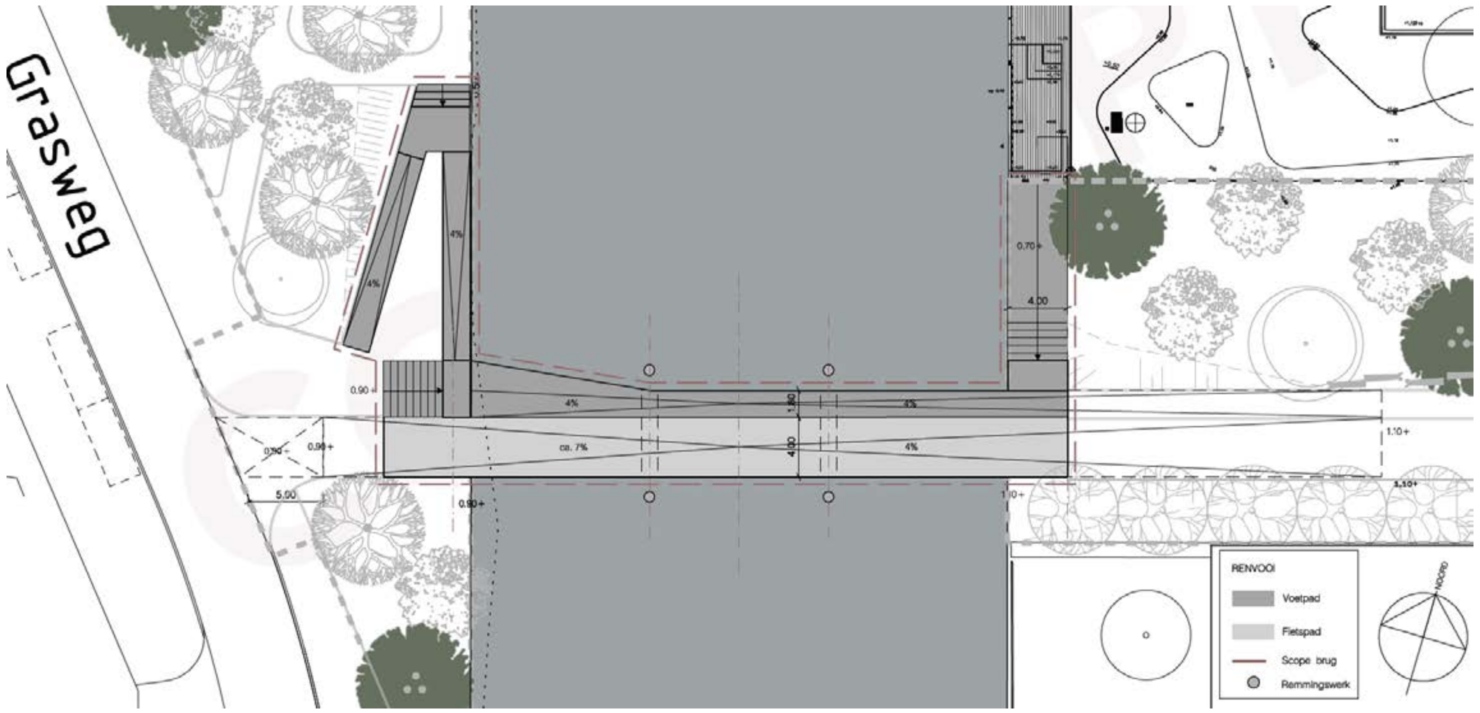


Fig 3.7: Plan drawing of the proposed Tolhuiskanaal Oost Bridge, with separate paths for pedestrian and cyclist.

3.3 SITE MAPPING & USER REQUIREMENTS

Site Selection & Analysis

In this section, the site analysis is organized from the urban scale down to the site to understand the confluence of factors – from the masterplans, transportation nodes, surrounding neighbourhoods and recreational green & blue spaces – which will inform the bridge design proposal. Through the masterplan, seven bridge connections are proposed and one was selected for further development in the thesis. Furthermore, an understanding of the current and upcoming urban composition informs the potential usage and users of the bridge which leads to an identification of their accessibility requirements. As was highlighted within the PoR in *Section 3.2 Design Brief*, the historical DNA of the site needs to be reflected within the bridge proposal. Thus a graphical study of the historically and industrially significant buildings were collated to establish an understanding of the identity of the site. Lastly, a Height Analysis was conducted to identify the maximum heights of the houseboats within Tolhuiskanaal Oost. This will inform the height clearance required for the bridge proposal.

An overview of all site analysis conducted is as below:

1) Gemeente Amsterdam Bridge Masterplan & Site Selection
2) Current Urban Composition
3) User Profiles & Accessibility Requirements
4) Site Historical DNA
5) Houseboats Height Analysis

3.3.1 | Gemeente Amsterdam Bridge Masterplan & Site Selection

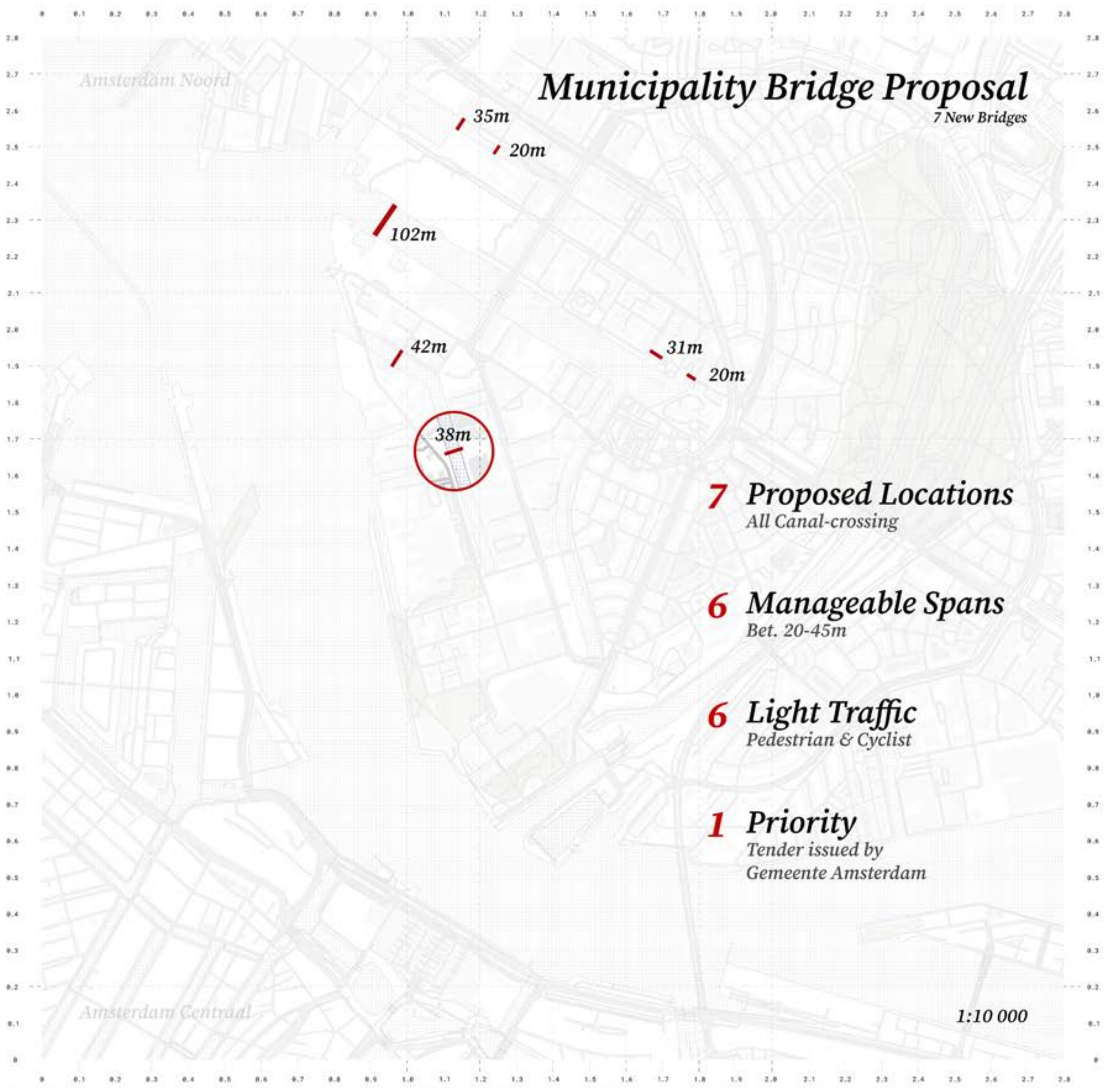


Fig 3.8: Municipality Bridge Masterplan for Buiksloterham & Site Selection.

The overall masterplan for bridges in Buiksloterham (Gemeente Amsterdam, 2020a) called for 7 canal-crossing bridges to be built, each with different function and lengths (Fig 3.8). As the thesis aims to select a feasible span and loading condition to test a novel timber bridge structure, the heavy traffic bridge crossing Johan van Hasseltkanaal of 102m is eliminated. This is primarily due to the *large span and high loading condition* required to withstand vehicular, cyclist and pedestrian traffic which will potentially limit the exploration and typologies of structures. With six other bridges on site, all are within a manageable span of 20-45m as well as light traffic loading conditions. However by the time of the commencement of the thesis, only one bridge crossing Tolhuiskanaal Oost, connecting Asterweg and Grasweg, has priority over the remaining bridges. This is mainly due to the issuance of a tender (Gemeente Amsterdam, 2021) on 7th December 2021 for the design and construction of it. Therefore, this *site is chosen for its importance as a local connection for Buiksloterham*.

3.3.2 | Urban Composition

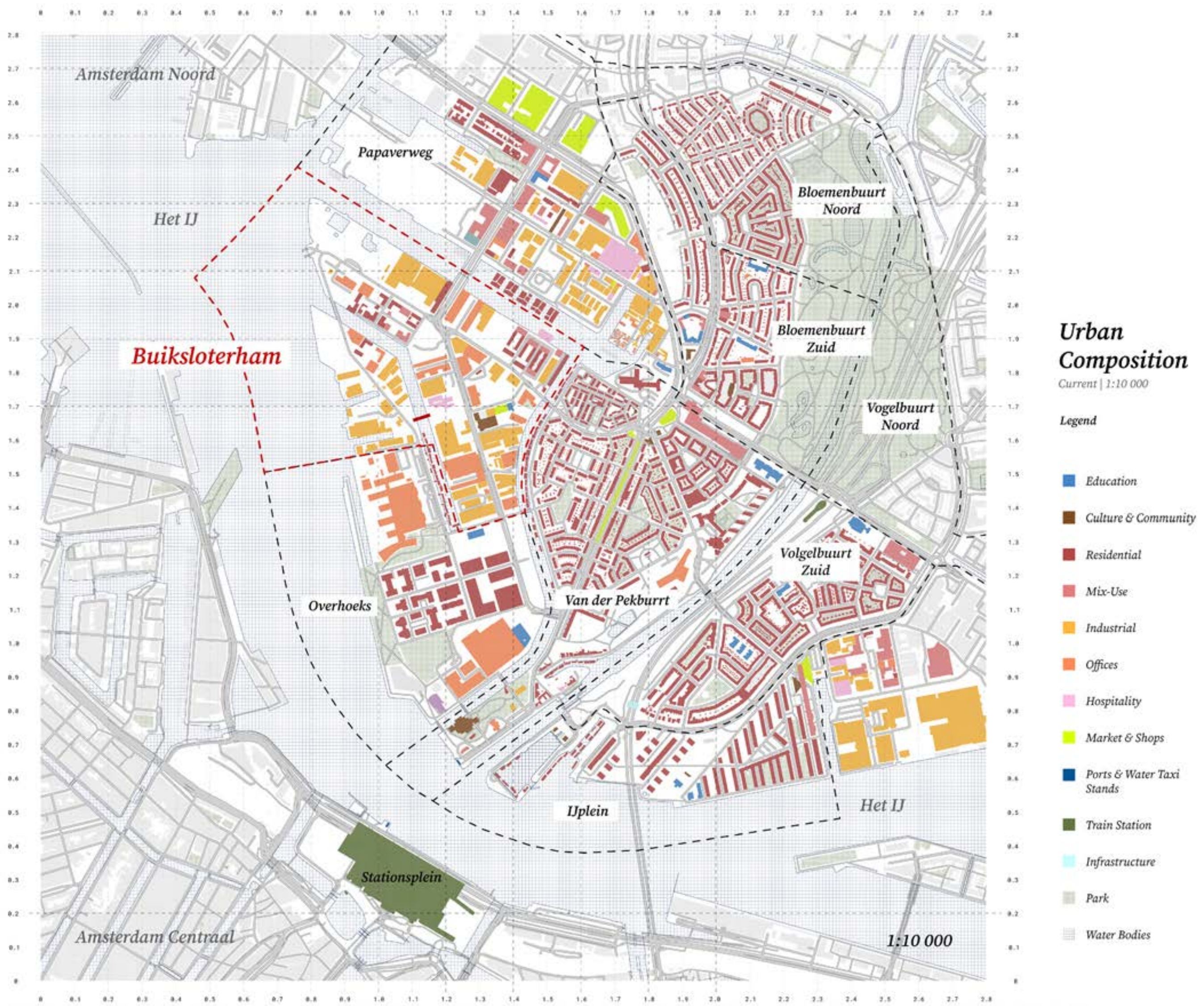


Fig 3.9: Urban composition of Amsterdam Noord.

As Buiksloterham began as an industrial estate which has gradually declined and redeveloped after 1980s, it is evident that *most residential estates (in dark red) are situated to the east of Amsterdam Noord* primarily in Van der Pekburt, Bloemenbuurt Noord & Zuid, IJplein and Volgelbuurt Zuid. This corresponds to earlier development during WWI where municipality housing were constructed and developed over time into neighbourhoods such as Disteldorp (1918) in Van der Pekbuurt. Buiksloterham, on the other hand is currently concentrated with industries and offices with few new residential buildings and construction towards the north and north-east.

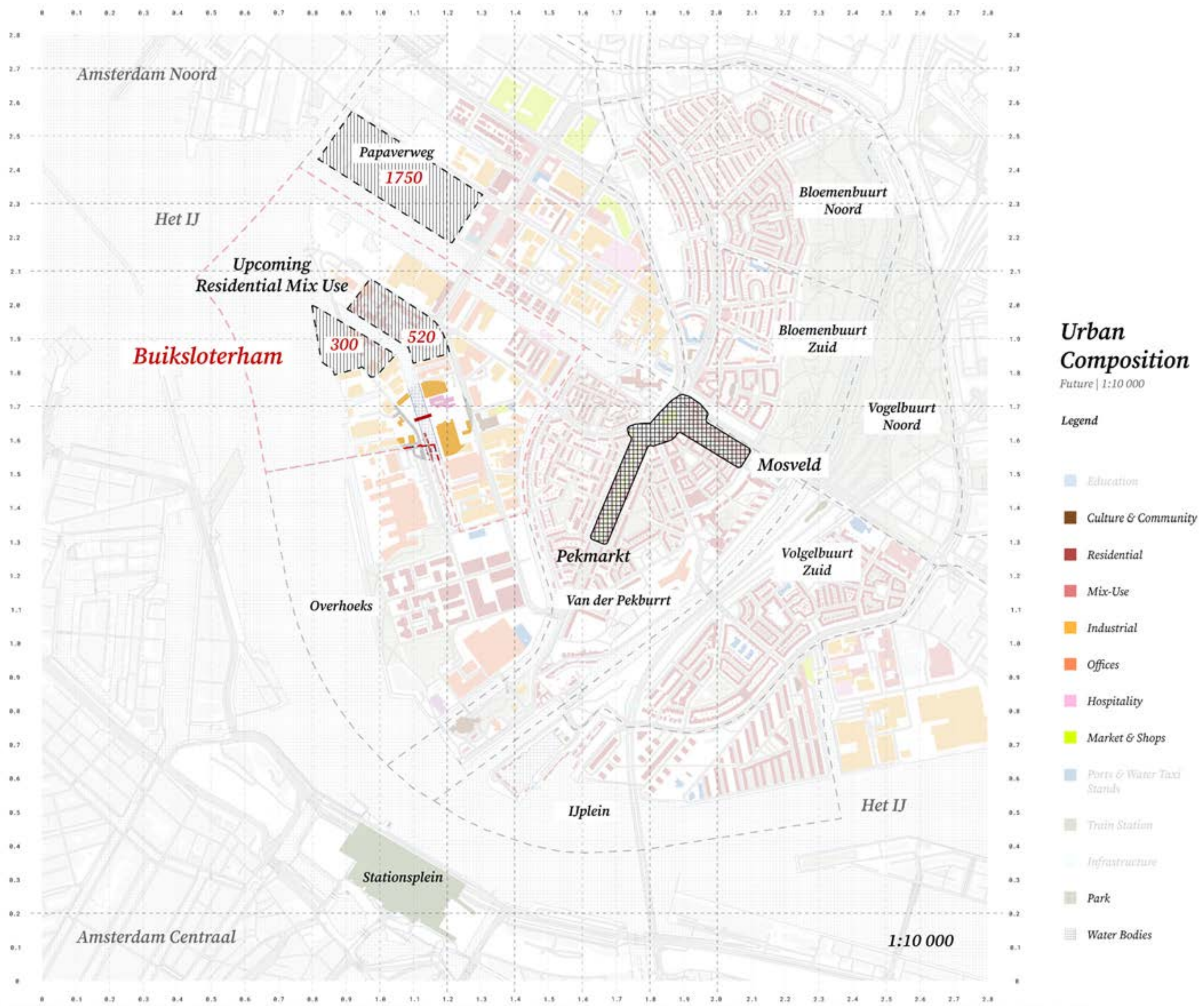


Fig 3.10: Future Urban Composition, primarily focussing on upcoming mix-use developments near Buiksloterham. The red bar represents the bridge site. Information extracted from Housing Plans (1-1-2022) by Gemeente Amsterdam (2022).

This is about to change for within the Housing Plans (1-2-2022) (Gemeente Amsterdam, 2022), it is estimated that about *2570 new mix use residential and offices will be constructed in the northern part of Buiksloterham and west of Papaverweg* (Fig 3.10). This signals an increase in density of families and office workers near the bridge location, as indicated by the red bar in the map. Being one of the key bridge users in the future, it is crucial to identify further their potential movement across the neighbourhoods to design with their accessibility requirements in mind.

3.3.3 | *User Profiles & Accessibility*

The categorization of demographics for analysis of profiles and accessibility requirements are formulated based on two factors – onsite observation during peak hours and the current and future urban composition as discussed in the previous section. The former provides a real-time and current understanding of user demographics based on existing programmes on site while the latter gives insights into the potential new mix of demographics in the future.

With the onsite observation conducted qualitatively during the peak hours of 0800 – 1000hrs and 1700 – 1900hrs, over the span of 5 months between November 2021 to March 2022, there are 3 main types of users around the bridge site, ordered accordingly to the frequency in which they are observed (more to less):

1) Working adults
2) Residents, Leisure & Recreation
3) Students & Children

Through the analysis on future masterplans of Buiksloterham, it can be expected that all types of users observed above will correspondingly increase with the upcoming mix-use developments in Buiksloterham. During the period of observation, due to the COVID-19 pandemic, the size of each demographics observed are influenced to a certain extent with the lockdown and subsequent re-opening of the workspaces in Netherlands. Hence, it is merely used qualitatively as a guide in understanding the local demographic mix instead of being a quantitative indicator.

Working Adults

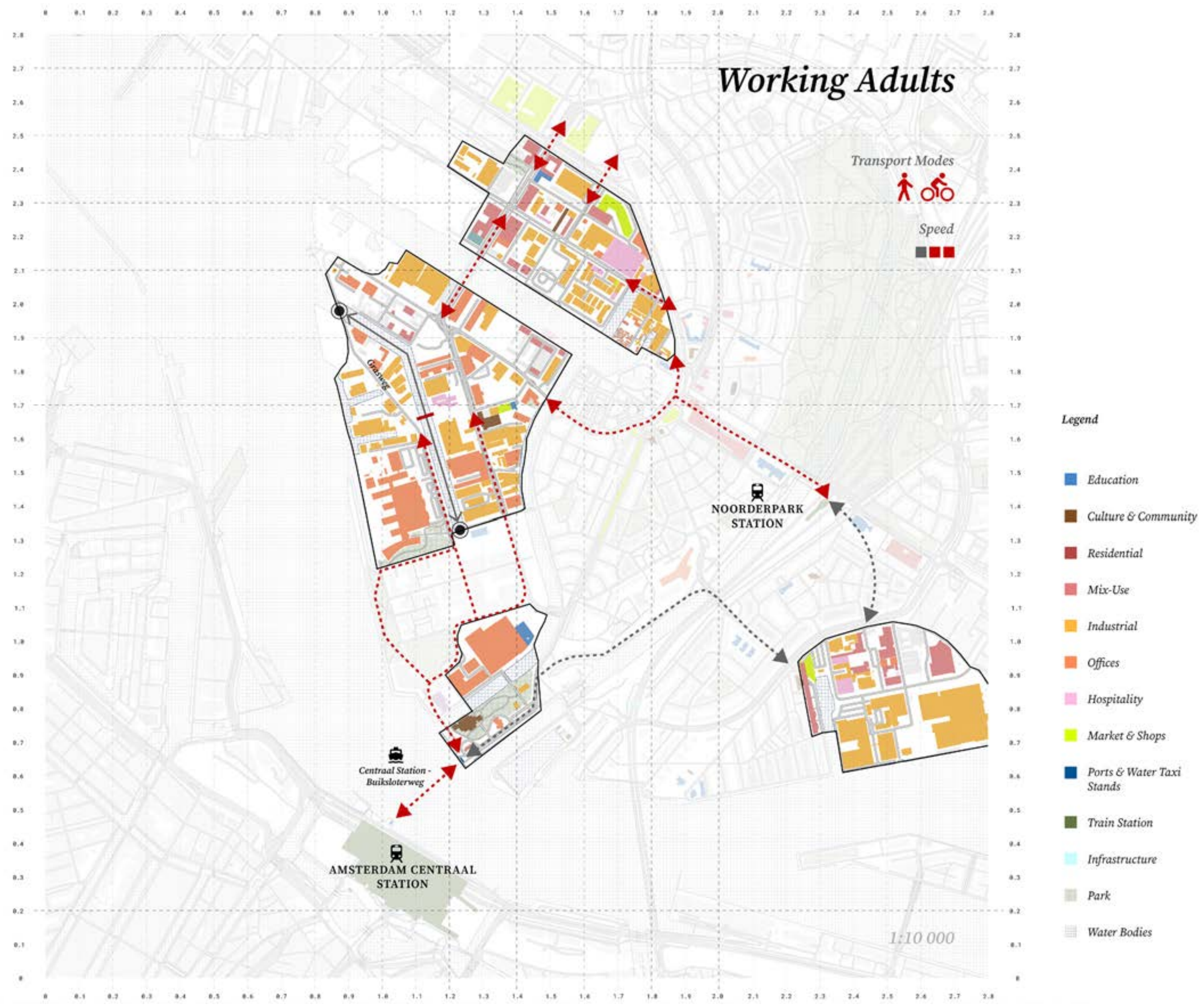


Fig 3.11: This map outlines the key zones of commercial, industrial and office areas whereby a large proportion of working adults travel towards from their own residence or key transport nodes around the area. The red bar represents the bridge site.

Within and around Buiksloterham, there are multiple zones where industries and offices are concentrated, such as Papaverweg and Oeverhoeks. Whilst there are multiple ways to access these workplaces, the main modes of transport consists of cycling from nearby residential estates and public transportation from train stations like Amsterdam Centraal via the ferry terminal at Buiksloterweg or Noorderpark Station (Fig 3.11). With the red dashed arrows indicates the flow and access of these workplaces, it is evident that the bridge crossing connecting Asterweg and Grasweg would be a *local and low traffic bridge* connecting both sides of Tolhuiskanaal within Buiksloterham since it does not lie directly along one of the main access points to the offices and industries in Buiksloterham. It is however *located very centrally along Tolhuikanaal*, thus providing a *quicker and closer crossing* to the workplaces and future residential estates in the middle of Tolhuiskanaal, as compared to the bridge at the start and end of Grasweg (indicated as black dot in Fig 3.11).

Residents, Leisure & Recreation

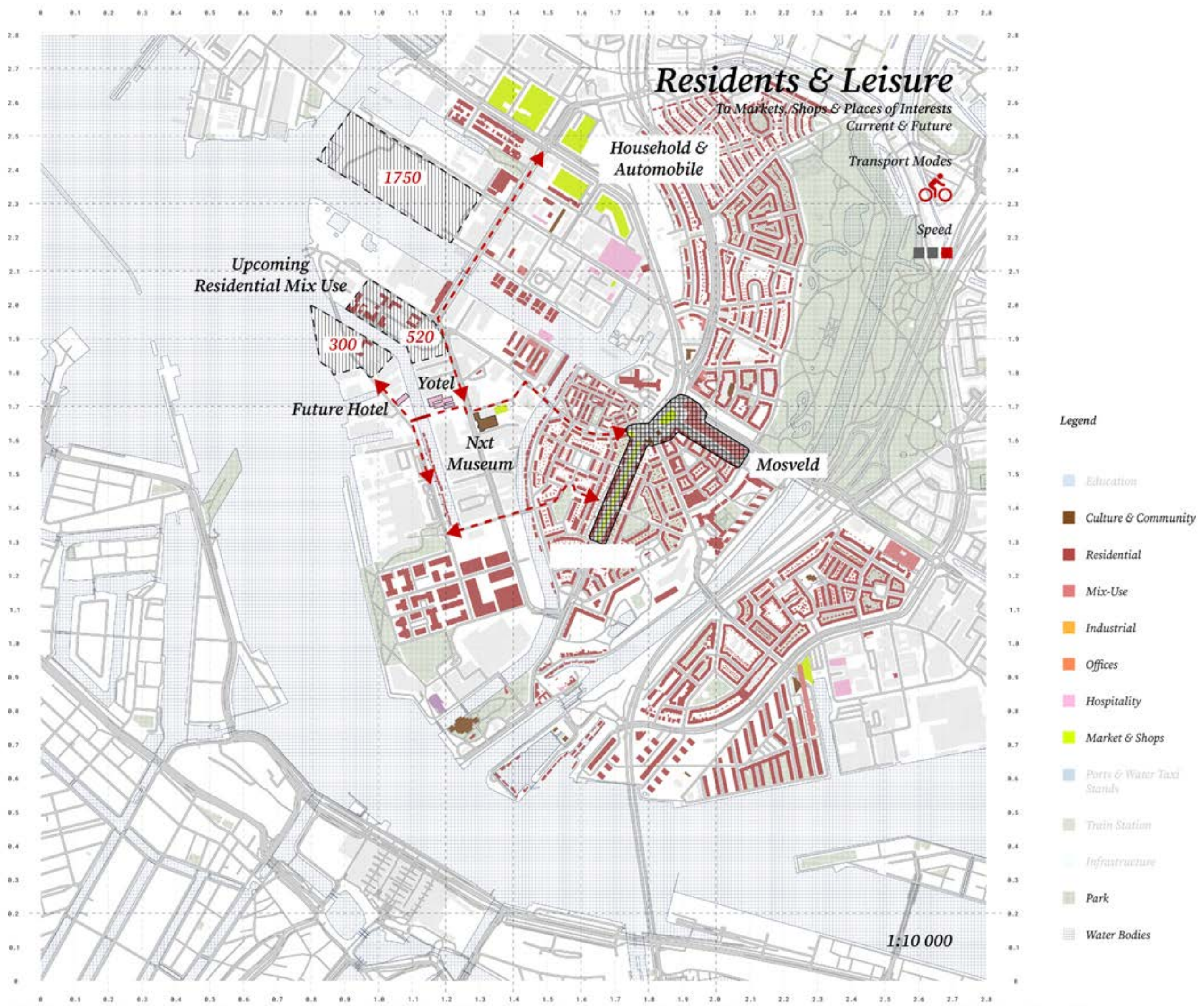


Fig 3.12: Residential estates, markets and cultural places of interests are currently more concentrated outside Buiksloterham in Pekmarkt and Mosveld, thus the bridge will typically serve residents & workers situated in Buiksloterham as they travel to-and-fro these areas.

Key areas of interest such as the market at Pekmarkt and Mosveld (Fig 3.12) will serve as prime location for residents within Buiksloterham to get their daily necessities as well as for leisure activities. As most cultural places of interest lies are more highly concentrated outside of buiksloterham, the bridge will more ***directly benefit accessibility to Yotel, the Nxt Museum and the upcoming Hotel Grasweg 46***, outlined in black in Fig 3.12. It is evident that the crossing of the bridge site is not the only way to get to the market centers, hence it will ***likely be of low to moderate traffic***.

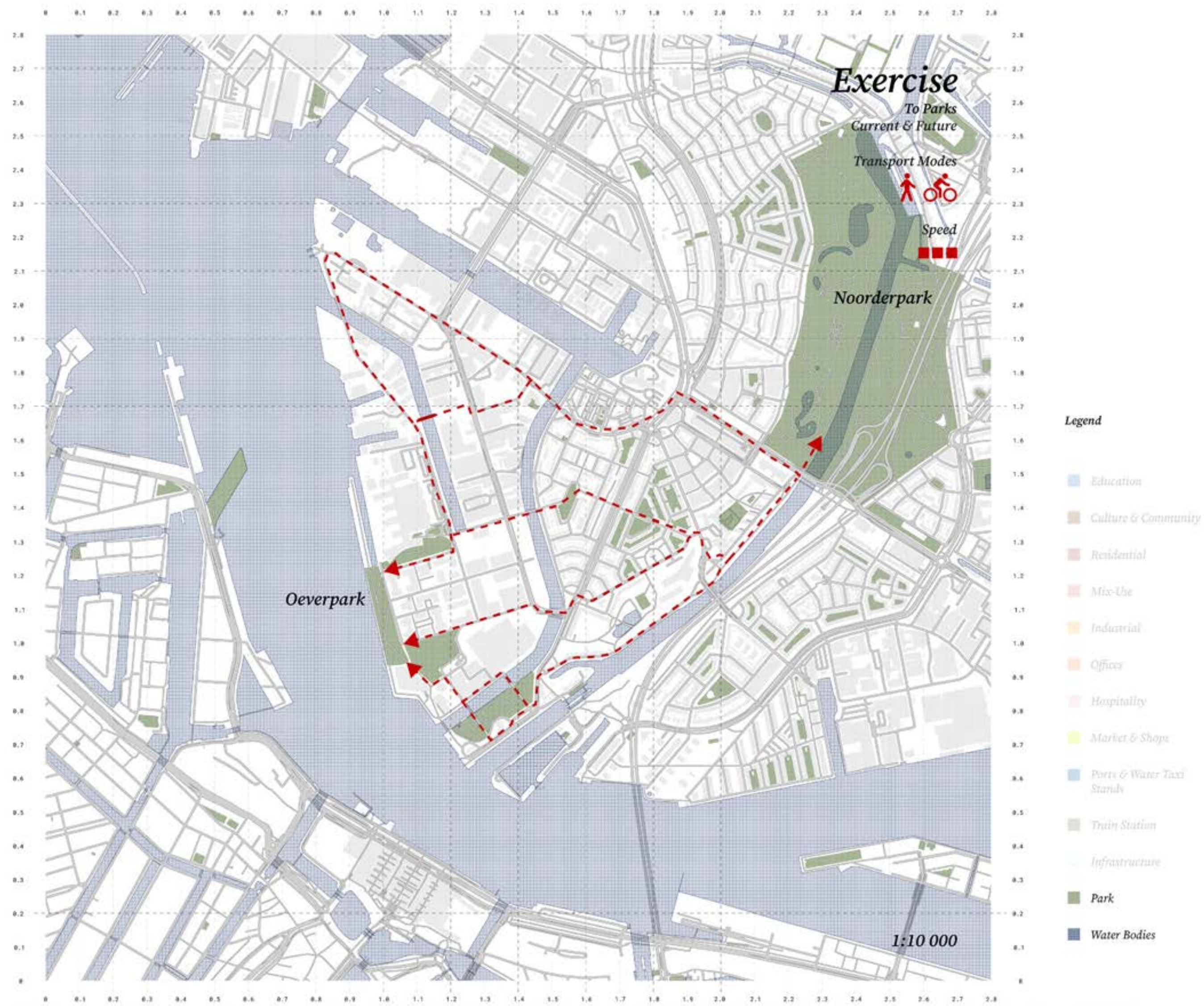


Fig 3.13: Green and blue spaces around Buiksloterham where people who exercise usually move towards, more specifically within established parks like Noorderpark and Oeverpark. The red dash indicates the possible access points connecting both parks, where the proposed bridge location could serve as a new recreational green & blue space between these parks & waterfront along the IJ.

In addition, green and blue spaces mapped in Fig 3.13 shows the relative discontinuity of green spaces between the bigger parks like Noorderpark and Oeverpark. Since it has been established by Gemeente Amsterdam within the PoR of this bridge to preserve the green spaces on both sides of the bridge, it will potentially be one of the ***new green space as one travels between the 2 main parks***. While the proposed bridge will lie along one of many alternative routes which connects the parks and waterfronts, it reinforced the previous deduction that the ***traffic on this bridge will likely be low to moderate***.

Students & Children

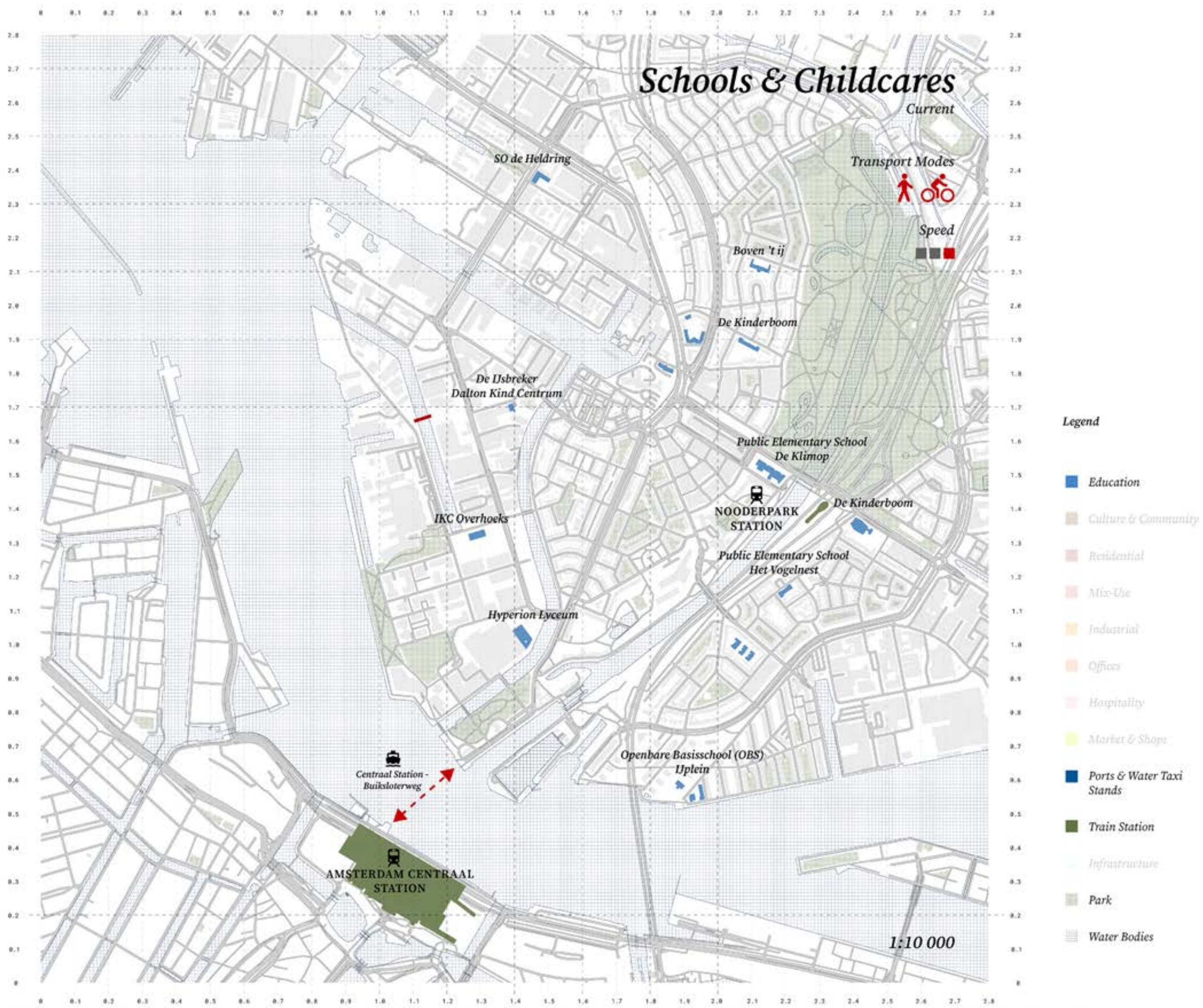


Fig 3.14: The distribution of schools and childcares in the area are indicates a higher concentration outside Buiksloterham while the main modes of travelling comes in the form of walking and cycling either from key transport nodes or from nearby residences.

Based on Fig 3.14, the distribution of schools and childcares are largely concentrated outside Buiksloterham. From the on-site observations conducted, students are also travelling from their own residences and main transport nodes – such as the train stations and ferry terminals – towards their schools. As the *bridge is not situated along key roads directly leading to any schools*, it is likely that it will not be frequented by students & children on the way to school. However this might change in the future when more housing developments further populate the western waterfront of Buiksloterham. Therefore it will still be wise to design the bridge with children in mind.

Conclusion

User Type	*Mode*	*Speed*	*Stairs*	*Ramp & Gradient*
Working Adults			√	√, 1,75 - 7,5%
Cyclists / Skaters*			X	
Joggers*			√	
Residents & Leisure			√	
Students & Children			√	√, < 4% (landing every 0,5m height)
Disabled			X	

Fig 3.15: Consolidated table of accessibility requirements to design for specific user types. Data extracted from Brief Dutch Design Manual for Bicycle and Pedestrian Bridges (ipv Delft, 2015).

Consolidating all the mapping analysis of the various user types of the bridge, it can be deduced that the bridge will be a *fairly local and low traffic bridge* in current times, while in the future, the *growth of mix-use functions on both sides of Tolhuiskanaal will certainly boost the traffic of the bridge across all user types*. This this can be consolidated in Fig 3.15 where the accessibility requirements of each user types has been specified and ordered from fastest to slowest speed.

To design a suitable bridge for all user types specified, it is evident that *stairs will be less important than having a ramp* since cyclists and the disabled are unable to use it. Ramps have to be less than 4% in gradient and a landing every 0,5m climb such that kids and the disabled could access the bridge easily. In addition, the *ramps should be designed with a decreasing gradient towards the center to ease the ascend by any user types*. As adults travelling to work and cyclists might travel at high speed onto the bridge, any curves will need to have a *minimum 10-20m turning radius* to allow a smooth navigation rather than having to slow down. As more residential developments are taking place in Buiksloterham, the bridge will need to be child-friendly, with *railing openings no larger than 0,1m*. The *height of railings will also be minimally 1,2m* so as to make the cyclists feel safer due to their elevated center of gravity (ipv Delft, 2015).

3.3.4 | Site DNA

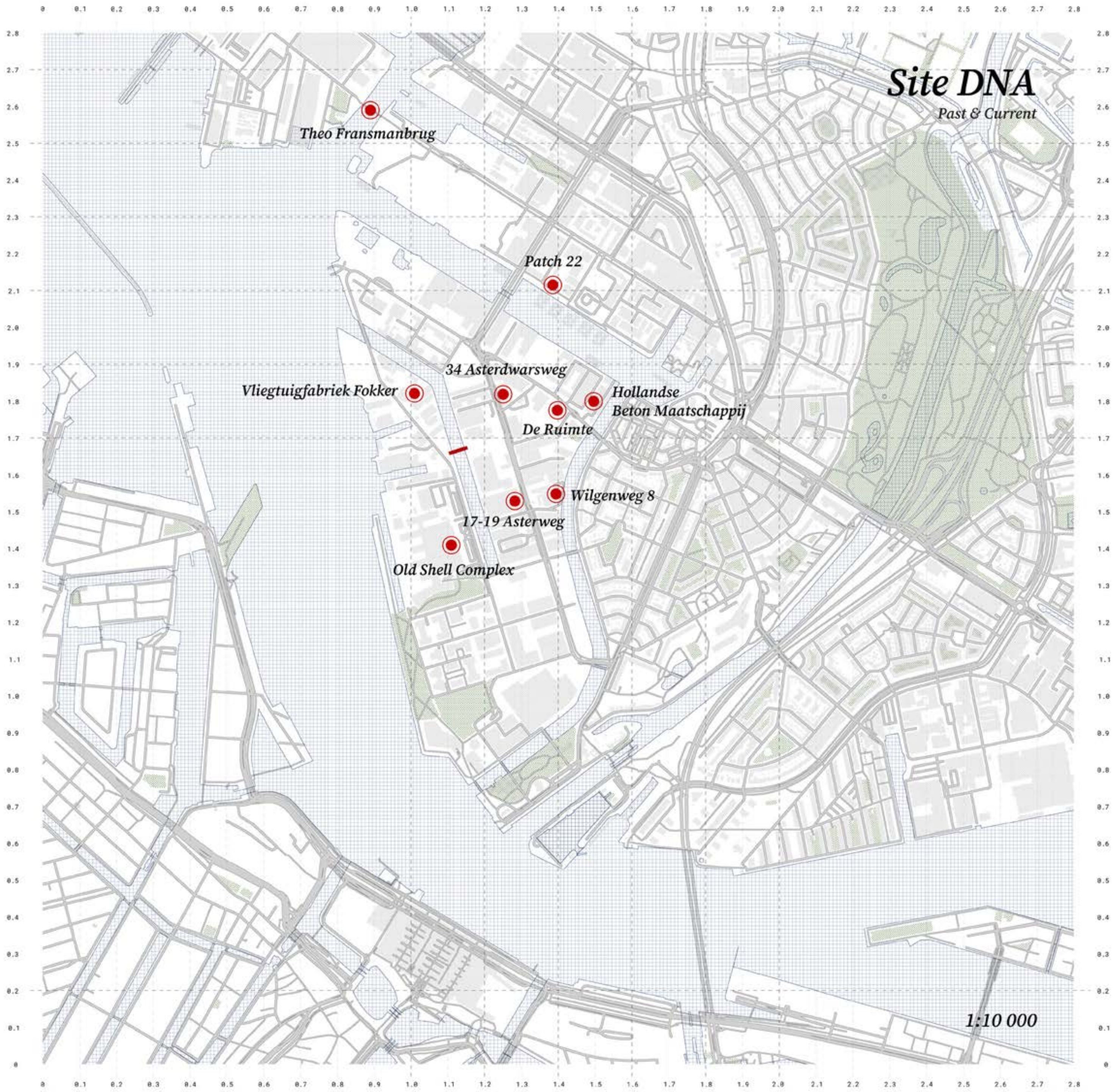


Fig 3.16: Buildings of significance from the past and present near to bridge site.

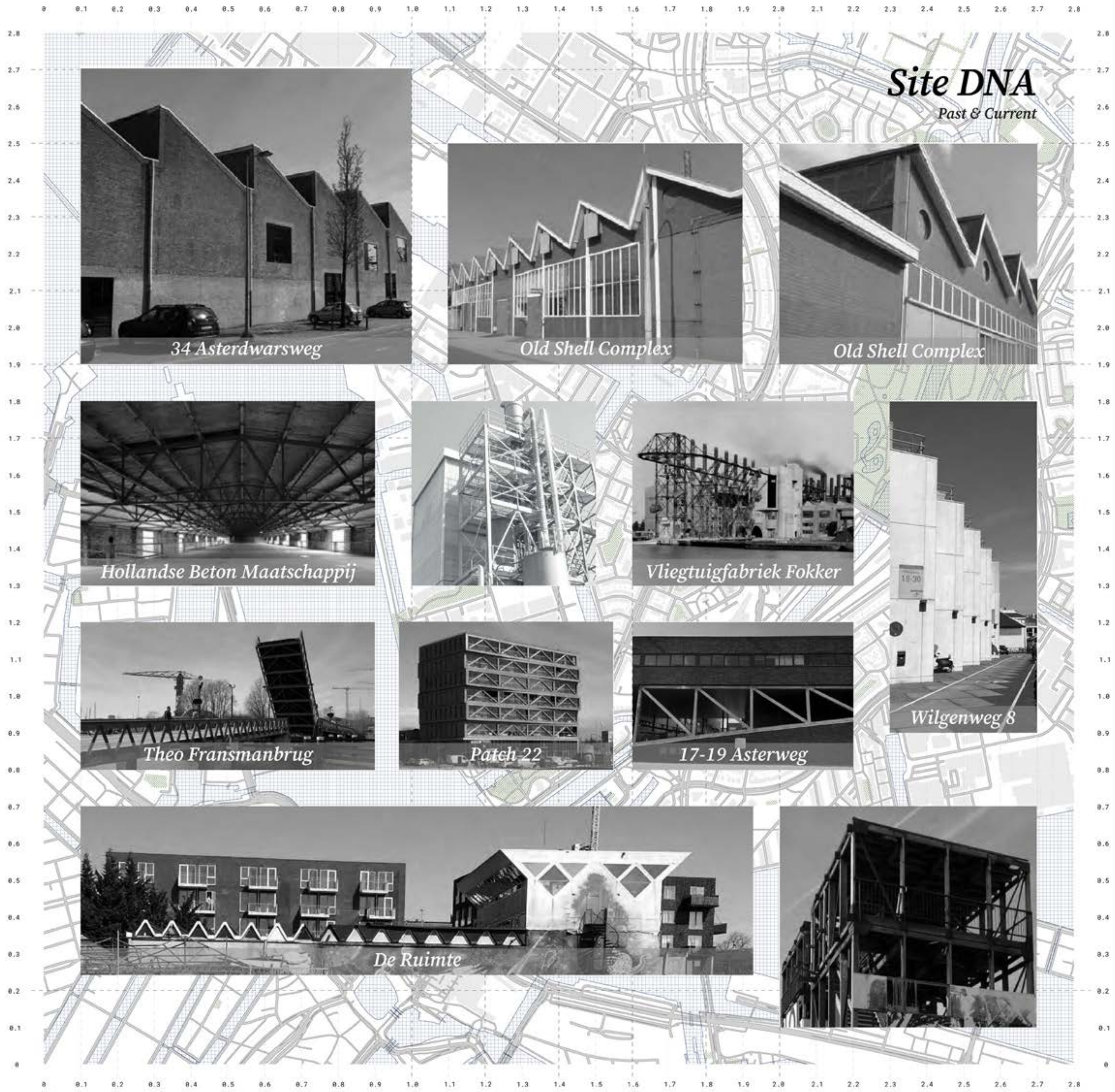


Fig 3.17: Visual composition of significant buildings near to bridge site. The common thread of structural triangulation resonates from the past economical construction of industrial factory such as Vliegtuigfabriek Fokker in steel to current structural expression of timber in Patch 22.

As stated within the PoR in *Section 3.2 Design Brief*, it is crucial to incorporate the identity of the site into the design. Hence an analysis was conducted to identify the expression of the buildings around the bridge site in Fig 3.16. Historically, Buiksloterham has housed numerous industries with factories and warehouses built economically to span as wide as possible. It is evident to observe the common structural expression of various forms of steel trusses in Fig 3.17 from bridges to warehouses and offices. This language is also embodied in the form of concrete across various mediums from floor, wall to roof. While the tectonic mix of concrete and steel structures reinforces the austere identity of the industrial and modern era, it presents an opportunity to introduce another material to herald a new age of sustainable, mix-use developments in the digital era. Although timber as a building material has been as old as human civilizations, the use of engineered timber with its enhanced strength broadened the range of structural typologies and spans possible. Thus, the use of timber for the bridge proposal is beyond sustainability, but also represents the technological potential of the current times. To adopt the structural language of triangulation from the site, a novel timber structure will be developed and proposed.

3.3.4 | Height Analysis

With Tolhuiskanaal home to 18 houseboats docked to its shores, the size and height of these houses are crucial to ensure that they can be tolled out of the canal for maintenance every few years. This forms the basis for the requirement of an occasionally movable bridge design. With the height map extracted from AHN Viewer, the maximum height of these houseboats is 6,40m. Through correspondence with Cyrus Clark from Gemeente Amsterdam and online research of municipality guidelines on height of houseboats, no definitive nationwide standards and regulations is stipulated. Hence based on the above analysis and a study on the maximum heights of neighbouring houseboats, it is advised that *a maximum height of the water passage of 7m should be able to allow free passage of all the houseboats*.

Fig 3.18: Houseboats in Tolhuiskanaal.

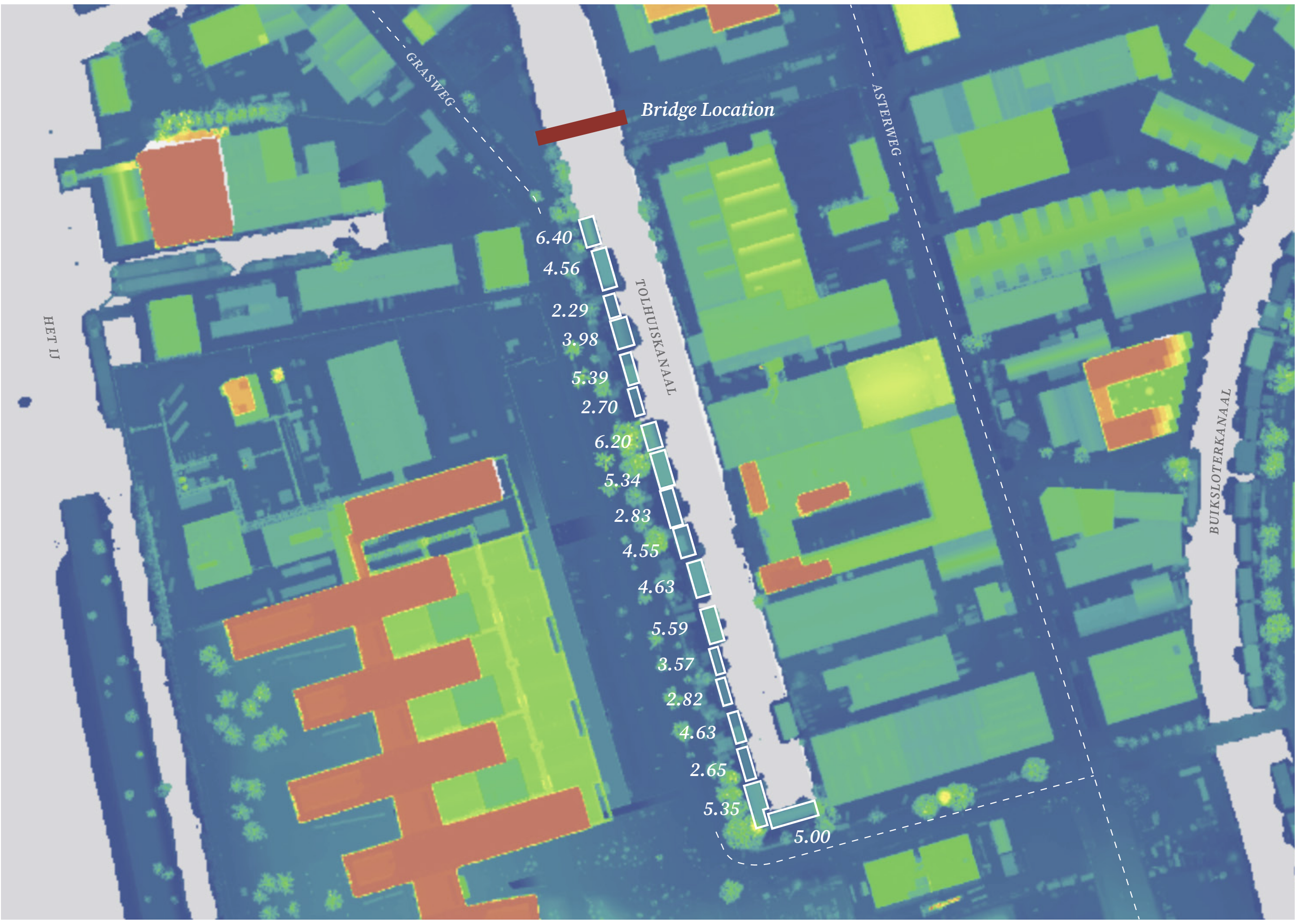


Fig 3.19: Height analysis of surrounding buildings in Tolhuiskanaal Oost, primarily focussing on the houseboats. Data extracted from AHN Viewer.

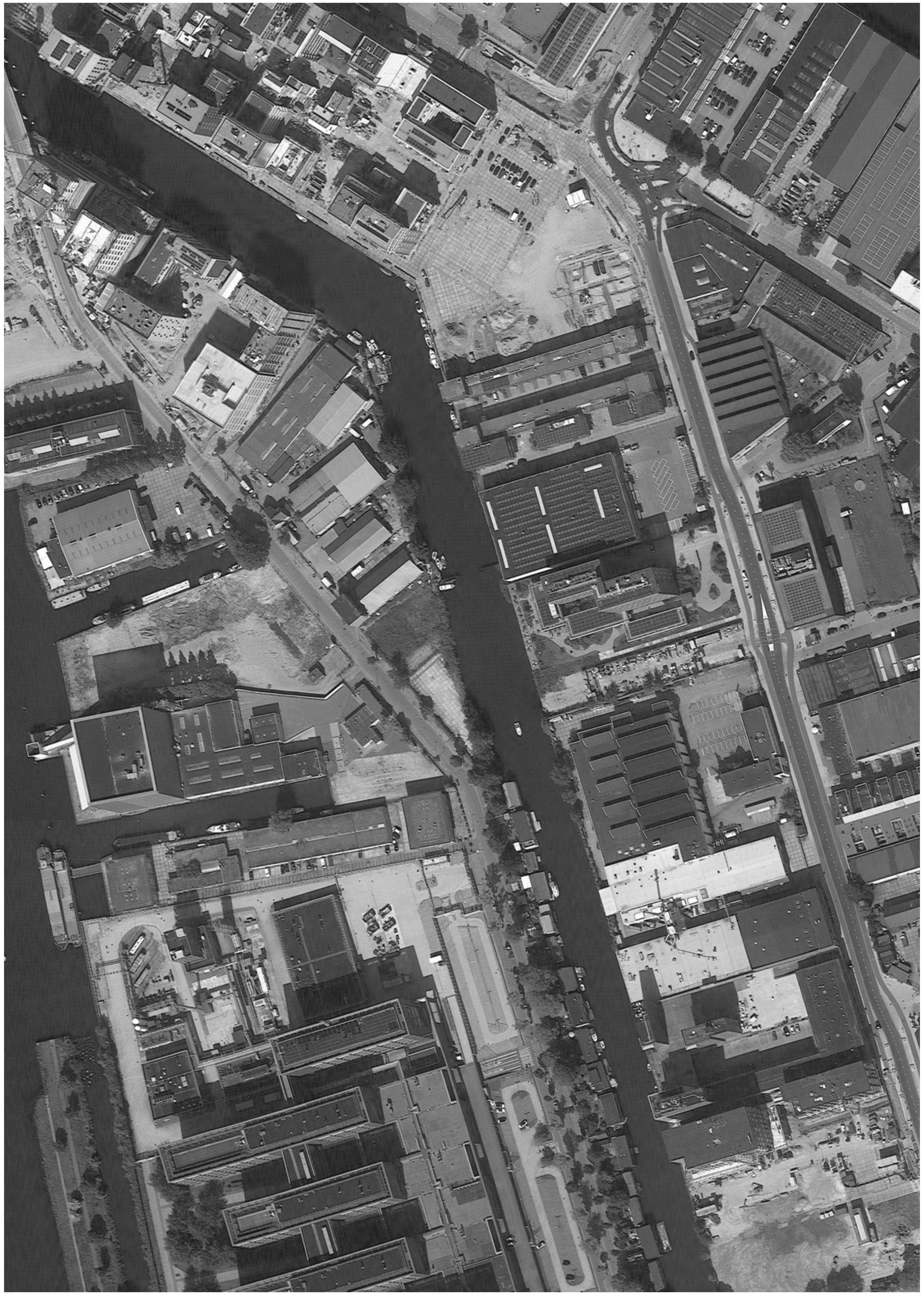
3.4 DESIGN VISION & GOALS

Urban & Architecture

As Buiksloterham sheds its industrial past and transform into an exciting work-live neighbourhood along the IJ River bank, the vision for the bridge design aims to encapsulate this transformative time with the proposal of a *novel timber structure for the digital age*. With many buildings on site built during the industrial era primarily in concrete and steel, it embodied the agenda of automation, mechanization and mass production. As the advancement of digital technology ushers in the 4th Industrial Revolution, there is an opportunity for this bridge to be a *landmark* to represent the potential of the digital age while reintroducing timber as the sustainable material for this new age.

With the municipality's aim of incorporating circularity into all new developments in Buiksloterham (Metabolic et al., 2014), the bridge will also be designed for disassembly such that the individual components of the bridge can be dismantled and reused or upcycled to other purposes beyond the lifespan of the bridge. The use of timber in this case aligns with the objective of Gemeente Amsterdam circular goals as a *bio-based, renewable material* sourced from sustainably managed forestry in Europe.

Lastly, it is crucial that the *bridge is designed to allow house boats to pass once or twice a year*. The conceptual approach provided by Gemeente Amsterdam in Fig 3.6 and Fig 3.7 indicated the proposal of having 3 independent bridge segments with a removable portion in the middle. Within the scope of this thesis, to fully explore and test the potential of a novel bridge structure, the full span strategy is adopted without divisions in the structural elements of the bridge. This also resulted in a novel method of moving and segmenting the bridge which will be outlined in the following *Sections 3.6.2 - 3.6.3*.



3.5 URBAN DESIGN STRATEGY

Promenade by Tolhuiskanaal

The urban design strategy of the site begins with understanding the existing and upcoming programmes around the immediate site of the proposed bridge. Currently, a diverse mix of residential (houseboats), factories and offices, as well as hotels are directly adjacent to the bridge location. With the redevelopment of Buiksloterham, two new green spaces are outlined in the masterplan (Gemeente Amsterdam, 2020a) on the Grasweg and Asterweg landing points of the bridge and a new hotel, Hotel Grasweg 46 will be built in the future. This zoning strategy by the municipality provides clear distinction between the north and south side of the bridge, whereby varying degrees of public and less public spaces can be demarcated by the introduction of the bridge. In the north, the hotels and waterfront promenade defined the more public side of the site whereby in the south, the houseboats, factory and offices resides in the less public domain of the site. The *bridge and park design reinforces this distinction between the more public north side and less public south side* by having a smaller park on the south of Grasweg while a larger park with waterfront seats allows for larger groups in the north. This allows the bridge to act as a buffer zone between the north and south side of Tolhuiskanaal, from the more commercial and open public spaces of the north into the more private and quiet residential and office spaces in the south. A sketch of this urban strategy proposal is illustrated in Fig 3.20.

Fig 3.20: Sketch proposal for the urban design strategy of Tolhuiskanaal Oost.

3.5.1 | Bridge Approach Iterations

To determine the approach towards the bridge, multiple factors were considered such as the gradient of the approach span, its turning radius as well as how it affects the division of the park spaces on both sides of Tolhuiskanaal. The primary objective is to *maintain a reasonably comfortable approach gradient less than 4%* as indicated in Fig 3.15 to allow all user groups to access the bridge with ease, while not having an excessively long approach path which will inconvenience any user looking to cross the bridge. Multiple iterations of the approach are tested with gradients and lengths determined in Fig 3.21, A to E.

After evaluating all the iterations, the need for an excessively long approach span to minimize the gradient of the approach span is not necessary as a straight path crossing directly from Grasweg to Asterweg fulfils the 4% gradient criteria. While the Grasweg side posed a tighter landing condition of between 14 to 26m when measured as a straight approach span from the shore of Tolhuiskanaal, an appropriate gradient was chosen as close to 4% along Grasweg which resulted in Fig 3.21, F. Based on the division of the park spaces, the accessibility gradient and directness of the approach span, this resulted in the final proposed urban strategy in the following section.

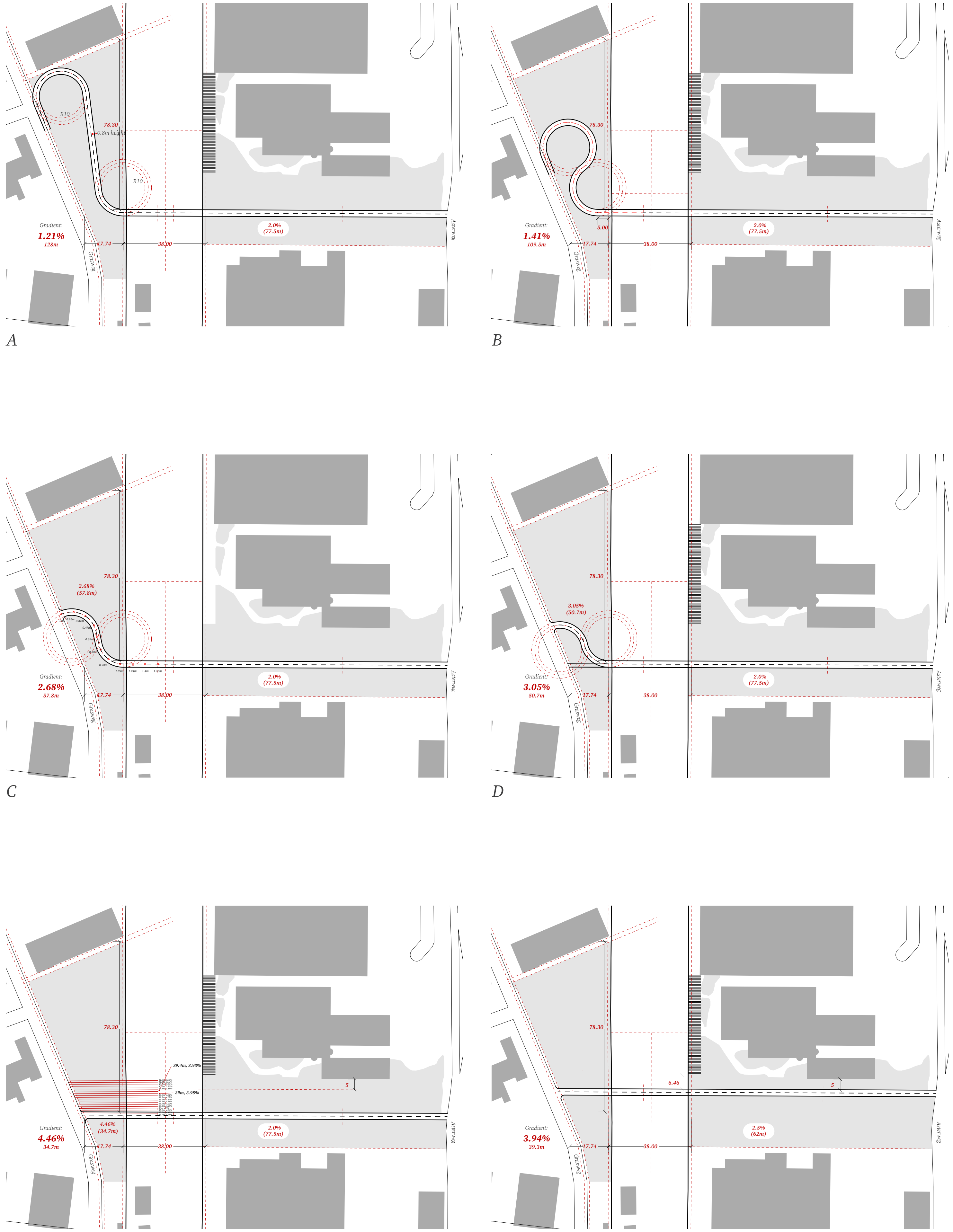


Fig 3.21: A – F, Iterations of bridge approach span to determine a suitable and sound strategy.

3.5.2 Proposed Urban Strategy

The eventual proposed urban strategy is as depicted in Fig 3.22 and more detailed in Fig 3.23 whereby the bridge is positioned closer to Yotel Buiksloterham to maximise the remaining park spaces on the Asterweg side of the landing. This resulted in an approximately 4% ramp gradient approach spans from both Grasweg and Asterweg, thereby fulfilling the requirement for all user types to access. A slight bent is introduced on the approach path on the Grasweg side to allow the turn from the cycling paths on Grasweg to be maintained at a maximum of 90 degrees – coming from north or south of the road – and the path maintained a turning radius of 10m.

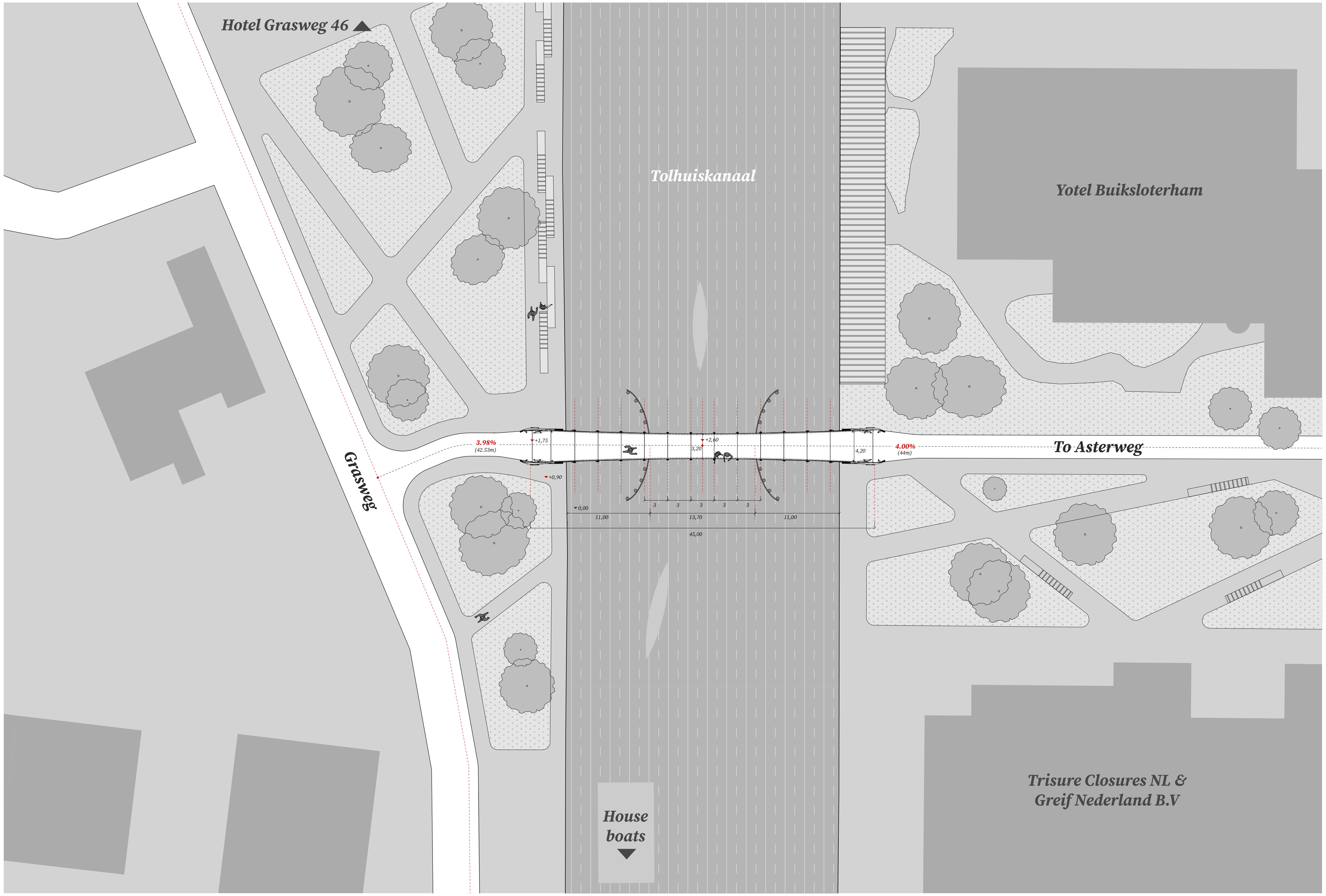


Fig 3.22: Urban site plan with the proposed bridge in relation to adjacent buildings on site.

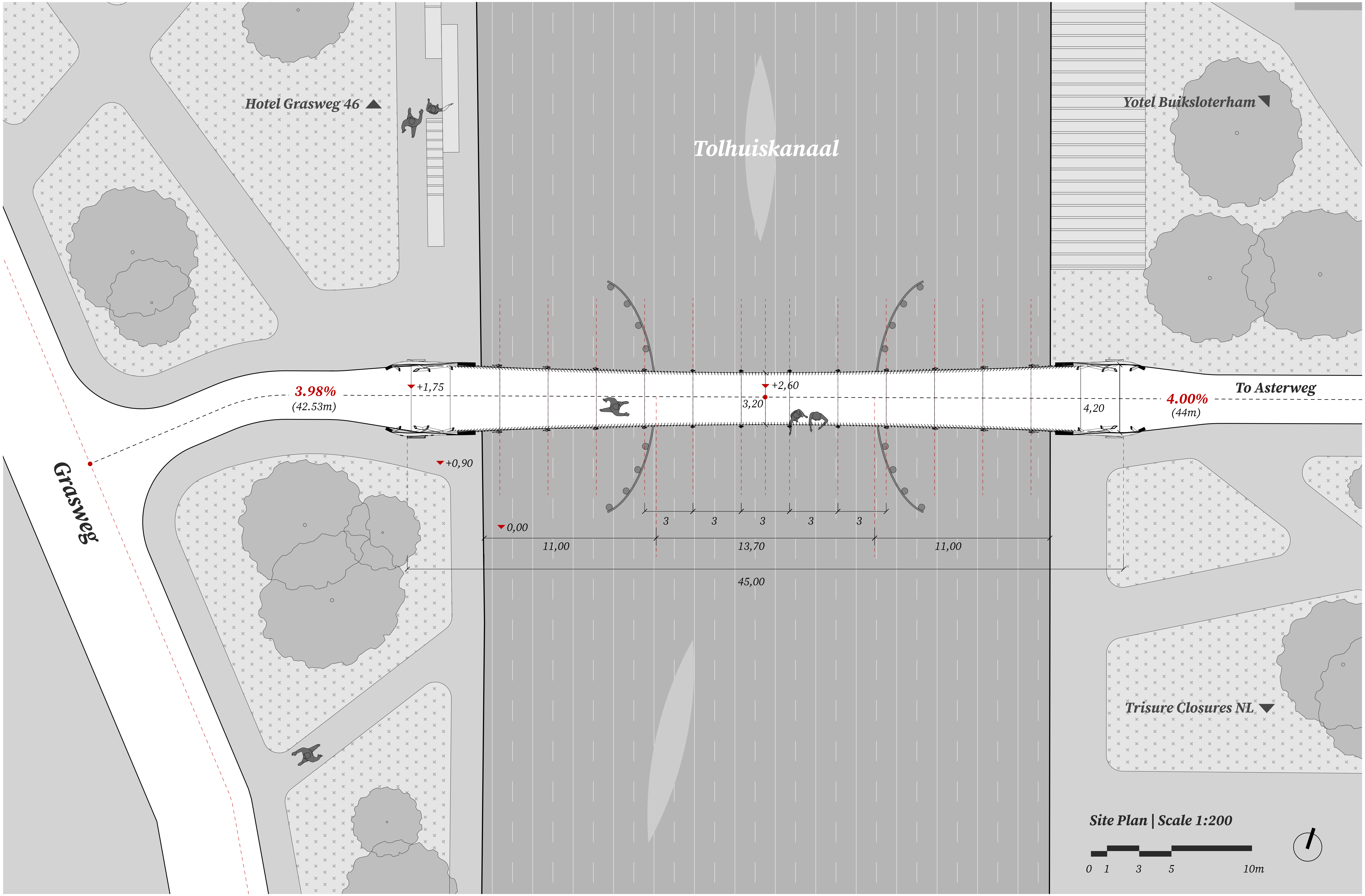


Fig 3.23: Proposed bridge approach and site strategy.

3.6 ARCHITECTURAL DESIGN STRATEGY

Change to something

3.6.1 | Division & Movability

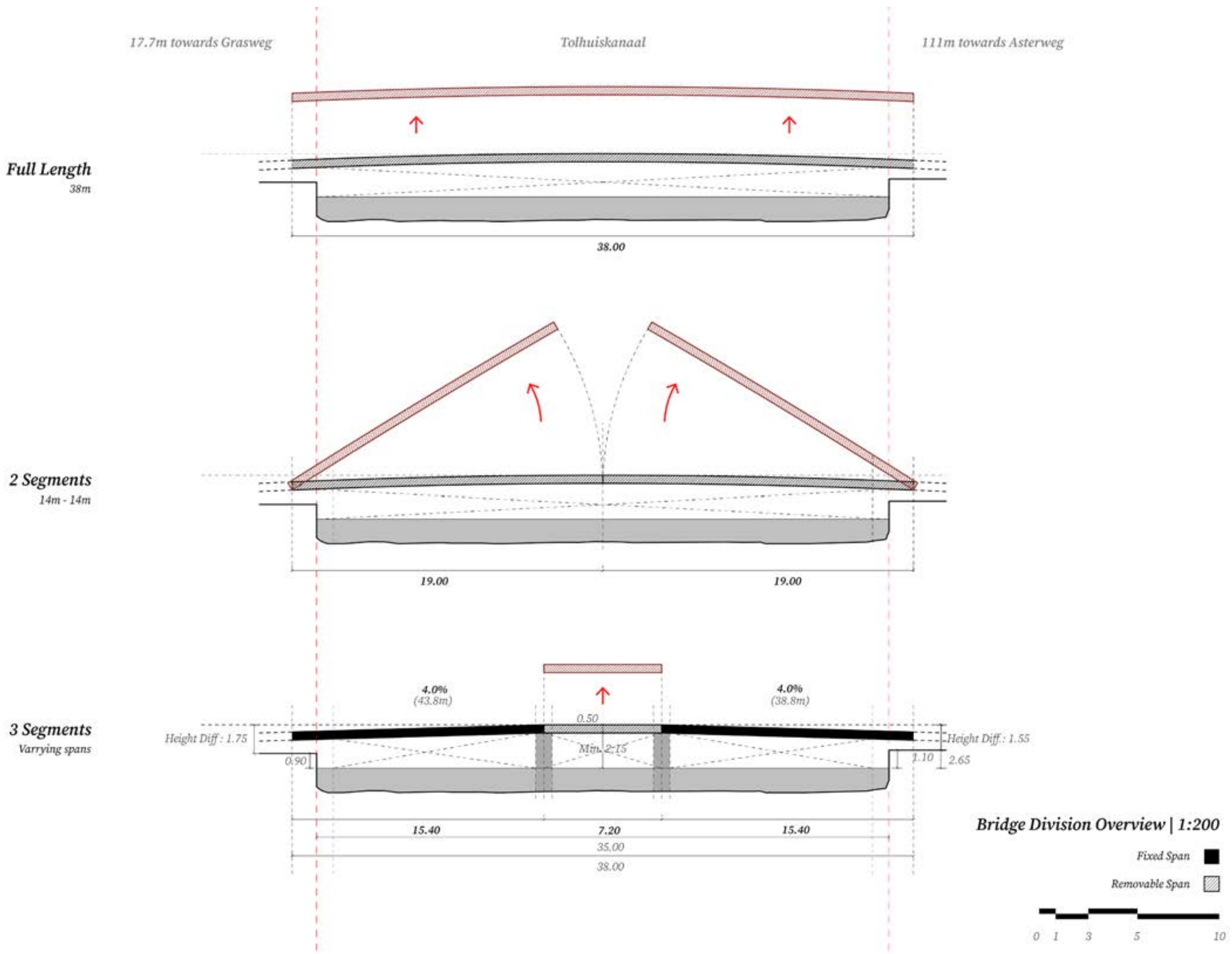


Fig 3.24: Overview of the 3 ways of span division explored.

3.6.1.1 | Bridge Span Division

Integral to the bridge design is the rhythm and logical division of the bridge span to allow for a structurally functional and visually balanced design. Based on the proposal by Gemeente Amsterdam in Fig 3.7, a three-span division was adopted whereby the middle section is a movable segment which could be lifted by a crane. As the division of the bridge meant that each individual segment had to be structurally independent from each other, the division thus heavily influence the structural typologies required. With increased divisions, each span reduces. A minimum of 38m span is required to keep the quay free from the abutments and foundations of the bridge. Therefore, a series of exploration for each span divisions – full length, 2 and 3 segments – is depicted in Fig 3.24 and elaborated with further drawings.

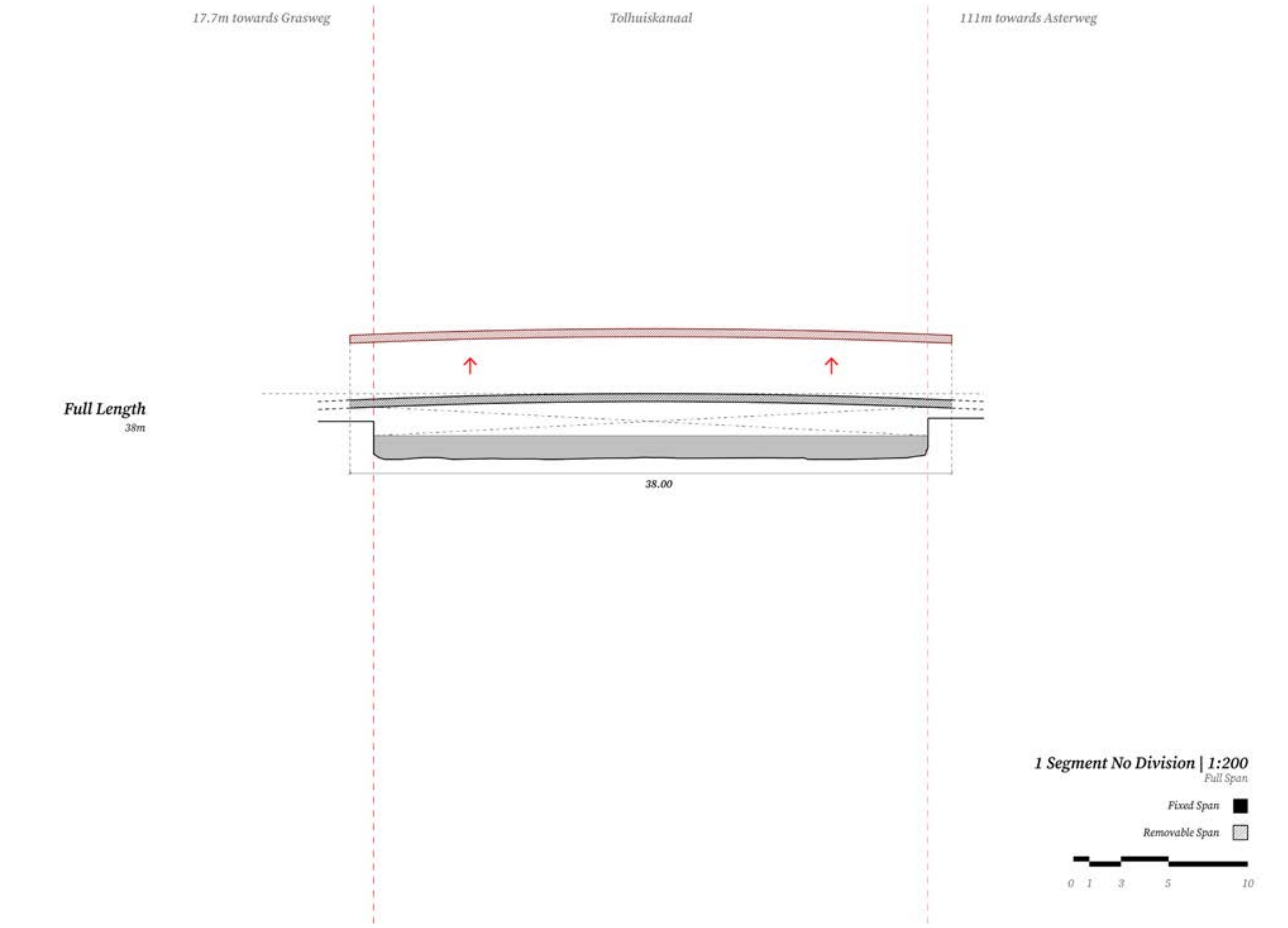


Fig 3.25: Full length bridge with no divisions.

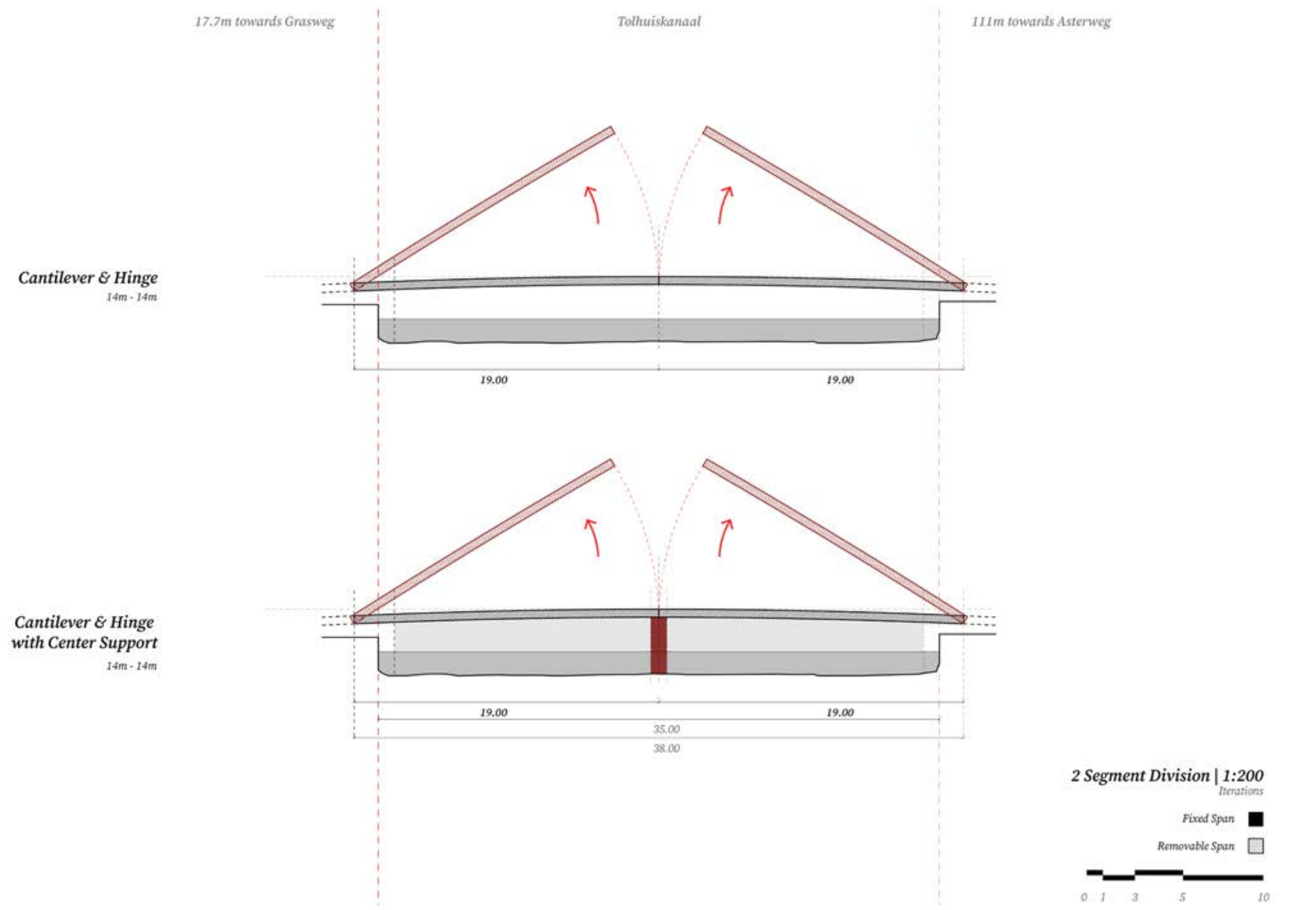


Fig 3.26: Design strategies for a 2 segment bridge division.

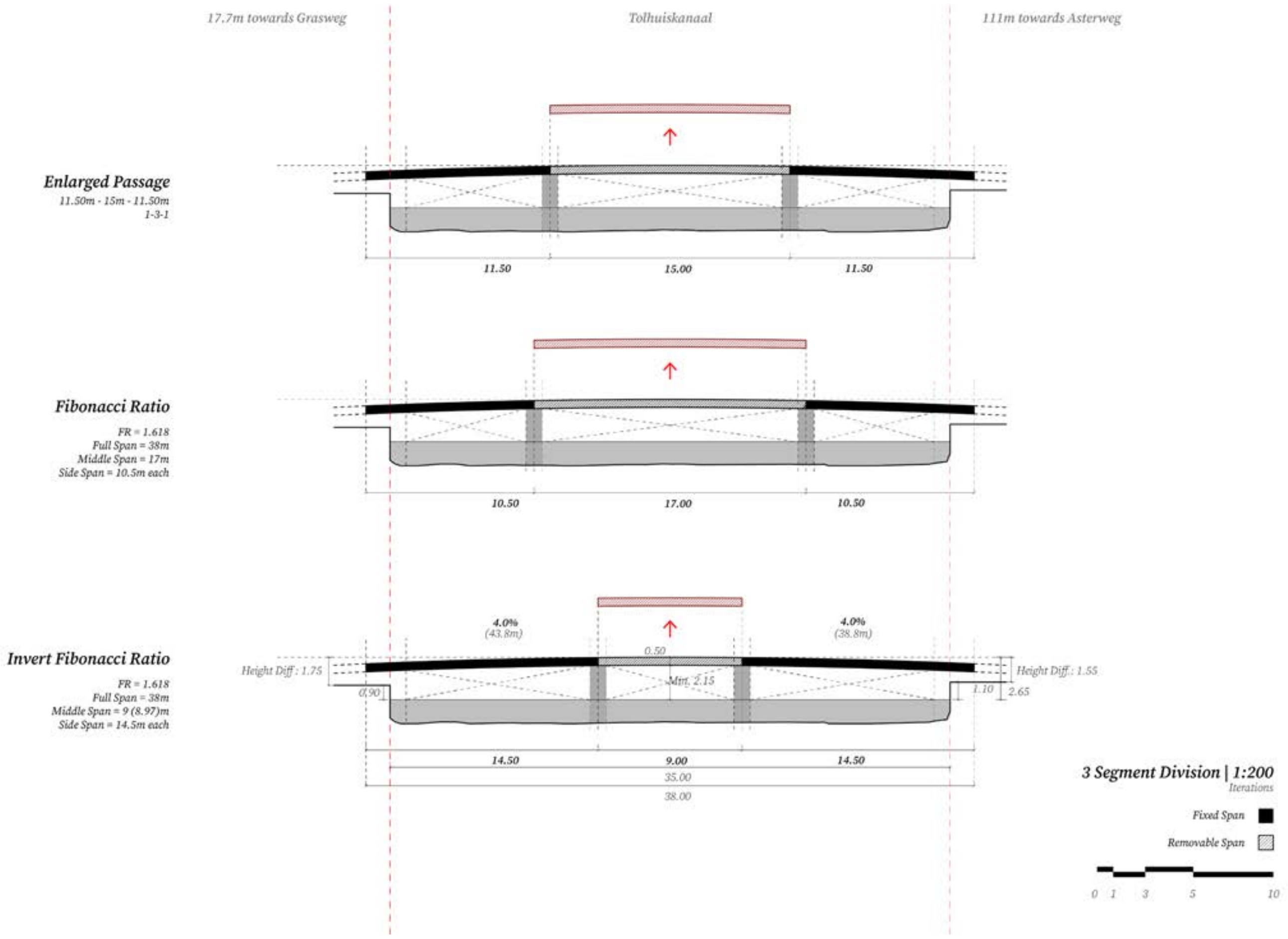


Fig 3.27: Design strategies for a 3 segment division.

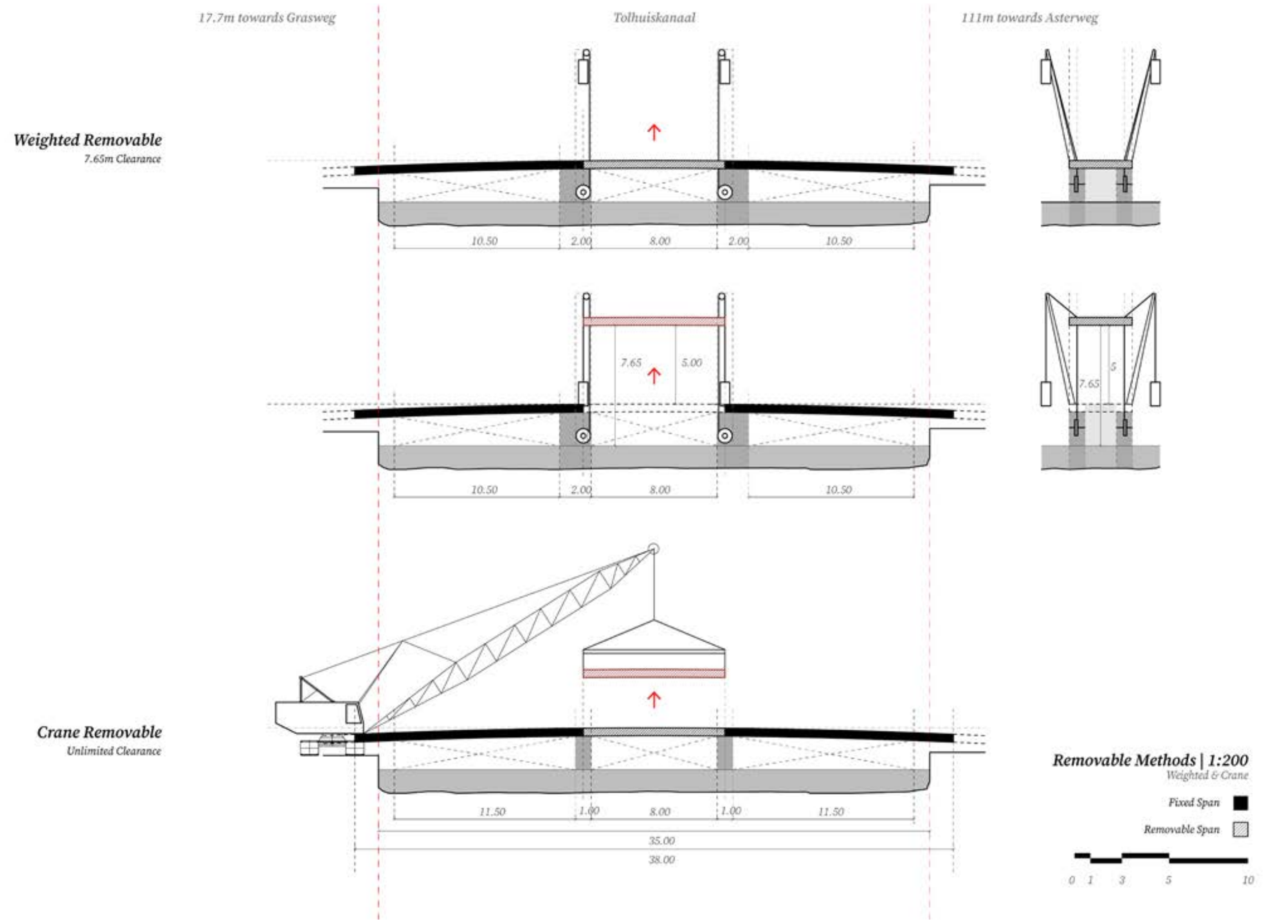


Fig 3.28: 3-segment bridge division movable methods.

With each additional division, each individual bridge span decreases. As the thesis aims to fully explore the potential of a novel timber structure in spanning long distances, the 3-segment division strategy was dropped. This is because it would require each individual spans to be structurally independent from each other for a segment to be removable. With each individual span ranging between 10.5 to 17m (Fig 3.27), a sensible solution for it would be to simply design 3 independent beam structure.

However, *the priority of the thesis, in designing a novel structure with large span, favours a full-length bridge with no divisions*. Conventionally, it would also entail that a large crane capable of lifting the entire weight of the bridge will need to be employed to open the canal. But given that the bridge does not require an unlimited height clearance and will only be opened once or twice annually, a simpler movability approach was designed.

3.6.1.2 | Movability Strategy

As outlined in the previous section, the span divisions heavily influence the movability strategy required. During the earlier phase of the thesis, methods to open the canal are explored with a 3-segment span division as depicted in Fig 3.28. However with the shift in design decision to adopt the full length bridge span with no division, a novel movable method was proposed in Fig 3.29. Within this strategy, the bridge decks are designed to be lightweight and suspended from a glulam arch beam structure overhead. These decks will feature joints which allows for disassembly by trained personnel on boats, thereby allowing free passage for houseboats through Tolhuiskanaal without the need to remove the entire bridge structure overhead. Based on the height analysis conducted (Fig 3.19), a maximum of 7m clearance will be required for all houseboats in Tolhuiskanaal to move through the bridge. With Tolhuiskanaal being a canal which comes to an end shortly towards the south, it is unlikely for it to be a quay where large recreational sailboats will enter and dock. Hence a 7m clearance is sufficient given the current and future developments of Buiksloterham. This is an integral design parameter for the minimum height of the overhead bridge structure and will be further elaborated in the next section.

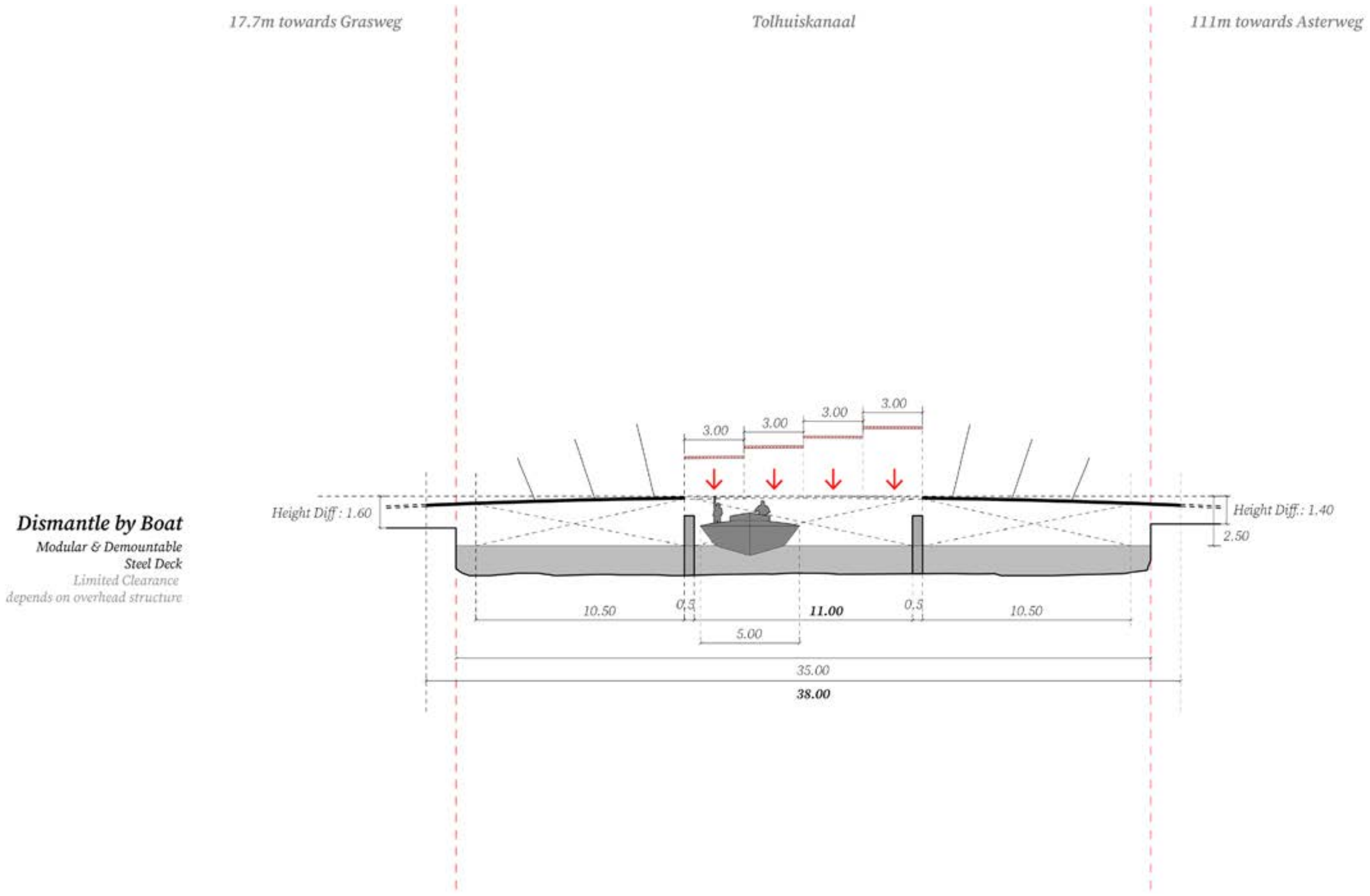


Fig 3.29: Movable strategy for full length bridge with removable decks.

3.6.2 | Structural Strategy

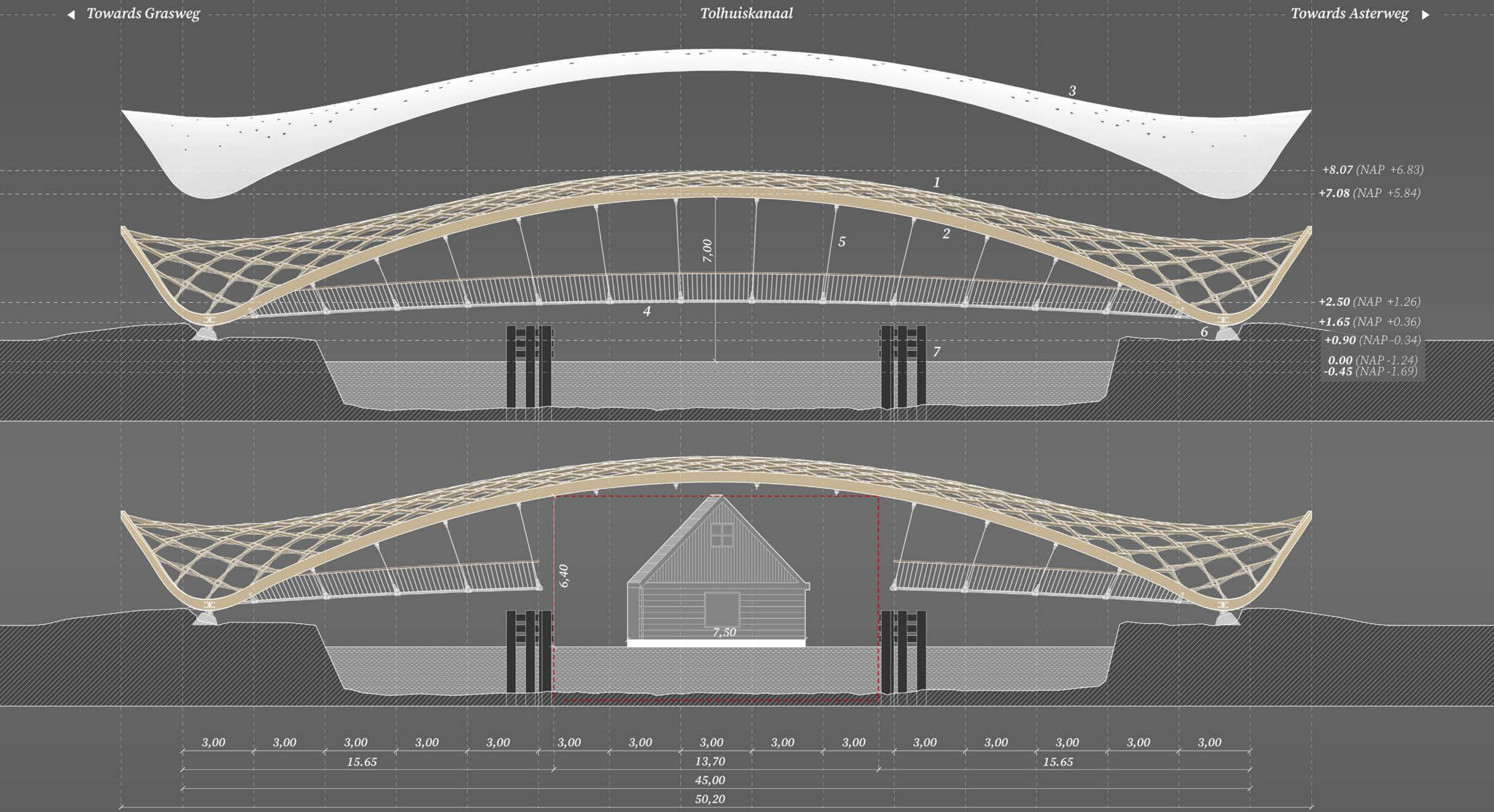
Based on previous case studies conducted in *Section 2.4 Conventional Timber Structures*, most conventional structural typologies such as beam, truss and arches could efficiently span a distance of 38m. With the rise in development of long spanning shell structures based on the case analysis of *Section 2.5.1 Novel Timber Structures*, a combination of shell and arch typology was explored and culminated in *a catenary tied arch with RF grid shell structure* as illustrated in Fig 3.30.

The bridge is composed of 4 main structural components, the RF grid shell, glulam catenary arch edge beams, a lightweight steel deck and stainless-steel cables connecting the deck to the edge beams. With the glulam arch edge beams and RF grid shell, the structure would result in a strong lateral outward thrust along its longitudinal axis. This led to the need for a large lateral force, provided by the bridge abutments to counteract the thrust. It would be costly and resource intensive since longer, lateral piles will need to be constructed. However, with the use of the steel deck as a tie to the outwards lateral forces of the shell and arch edge beam, this *makes the bridge structurally stable independent of the abutments as it resembles a tied arch structure*.

Assuming a uniformly distributed load of 7.5kN/m2 – based on a 1.5 factor of the required 5kN/m2 for light traffic usage – exerted on the steel deck, the flow of forces is as described in Fig 3.31. As the uniformly distributed load exerts a downwards force on the steel deck, it is transferred as tension to the cables and subsequently as compressive force on the edge beams. This compressive force results in an outward thrust acting towards the abutments on both sides of the canal which is then counteracted by the tension of the steel deck towards to the center of the bridge structure.

However, the movability of the bridge entails that the steel deck will be disengaged during its opening, hence unable to counteract the outward lateral forces of the arch edge beams. This implies that the *abutments will still be required to withstand the lateral outwards forces of the bridge when it opens*. Since the bridge will not need to support any live loads during that time, the abutments can be dimensioned to simply support the dead load of a lighter bridge without a number of steel decks (Fig 3.31).

The method to *disengage the steel decks requires the middle 5 sections of the deck to be pre-tensioned towards the center of the bridge* such that the connections between the cables and deck can be removed with smaller tensile forces exerted by the arch and shell (Fig 3.31, red arrows indicating point of pre-tensioning). As this is a novel method of opening the bridge, further design and evaluation needs to be developed as it potentially could result in a more cost and resource efficient method than utilizing a crane. Within the timeframe of the thesis however, it was not possible to further develop this movability strategy with more depth, hence this remains a proposal for future research.



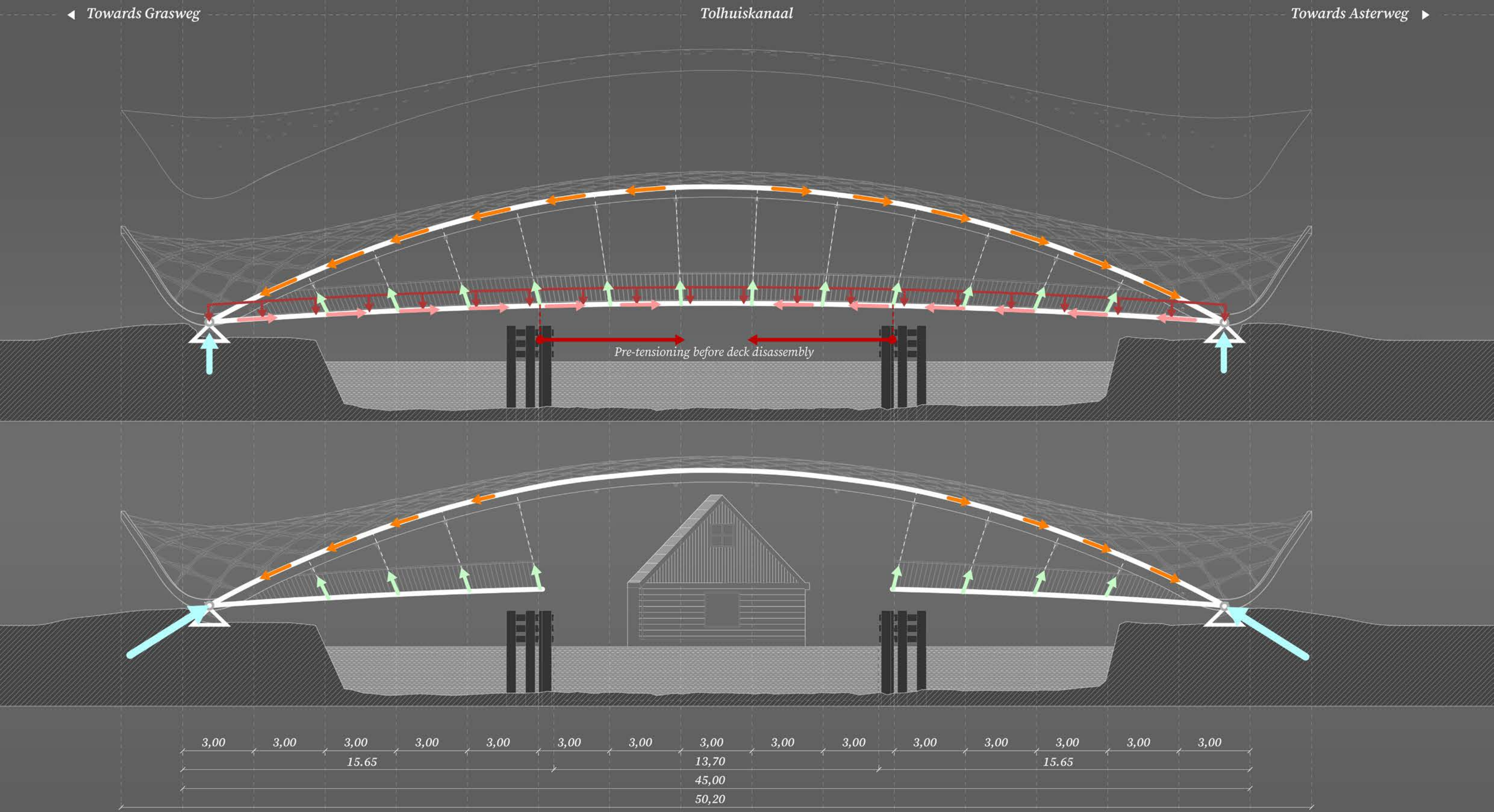
Bridge Elevation | 1:150

Accessible Waterway Width
Ground
Tolhuiskanaal

ø24mm Stainless Steel Cable | 5
Reinforced Concrete Abutments with Piles | 6
Canal Fenders | 7

50x150mm Accoya Beech Glulam RF Gridshell | 1
450X225mm Beech Glulam Edge Beam | 2
3mm White ETFE Membrane Canopy | 3
10mm Stainless Steel SHS Box Beam Deck | 4

0 1 3 5 10m



Force Breakdown | 1:150

Deck Removal Pre-Tensioning

Uniform Load (7.5kN/m²)

Tension in Deck (Tie)

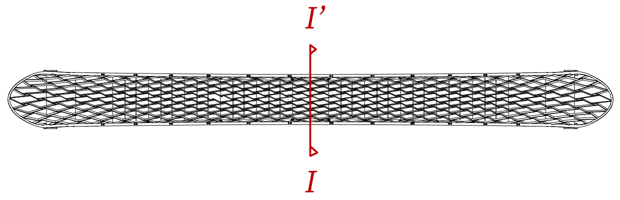
Load carried by tension in cables

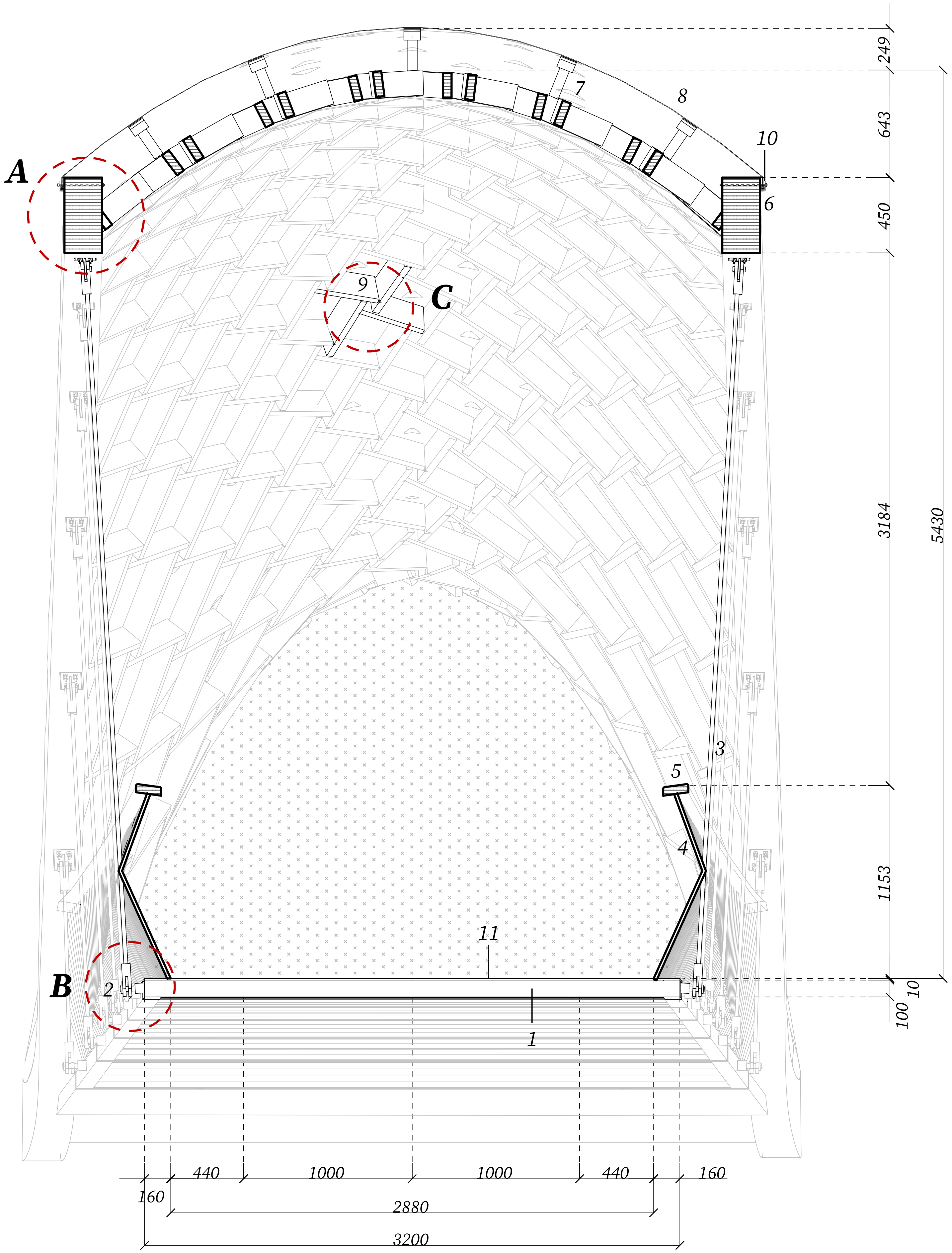
Support by Concrete Abutments

Thrust in Arch

0 1 3 5 10m

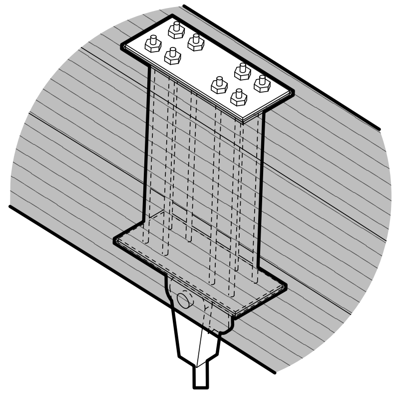
3.6.3 Key Connection and Support Details



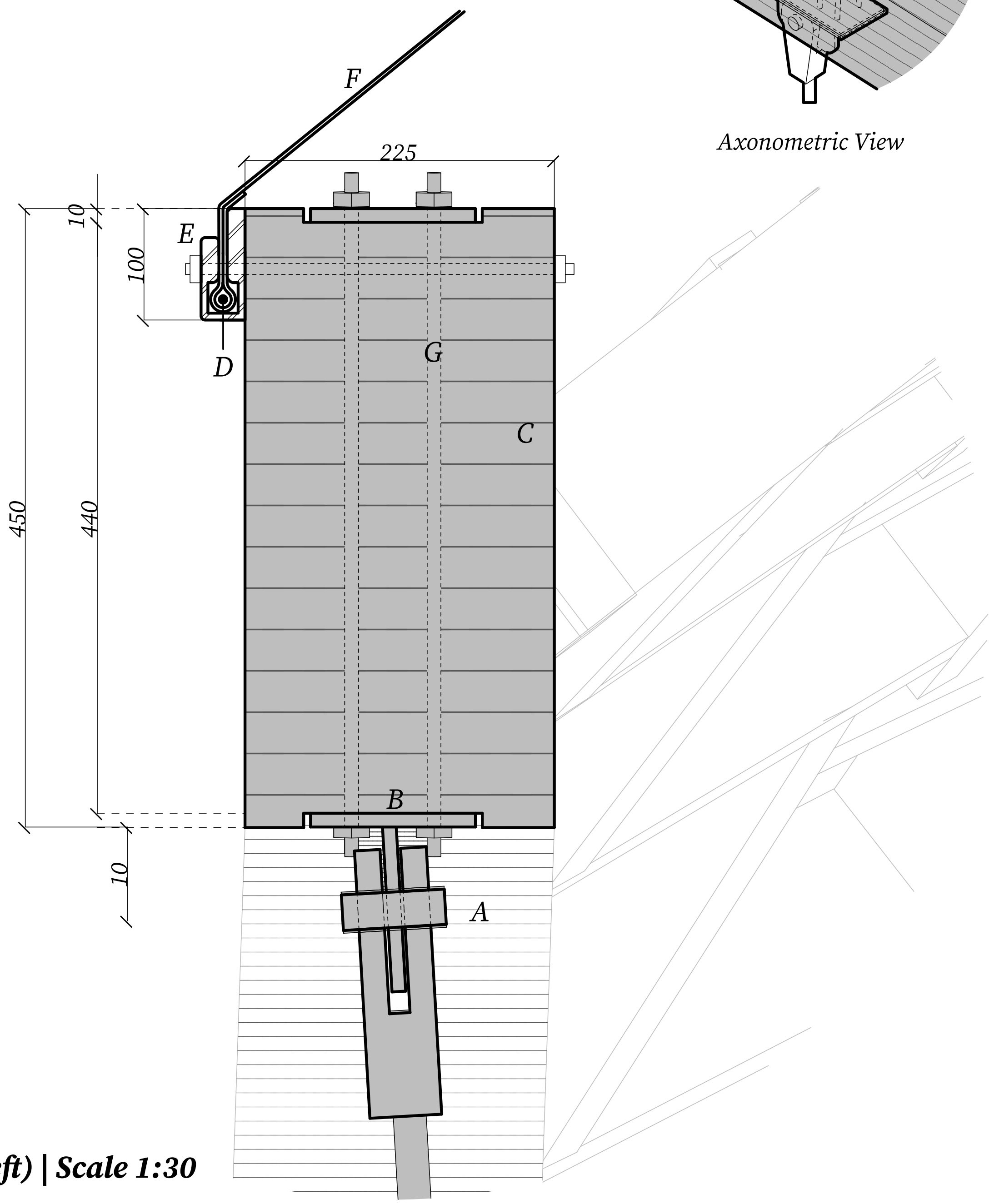


Detail A: Edge Beam to Deck (right) | Scale 1:5

A | Pfeiffer Open Swagged Fitting Cable Connector
B | 12mm Stainless Steel Plate w Hinged Plate
C | 450x225mm Beech Glulam
D | Bolt Rope
E | Profile Bend Stainless Steel ETFE Connector
F | 3mm ETFE Membrane Canopy
G | ø12mm Threaded Rod w Bolts

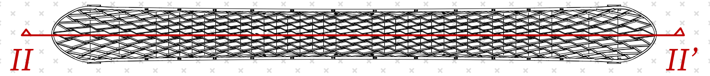


Axonometric View



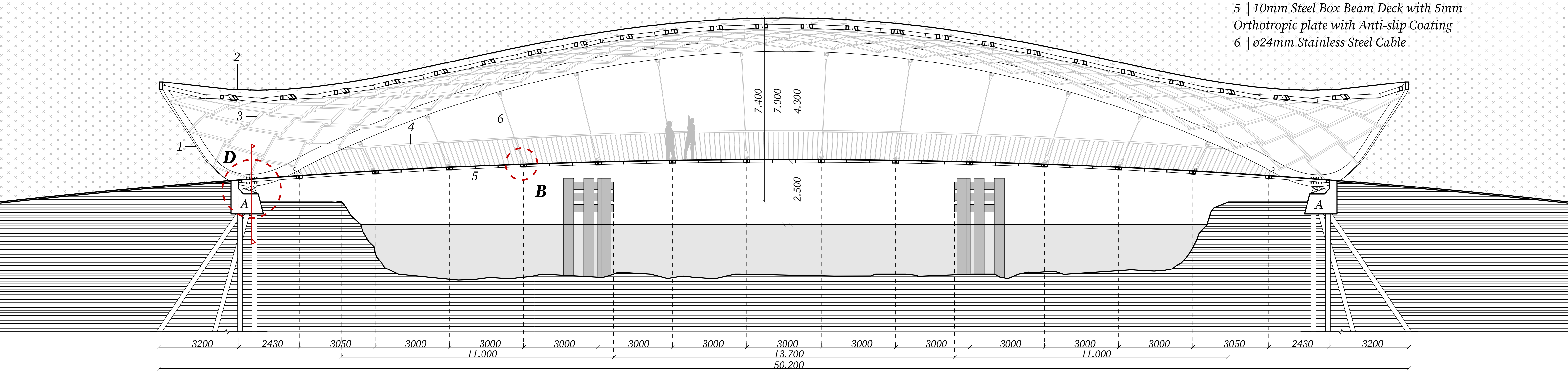
Short Section I-I' (left) | Scale 1:30

1 | 10mm Stainless Steel SHS Box Beam Deck
2 | Pfeiffer Open Swagged Fitting Cable Connector (Detail B)
3 | ø24mm Stainless Steel Cable
4 | ø20mm RHS Stainless Steel
5 | Larch Wood Hand Rails (Heat/Accoya treated)
6 | 450x225mm Beech Glulam
7 | Steel Profile for membrane support
8 | 3mm ETFE Membrane Canopy
9 | 50x150mm Accoya Beech Glulam
10 | ETFE Membrane Connection
11 | 5mm Orthotropic plate with Anti-slip Coating



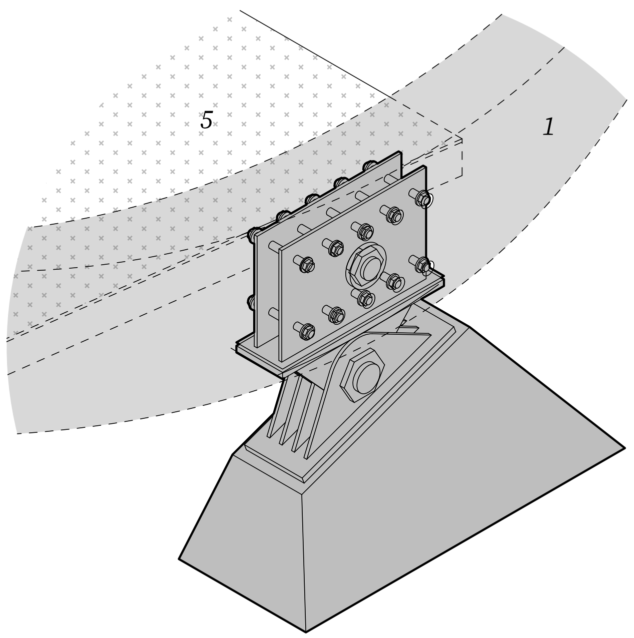
Long Section II-II' | Scale 1:150

1 | 450x225mm Beech Glulam
2 | 3mm ETFE Membrane Canopy
3 | 50x150mm Accoya Beech Glulam
4 | Larch Wood Hand Rails (Heat/Accoya treated)
5 | 10mm Steel Box Beam Deck with 5mm Orthotropic plate with Anti-slip Coating
6 | ø24mm Stainless Steel Cable

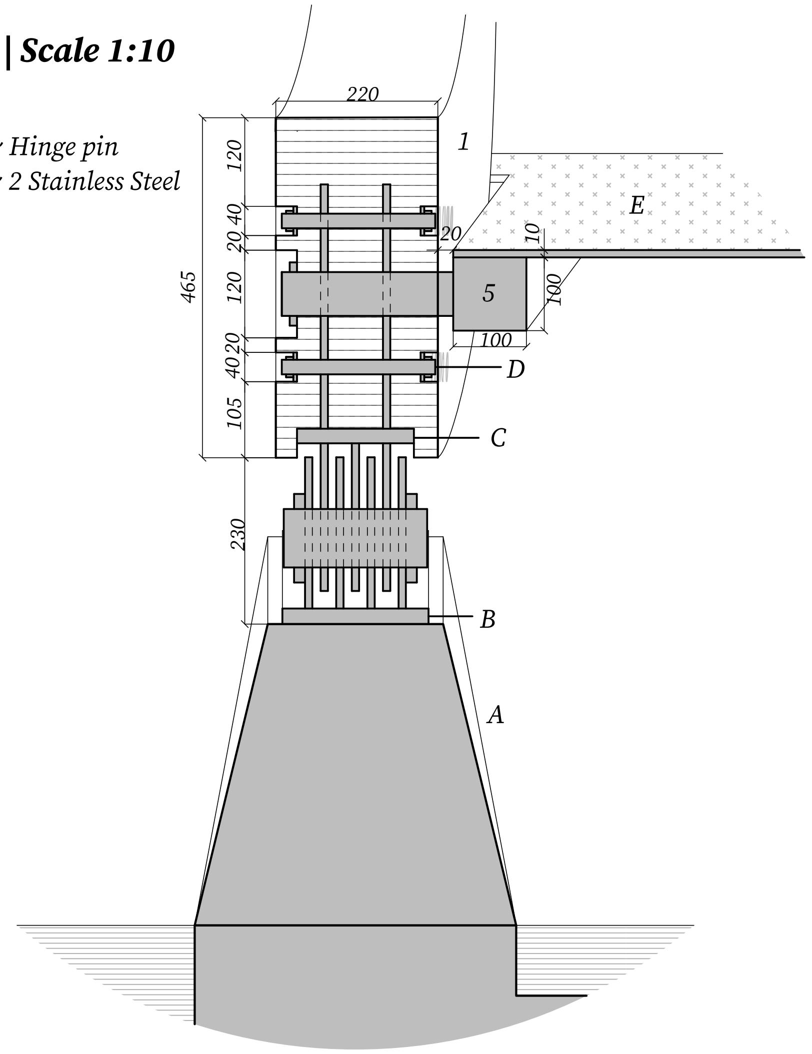


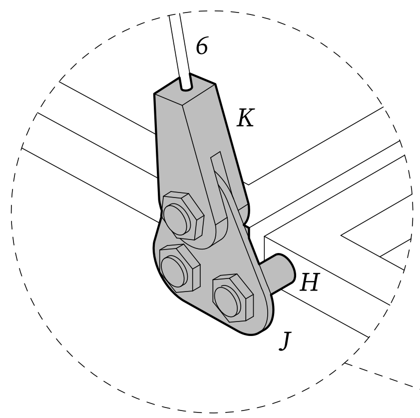
Detail D: Edge Beam & Deck to Abutments | Scale 1:10

A | Reinforced Concrete Abutment on Piles
B | 20mm Stainless Steel Plate w 4 Hinged Plate (10mm) & Hinge pin
C | 20mm Stainless Steel Plate w 3 Hinged Plate (10mm) & 2 Stainless Steel Plate, with 11 Dowel holes, inserted into Glulam (1)
D | ø20mm Threaded Rod w Bolts
E | 5mm Orthotropic plate with Anti-slip Coating

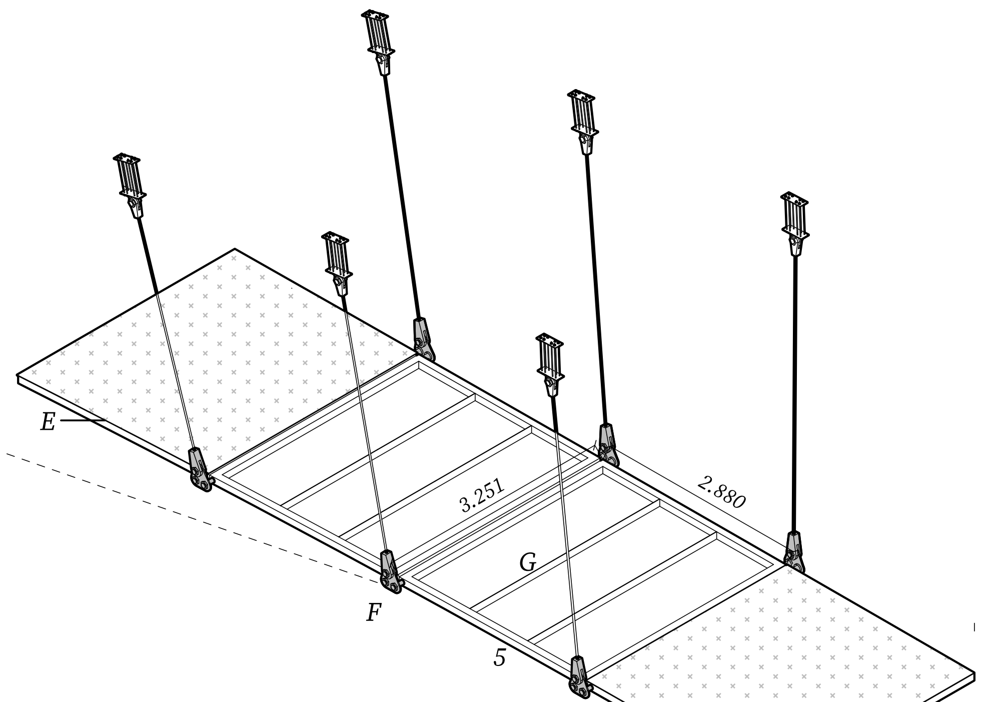


Axonometric View





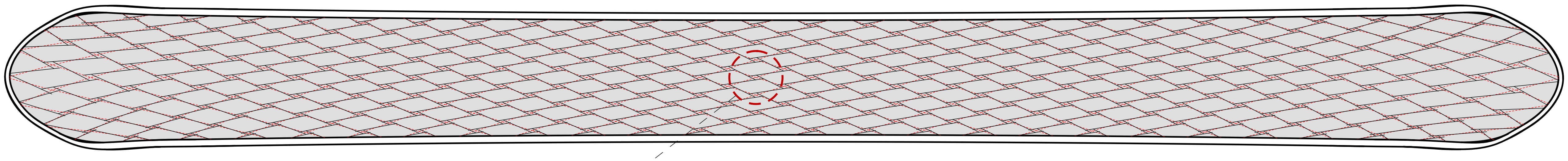
Detail Part F



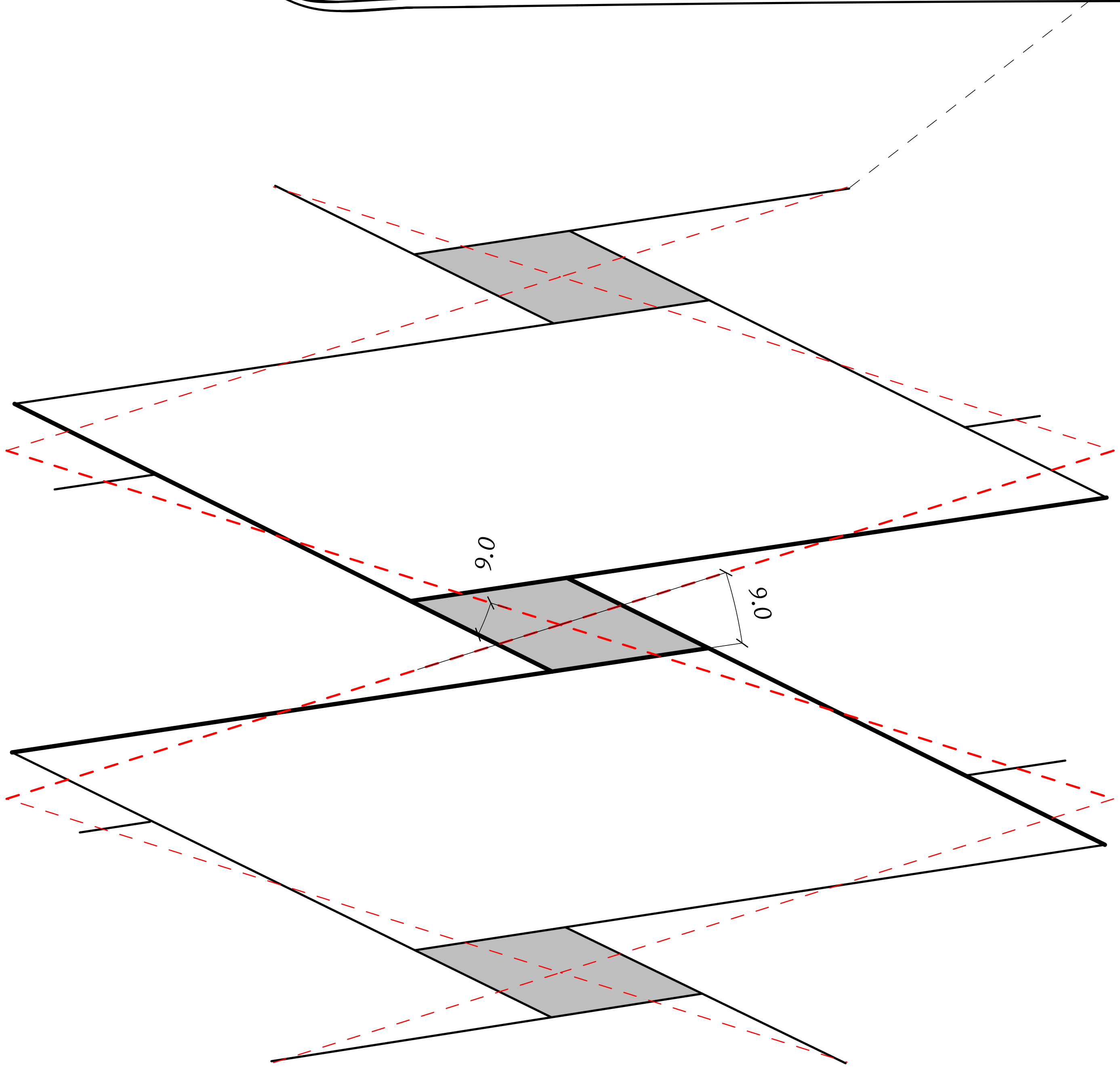
Axonometric View

Detail B: Edge Beam to Deck

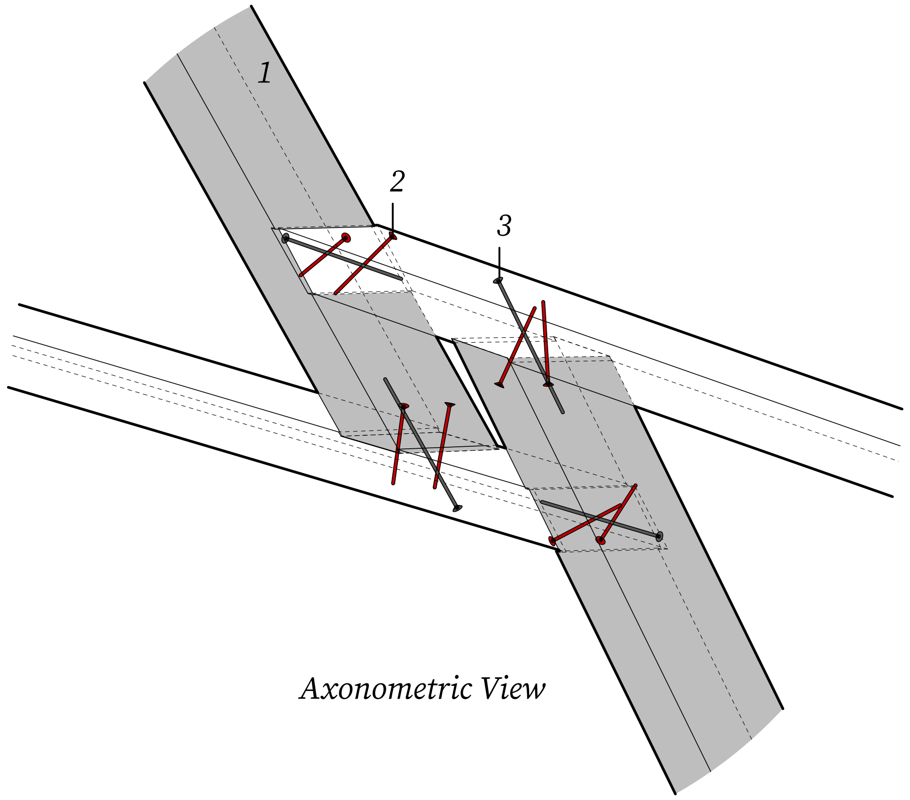
F | Deck to Cable Connection
G | 5mm Stainless Steel Plate
H | ø60mm Welded Stainless Steel RHS
J | 15mm Stainless Steel Plate w 3 ø60mm holes
K | Pfeiffer Open Swagged Fitting Cable Connector



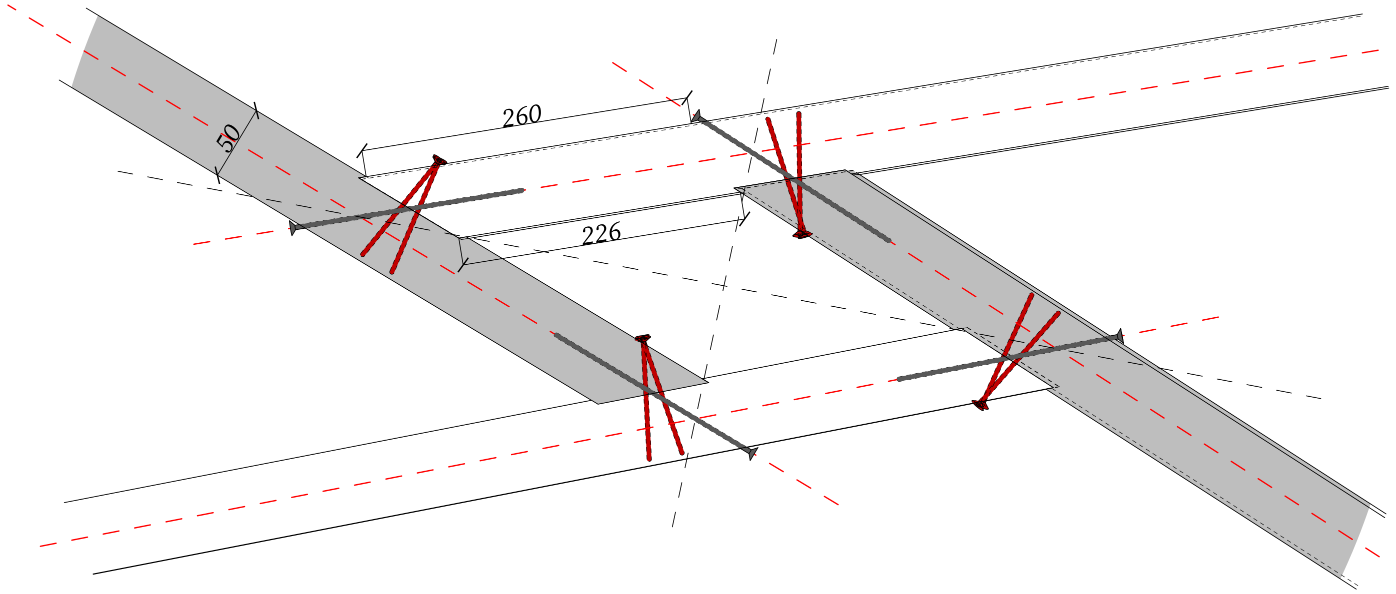
Top View, 1:150



Top View, 1:10



Axonometric View



Planar View

Detail C: RF Shell Timber-Timber Connections

1 | 50x150mm Accoya Beech Glulam
2 | Shear Bearing Screw (VGZ EVO, Class 3, Countersunk)
3 | Tension Bearing Screw (HBS EVO, Class 3 Outdoor Screw w Flange Head, Countersunk)

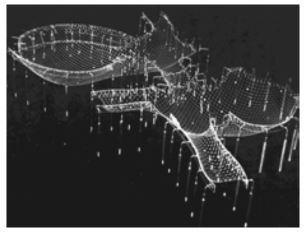
3.6.4 | *Form Generation Computational Workflow*

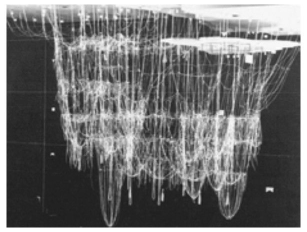
The structural typology of the bridge is a combination between a shell and tied arch and in order to generate the form of the shell incorporating all the constraints and anchors of the structure, it is akin to conducting a soap film or hanging chain model. Most prominently these techniques feature significantly in the works of Frei Otto and Antonio Gaudi whereby soap film, fabric or chains with loads are used to find the isotropic stress state and form (Aish et al., 2015) of shell structures (Fig 3.32 & Fig 3.33). Through the development of computational design tools such as Grasshopper in 3D modelling software, Rhinoceros 3D, a similar approach can be conducted with the Kangaroo component developed by Daniel Piker. Therefore a computational workflow in generation of the bridge form is developed within Grasshopper as it allows for a seamless platform to generate subsequent digital fabrication data for the HRC applications covered in *Chapter 4: Human-Robot Collaboration (HRC) Design-To-Build Workflow.*

The form-finding workflow executed using Kangaroo seeks to find structural sound shell structure through dynamic mesh relaxation, however it does not result in an optimized structural form. The optimization stage of the form-finding process is left out due to the time and depth it requires for iterative simulation and alterations. Rather, this computational workflow outlines a process for *generating a formally sound structure based on the input constraints, boundary conditions and geometric elements*.

The workflow illustrated in Fig 3.34 contains 4 main process labelled A to D, whereby each processes contains a series of inputs and outputs generated through a scripted procedure, which is then transferred to a following process in generating the form. Beginning with A, key boundary conditions, anchors and design requirements are determined, thereby generating anchor curves, the outline of a planar shell surface and the geometry and curvature of the deck. The outputs are then used in processes B to D to further generate relevant geometries. Process B involves the simulation in Kangaroo, incorporating all the constrains and geometries established in A to generate a rectangular grid mesh shell. This generated shell mesh contains the topological data of a rectangular grid which was further evolved into a diamond grid and a RF grid in process B, through the rotation of individual Timber Members (TMs). In process D, other structural components of the bridge such as the cables, deck, and canopy are generated based on the mesh and grid from B and C. The timber edge beam is subsequently dimensioned according to the concentration of forces, increasing in size towards the supports.

In conclusion, this workflow describes the form generation for the bridge design and fits within the larger computational framework to allow for geometrical data to be translated into digital fabrication outputs required to facilitate a HRC construction system explored in the following chapters.





Left: Fig 3.32: Hanging chain model by Frei Otto, used in Mannheim Multihalle (University of Stuttgart, 1978).

Right: Fig 3.33: Hanging chain model of Colonia Guell Chapel by Antonio Gaudi (Hensel, 2015).

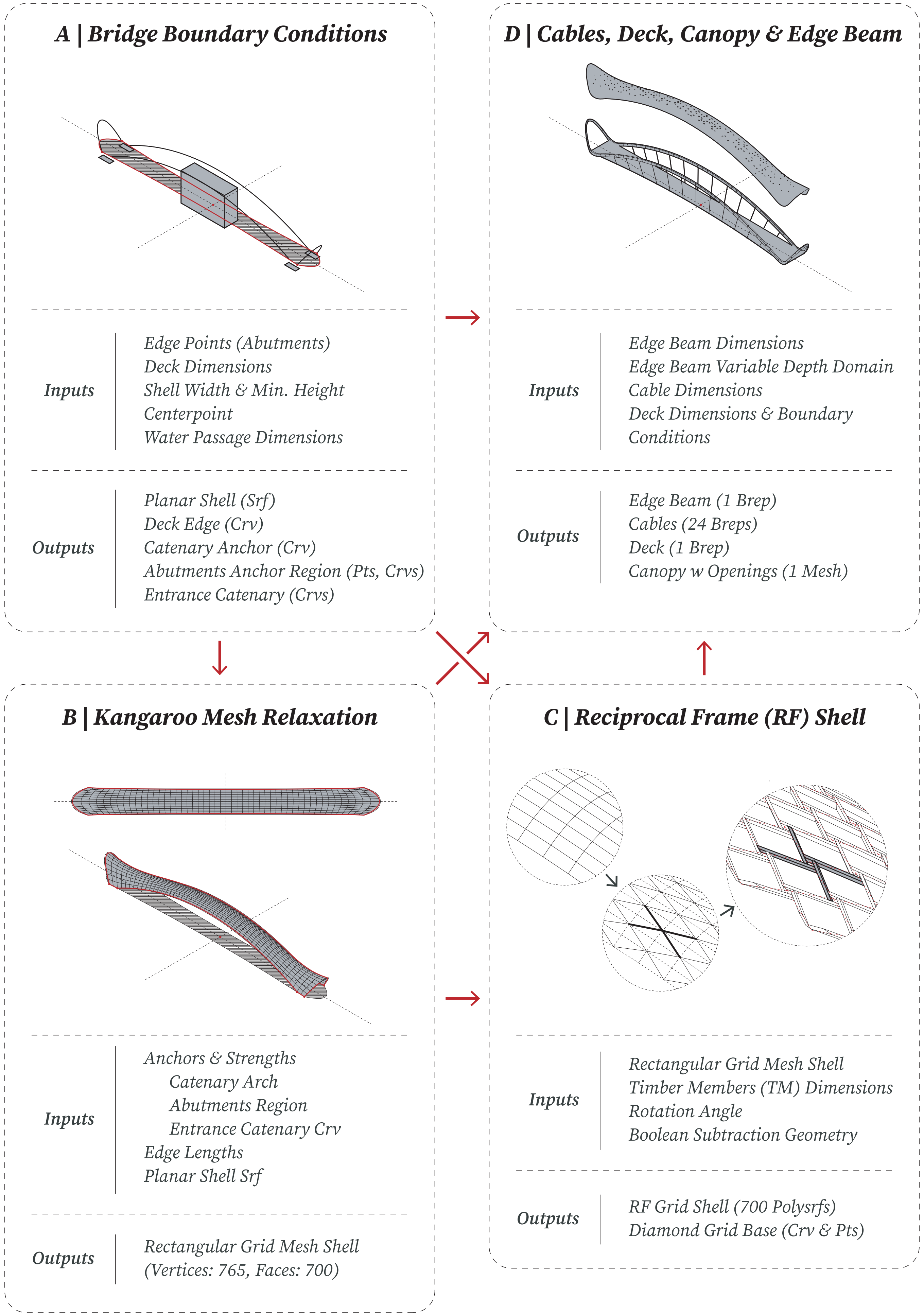
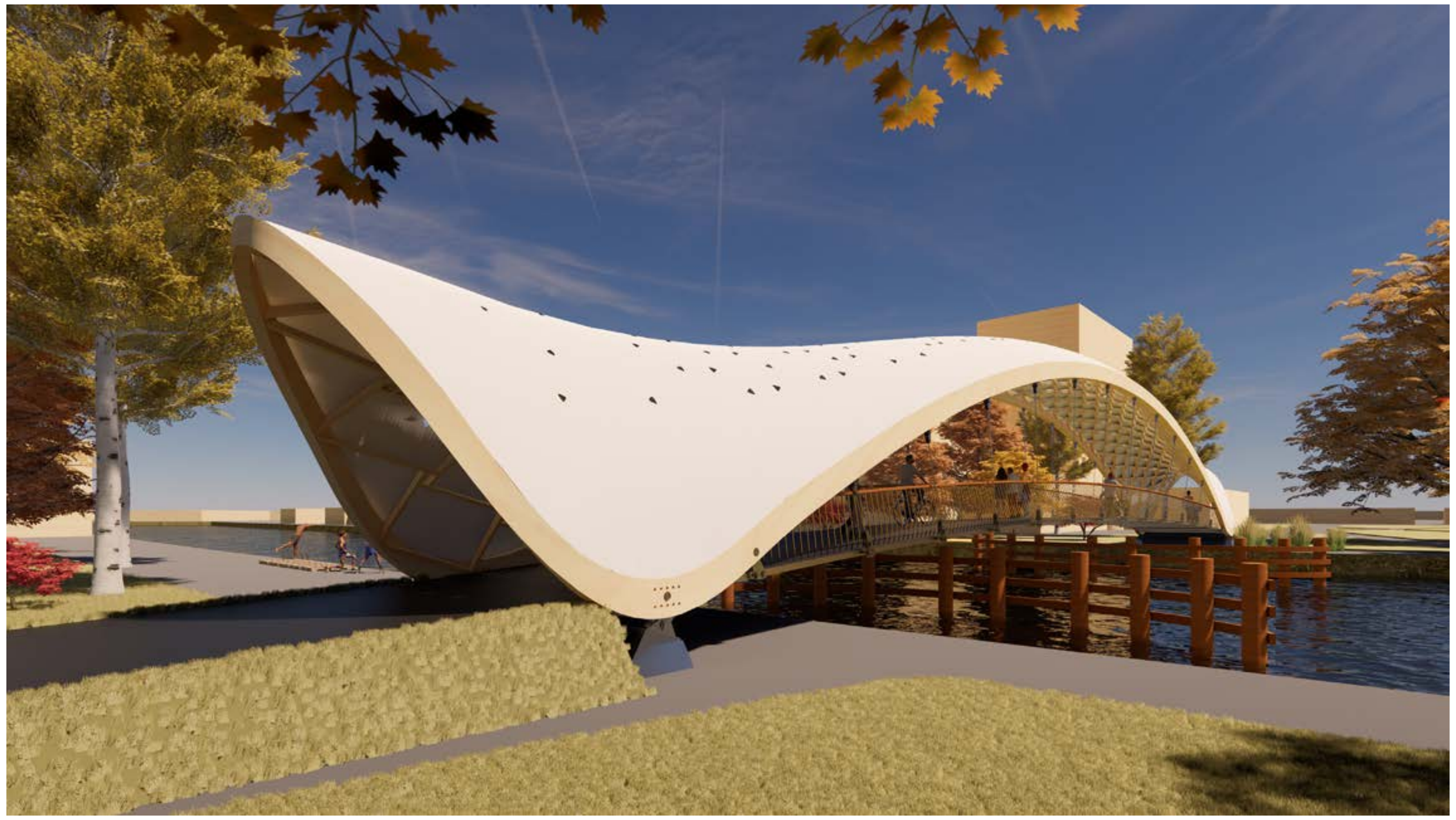


Fig 3.34: Computational workflow outlining the main processes (A to D), inputs and outputs generated and the flow of data from each process to another, thereby generating a formally sound model for subsequent digital fabrication processes.



Chapter 4:

HUMAN-ROBOT COLLABORATION (HRC) DESIGN-TO-BUILD WORKFLOW

4.1 INTRODUCTION

Human-Robot Collaboration (HRC)

Human-robot collaboration (HRC) as defined in TS/ISO 15066:2016, is an operation where a human worker and a purposely designed robot system can perform tasks in a defined collaborative space concurrently during a production operation. HRC is usually conducted with Collaborative Robots or Cobots which refers to robots that are capable for use in a collaborative operation – purposely designed robots working in direct cooperation with human within a defined workspace. Within a collaborative workspace, the robots and humans could concurrently perform tasks in close proximity without brakes being applied. To enable this seamless collaborative mode of production, multiple factors will need to be considered such as safety, precision, variability, adaptability and complexity of the task (Reinhardt et al., 2020).

Cobots are primarily used within HRC applications as they have embedded force-torque sensors within every joint to detect contact and pressure (Rossi & Nicholas, 2020). Industrially established brands such as ABB, Kuka and newer producers such as Rethink Robots and Universal Robots has developed cobots like YuMi-IRB 14000, LBR iiwa, Sawyer and UR Cobots respectively which features smooth contours and streamlined design to reduce harm to humans in close collaborations.

In the following sections, the state-of-the-art developments in HRC is studied to understand the latest advancements in HRC technology and extract key criteria to determine the suitability and applicability of HRC into the construction workflow of the thesis.

4.2 OVERVIEW OF HRC DEVELOPMENT

State-of-the-art literature review

This section contains the literature review with regards to the state-of-the-art development of HRC and especially in answering *Sub-Research Question 3a*: "What are the factors influencing the implementation of Human-Robot Interaction/ Collaboration in onsite and offsite building construction?" The literature review method and key words used is included in *Appendix Section 7.5 HRC Workflow*. Within this review, the focus is on robotic arm systems as subsequent design-to-build workflow centers around the translation of human tasks into robotic motions.

Through the reviewing of recent HRC developments and identifying the key factors which affects the implementation of HRC in construction sites, on- or off-, they can be broadly categorized into 2 main areas of *improving collaborative operation and calibration methods*. Unlike the pure automation of tasks into robotically executed ones, effective collaborative operation with human workers or operators requires intuitive and cogent communication between them. Furthermore, due to the variability of the site, human agents and tasks, the robots are required to adapt and calibrate accordingly, performing tasks with optimized precision (Reinhardt et al., 2020). Thus calibration and adaptability becomes key aspects which affects the effectiveness of the implementation of HRC in construction processes. With the latest developments into HRC, key fields such as Cyber-Physical System (CPS), Social Robotics and Human-Computer Interaction (HCI) are complementary to architecture robotics in refining the design-to-build workflow in the building construction industry (Reinhardt et al., 2020).

Improving Collaborative Operation

The premise for improving collaborative operation between robotic systems and human agents is to allow the robots to achieve the sensibility and modes of communication as close to a human-human collaboration. Thereby to achieve an intuitive and natural mode of communication, multiple developments focused on learning and recording human motions through machine learning. The various methods to translate a complex range of human motion and language into digital signals for the robots to understand includes:

- DMR as semantic robot control language to allow natural communication for robotic control (Andraos, 2015)
- Various robotic modes to allow for adaptive robotic protocols based on sensor information from human motion or a 3D Camera, incorporating human participation in robotic fabrication and real-world calibration (Braumann & Brell-cokcan, 2015)
- Adaptable 3D printing toolpath in response to real-time human force using Kuka LWR iiwa robot (Dubor et al., 2016)
- Using of haptic learning with neural networks to tune digital datasets and robotic trajectory (Rossi & Nicholas, 2020)
- Applying Machine Learning for training movements in humanoid applications (Schwartz, 2016)
- Tactile sensing in assembling building elements with HRC (Wibranek et al., 2019)

Various methods to improve collaborative assembly as outlined by Rückert et al., 2018, includes:

- intuitive programming
- adjusting the workplace for better ergonomics
- hand gestures for interactive HRC assembly processes
- auditory dialogue systems for human robot interaction
- Trajectory optimization, admittance control and image processing for ensuring safety of the worker during HRC
- Use of camera systems to enable HRC Assembly

Improving Calibration Methods

Furthermore, calibration is a crucial factor in HRC assembly because the robotic system has to respond to the changes in the external environment and building elements, informed either by the worker in collaboration or additional sensors it is equipped with. Multiple methods of calibration includes vision based calibration involving markers, ground truth scale and also stereo hand-eye system with moving camera coordinates (Rückert et al., 2018). Due to the abundance of literature outlining the various methods of calibration, with a broad range of technology used, within the scope of the thesis, a simplified and direct solution to calibration will be adopted, without the involvement of complex algorithms and equipment as the time span to develop it is short.

4.3 AGENTS OF HRC & ITS SKILLSETS

Breakdown & comparison

Within HRC, the two main agents – humans and robots – each have distinct strengths and weaknesses which could be complementary in allowing for a productive and effective collaboration process. Table 4.1 summarised the strengths and limitations of each agents. This provides a better understanding on how to specify tasks according to their strengths while complementarily overcoming the limitations inherent in each agent. Although it is highly simplistic and erroneous to assume the same general characteristics for all robotic systems developed, these traits served as the baseline characteristics of a basic robotic arm system without additional sensory and learning feedback control systems. This provides a better understanding of the relative merits of each agent involved in HRC and how each could potentially complement another in the process.

Based on the strengths, it is evident that humans have better dexterity, judgement and intuition based on their experience and ability to react to a variety of complex situations. This makes them suitable for tasks which has high level of variability whereby dynamic decision making based on a broad range of uncertain factors needs to be made. Robots on the other hand excel in tasks like handling high loads, repetitive, dangerous and precise ones which complements the limitations of the human agent.

	Strengths / Benefits	*Limitations*
Humans	i. ***Dexterity*** *– Agility and flexibility in handling objects.* ii. ***Judgement (based on experience)*** *– Rapid adaptability and decision making required based on task requirement (e.g. project management)*	i. ***Physically Weak*** *- Low Physical Strength* ii. ***Hazard Averse*** *– Should only be employed to work in safe environment that minimizes risk of short- and long-term injury.* iii. ***Limited Computational Capabilities*** *– Not built to compute & process large datasets within a short amount of time.*
Robotic System *(Basic robotic arm systems without additional sensory and learning feedback control systems)*	i. ***Mechanical Strength*** *– Suited for a large range of loads* ii. ***No Repetition Fatigue*** *- Less fatigue to repetitive tasks* iii. ***Precise*** *– High precision can be achieved* iv. ***Hardy*** *– Suited for tasks in hazardous environment*	i. ***Poor Intuition & Object Recognition/Object Differentiation*** *- Computationally expensive at Object Recognition* ii. ***Not Contextually Awareness*** *(without positioning strategy)* iii. ***No Operator awareness*** *(without feedback strategy)*

Table 4.1: Comparison of strengths and limitations between human and robots.

4.4 EVALUATION CRITERIA FOR HRC IMPLEMENTATION

To evaluate the feasibility and applicability of implementing HRC to the design-to-build workflow processes, it is important to identify and analyze the types of tasks involved within the entire workflow and the safety levels associated to it (Reinhardt et al., 2020). The different nature of tasks could determine the type of collaborations and number of tasks included within the collaboration, as shown in Fig 4.1. In combination with the previous section, a list of criteria is consolidated for evaluation for the subsequent workflows where HRC could be applied:

- *Task Complexity* (Simple to Complex)
- *Level of Safety* (Safe to dangerous)
- *Scale of construction* (Within static workstation, larger than robot = requires robot mobility)
- *Variability of Working Condition* (Levelled/ Uneven, Constant (Controlled, Certain)/Dynamic (Uncontrolled, Uncertain, Uncluttered/Tight (cluttered))
- *Complexity of Assembly* (Assembly scale, Orientation, Precision, Weight of individual members, Tools required, etc.)

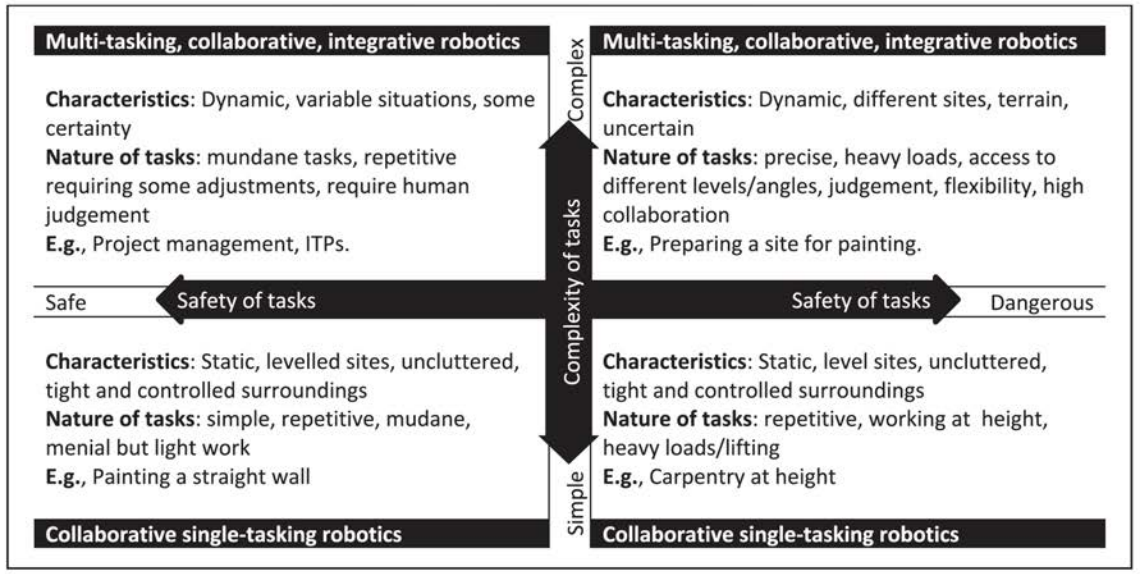


Fig 4.1: Differentiation of tasks groups in relation to complexity and safety, extracted from CoBuilt 4.0, Investigating the potential of collaborative robotics for subject matter experts (Reinhardt et al., 2020).

4.5 WORKFLOW EVALUATION FOR HRC IMPLEMENTATION

With the proposed design-to-build workflow proposed, a detailed breakdown of all the tasks involved in the fabrication to assembly of the RF Shell is established in Table 4.2 (right). The entire process consists of 4 main stage, from the preparation of timber members, pick and place, installation of wood screw connections and the repeat of all previous stages depending on extent of pre-fabrication. Each process contains multiple steps whereby the actions, resource and equipment required is established. Based on the evaluation criteria defined in *Section 4.4 Evaluation Criteria for HRC Implementation*, each task is evaluated on 3 criteria: complexity, safety level and scale. With the evaluation conducted for each task or group of tasks, its suitability for HRC application is determined.

To tap on the strength of HRC, particular focus of the evaluation is to identify tasks which are highly complex, have a certain level of danger and of a local scale to ease its implementation. As such, Stage 1,2 and 3 – the first 2 relating to fabrication and the last focusing on assembly – all has specific tasks which involves a high level of complexity, danger and is of a local scale. With the timber construction industry capable of fabricating the timber slats using 5 axis CNC milling without the need for a human worker to further assist in it, it is hence identified that focusing on the more complex placement and screwing of the joints would justify the involvement of HRC. As the geometrical complexity of the shell structure results in a highly intricate 3D positioning of the timber members and intricacy in the angle of the screws to avoid clashing. Therefore, *Stage 3 is chosen as the workflow whereby HRC is developed further as it taps on the strength of the robot in computing precise spatial positioning and the agility of the human worker in assembling parts which are intuitively marked and notched*.

This process will entail the following tasks to be executed by the human worker and 6 axis robotic arm respectively:

Worker

- Pick & identify the timber member to be placed
- Match the labelled joint number to the respective joint location
- Placed timber members into the notches to secure the joint

Robotic Arm

- Equipped with a screw gun
- Compute trajectory to screw position
- Insert screws based on specific angles of the timber members, while worker holds the timber member to be assembled

The process outlined above is executed in sequence and repeated for each following timber member. To describe an ideal situation, the worker and robotic arm will be able to communicate verbally, through gestures or haptic touch to proceed with the task or to recalibrate based on the repositioning of the robotic arm tool. The robotic arm would then be able to recalibrate its computational data to the readjusted positioning through machine learning, hence improving the precision of the collaboration. This HRC process will be further detailed in Fig 4.4 in the following section.

Workflow Breakdown				*Evaluation Criteria*			*Results*
Key Stages	**Tasks**	**Actions**	**Resource & Equipment**	**Complexity** (Simple/Complex)	**Safety Level** (1-5: Dangerous)	**Scale**	**HRC Applicability**
Stage 1: Preparation of Timber Members (TM)	**1.1: Marking Cut Positions** (Optional)	Interpret Fabrication Data, Visual Recognition & Alignment, Grip, Measure, Mark	1-2 Operators 1 Data Processor Marker	Complex	0	Local	√ Human Positioning to Robot Gripper OR No Human, Calibrated Dispenser to Robotic Arm
	1.2: Holding TM						
	1.3: Bringing TM to Saw				3		
	1.4: Adjust angle of Saw	Move (Adjust Saw Angle) OR Move (Adjust Approach Angle) Grip & Orientate	1-2 Operators Rotational Saw	Simple	3		Only Robot Execution
	1.5: Accurate Positioning of TM on Saw						
	1.6: Cutting to length						
	1.7: Labelling of Members (If not used directly, optional)	Grip & Mark	1 Operator Marker/Label	Simple	0		Robot/Human
Stage 2: Pick & Place (Assume used directly from Stage 1 without storing)	**2.1: Identify Grip position of TM based on its current position** (OR directly from 1.2, depending on 1.7)	Visual Recognition & Alignment	1 Operator	Complex	0	Local	√ Human Positioning to Robot Gripper
	2.2: Grip TM (Depends on 1.7)	Grip					
	2.3: Identify position on Edge Beam to position (trajectory)	Interpret Assembly Data, Visual Recognition, Alignment (Orientate to Actual Conditions), Generate Approach (Trajectory)	1 Operator with External Sensors/Feedback Required	Complex	0	Beyond	√ Human perform final calibration after Robotic Placement, thus training robot
	2.4: Bring to Position (Trajectory execution)	Grip & Move (Follow Approach)	1 Operator	Simple	1	Beyond	
	2.5: Hold in Position	Grip		Simple	1		
Stage 3: Connections – Wood Screws (WS)	**3.1: Identify position and orientations of all WS in a joint**	Interpret Assembly Data	1 Operator	Complex	0	Local	√ Human perform final calibration after Robotic Placement, thus training robot
	3.2: Establish trajectory of drill	Visual Recognition, Alignment (Orientate to Actual Conditions), Generate Approach (Trajectory)	1 Data Processor	Complex	0		
	3.3: Check WS sufficiency	Visual/Auditory/Haptic/Mechanical Feedback, Refill cartridge	1 Operator with V/A/H/M Feedback 1 Operator to refill	Complex	0		Human check & Refills follows signal
	3.4: Alert & Refill if insufficient						
	3.5: Load WS	Dispense from cartridge	1 Operator	Simple	0		
	3.6: Approach Joint & Grip around / Secure it (OR 2.5 Already secured)	Move (Follow Approach) & Grip/Clamp	1 Operator	Simple	1		√ Human perform final calibration after Robotic Placement, thus training robot OR √ Human placement and robot screws joints
	3.7: Drill WS	Drill	1 Operator	Simple	2		
	3.8: Release WS & Grip	Move (Release & Exit)	1 Operator	Simple	0		-
	3.9: Move away from Structure						
Stage 4: Adjust into next Position	**Repeat from Stage 1 if assembly is incomplete**						

Table 4.2: Detailed breakdown of tasks within fabrication and assembly process of RF Shell with evaluation of its suitability for HRC.

4.6 DESIGN-TO-BUILD WORKFLOW PROPOSAL

Further developing the digital design of the bridge into fabrication data for digital fabrication and construction, 4 main phases are proposed as the Design-to-build workflow. Broadly the 4 phases cover the pre-fabrication of individual components, the abutment construction, an onsite HRC assembly of the RF shell as well as the final full assembly of the bridge.

Phase 1: Component Pre-Fabrication

The first phase concerns the off-site pre-fabrication of all key components of the bridge from timber to steel and ETFE canopy components as consolidated in Fig 4.2. The RF Shell consisted of 698 individual timber slats, measuring 50x150mm, cut to various lengths and angles. Each piece is also engraved with the label of its index and the joint number it connects to which will be used for the subsequent HRC assembly of the RF Shell. The edge beam is segmented into 10 segments with the longest component within 3,5m and 21,45m, thus ensuring that it could be transported easily to site by means of a water vessel or truck. The timber members will be fabricated by a timber constructor with a 5-axis milling facility, using the digital geometry data generated in performing the CNC operation.

The steel elements ranges from the box beam for the deck, the cables & its connectors and the abutments and edge beam connectors. Lastly, the 3mm ETFE membrane canopy is split into 6 segments of approximately 9m which could subsequently be stitched together to form the canopy which will be draped over the RF Shell.

Phase 2: Abutment Construction

Concurrently with Phase 1, Phase 2 will be the construction of the abutments and foundation required to support the bridge (Fig 4.3). Reinforced concrete will link both landings of the glulam edge beam on each side before transferring the forces into the piles drilled into the stiff soil layer beneath. The abutment positioning is offset from the banks of Tolhuiskanaal based on a 1.5m offset required by the municipality to maintain visual continuity along the canal.

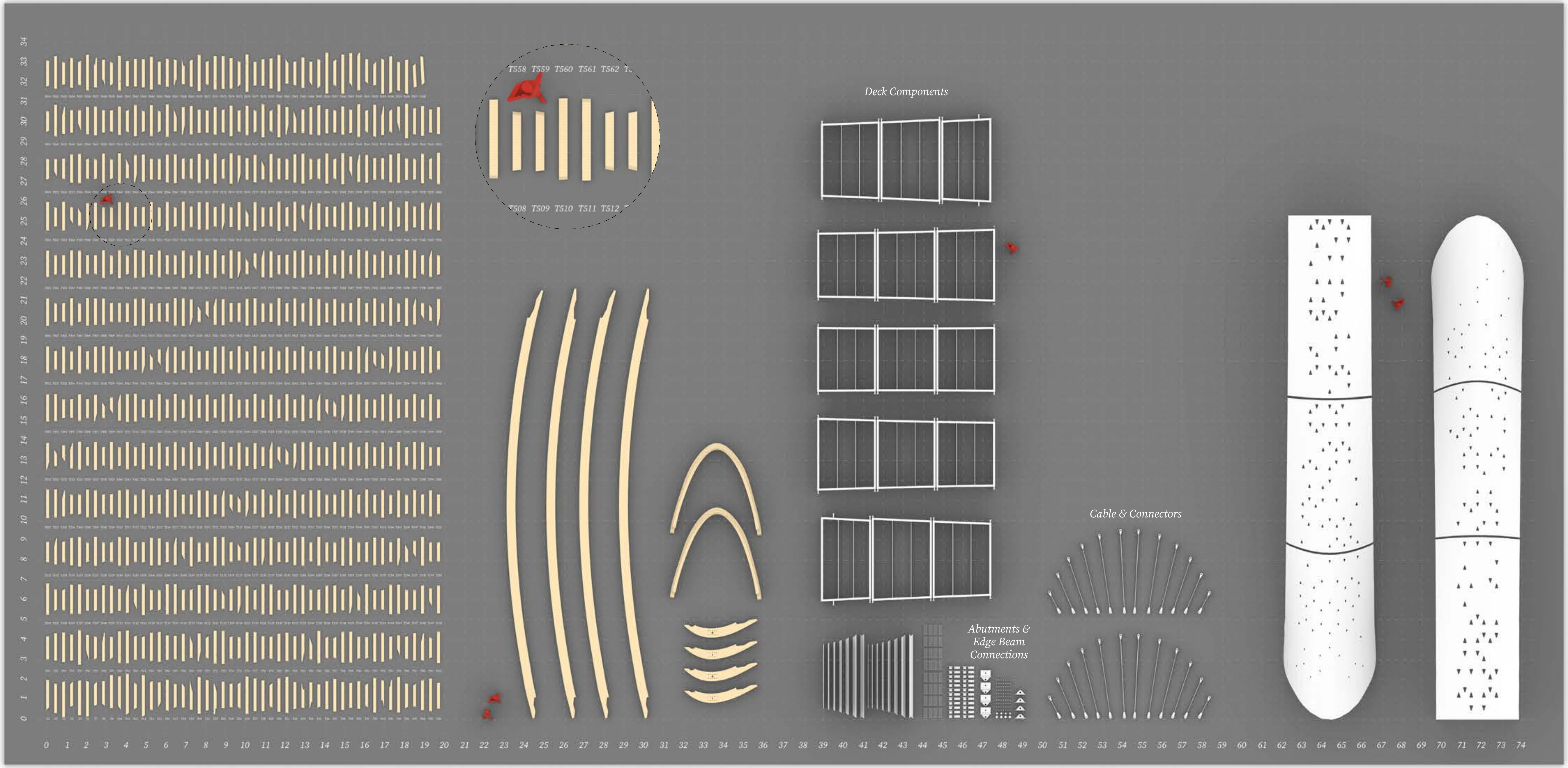
Phase 3: RF Shell Sub-Assembly

With the prefabricated timber edge beams and individual timber slats for the RF shell, an on-site construction zone is setup on the Asterweg side of the site as it has more vacant space than the one along Grasweg. The layout, as illustrated in Fig 4.4, measures approximately 72 by 22m is arranged in the position where each segment will eventually be placed into assembly. Two mobile robotic platform with ABB IRB 6640 robotic arm on movable rails will be required for a simultaneous HRC assembly process alongside the constructors. Each robotic arm will follow specific route and positioning along the edge beams – namely Route A (A1-5) and Route B (B1-5) – and begin in opposite direction to prevent the potential clash of the mobile platforms. Each robotic arm has a maximum payload of 235kg and a reach of 2,55 to 3,2m, hence allowing it to reach the top of the shell, which is approximately 2m, and also have sufficient strength required to insert screws into the timber slats. Further details and application of the HRC workflow will be outlined in *Section 4.6 Workflow Evaluation for HRC Implementation*.

Phase 4: Full Assembly of Bridge

The final phase in the construction involves the assembly of the individual RF Shell segments A to D, the cables and deck as well as the ETFE canopy. Temporary steel scaffolding supports the pre-assembled glulam edge beams to secure them in place while the other components are assembled. The scaffolding also allows for an easier lifting frame for the crane to eventually move the fully assembled bridge into position over Tolhuiskanaal. The final component to be installed will be the pin through the hinged plate connections, thereby securing the edge beam of the bridge to the abutments.

Phase 1: Component Pre-Fabrication



RF Shell

698 Timber Slats

Edge Beam

10 Segments
Max: 21.45m long
Min: 3.5m long

Steel Elements

Deck, Cable, Abutments

ETFE Canopy

Fabricated in 6 parts & stitched together

Fig 4.2: Glossary of pre-fabricated components for phase 1.

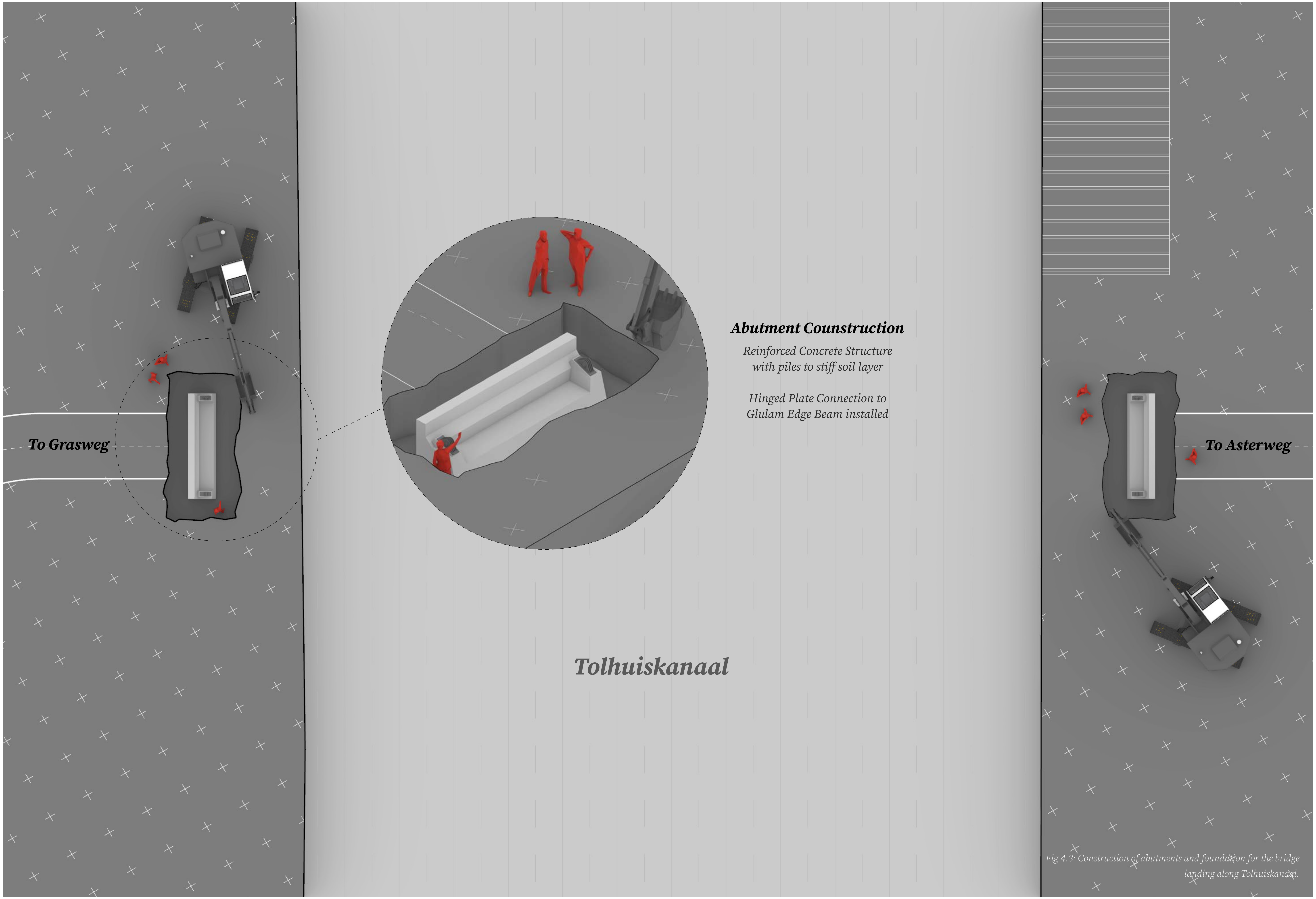


Fig 4.3: Construction of abutments and foundation for the bridge landing along Tolhuiskanaal.

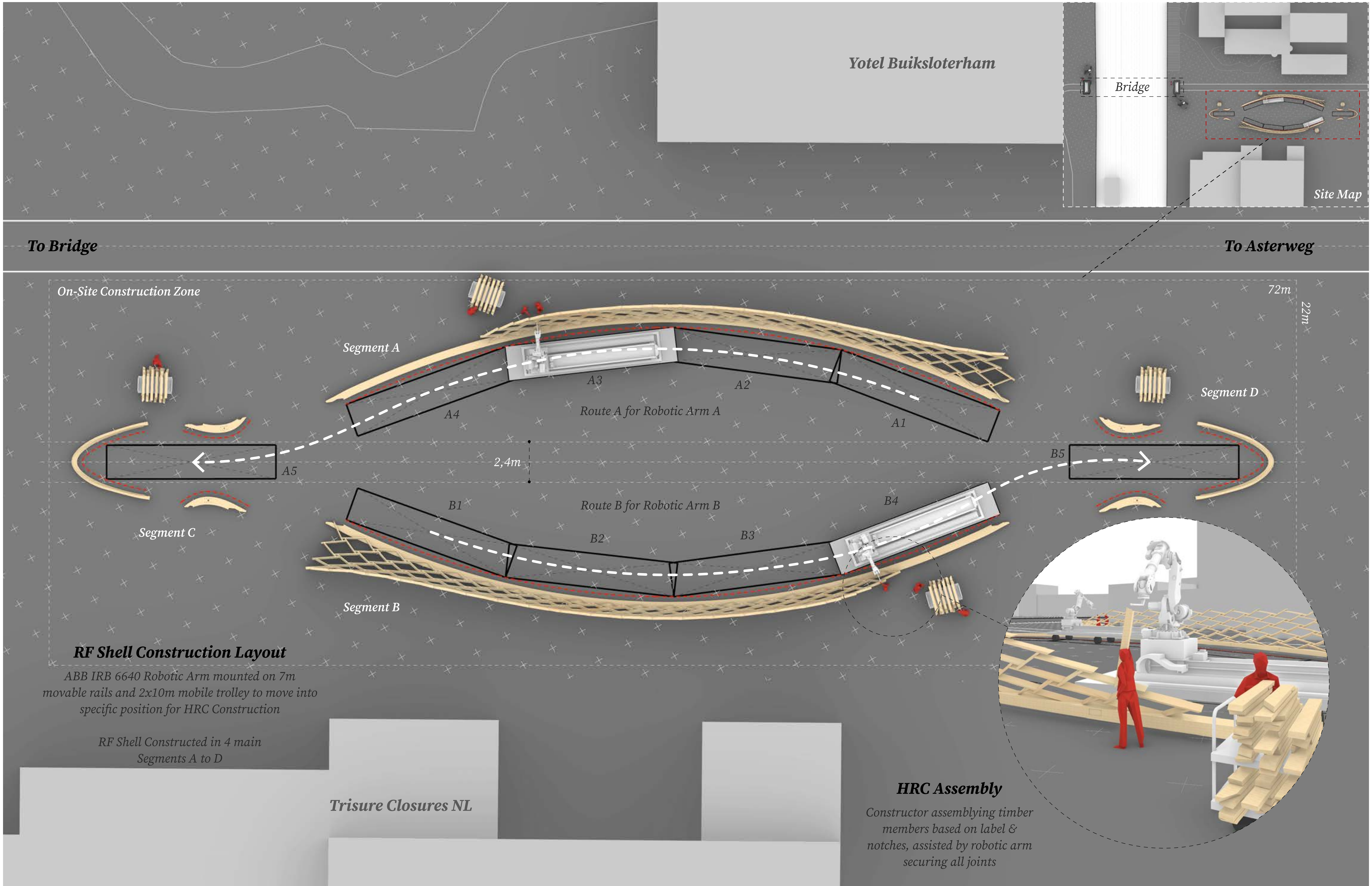


Fig 4.4: Construction layout for the assembly of the RF Shell on individual edge beam segments.

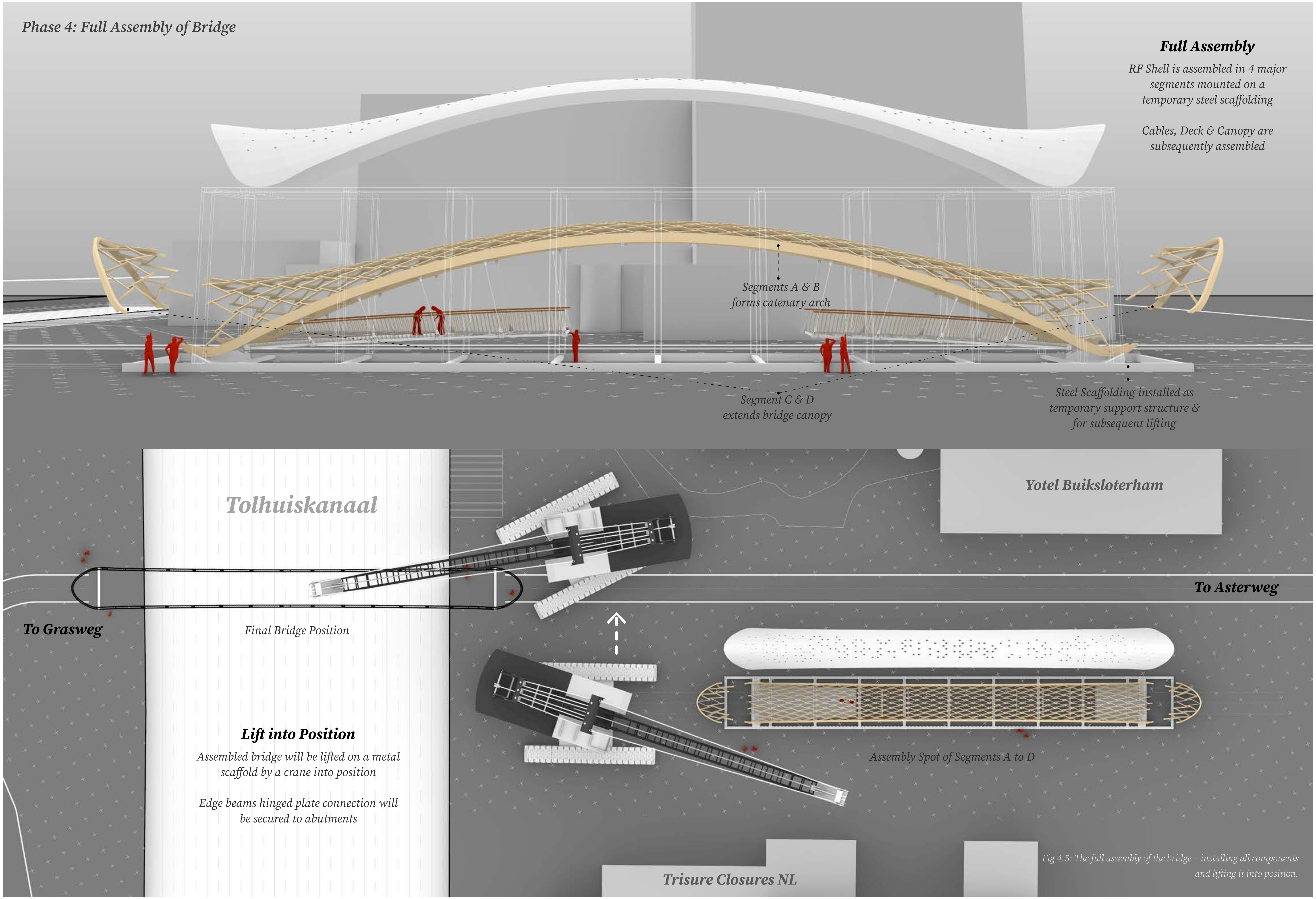


Fig 4.5: The full assembly of the bridge – installing all components and lifting it into position.

Chapter 5:

HRC PROTOTYPE

5.1 DEMONSTRATION SETUP & LOGISTICS

Overview

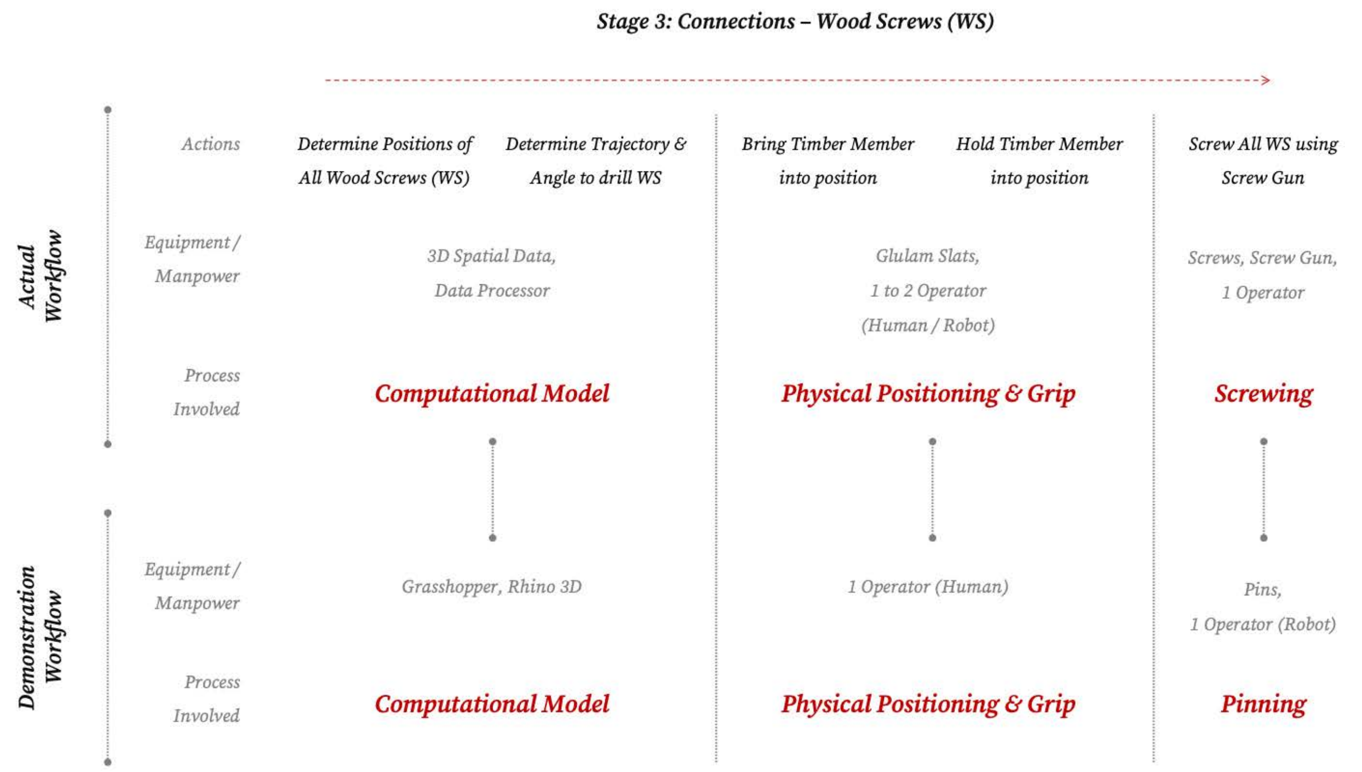


Fig 5.1: Conversion of key workflow into a smaller scale demonstration.

In this chapter, the selected HRC workflow as outlined in *Section 4.5 Workflow Evaluation for HRC Implementation* and *Section 4.6 Design-To-Build Workflow Proposal* is further developed into a demonstration whereby key task and processes can be shown as a proof of concept. These prototypes will serve to glean some insights of the actual implementation and help identify further areas of research and development to improve on in *Section 5.5 Results & Discussions*.

With Stage 3: Connections with Wood Screws (WS) being identified as the workflow for HRC demonstration, key processes are converted into a suitable scale and format to perform a scaled down demonstration. As illustrated in Fig 5.1, starting from the first 2 steps of establishing the 3D spatial data and generating a suitable trajectory to the position. This would be conducted with a suitable data processor capable of converting the 3D geometry digital information into URScript format readable by the UR5, 6 axis cobot. The *UR5 cobot was chosen as it was designed for HRC operations with built-in collision detection which triggers a safety brake upon impact*, hence improving the safety of the operator. Grasshopper, a computational platform in Rhinoceros 3D modelling software, has been chosen for this application because of the ease of digital workflow from the 3D geometrical data generated on the same software. Furthermore relevant plugins available in Grasshopper provides seamless communication with the UR5 robot, used for the demonstration, through direct LAN connection. The computational workflow will be further detailed in *Section 5.3 Computational Workflow for Robotic Process*.

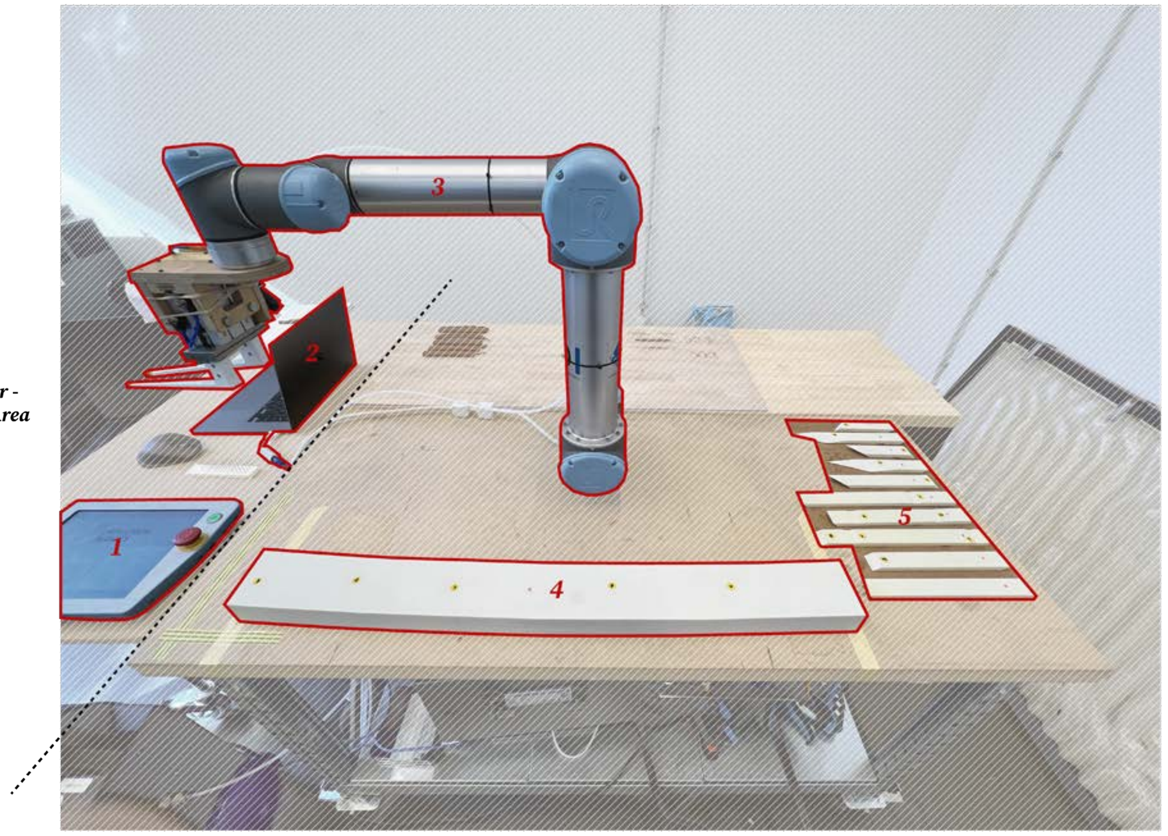


Fig 5.1: Conversion of key workflow into a smaller scale demonstration.

Subsequent actions of bringing the timber member into position and holding it in place will still be performed by 1 operator or worker since the timber components are labelled and notched, making it intuitive in assembling the structure. This process can similarly be performed with a second robotic arm, however given that only 1 6-axis robotic arm is available for demonstration, this process shall be executed by the worker. This also allows the worker to potentially recalibrate the positioning of the robotic arm should there be miscalibration. However this process requires further development of a machine learning model and relevant sensors, thus it is omitted due to the time constrains of the thesis.

Finally, in the actual workflow, the timber members will be screwed together by 3 wood screws per joint. This will be converted to 3 pins where the UR5 robot will simply grip and insert into foam pieces which substitutes the timber members.

The required demonstration setup and logistics are illustrated in Fig 5.2, with 2 distinct areas where the HRC can be facilitated. *Area A is the main robotic control area whereby the operator will convey the URScript data to the UR5 through a LAN cable and load the pins on the robotic arm.* It is set up as a separate space from Area B as it allows for a safe and distinct workspace for the worker to move around without encountering the robot besides loading the pin.

The teaching pendant is also located in Area A as the operator will have to respond to 2 popups, the first prompts to "Load Pin?" and the second prompts to "Proceed to pin?". These popups allow the operator to be in control of the robotic process before it proceeds with the following

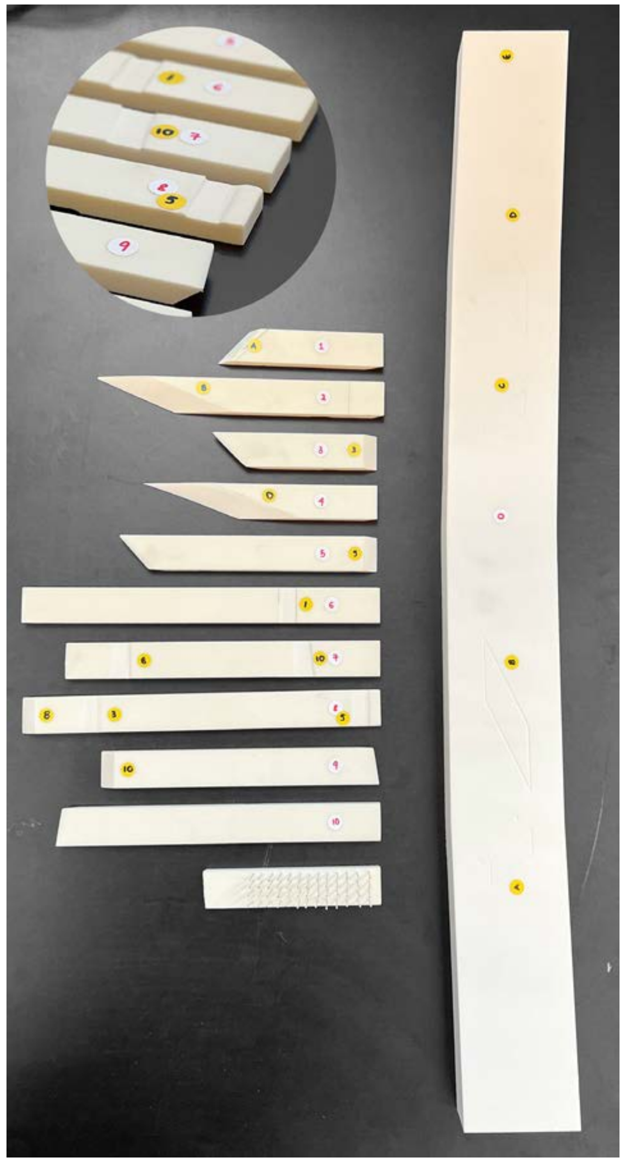


Fig 5.3: Labelling system of the foam slats and edge beam, white label indicates the member index while the yellow label indicates the joint index. Matching yellow labels with the same number indicates that they belong to the same joint.

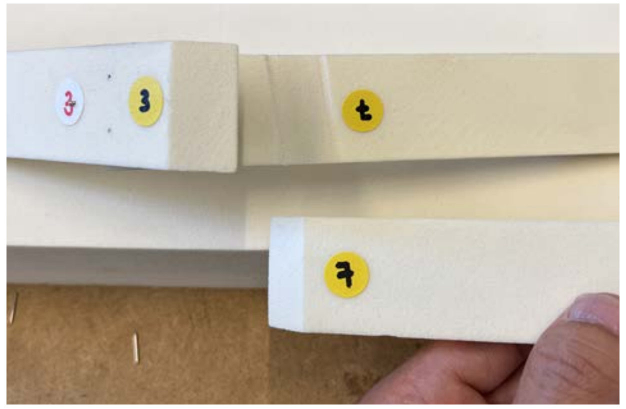


Fig 5.4: Matching joint index on yellow labels with notched section indicating the exact butt-joint position, thus making the assembly process intuitive and direct for the worker.

actions. It is also a key HRC interface whereby the operator communicates with the robot. It *represents a potential form of interaction which can be further developed into more natural, multi-modal communication akin to human-human interactions such as the use of gesture, haptic or voice command.* Within Area A, the robot is also programmed to not venture beyond the marked dashed line (Fig 5.2), hence marking an area where the operator can safely stay beyond reach of the robot and load the pin in a pre-defined position for each repetition of the pinning action.

In *Area B, it is where the operator and robot will engage in HRC and assemble the foam slats onto the glulam arch edge beam labelled 5 and 4 respectively in Fig 5.2.* The foam slats and edge beam are labelled and notched with white labels indicating the member index and yellow labels representing the joint index (Fig 5.3). Matching each yellow index with the same number indicates that they belong to the same joint and hence should fit exactly into the notch, butt-jointed with each other (Fig 5.4). While the worker holds onto the foam slats for assembly, the UR5 will execute a pinning motion with the use of a magnetic gripper. To *ensure further safety for the HRC assembly, the robot speed is deliberately kept between 10-50mm/s* during the pinning process, allowing the worker sufficient time to avoid in case of a malfunction or error in the 3D data conveyed. Therefore, the demonstration can be executed with a human worker and a robot, while the worker could move freely between Area A and B.

5.3 COMPUTATIONAL WORKFLOW FOR ROBOTIC PROCESS

Digital Design to HRC Fabrication

The computational setup for the robotic process inherits the digital data from the bridge design part to ensure a continuous workflow from design to construction. This workflow is reflected in Fig 5.6 and further supplemented by Fig 5.7. This workflow was developed on Grasshopper using the *Robots plugin*. The plugin was *chosen over the use of RoboDK and other softwares as it allows for a direct, seamless and stable connection between the Rhino environment and the UR5 robot*. Without the need for transferring or exporting data to another environment, this reduces the latency between design to execution by the robotic arm. This streamlines the computational process by translating geometrical and target information within Rhino into URScript which is directly transferred to the UR5 through the LAN cable connection. The workflow has been tested with RoboDK with mixed success as the connection with the robot appears to have frequent problems. Hence it is developed entirely with the Robots plugin in GH.

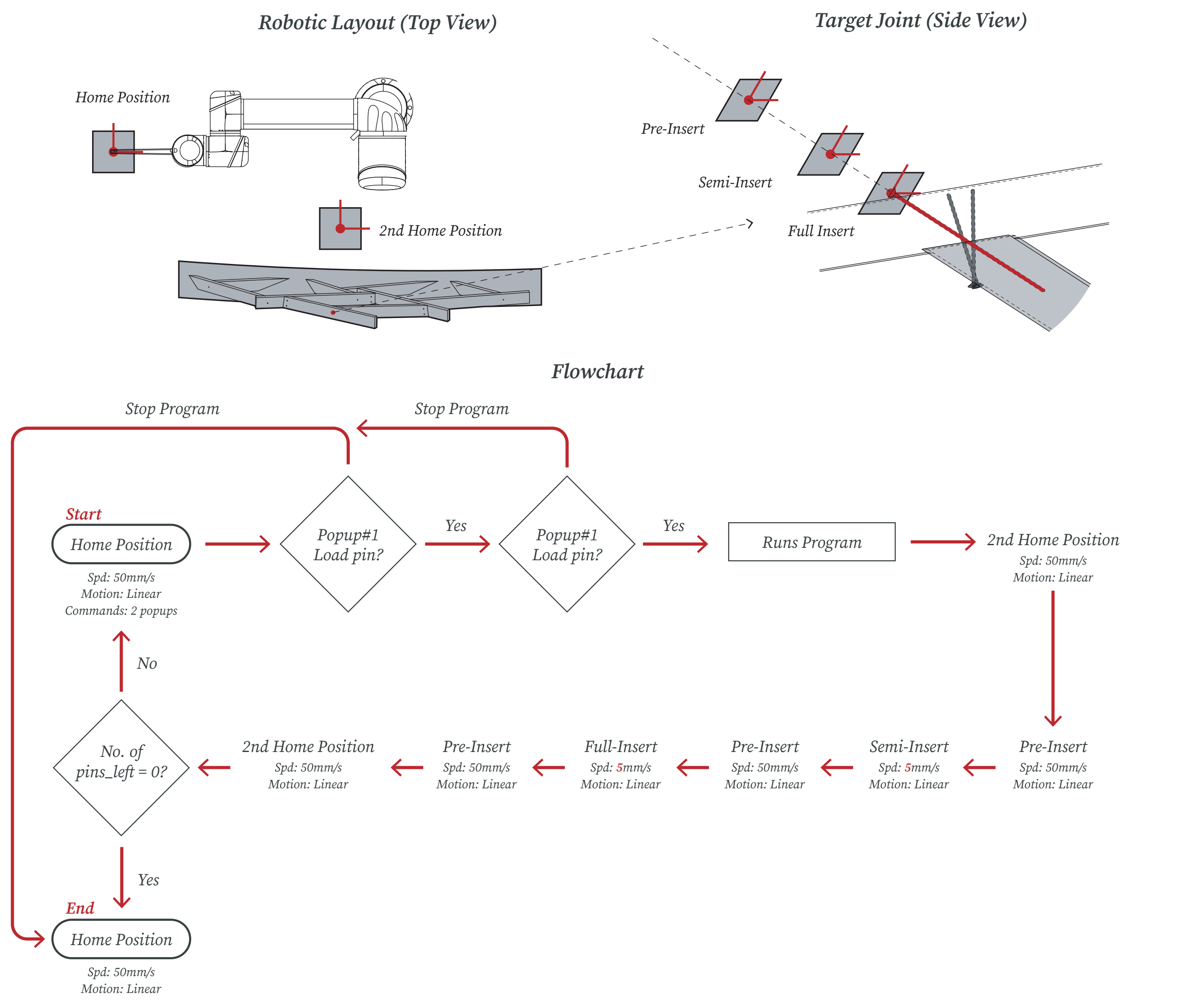


Fig 5.7: Target planes setup sequence for robotic execution with HRC.

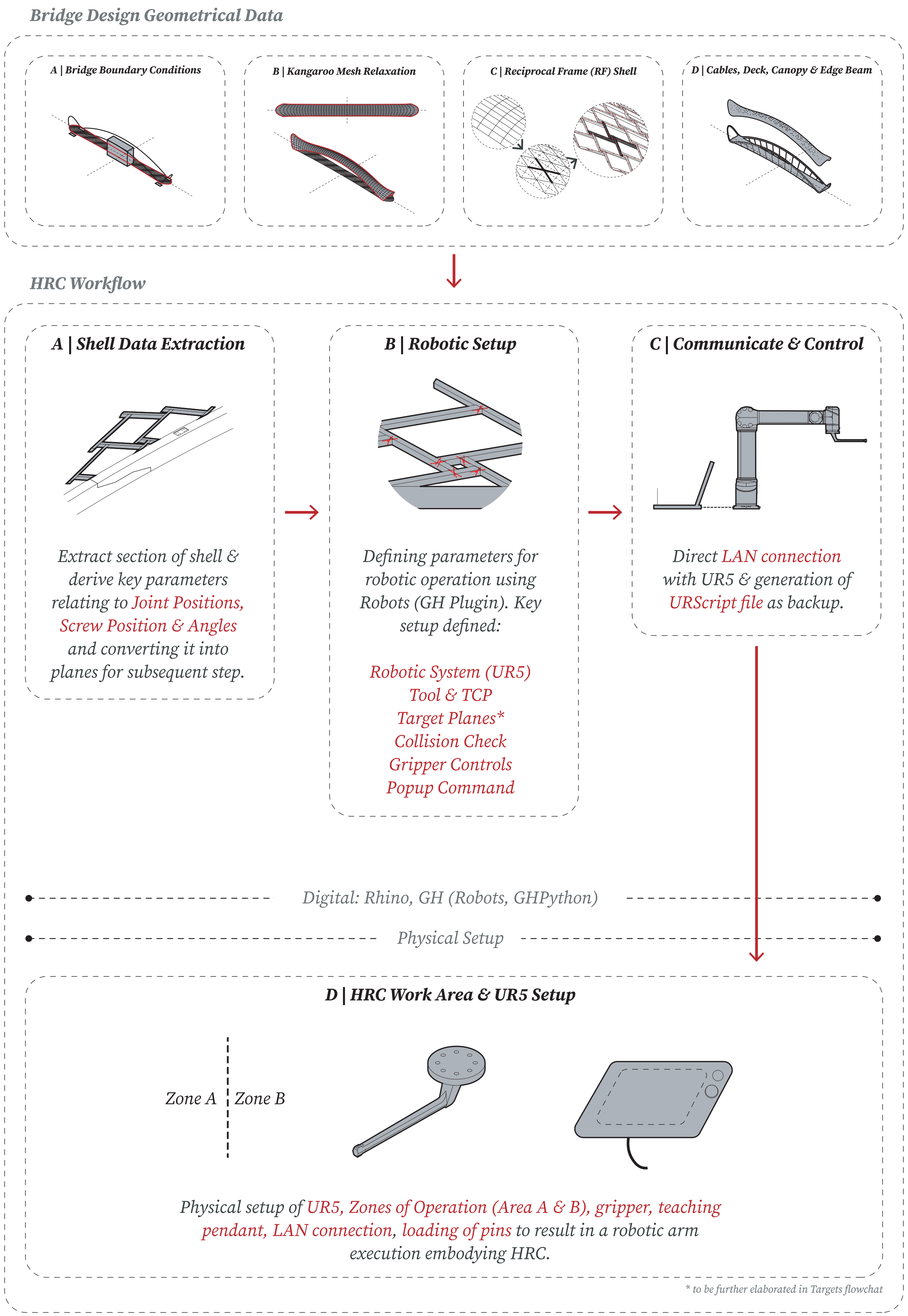
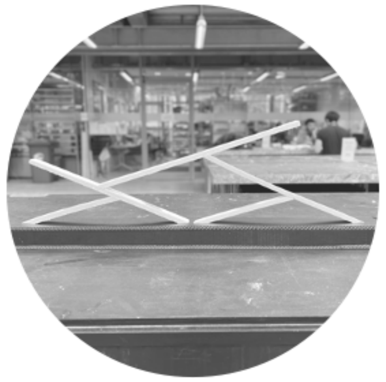


Fig 5.6: Computational workflow continuity from bridge design geometrical digital data to HRC implementation with UR5 robotic arm.

5.4 PROTOTYPE PHASES

Digital Design to HRC Fabrication



Phase 1: Linear Model

Hand Assembled, 2 pins Joint

Phase 2: Linear Model, R.

GH controlled, Robotic Assembly
Gripper Version 1 & 2, 2 pins Joint

Phase 3: Non-Linear Model, R.

GH controlled, Robotic Assembly
Collision Check Test, Gripper Version 3-5,
3 pins Joint

Phase 4: Improved Tool

Gripper Version 6 (Magnetic), no moving parts

Fig 5.8: Overview of the prototype phase and improvements made.

The robotic prototype was executed in 4 gradual stages as illustrated in Fig 5.8 beginning from Phase 1 which was a linear model assembled by hand followed by a subsequent development towards robotic assembly with the linear model and non-linear model. Each phase will be elaborated in the following sections. Throughout the phases, the gripper tool also underwent multiple phases of improvements from the initial short stout version (G1, G2) into the elongation form to improve reach into tight spaces and finally into a magnetic gripper which requires no moving parts. Although the development of the tool will not result in an actual use of it for the 1:1 construction, it is however crucial in achieving a similar procedure and motion as that of a screw gun. These developments are documented in Fig 5.9.

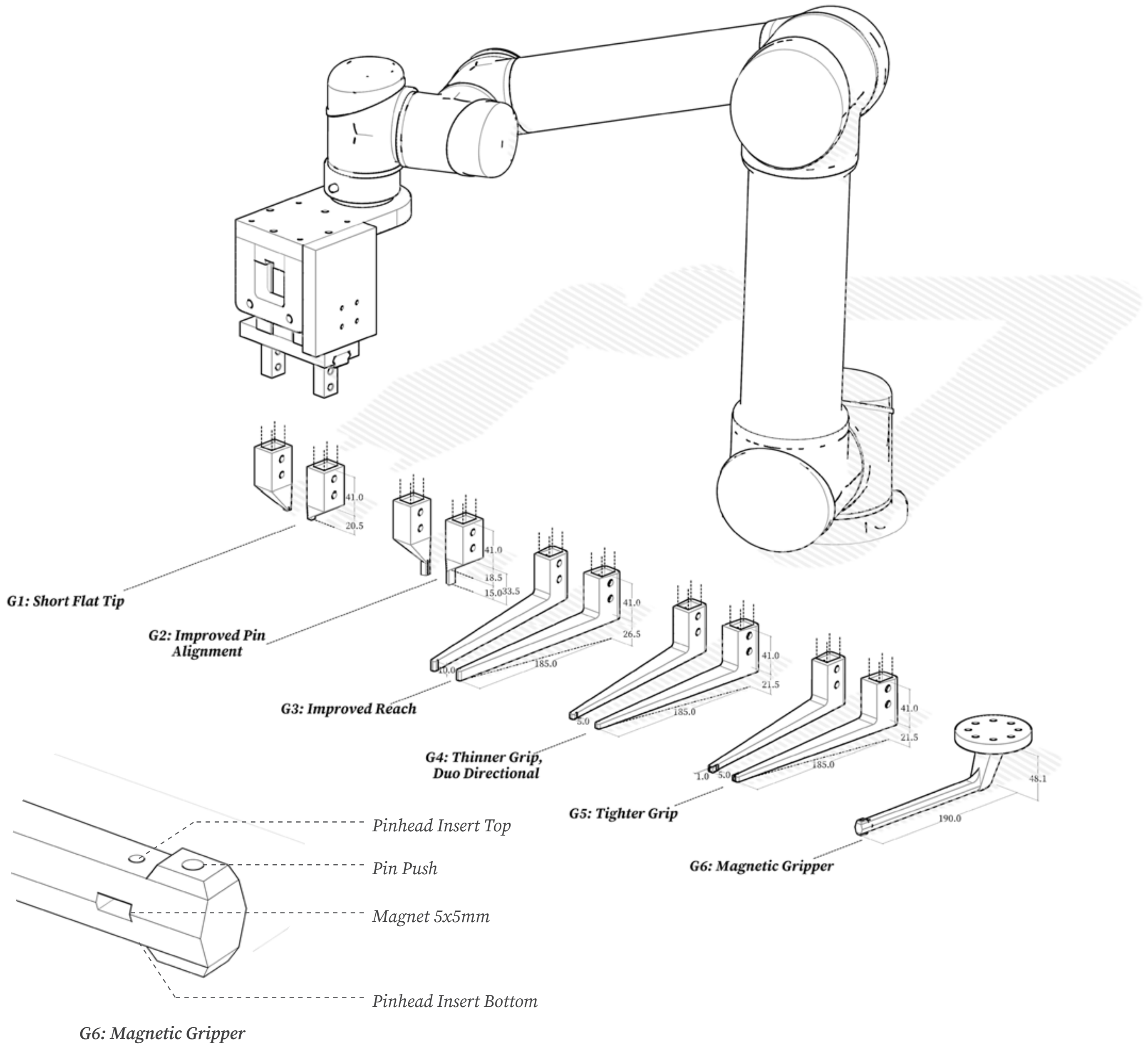


Fig 5.9: Gripper iterations and developments with details on magnetic gripper tool with bi-directional pinning capabilities.

Phase 1: Linear Model Manual Assembly

Description:

- Manual assembly of purple foam slats, cut to exact model dimension
- Test the insert of pins at joint locations (to mimic a screw gun)
- Establish main steps required to execute in GH

Results & Findings:

- Pins align to openings within the RF structure making it easier to gain access to pinning position
- Joints are rather weak, scissors joint diamond structure is not triangulated and hence less resistant to bending moments and shear at the joint
- Foam material is too weak and deforms easily

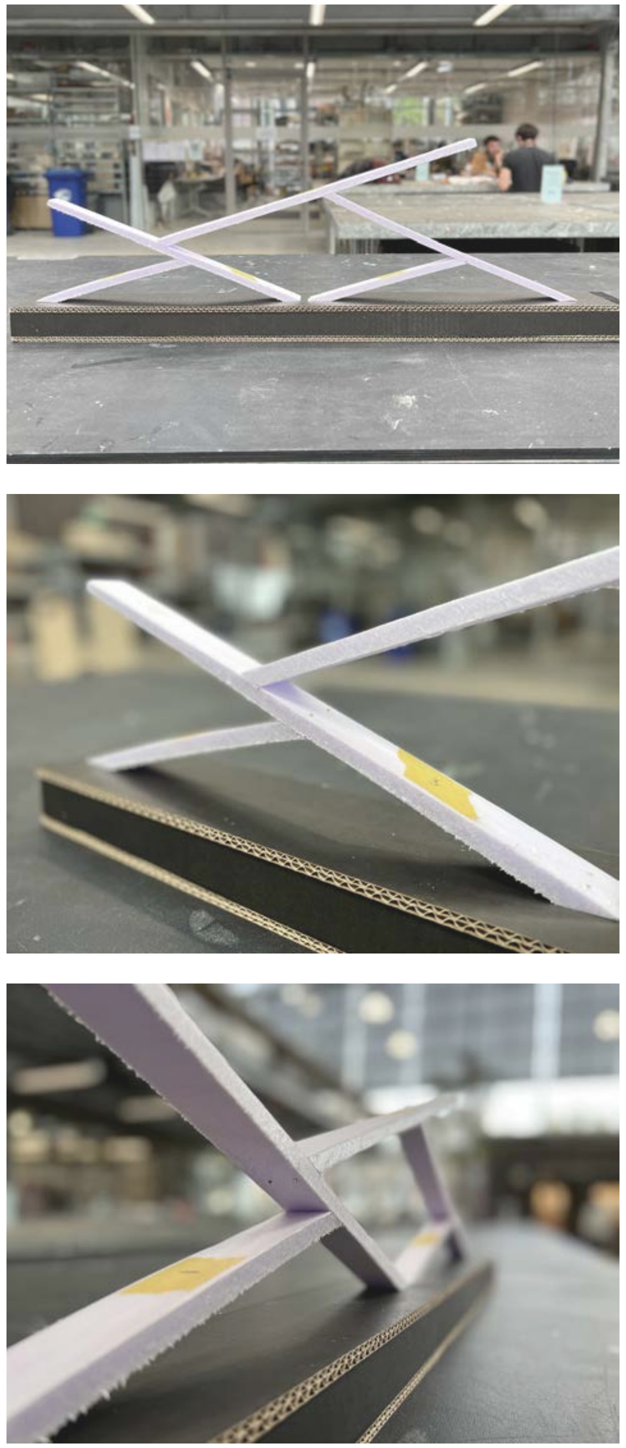


Fig 5.10: Photos of linear model using purple foam slats.

Phase 2: 2nd Linear Model Robotic Assembly

Description:

- Test insert and pushing in of pins (mimic screw gun motion) into purple foam slats
- Test run of Robots plugin with direct connection with UR5
- Adjust calibration of 3D Model with actual model
- Determine pre-stop distance before collision of gripper and model

Results & Findings:

i. Calibration:

- Calibration of 3d model and robotic position in reality not matching because physical model is not digitally fabricated with high accuracy. Therefore there is a need to digitally fabricate the base and each foam components to better precision
- Instead of having a fix location to pick up pins, robot will pick pins from a human operator, to reduce the need for multiple areas of alignment

ii. End Effector:

- Gripper head (G1) requires a flat surface in order to push pins in. Hence, make flatter gripper head to enable a push pin surface.
- Grip point (G1) has a very small point of contact with the pin so it was unable to fix the pin angle exactly. There is a need to extend gripper head to align pins better (G2).
- TCP is too close to the gripper mechanism casing, will collide with model due to direction of inserting pin, so the gripper needs to be extended outwards, away from current gripper casing. This results in Gripper G3.

iii. Timber Members (foam slats):

- Foam slats do not have much indication for human operator to intuitive assembly it, so it needs to include shallow notches and labels so it becomes intuitive to match them.
- Purple foam is structurally too weak, deforms too easily and doesn't hold weight well, a stiffer, denser foam is necessary.

iv. Grasshopper:

- To include wait time at key moments – before and after grabbing pins, before and after pinning pins and when reaching the position to pin
- Collision check needs to be conducted
- Include a fixed home position for human operator to know where to go when loading pin
- Include 2nd home position outside of model to prevent collision of robotic arm with built parts of the model

v. Non-Linear Model:

- Conduct test with the actual 3d model of the RF Shell in the bridge design
- Non-linearity of the model will justify the need for robotic arm operations to accurately position pins without them colliding into each other

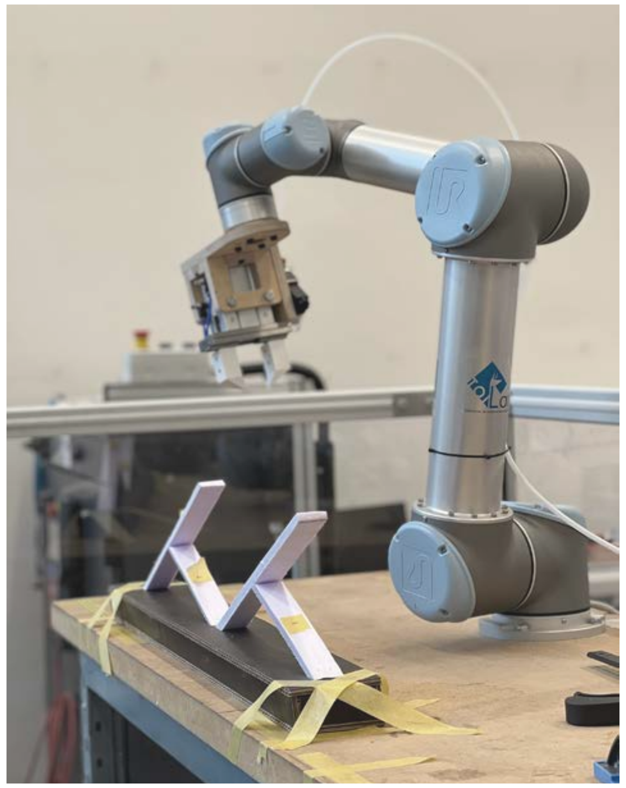


Fig 5.11: Phase 2 prototype with robotic setup and gripper sequence of inserting pins.

Phase 3: Non-Linear RF Shell

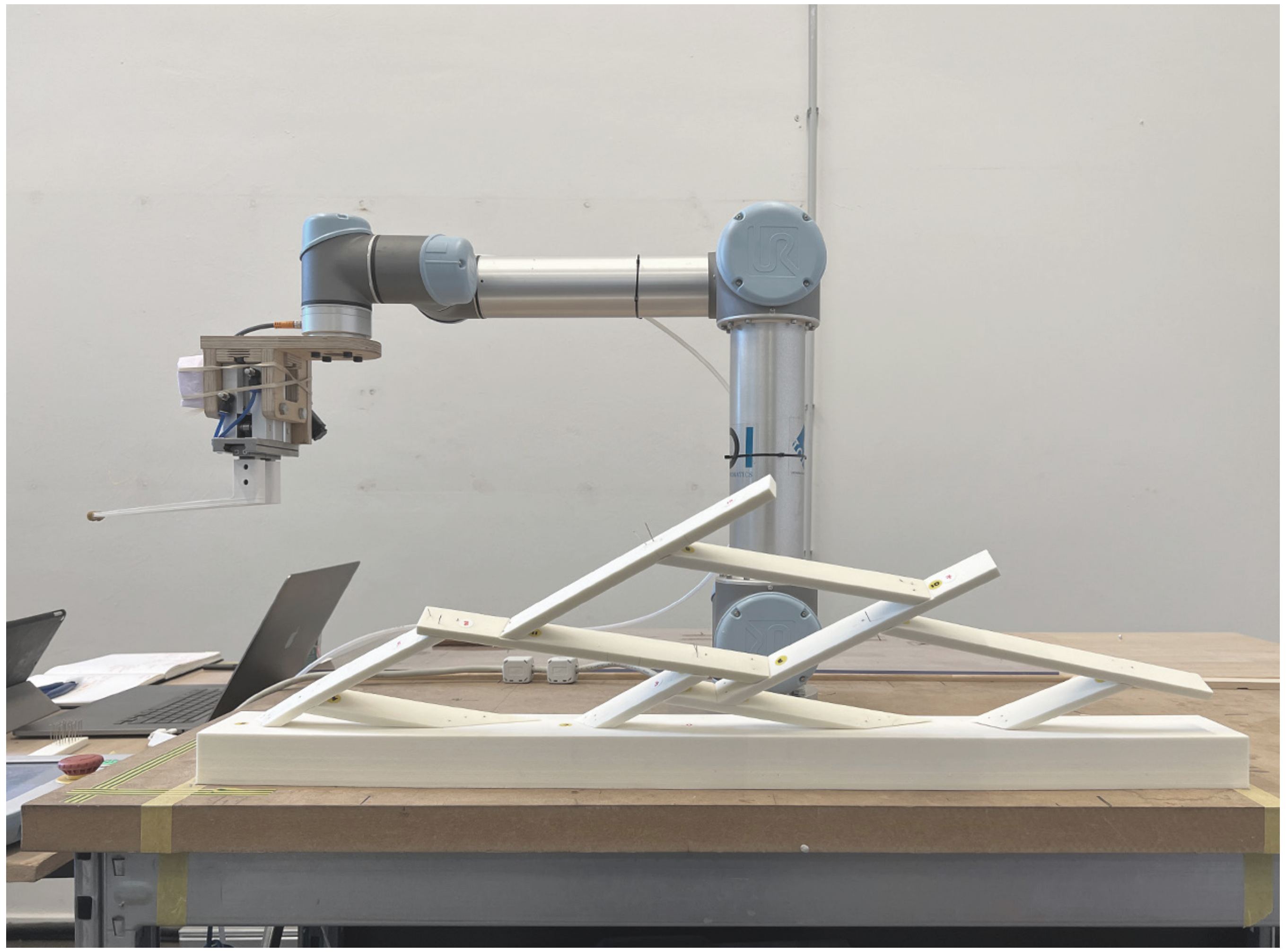


Fig 5.12: Phase 3 RF Shell assembly setup with robotic arm in Home Position where pins are loaded.

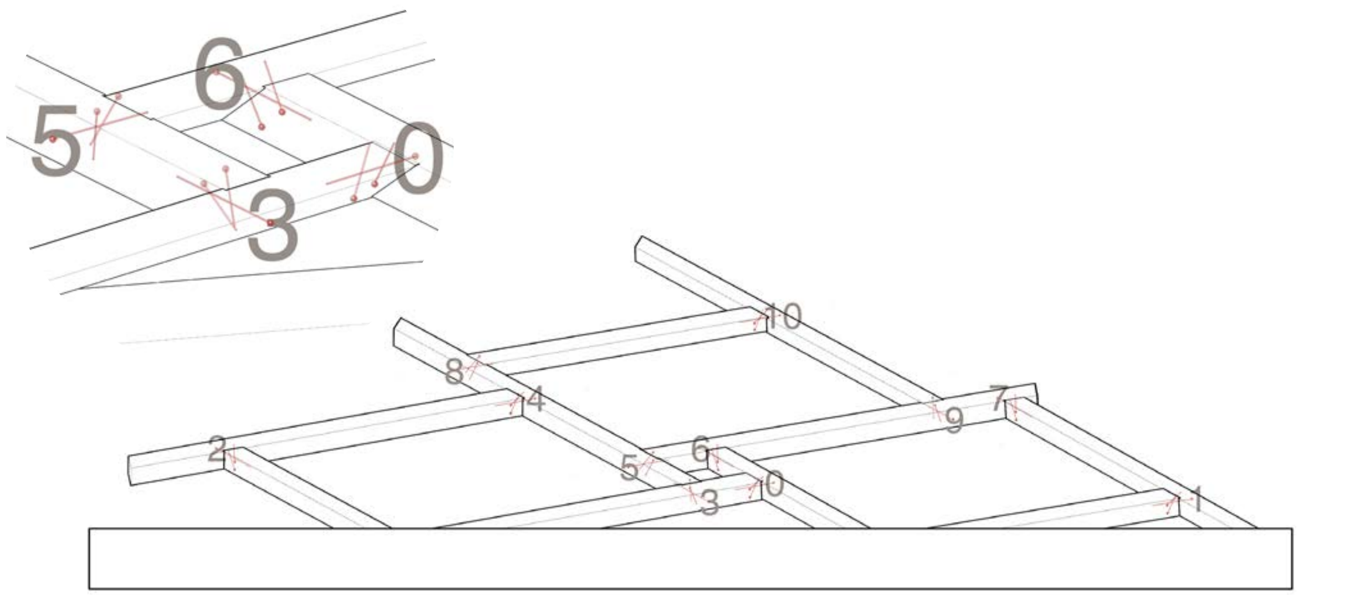


Fig 5.13: Pin position and orientation (red) within RF Shell demonstration model, consisting of 11 joints between foam slats (grey label) and 5 joints with edge beam (red label).

Description:

- Actual Non-Linear RF Shell from bridge is extracted for test
- Each joint consists of 3 pins/screws – 1 Tension screw, 2 shear screws
- New gripper (G3-5), sticks further outwards from gripper housing
- Gripper (G5) head has added rubber pads to improve the tightness of grip (Fig 5.14)
- Only 6 joints (4,5,7,8,9,10) are possible to be assembled by the robotic arm, 4 of them (0,1,2,3,6) are not possible due to the tight conditions of the joints makes pinning it impossible at this scale (Fig 5.13)
- Collision checks conducted in simulation, but needs to be verified by actual robot test
- 2 Popup prompts added (1 to load pins, 1 to proceed to pin location and continue pin) to allow the robot to receive further human instruction before proceeding (Fig 5.15)

Results & Findings:

i. Calibration:

- Base was CNC milled, thus has very high accuracy
- Individual foam slats are fabricated by hand, has accuracy to +- 1-2mm (Fig 5.16 & 5.17)
- Base was used as calibration piece with 3d model, to mark out on table top where the exact base position is.
- Misalignment of pinning position increases as the joints are higher, due to the cumulative sum of tolerances at each successive joint (Fig 5.18)

ii. HRC:

- Joints are intuitive enough to position (Fig 5.17)
- However there are slight shifts in each individual joint where it is not always an exact butt joint positioning (Fig 5.18), is not informed by the presence of the notch. An improved notched should reflect the exact shift in joint position which can be digitally fabricated into each foam slats.
- Extent of HRC is limited, primarily taking place

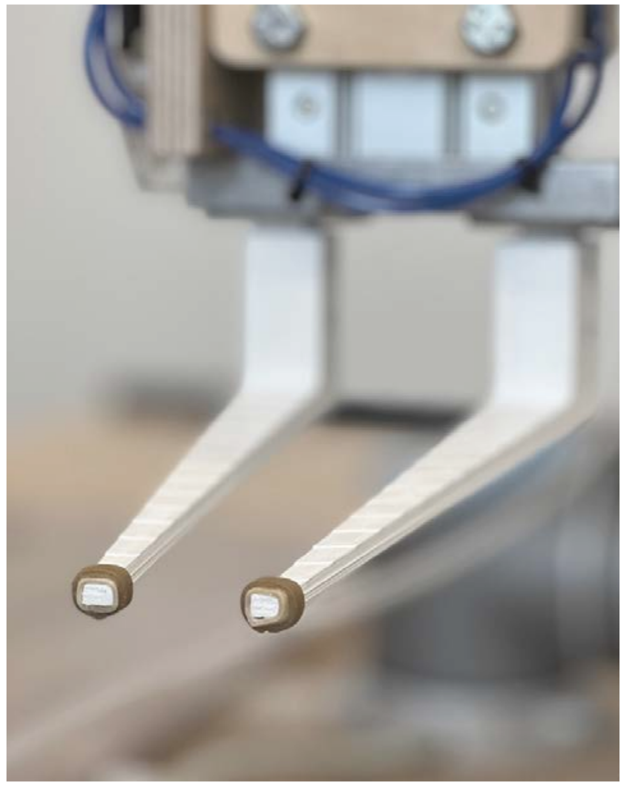


Fig 5.14: Gripper G5 with extended reach and rubber pad grip.

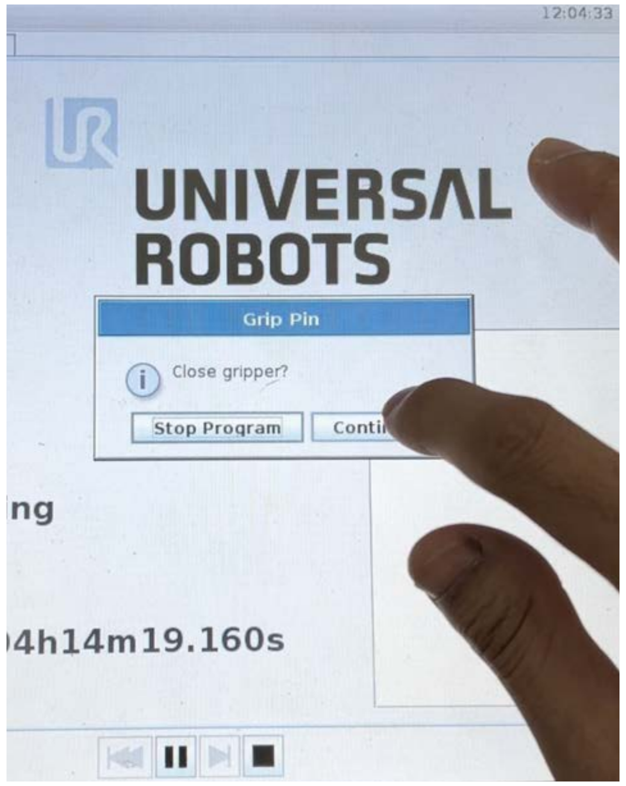


Fig 5.15: Popup prompts on teaching pendant to allow the operator a control of the robotic assembly and a simplified form of HRC.

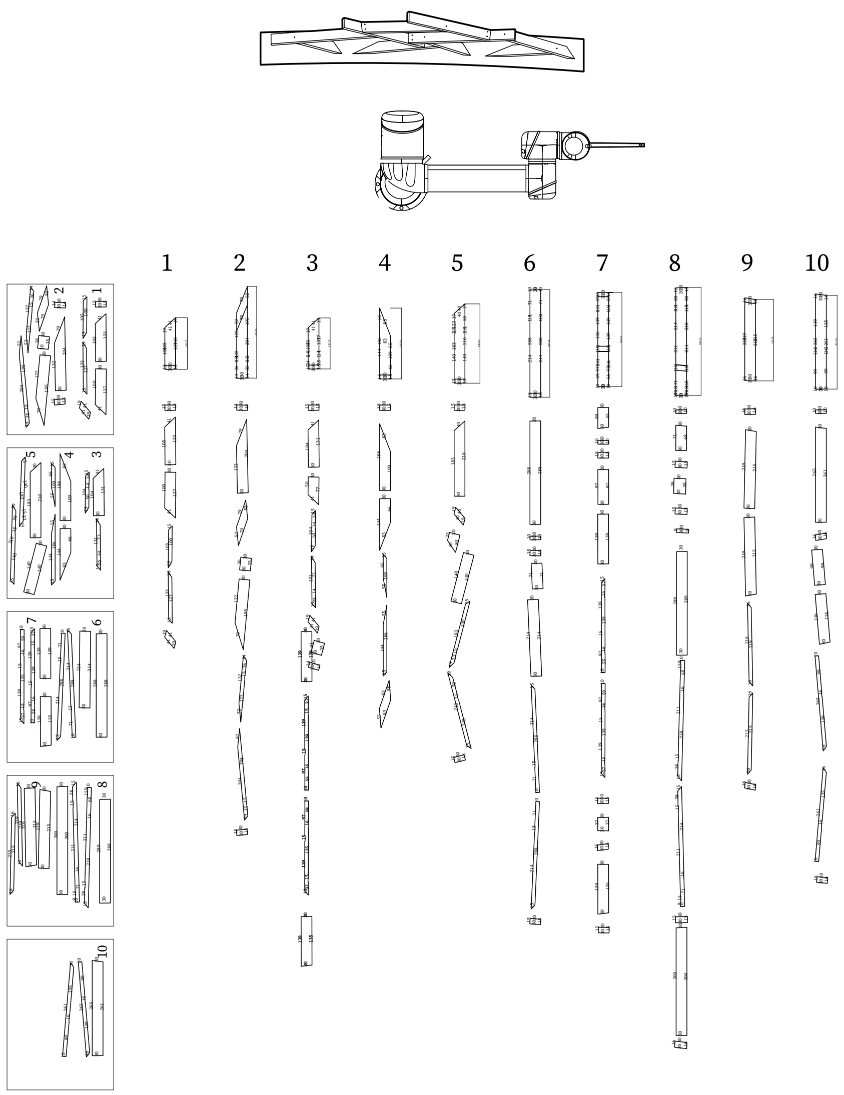


Fig 5.16: Fabrication data of all foam slats involved.

through positioning the foam slats, feeding pins and popups on the teaching pendant. Could be extended to more natural means of collaboration, such as haptic, gesture and voice command

iii. End Effector:

- New Gripper (G3-5) extends reach of the original robotic gripper setup, allowing for bi-directional pinning - upwards or downwards - increasing the versatility in terms of pinning and TCP configuration of the trajectory.
- Gripper contact area still too small, alignment of pin is not exact each time.
- Gripper head (G5) area is too small + padded with rubber makes it difficult to push the pins in firmly (Fig 5.14)
- Opening motion of gripper is too wide such that it hits the model as it releases the pin. Hence a new gripper which does not have an opening motion is required, resulting in Gripper G6, the magnetic gripper. It also results in a more streamlined tool since the robotic gripper setup with air pump is no longer necessary.

iv. Timber members (Necuron foam slats):

- Necuron foam slats are much firmer and denser than purple foam
- Density also makes it harder to pin, but

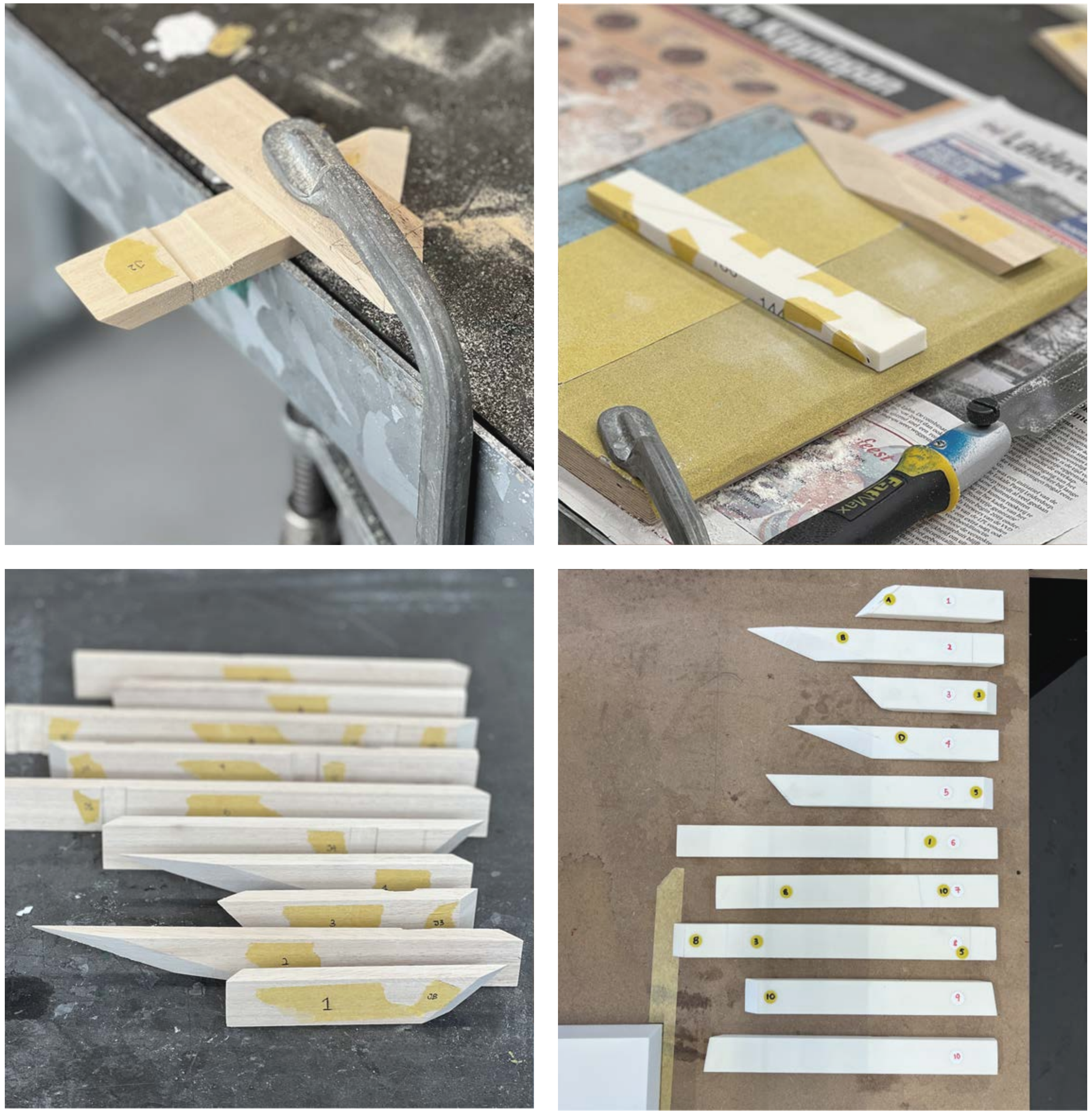


Fig 5.17: Fabrication of Timber and Foam slats with labelling and to allow for more intuitive matching of joint index (yellow sticker) and identification of member index (white sticker)

resulting structure is also stiffer.

- Due to high resistance in pinning, robotic speed during insertion needs to be slow
- Higher accuracy in fabricating individual foam slats based on print outs and timber mold fabricated beforehand
- Labels and notches helps makes timber members and joint positions more clear. (Fig 5.17)

v. Grasshopper:

- Collision check hiccups are ironed out when tested physically with robot
- However, collision check is conducted manually for each individual approach plane.

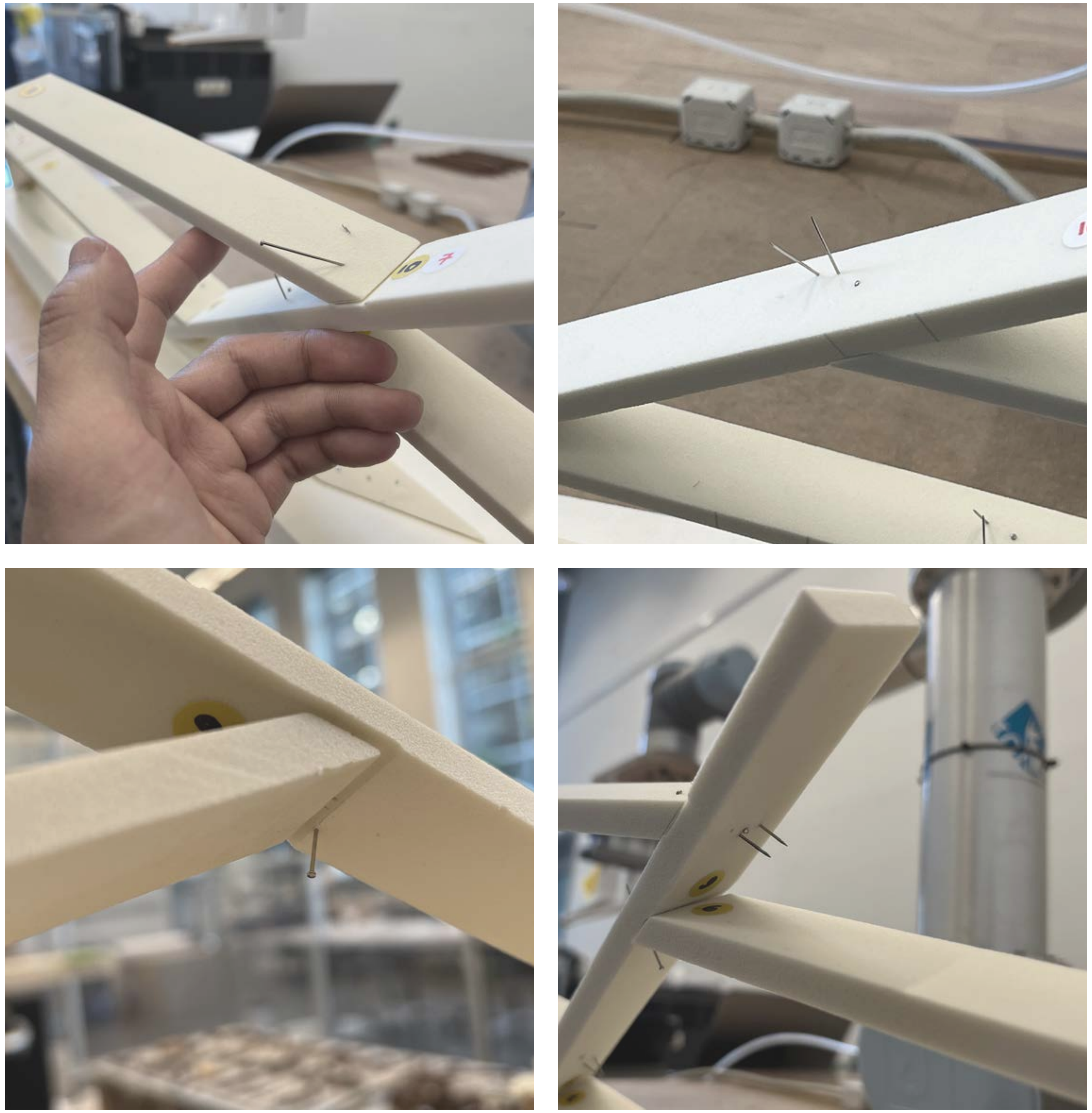


Fig 5.18: Misalignments in prototyping assembly due to the cumulative sum of tolerances with each successive joint. A more robust method of calibration and ensuring higher precision is required.

Phase 4: Improved Gripper Tool

Description:

- To test the improved gripper G6 which is magnetic (Fig 5.9)
- Evaluate the possibility of eliminating the need for the gripper setup as G6 is more streamlined and does not have a large casing which inhibits movement in tight spaces.

Results & Findings:

i. End Effector:

- Magnetic gripper G6 works bi-directionally and has a rigid and secure hold on the pins, just enough strength to ensure it does not remove the pin from the foam after inserting it
- Separate push pin surface added in front of Gripper G6 such that the pin can be completely inserted into the foam slats.

Fig 5.19: New HRC Setup with gripper G6.

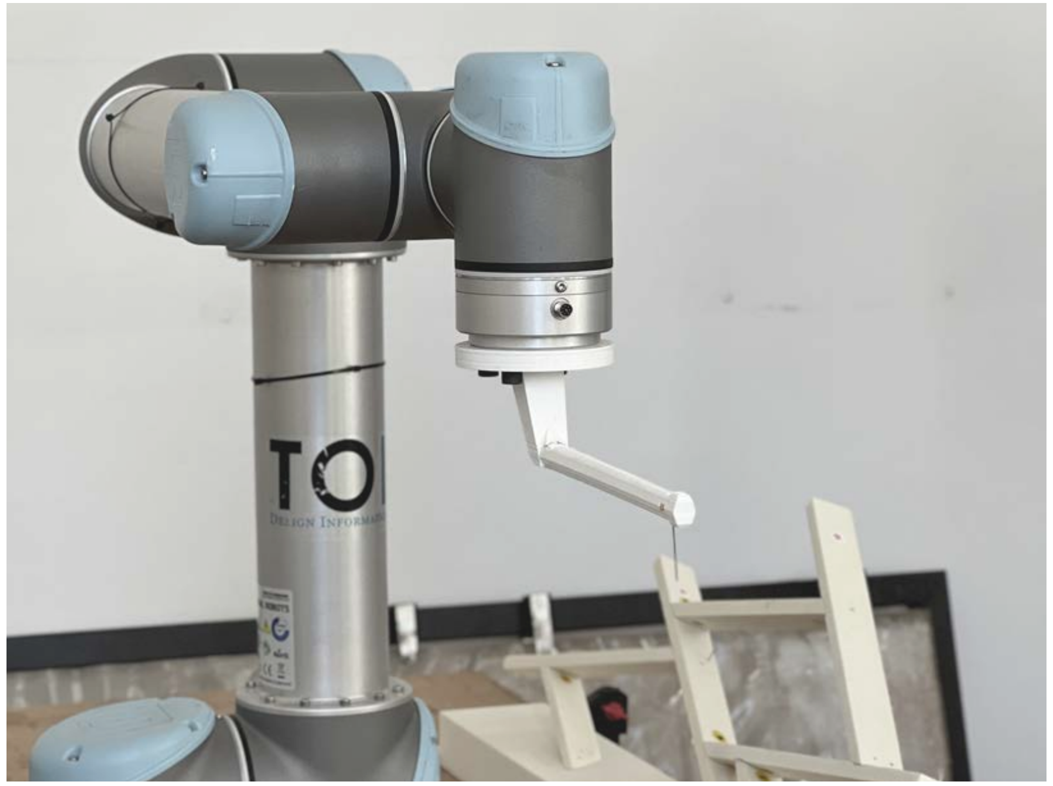
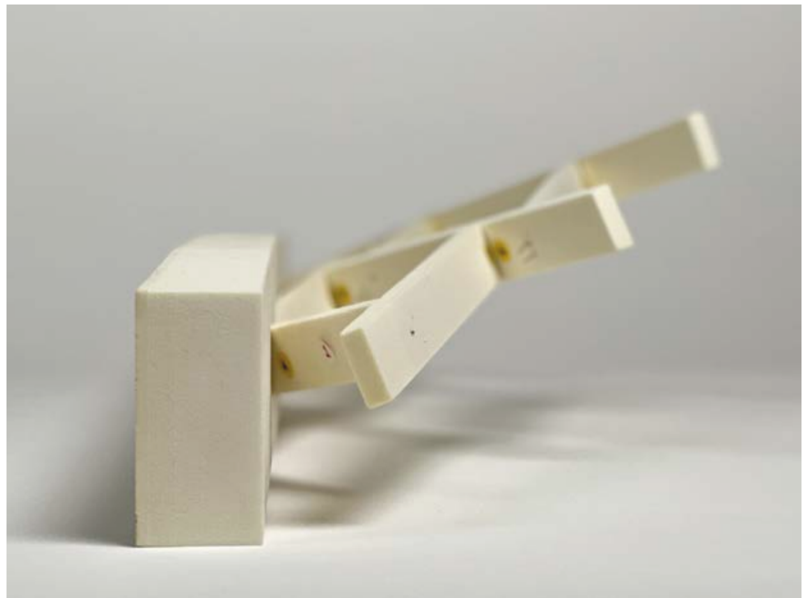
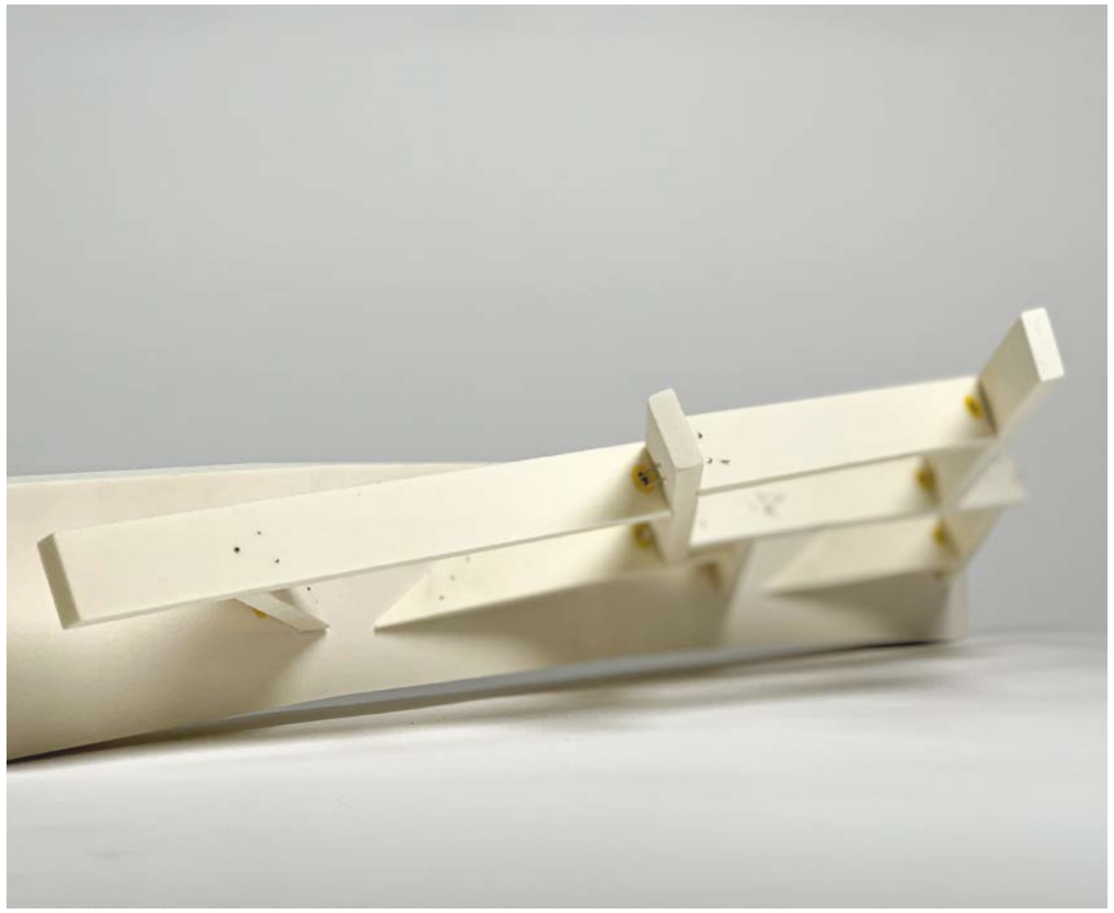
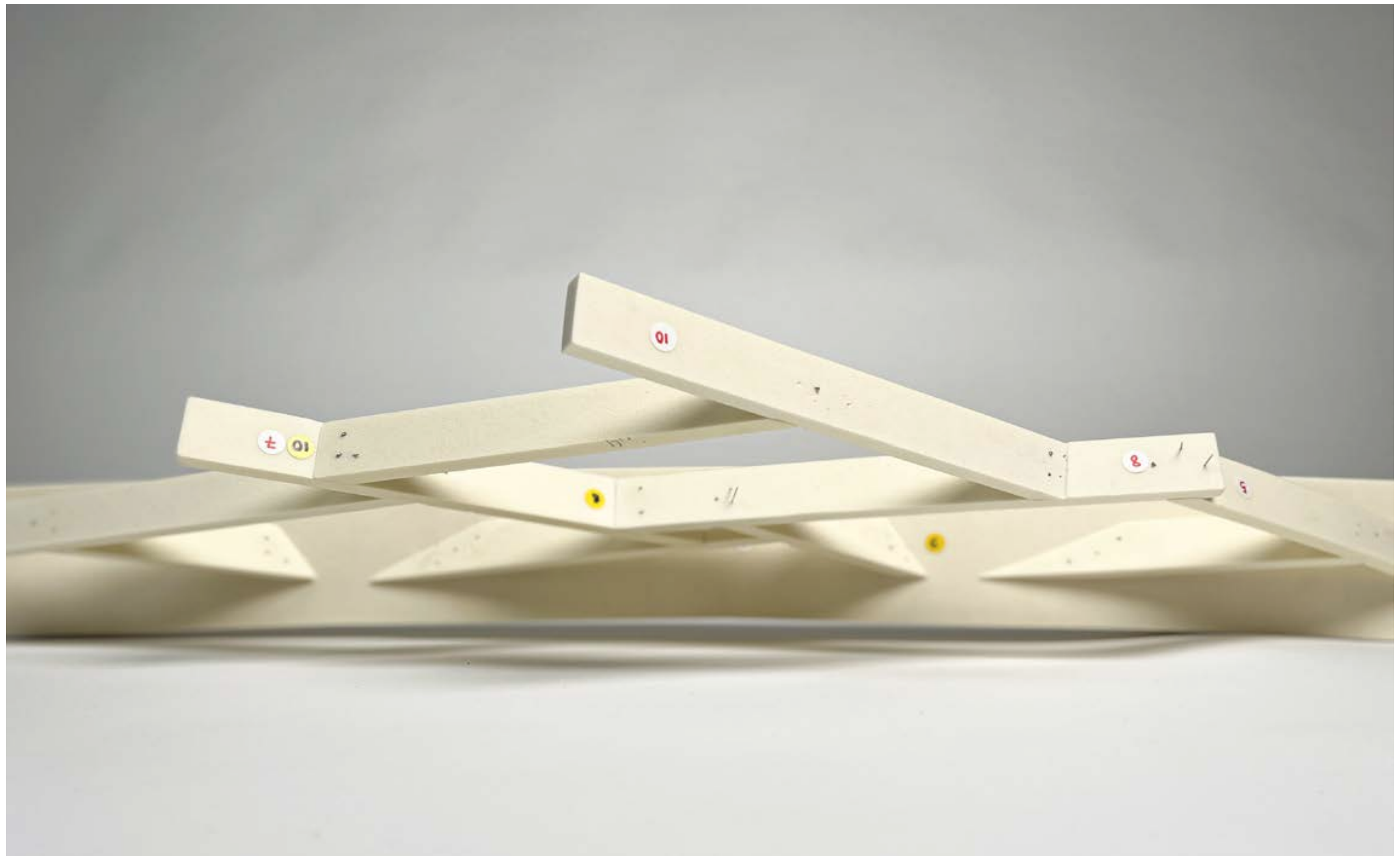


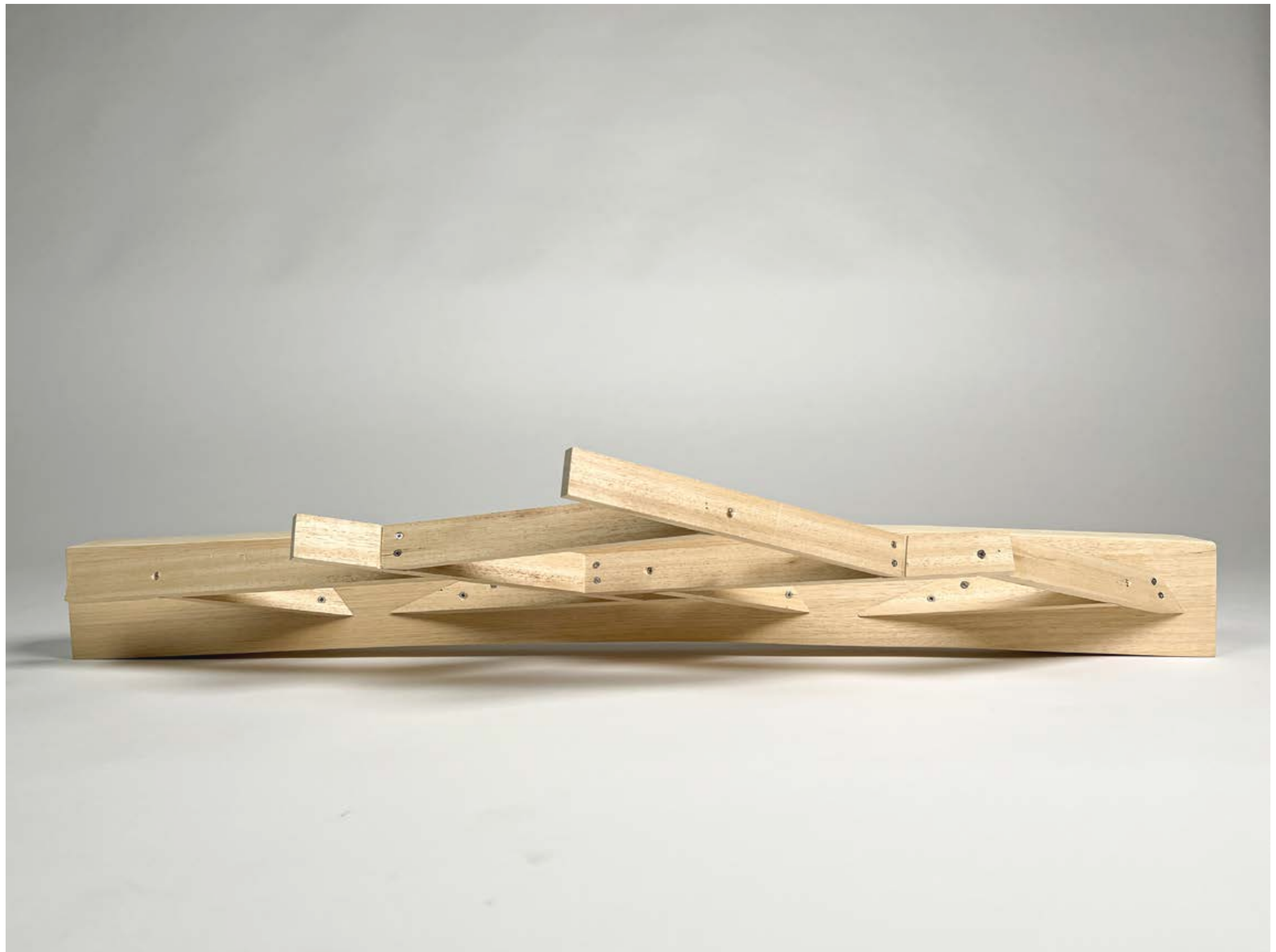
Fig 5.20: New magnetic gripper G6 with a pin attached.



Foam Slats Final Model







Timber Slats Final Model

5.5 RESULTS & DISCUSSION

Overview of HRC Design-to-Build Workflow

Through the development of the prototype, end effector tool and HRC setup over the 4 phases, key factors crucial to address the shortfalls and limitations of the approach are listed below for further research and development.

Calibration

A robust system of calibrating the physical model with the digital model is required. This is especially crucial because in the 1:1 construction, the robotic platform will have to shift to multiple locations along the edge beams to assemble the RF Shell. These incremental shifts in accuracy could result in a large cumulative shift in precision of the structure. *Further improvement to calibration such as the use of 3D Scanning or AR calibration tool could ideally improve the precision of the assembly* (Brugnaro et al., 2019).

End Effector Tool

In the 1:1 construction, the end effector would be a screw gun mounted on the ABB IRB 6640. Hence *the gripper tool developed within this demonstration is purely created to showcase the collaboration of a robotic system with a worker in assemblying a timber structure at 1:5 scale*. Within the scope of this demonstration, the initial issues of the large gripper casing, the short reach, the lack of alignment and the opening motion which disrupts the model has all been largely resolved in the latest version of the gripper G6. Without moving parts and a magnetic pin attachment system, it resembles more closely the streamline mechanism of a screw gun and hence could function as a proxy to the screw gun in 1:5 scale.

HRC Workflow

The current proposed HRC workflow showcases the potential of *combining the computational strengths and precision of the robotic system with the quick judgement and intuition of a human worker in assemblying a timber structure*. However this workflow can be improved further by means of achieving a more natural mode of communication between the robot and the worker. As previously reviewed in *Section 4.2 Overview of HRC Developments*, various methods of improving the collaborative operation through haptic learning, voice command and gestures all helps to improve the mode of communication between humans and robots. The thesis barely scratched the surface in exploring more meaningful forms of HRC while opting to demonstrate the collaboration on 2 main areas, during the screwing process of the timber members as well as to signal the robot to continue using the teaching pendant. As these *collaborative tasks are largely scripted and executed without any adaptation, this HRC workflow would be unable to respond to changes in the work environment or respond to other intentions of the human worker*. Hence the lack of adaptability and flexibility in the HRC system proposed is naturally its largest limitations. While existing research has developed machine learning systems to adapt to the responses of the human worker or to external stimulus (Dubor et al., 2016), it does entail a more computationally complex system which could not be developed within the short time span and scope of the thesis. Hence the further development of collaborative operation, communication and calibration is key to furthering this HRC process.

The *HRC roles could also be flipped* such that the human worker is performing the more lightweight tasks of screwing, while the robot holds and secures the timber members into position. Alternatively, *2 robots could also be employed* such that the role of the human worker can be substituted. These alternatives were omitted for this thesis because in the former, the screwing tasks is highly complex while the positioning of the timber pieces could be performed quite intuitively when the assembly information is etched into each individual piece. Furthermore, each timber piece is sized with lengths between 0.8 – 2.0m and weighs between 3 to 8kg and notched slightly at joint positions such that they can be supported and matched easily by a human worker. While in the latter alternative, it is likely that 2 robots could work in tandem in assemblying the structure, however as *the thesis prioritise the exploration of collaboration between robotic systems and human workers*, this alternative was omitted.

Timber Members

Through the design of the individual timber members for the RF Shell, the *use of a robotic system in screwing the structure entails that there is no pre-drilling required to guide assembly of the joints*. However through the prototyping of the timber model (INSERT FIGURE), the lack of pre-drilling might lead to cracks along the grain of the timber slats. Since the timber slats are to be milled by a 5-axis milling machine, *pre-drilling of the holes required in the timber slats could ease the subsequent assembly process, thereby possibly omitting the need for a robotic arm in executing the complex screwing task*. To realistically bring this design to fabrication and construction, pre-drilling of the holes is highly recommended due to the small cross-sectional area of the timber slats (150x50mm). While pre-drilling the holes omits the need for a robotic arm, the thesis prioritized the research into HRC workflow to provide a scientific contribution to the ongoing research developments. Hence the pre-drilling process is omitted.

It is acknowledged that *other methods are available in assembling this timber structure such as having a deeper notch which interlocks each joint* much more making it straightforward to fabricate however while considering the factors of circularity, the *timber slats are designed to remain as uncut as possible to maximise the useful sections of it for further upcyling and reuse*.

Chapter 6:
CONCLUSION

6.1 CONCLUSIONS & RECOMMENDATIONS

Summary

Bridge Design

In addressing the design vision and goals for the bridge design, to a large extent the design is representative of the potential of timber structures in the Digital Age, with the incorporation of digital design and HRC construction in fulfilling the eventual structure. Its design has taken into consideration the user's accessibility limits and needs while being forward looking in establishing an understanding of the upcoming change in demographics of Buiksloterham. Furthermore, it has also integrated green spaces on both sides of Tolhuiskanaal and incorporated a novel strategy for an annually movable bridge. Circularity goals of design for disassembly has also been embodied through the use of non-glued joints, repetitive components and renewable, bio-based material. Overall, the design has been fulfilled with some challenges yet to be addressed.

Firstly, the complexity of the design and construction workflow proposed is in its early development and will need to be further tested and structurally optimized. Due to the time constraints of the thesis, the FEM analysis and optimization for the bridge structure was not performed which would further influence the dimensioning of the components. In addition with the HRC construction and assembly process proposed, it has proven to work within a scale of 1:5 under controlled and non-dynamic conditions. However, the 1:1 construction of the RF Shell on site would prove to be the most challenging phase of the construction due to its novelty and scale. Hence a 1:1 prototype testing has to be conducted in order to determine the feasibility of this workflow.

Secondly, a novel bridge opening method was proposed whereby decks and cables can be removed from the bridge instead of having to lift an entire segment of the bridge structure. Due to the high tension force exerted by the glulam edge beams on the steel deck, this would prove to be challenging to disassemble the decks and its joints. A method of pre-tensioning the structure to reduce the tension on removable joints was proposed and would need to be tested and further developed before evaluating its feasibility.

In conclusion, despite the potential challenges, the bridge design aims to inspire and challenge the convention in timber and bridge construction, thereby shedding new light on the possibilities of sustainable design with timber.

HRC Design-to-Build Workflow

With increasingly complex structures and buildings, the need for a seamless digital design to construction process is important. The strengths of pursuing a HRC construction workflow lies in the potential to tap on the strengths of both agents in enhancing the efficiency and productivity of the construction sector which has largely been manual and dangerous. Within the scope of the thesis, a 1:5 demonstration was performed to prove that the collaboration between a human worker and robotic arm could ease the assembly and construction of a complex structure. However many challenges are yet to be overcome such as the variability of the site, more natural mode of collaboration and communication, as well as improved methods of calibration and adaptation.

Since the prototypes were tested within a controlled and non-dynamic environment, it is not directly representative of the conditions of a 1:1 onsite construction. A controlled and leveled environment, protected from the weather, would have to be set up on site before the implementation of the proposed workflow. Logistically it is possible for the given site location, however it might not always be the case for other bridge sites.

Furthermore, the demonstration did not involve the movement of the robotic arm to various different locations along the edge beam to simulate the 1:1 workflow. With this movement, across a terrain which might not be entirely levelled and precise begets the need for a robust calibration method to ensure that precision is in check. Due to the intricacy of the design, the cumulative sum of tolerances might result in misalignment when the individually assembled shell has to be assembled together. Therefore, further exploration for the use of AR, XR or other vision, haptic or tactile method of calibration will need to be incorporated to allow for more robust calibration system.

In conclusion, the HRC workflow developed in this thesis is merely in its infancy compared to the other HRC technology developed in the literature which was reviewed. However using the construction of a bridge structure as a case study in evaluating the applicability of HRC, the insights shed on the possible methods of collaboration aims to contribute towards the larger academic and industrial development of HRC in the building construction industry.

6.2 PERSONAL REFLECTION

How is your graduation topic positioned in the studio?

My graduation thesis titled “Sustainable Timber Bridge Design with Design-to-Build Workflow involving Human-Robot Collaboration” is positioned under 2 respective chairs of Design Informatics and Structural Design & Mechanics. It is conducted under the guidance of Serdar Asut (Chair of Design Informatics) and Joris Smits (Structural Design & Mechanics) from TU Delft as well as external advisors, Cyrus Clark (Lead Designer of public Space, Gemeente Amsterdam) and Laurane Néron (Timber Structural Engineer, Ney & Partners WOW).

Within the Chair of Design Informatics, the thesis project identifies the potential of advancing the construction technology of timber structures through human-robot collaborations (HRC), thereby bridging the gap of productive collaborations between robots and the timber builders.

Furthermore, this thesis explores the design and development of a novel bridge structure constructed in timber as a sustainable and circular bridge design connecting pedestrians and cyclists in Buiksloterham, Amsterdam. This involves tackling the urban and architectural context of the site as well as the structural design involved in developing a safe and durable timber bridge.

How did the research approach work out (and why or why not)? And did it lead to the results you aimed for? (SWOT of the method)

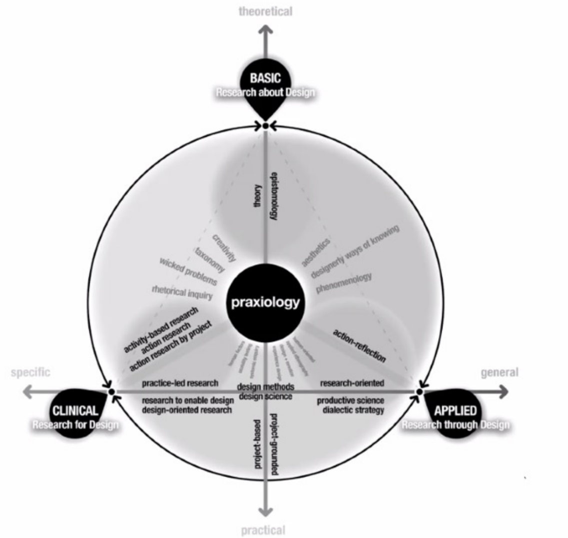


Fig 6.1: Map of Design Research (Frankel & Racine, 2010).

According to the Map of Design Research proposed by Lois Frankel and Martin Racine, the approach of my thesis project can be categorized under Research for Design or Research to Enable Design (Frankel & Racine, 2010). The thesis project lies largely on the left side of the map which relates strongly to a specific solution, rather than a general one, as well as more emphasis on the practicality as opposed to being theoretical. This is because a specific context, requirements and functionality has been prescribed and crafted in collaboration with my thesis mentors and the Municipality of Amsterdam. The thesis project also lies between the spectrum of theoretical and specificity because the integration of HRC into building construction is currently still a pioneering field which requires further groundwork.

Throughout the course of this thesis project, research into 3 main areas has been conducted to inform and craft a comprehensive design suitable for the site context while also having an academic contribution towards timber structures and HRC in the building and construction industry. The 3 main areas of research includes a study into the state-of-the-art of conventional and novel timber structures, an overview of reciprocal timber structures and joints as well as the state-of-the-art implementation of HRC in robotic construction processes.

How does the research lead to the design?

The research identified prevailing trends towards the design of long spanning timber structures with minimal material such as shell structures as well as the applicability of implementing HRC into the construction process. Together with the site analysis study, this informed the exploration of designing a structurally balanced and novel timber structure as a combination of the shell and tied-arch typology. The need to implement HRC and robotic construction influenced various factors of the design including the need for suitably sized timber members as well as easily accessible and assembled joints to meets the constraints of the construction system. This tectonic relationship whereby the construction technology becomes a crucial part of the design while dynamically influences it results in the design and construction proposal puts forth by this thesis project.

The research for design process has been largely fruitful as it provided a broad overview of the progression of current timber structure and HRC technology, establishing a consolidation of knowledge and understanding for my thesis project to build upon. It was instrumental in identifying the areas of contribution for my thesis project – particularly in novel timber structures typologies which exists between established structural typologies as well as the potential HRC systems to be further developed. Through the process, HRC applicability across multiple case studies has been studied and consolidated as key criteria to evaluate its applicability to this thesis project's design-to-build workflow.

However, the focus on addressing a specific design proposal meant that the research conducted has to be highly specific and applicable to this context and construction system. While the thesis project attempts to tackle significant challenges with the use of timber and HRC in the building and construction industry, the prescribed proposal addresses the conditions of a bespoke timber structure and might have limited transferability to other timber structure typologies.

Nevertheless, the thesis aims to provide a use case whereby the application of HRC to the design and construction process is explored and the insights drawn from this could guide further research and development of its integration.

Societal impact

To what extent are the results applicable in practice?

Firstly, from the materiality and fabrication perspective, the timber manufacturing industry is highly developed and capable of producing the timber products used for this thesis project, specifically glue-laminated timber (Glulam) with Accoya treatment. Thus from the material procurement aspect, it will not be a challenge.

Secondly, in terms of the design proposal with an unconventional method of "opening" the bridge, it requires further testing and evaluation to determine if it is easier and more economical than using a crane to lift the entire bridge. A potential challenge in the proposed method of removing the steel decks would be the high tension force exerted outwards by the shell on the deck. This might require a substantial amount of tensioning on the deck exerted from both sides of the opening towards the center before it can be removed with more ease. Further evaluation and development of this method will need to be conducted to determine its feasibility.

In addition, the complexity of the current shell structure which serves to provide lateral stability to the edge beams could be simplified much further to straight timber cross beams for ease of fabrication and assembly. However, this is at the expense of the design intention to create a unique and novel timber structure which celebrates the potential of digital design and fabrication in the digital era. Furthermore, within the scope of this Master thesis, it is more insightful and scientifically significant to explore and develop our understanding of the tectonics and structural capabilities of novel structural typologies instead of a purely economical and pragmatic solution. Thus as further research is developed in this aspect, its application to industry and practice in the future will become more possible.

Thirdly, in terms of the design-to-build workflow proposed, despite being a novel structural typology, it can be constructed and fabricated with existing machineries and robotic systems as outlined in Chapter 4Error! Reference source not found.. Although it was only possible to demonstrate and test a small segment of the construction in Chapter 5 Error! Reference source not found., the demonstrated workflow is one of the more challenging ones to implement. Hence while the challenges of calibration, multi-modal interaction and collaboration and a real-time feedback loop for an adaptive robotic system can be met, this thesis serves to identify the avenues for potential further research. As HRC technology is still emerging and being developed, the proposed HRC construction process will not be a widely available capability which the industry can simply adopt. Its integration into the building and construction industry has been primarily explored by research groups like Gramazio Kohler Research (GKR) in ETH Zurich and Institute of Computational Design (ICD) in University of Stuttgart. This demonstrates the need for further development of HRC technology before it could be implemented widely in practice.

In conclusion, from the design proposal to the bridge removable strategy and HRC design-to-build workflow, it was expected that there are multiple areas where gaps exist between the thesis project and practice. This is precisely how the research conducted serves to advance the design and constructional possibilities of the industry. Thus, based on the recommendations provided in *Section 6.1 Conclusions & Recommendations*, further branches of research can be pursued.

Does the project contribute to sustainable development? What is the impact of your project on sustainability (people, planet, profit/prosperity)?

Yes. With the use of timber, from sustainably managed forestry as regulated by FSC (Forest Stewardship Council) or PEFC (Programme for the Endorsement of Forest Certification), the project showcases and inspires the potential for timber to be a durable and elegant design for a bridge. Furthermore, with the key criteria of being circular, the design is constructed for the ease of disassembly and reuse into other cycles and applications. This will allow the timber used in the design to have further cascade of functions before it is incinerated for energy. During the multiple use cycles of the timber, the forests would have also gone through multiple growth cycles, hence further removing carbon dioxide from our atmosphere. Thus, it is evident how designing this structure in timber has many benefits. However, this is highly conditional, depending on the proximity to sustainable forestry and timber processing plants. So, it is inaccurate to declare timber as a panacea to all our problems in the built environment because it depends largely on the context and design conditions. Since the use of bio-based materials and circular concepts aligned strongly with Groenevisie 2020-2050 published by Gemeente Amsterdam (2020b), regarding the future sustainable development of Amsterdam and Netherlands. Therefore, this thesis would contribute directly towards this direction for the betterment of the built environment in Amsterdam.

Furthermore, with the involvement of Human-Robot Collaboration (HRC) within the construction process, the exploration of its potential within the rapid transformation of Industry 4.0 could broaden our potential of a more efficient and streamlined design-to-build process. This has significant impact on the construction technology currently employed to fabricate and construct the building components as HRC opens up the potential to complement the strengths of robots with the weaknesses of humans, and vice versa. Thus the contribution towards a more seamless construction process involving HRC could highly influence the energy efficiency of the construction industry.

Therefore, in summary, this thesis contributes on 2 front for sustainability in terms of renewable building materials with negative carbon footprint as well as a potential for more energy efficient construction system involving HRC.

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Chapter 7:

APPENDIX

7.1 CONVENTIONAL TIMBER STRUCTURES

Literature Review Approach

SRQ 2a: What are the conventional typologies of timber bridge structures?

Concepts**: combine with **AND

Synonyms and/or related terms: combine with OR

Concept 1: structural typology	*Concept 2: timber*	*Concept 3: bridge design*
Structure	Engineered timber	Infrastructure design
Structural systems	Sawn timber	Civil design
Structural engineering	Cross-laminated timber	Structural design of bridges
Structural design	Laminated Veneer Lumber	Bridge
Construction type	Timber	
types	Plywood	

Main Structural Typology	Structure Sub-Typology	Project	Material	Main Span (m)	Year	Location	Type	Architect / Engineer
Beams	Simply Supported & Cantilever	Japanese Pavilion'92	Glulam	10-15	1992	Spain	Roof	Tadao Ando, Ingeniera Obra Civil, Seville
	Column-Beam (3 point support - Dougong, timber bracket)	Yusuhara Wooden Bridge Museum	Glulam (Sugi-Red Cedar)	47 (23.5, 23.5)	2011	Japan	Pedestrian	Kengo Kuma & Associates, Katsuo Nakata & Associates
	Hinged Girder	Curved Girder Bridge Neckartenzlingen	Glulam (Accoya)	44.5	2017	Germany	Pedestrian & Cyclist	Ingenieurburo Miebach, Schafferer Holzbau
	Girder	Bow River Footbridge	Glulam	80	2013	Canada	Pedestrian & Cylist	Fast+Epp Structural Engineers
	Strut Frame	B533 Highway Crossing, Schwarzach/Hengersberg	Glulam	8.2, 11.50, 8.2	2011	Germany	Vehicles	Ingenieurburo Miebach
	V-Supports	Mistissini Bridge	Glulam + CLT	~40 x 4	2014	Canada	Vehicles	Stantec, Nordic Structures
		Aggerbridge			2010	Germany	Pedestrian & Cyclist	Miebach Ingenieurburo
Arch	Tied-Arch	Scout Bridge	Sawn Bridge	93				-
		Tynset Bridge						
		Wenerbruke Bridge						
Suspension	Suspended Structures	Momosuke Bridge	Sawn Timber + Steel Cables & Joints	104.5	1922 (1993)	Japan	Pedestrian	-
		Ponte di Morca	Sawn Timber + Steel Cables & Joints	93.6	1928	Italy	Pedestrian	-
Cable-Stay		Cable Stayed Bridge Engelskirchen	Block Laminated Glulam (Spruce)	35.5	2020	Germany	Pedestrian & Cyclist	Ingenieurburo Miebach
		Water of Leith Bridge	Glulam Beams + Steel Cross Beams	45	2018	New Zealand	Pedestrian & Cyclist	DC Structures Studio
	Tensioned Rod System	Cable Stayed Bridge Aggerbogen	Glulam (Spruce)	40	2013	Germany	Pedestrian & Cyclist	Ingenieurburo Miebach, Schaffitzel Holzindustrie
		Älvsbacka Bridge	Glulam (Untreated Spruce) & Steel Cables + Connections	130	2011	Sweden	Pedestrian & Cyclist	Martinsons Träbroar, Cowi
		Dunajec River Bridge	Glulam	90	2006	Poland	Pedestrian & Cyclist	Mosty Wroclaw Test & Design Office, Schmees & Lühn Holz- und Stahlingenieurbau GmbH
Truss	Through Truss	Placer River Trail Bridge (longest clear span glulam timber bridge)	Glulam	85.4	2013	US	Pedestrian	Paul Gilham, Western Wood Structures / R&M Engineering
	Through Truss	Sneek Bridge	Accoya Glulam	32 W: 14	2008	Netherlands	Vehicular	Achterbosch Architectuur, Onix bv, Titan Wood
		Vilhantasalmi Bridge			1999	Finland	Vehicular	
	Through Truss	Remseck Neckar River Footbridge	Glulam	80	1988	Germany	Pedestrian & Cyclist	-

7.2 NOVEL TIMBER STRUCTURES INVOLVING ROBOTICS

Literature Review Approach

SRQ 2b: What are the novel timber structures involving robotics which has been explored?

Concepts**: combine with **AND

Synonyms and/or related terms:** combine with **OR

Concept 1: *Novel timber structure*	*Concept 2:* *robotics*
Wood structur*	Robot* fabrication
Engineered timber structure	Robot* assembly
Timber assembly	Digital design and fabrication
Timber fabrication	Digital design
Wood construction*	Digital fabrication
Timber construction*	CNC
Novel W/15 timber structures OR (GS): Novel AROUND(15) timber structur*	

Main Structural Theme	*Structure Typologies*	*Project*	*Material*	*Main Span (m)*	*Year*	*Location*	*Robotic Processes Involved*	*Type*	*Architect / Engineer*
Shell-Bending Active	Bending-Active – Double layer	Bending Bridges	Plywood	12	2018	Santa Catarina, Mexico	CNC	Pedestrian Bridge	Centro de Estudios Superiores de Diseno de Monterrey, CEDIM / Kenryo Takahashi
	Reciprocal Frames (RF) with Bending Active – Double Layer	ReciPlyDome	45 identical 12mm Birch Plywood, 2.2m length	5 (dia)	2017	KADK, Denmark	Nil	Dome Pavilion	KADK - Olga Popovic Larsen (Professor in the Institute of Architecture and Technology), Niels De Temmerman, Lars De Laet and Stijn Brancart (VUB - Belgium), Mikkel A. Andersen, Niklas Munk-Andersen and Christian Jespersen (DTU)
	Bending Active – Plate structures with weave	ICD/ITKE Research Pavilion 2015-16	Plywood	9.3	2016	Stuttgart, Germany	Industrial Sewing with separate robotic arm	Pavilion	ICD/ITKE University of Stuttgart
	Bending Active Double Layer	Bend9 2016	3.5mm Plywood	5.2	2016	San Francisco, US	CNC Milling	Pavilion	ITKE University of Stuttgart, UC Berkeley
Shell – Plate	Plate with finger joints & nails	Skilled-In Office	Plywood	8	2017	Rotterdam, Netherlands	CNC Milling with ABB Robot Arm	Pavilion	Studio RAP
	Folded Plate Structure	Vidy Theatre	CLT Plates	20	2016	Lausanne, Switzerland	CNC Milling	Building Roof & Support	IBOIS EPFL, Yves Weinand, Herman Blummer
	Polygonal Plates with Finger Joints	BUGA Pavilion	Plywood	30 (38kg/m2)	2019	Stuttgart, Germany	Robotic milling, assembly, gluing, drilling	Pavilion	ICD, ITKE University of Stuttgart – Achim Menges et. Al
	Polygonal Plates with Finger Joints	Landesgartenschau Exhibition Hall	Plywood	10	2014	Germany	Robotic Milling	Building Roof Support	ICD, ITKE University of Stuttgart – Achim Menges et. Al
Shell – Grid	Grid Shell	Venue B (2018 World AI Conference)	Glulam/CLT Beams with Steel Columns & Components	40	2018	Shanghai, China		Roof Structure	Archi-Union Architects (Philip Yuan)
	Grid Shell	Swatch HQ	CLT	35	2019	Biel, Switzerland	CNC Milling	Roof Structure	Shigeru Ban, Creation Holz (Herman Blumer)
	Timber Lattice	Metropol Parasol	Kerto (micro-laminated veneer, 3mm) + steel connections + polyurethane coating	40-50	2005 - 2011	Spain	CNC Milling	Pedestrian	Jürgen Mayer H, ARUP
	Timber Lattice Grid Shell	Centre Pompidou-Metz	Glulam (95% Austrian & Swiss Spruce, 5% beech & larch) + 8,000sqm Fibreglass, Teflon Membrane (PTFE, Polytetrafluoro-ethylene)	40	2010	France	CNC Milling, design modelled with proprietary form-finding software (Shigeru ban)	Roof Structure	Shigeru Ban Architects, Jean de Gastines,
	Timber RF Hexagonal Lattice	Future Tree Pavillion @ Basler & Hoffman	Accoya timber members	3-8.5	2020	Esslingen, Switzerland			Gramazio Kohler Research, ERNE AG Holzbau
Truss	Reciprocal Frames	Complex Timber Structures (Novel non-standard timber structures)	Softwood Bar elements (slat)	Undefined	2018	Zurich, Switzerland	Sawing, Incision, Robotic Arm Assembly	Prototype	Gramazio Kohler Research, ETH Zurich – Anna Aleksandra Apolinarska
	Lap Joints	Joyn Pavilion	Spruce Slats/laths & wood dowels	-	2018	Berlin, Germany	CNC Fabrication (Joyn Machine with 3 axis milling machine with rolling conveyor)	Pavilion	Patrick Bedarf, Studio milz
	Space Frame with Glued Joints	House 4178, ETH Zurich Digital Fabrication Pavilion	Spruce Timber slats bet. 400-1500mm	~5	2015-16	ETH Zurich, Switzerland	Robotic Sawing, Assembly (Gripper, drilling)	2-storey Building	Gramazio Kohler Research, ETH Zurich
	Reciprocal frames & Zollinger System	The Sequential Roof	48, 624 Small scale, low-engineered Softwood elements	14.7	2010-16	ETH Zurich, Switzerland	Robotic sawing, Assembly – positioning, Nailing	Roof Structure	Gramazio Kohler Research, ETH Zurich
Beam	Removable Bolted Joints	Reversible Robotic Timber Beam	Timber slats with 696 custom components, 1464 reversible bolted connections	4	2021	Denmark	Human-Robot assembly, CNC Mill, robot: Pick&Place and screwing	Prototype beam	CREATE Group, SDU Robotics, University Of Southern Denmark
	Self-correcting Joints	Reversible Timber Structures	Structural Timber (Eastern white pine wood)	4	2021	Denmark	CNC Milling of joints	Prototype for material test of shear keys	CREATE Group, University Of Southern Denmark, COWI
	Continous Beam	Drift Bridge	Stack-laminated timber planks (Spanish Cedar), 1-inch layer	19.15	2021	US	Digital Design, CNC	Bridge	Volkan Alganoku, CMID Engineers, AKT II
	Box Beam, cantilever	The Smile, London Design Festival 2018	CLT	-	2018	London, UK	Dfab Joints	Pavilion	Alison Brooks Architects, Arup, American Hardwood Export Council
	Stepped Beam	Peitian Village Stepped Timber bridge	Sawn Timber slats		2016	China	Digital Design	Bridge	Donn Holohan, University of Hong Kong
	Box Beam	Curved Box Beam	Thin Wooden Plate (Plywood/LVL)	Undefined	2010	Switzerland	Digital Fabrication, CNC	Research	Hani Buri, EPFL
Weave	Bending Active	ICD/ITKE Research Pavillion 2010	6.5mm Birch Playwood	10-15 (~12.5)	2010	Germany	Digital Design & Fabrication, FEM simulation of bending action, Robotic milling of individual plates	Pavillion	Achim Menges, ICD, University of Stuttgart, Jan Knippers, ITKE
	Natural Sawn Timber	Wood Chip Barn	Beech wood (forks)	25x20x8	2016	UK	3D Scan, Optimised force structure, Robotic Milling	Pavilion/ Shelter	AA
Curved Plate	Curved Plate Structure	Urbach Tower	90mm CLT	14m height	2019	Urbach, UK	Autonomous bending of dried CLT panels, CNC Machined, Design simulated digitally of timber drying behaviour	Tower	Achim Menges, ICD, University of Stuttgart

7.3 HRC WORKFLOW

Literature Review Approach

SRQ 3a: What are the factors influencing the implementation of Human-Robot Interaction/ Collaboration onsite and offsite building construction?

Concepts:** combine with **AND

Synonyms and/or related terms:** combine with **OR

Concept 1: *Human-Robot Collaboration / Interaction*	*Concept 2:* *Onsite & off-site building construction*	*Concept 3:* *factors*	*Concept 4:* *implementation*
Human-robot interaction*	On-site W/15 construction Or On-site AROUND(15) construction	Input	Implement*
Human-Robot collaboration*	off-site W/15 construction Or off-site AROUND(15) construction	Criteria	Application*
	In-situ W/15 construction Or In-situ AROUND(15) construction	Setup	
	Building construction	Condition*	
	Construction	Requirement*	
		Factors	

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Chapter 8:
BIBLIOGRAPHY

Aish, F., Joyce, S., Malek, S., & Williams, C. J. K. (2015). The use of a particle method for the modelling of isotropic membrane stress for the form finding of shell structures. CAD Computer Aided Design, 61(October 2018), 24–31. https://doi.org/10.1016/j.cad.2014.01.014

allchartsinfo. (2021). Buiksloterham Population Data. https://allcharts.info/the-netherlands/neighbourhood-buiksloterham-amsterdam/#map

Andraos, S. (2015). DMR: A Semantic Robotic Control Language. Ecaade 2015: Real Time - Extending the Reach of Computation, Vol 2, 2(l), 261–268.

ARUP. (2019). Rethinking Timber Buildings. 100.

Bachmann, E. (2009). Optimierungspotenzial Vorfertigung. Conference Top Programm Holz.

BCA. (2018). Design for Manufacturing and Assembly (DfMA) | Mass Engineered Timber.

Bell, K. (2008). Timber Bridges. In Handbook 1 - Timber Structures, Educational Materials for Designing and Testing of timber Structures - TEMTIS (pp. 209–227).

Braumann, J., & Brell-cokcan, S. (2015). Adaptive Robot Control - New Parametric Workflows Directly from Design to KUKA Robots. Proceedings of the 33rd ECAADe Conference, 2, 243–250. http://papers.cumincad.org/cgi-bin/works/Show?_id=ecaade2015_100&sort=DEFAULT&search=robot&hits=109

Brugnaro, G., Figliola, A., & Dubor, A. (2019). Negotiated materialization: Design approaches integrating wood heterogeneity through advanced robotic fabrication. Lecture Notes in Civil Engineering, 24, 135–158. https://doi.org/10.1007/978-3-030-03676-8_4

Buri, H., & Weinand, Y. (2013). The tectonics of timber architecture in the digital age. Building with Timber - Paths to the Future, 56–62.

Cristescu, C., Honfi, D., Sandberg, K., Sandin, Y., Shotton, E., Walsh, S. J., Cramer, M., Ridley-, D., Arana-fernández, M. De, Llana, D. F., Barbero, M. G., Nasiri, B., & Krofl, Ž. (2020). Design for deconstruction and reuse of timber structures – state of the art review. In ForestValue - InFutUReWood. https://doi.org/10.23699/bh1w-zn97

Crowther, P. (2005). Design for Diassembly - Themes and Principles.

Dubor, A., Camprodom, G., Diaz, G. B., Reinhardt, D., Saunders, R., Dunn, K., Niemel, M., Horlyck, S., Alarcon-licona, S., Connor, D. W., & Watt, R. (2016). Sensors and Workflow Evolutions: Developing a Framework for Instant Robotic Toolpath Revision. Robotic Fabrication in Architecture, Art and Design 2016, 411–426. https://doi.org/10.1007/978-3-319-26378-6

Ellen MacArthur Foundation. (2019). Circular Economy.

Frankel, L., & Racine, M. (2010). The Complex Field of Research: for Design, through Design, and about Design. International Conference of the Design Research Society, 1–12. http://www.designresearchsociety.org/docs-procs/DRS2010/PDF/043.pdf

Galin, R., & Mamchenko, M. (2021). Human-Robot Collaboration in the Society of the Future: A Survey on the Challenges and the Barriers. Communications in Computer and Information Science, 1395 CCIS, 111–122. https://doi.org/10.1007/978-981-16-1480-4_10

Gemeente Amsterdam. (2020a). Bruggen Buiksloterham, Programma van Eisen - Algemeen.

Gemeente Amsterdam. (2020b). Groenvisie.

Gemeente Amsterdam. (2020c). Investment Memorandum Buiksloterham (Issue November).

Gemeente Amsterdam. (2021a). Bruggen Buiksloterham 1.

Gemeente Amsterdam. (2021b). Selectieleidraad Inhoud.

Gemeente Amsterdam. (2022). Housing Plans (1-1-2022). https://maps.amsterdam.nl/woningbouwplannen/?LANG=en

Granta Design Limited. (2009). CES Edupack software.

Guy, B., Ciamrimboli, N., & Hamer Center for Community Design. (2008). DfD : Design for Disassembly in the built environment : a guide to closed-loop design and building. University Park, Penn,.
Helm, V., Knauss, M., Kohlhammer, T., Gramazio, F., & Kohler, M. (2017). Additive robotic fabrication of complex timber structures. In Advancing Wood Architecture: A Computational Approach (pp. 29–43).
Hensel, D. S. (2015). Developmental route to functional and adaptive integration. International Journal of Design Sciences and Technology, 21(2), 153–178.
Herzog, T., Natterer, J., Schweitzer, R., Volz, M., & Winter, W. (2008). Timber Construction Manual Edition Detail Munich. Birkhäuser.
Hradil, P., Talja, A., Wahlstr, M., Huuhka, S., Lahdensivu, J., & Pikkuvirta, J. (2014). Re-use of structural elements Environmentally efficient recovery of building components (Issue December). https://doi.org/10.13140/2.1.1771.9363
ipv Delft. (2015). Brief Dutch Design Manual for Bicycle and Pedestrian Bridges.
Kaufmann, H., Krötsch, S., & Winter, S. (2018). Manual of Multi-Storey Timber Construction.
Knapp, R. G., Miller, T. E., & Liu, J. (2020). China's corridor bridges: heritage buildings over water. Built Heritage, 4(1). https://doi.org/10.1186/s43238-020-00010-w
Larsen, olga P. (2008). Reciprocal Frame Architecture.
Lugt, P. van der, & Harsta, A. (2020). Tomorrow's Timber. MaterialDistrict.
Menges, A., Schwinn, T., & Krieg, O. D. (2016). Advancing wood architecture: A computational approach. In V. Helm, M. Knauss, T. Kohlhammer, F. Gramazio, & M. Kohler (Eds.), Advancing Wood Architecture: A Computational Approach (pp. 1–232). https://doi.org/10.4324/9781315678825
Metabolic Lab. (2014). De Ceuvel Sustainability Energy Flows. https://deceuvel.nl/en/about/sustainable-technology/
Metabolic, Studioninedots, & DELVA Landscape Architects. (2014). Circulair Buiksloterham, Transitioning Amsterdam to a Circular City.
Moffatt, S., & Russell, P. (2001). Assessing Buildings for Adaptability: Annex 31, Energy-Related Environmental Impact of Buildings. November, 1–13. http://www.iea-ebc.org/Data/publications/EBC_Annex_31_Assessing_Building.pdf
Partov, D., Maślak, M., Ivanov, R., Petkov, M., Sergeev, D., & Dimitrova, A. (2016). The development of wooden bridges through the ages: A review of selected examples of heritage objects, Part I – The milestones. Technical Transactions, 2-B, 93–106. https://doi.org/10.4467/2353737XCT.16.161.5772
Popovic Larsen, O. (2014). Reciprocal Frame (RF) Structures: Real and Exploratory. Nexus Network Journal, 16(1), 119–134. https://doi.org/10.1007/s00004-014-0181-0
Ramage, M. H., Burridge, H., Busse-Wicher, M., Fereday, G., Reynolds, T., Shah, D. U., Wu, G., Yu, L., Fleming, P., Densley-Tingley, D., Allwood, J., Dupree, P., Linden, P. F., & Scherman, O. (2017). The wood from the trees: The use of timber in construction. Renewable and Sustainable Energy Reviews, 68(September 2016), 333–359. https://doi.org/10.1016/j.rser.2016.09.107
Reinhardt, D., Haeusler, M. H., London, K., Loke, L., Feng, Y., De Oliveira Barata, E., Firth, C., Dunn, K., Khean, N., Fabbri, A., Wozniak-O'Connor, D., & Masuda, R. (2020). CoBuilt 4.0: Investigating the potential of collaborative robotics for subject matter experts. International Journal of Architectural Computing, 18(4), 353–370. https://doi.org/10.1177/1478077120948742
Rossi, G., & Nicholas, P. (2020). Haptic Learning Towards Neural-Network-based adaptive Cobot Path-Planning for unstructured spaces. September, 201–210. https://doi.org/10.5151/proceedings-ecaadesigradi2019_280
Rückert, P., Adam, J., Papenberg, B., Paulus, H., & Tracht, K. (2018). Calibration of a modular assembly system for personalized and adaptive human robot collaboration. Procedia CIRP, 76, 199–204. https://doi.org/10.1016/j.procir.2018.01.041
Schwartz, M. (2016). Use of a low-cost humanoid for tiling as a study in on-site fabrication: techniques and methods. ACADIA 2016.
Schweitzer, R. (2004). Wood as a building material - from beginnings to the 19th century. In Timber construction Manual (pp. 24–29). Birkhauser.
Swedish Standards Institute (SIS). (2017). SS-EN 14298:2017.
Swedish Wood. (2016). Design of Timber Structures Volume 1. In IABSE reports, Rapports AIPC, IVBH Berichte (Vol. 1). www.swedishwood.com
University of Stuttgart, I. for L. S. (1978). Announcements from the Institute for Lightweight Structures (IL) - No.: 13. Multihalle Mannheim.
Volz, M. (2008). Protecting Wood. In Timber construction Manual (pp. 60–63).
Wibranek, B., Belousov, B., Sadybakasov, A., Peters, J., & Tessmann, O. (2019). Interactive Structure Robotic Repositioning of Vertical Elements in Man-Machine Collaborative Assembly through Vision-Based Tactile Sensing. Proceedings of the International Conference on Education and Research in Computer Aided Architectural Design in Europe, 2(July 2020), 705–713. https://doi.org/10.5151/proceedings-ecaadesigradi2019_387
Wiegand, T. (2008). Grading and improvement of solid timber products. In Timber Construction Manual (pp. 55–59).
Willmann, J., Gramazio, F., & Kohler, M. (2019). New paradigms of the automatic. In Advancing Wood Architecture (pp. 13–28). https://doi.org/10.4324/9781315678825-2

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