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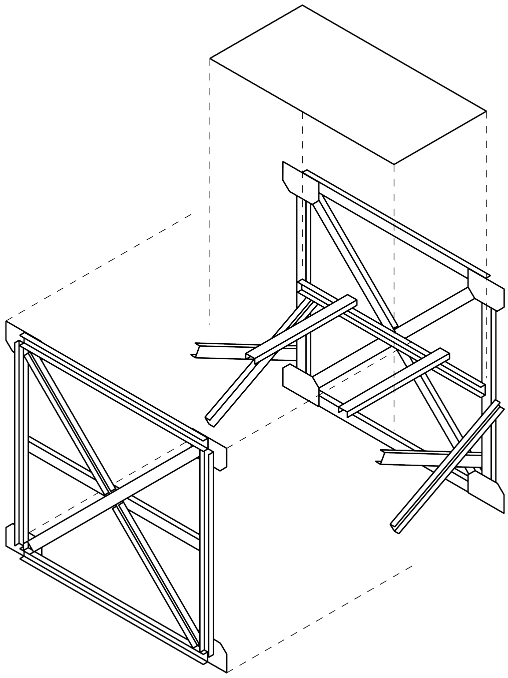

Conceptual design of bridges suitable for rurally isolated areas

Development of a conceptual design process for bridges in rural Rwanda

Master's Thesis in Structural Engineering and Building Technology

LISA RYRSTEDT

PETER STANEK SÖRNER

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
DIVISION OF STRUCTURAL ENGINEERING
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Master's thesis ACEX30
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Department of Architecture and Civil Engineering
Division of Structural Engineering
Division of Architectural Theory and Methods
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone +46 31 772 1000

Cover:

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ABSTRACT

The bridges being built in Europe today are often designed with a focus on either aesthetical qualities or on technical innovation. This leads to complex structures requiring access to high performance materials and specialised knowledge, which is only available in certain parts of the world. But bridges are needed all over the world, not least in rural areas where the resources are limited. In Rwanda, one example of a third world country with large rurally isolated areas, one bridge can provide access to vital resources such as education and healthcare for a whole community. But the available knowledge regarding how to design bridges for rural areas is limited. Therefore, information about the context of rural Rwanda is gathered as basis for developing an alternative design process adapted to the critical design challenges of rural areas. Historical bridges and structures from other disciplines are also explored as references for this conceptual design process. Since the technical knowledge of the people building the bridge will vary drastically, a plan for how to communicate the design to different target groups is also made. This design process results in a bridge concept consisting of a modular steel truss. The details are designed to enable assemblage by hand, and all elements chosen such that they are possible to transport without the use of vehicles or machines for up to 2 kilometres. The final concept is a bridge suitable for a variety of sites and spans, but might not be the optimal solution for each individual site.

Key words: Conceptual design, Rural isolation, Bridge design, Steel truss bridge

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Examensarbete inom masterprogrammet Konstruktionsteknik och Byggnadsteknologi

LISA RYRSTEDT

PETER STANEK SÖRNER

Institutionen för arkitektur och samhällsbyggnadsteknik
Avdelningen för Konstruktionsteknik
Avdelningen för Arkitekturens teori och metod
Chalmers tekniska högskola

SAMMANFATTNING

Broar som byggs i Europa idag designas ofta med ett fokus på antigen estetiska kvalitéer eller teknisk innovation. Detta leder till komplexa strukturer som kräver tillgång till högpresterande byggnadsmaterial och specialistkunskap, vilket bara finns i vissa delar av världen. Broar behövs emellertid överallt, inte minst i landsbygdsmiljöer där tillgången till både material och kunskap kan vara begränsad. I Rwanda, ett exempel på ett land med stora isolerade områden på landsbygden, kan en enda bro ge hela samhällen tillgång till livsviktiga samhällsresurser som utbildning och sjukvård. Men kunskapen kring hur broar bör designas för landsbygdsmiljöer är begränsad. Därför har information kring förutsättningarna för att bygga broar på Rwandas landsbygd samlats ihop för att utveckla en alternativ designprocess anpassad efter designutmaningarna som finns i dessa miljöer. Historiska broar och konstruktionskoncept från andra discipliner har också undersökts för att kunna användas som referenser i denna konceptuella designprocess. En plan för hur konceptet kan kommuniceras till olika grupper som ska arbeta med bron har också upprättats. Denna designprocess resulterade i ett designförslag bestående av en modulär fackverksbro i stål. Detaljer har designats så att hela bron ska vara möjlig att bygga för hand, och alla element i konstruktionen är valda så att de ska vara möjliga att transportera upp till 2 kilometer till fots. Denna brodesign kan användas för flera olika spann och på platser med olika markförhållanden, men är inte nödvändigtvis den optimala lösningen för någon enskild plats.

Nyckelord: Konceptuell design, Isolerade områden på landsbygden, Brodesign, Fackverksbro, Stålbro

Contents

Acknowledgement

In this thesis the challenge of designing a bridge that is suitable to build in rurally isolated areas of Rwanda is taken on. The context and background is explored through literature as well as meetings with people working at Bridges to Prosperity. A massive thank you to Kyle Shirley who has been our main contact at B2P, and who has provided us with answers to all our questions along the way. We also want to thank Simon Niyitegeka and Etienne Mutebutsi for giving us additional support in figuring out what is possible in rural Rwanda. Additionally, we highly appreciate the scholarship from Chalmers Mastercard program that made an inspiration trip possible. The design process and calculations are conducted with information that we have gathered over the past four and a half years of studies, as well as from meetings with Viktor Eriksson, Industrial Doctoral Student at Chalmers, and Christoffer Svedholm, ELU. We also want to say a special thank you to our examiner and supervisor, Mats Ander and Rasmus Rempling. This project would not have been possible without our continuos discussions, and your around the clock feedback! Finally a huge thank you to our opponents and colleagues for all their feedback and support; Annie Skeppstedt, Linn Vernersson and Vendela Örndal.

Gothenburg, June 2025
Lisa Ryrstedt
Peter Stanek Sörner

Nomenclature

B2P	Bridges to Prosperity
CALFEM	A computer program for solving static and dynamic problems (Computer Aided Learning of the Finite Element Method)
MATLAB	A programming and numeric computing platform used to analyse data and create models. Developed by MathWorks
SLS	Service Limit State
ULS	Ultimate Limit State

A_{chord}	Cross sectional area of chords	$[m^2]$
F	Combined load	$[N]$
G	Permanent loads	$[N]$
G_k	Dead load	$[N]$
L	Length of span	$[m]$
P_{live}	Point live load	$[N]$
Q	Variable loads	$[N]$
V	Volume	$[m^3]$
d_{bolt}	Diameter of bolts	$[m]$
$e_{1,diagonal}$	Distance from centre of hole to end in diagonals, in load direction	$[m]$
$e_{1,horizontal}$	Distance from centre of hole to end in horizontal elements, in load direction	$[m]$
$e_{1,vertical}$	Distance from centre of hole to end in vertical elements, in load direction	$[m]$
$e_{2,diagonal}$	Distance from centre of hole to edge in diagonals, perpendicular to load	$[m]$
$e_{2,horizontal}$	Distance from centre of hole to edge in horizontal elements, perpendicular to load	$[m]$
$e_{2,vertical}$	Distance from centre of hole to edge in vertical elements, perpendicular to load	$[m]$
f_u	Ultimate tensile strength	$[Pa]$
f_{ub}	Ultimate tensile strength of bolts	$[Pa]$
f_y	Yield strength	$[Pa]$
f_{yb}	Yield strength of bolts	$[Pa]$
g	Gravity of Earth	$[\frac{m}{s^2}]$
l_{chord}	Length of chords	$[m]$
l_{diag}	Length of diagonals	$[m]$
$p_{1,diagonal}$	Space between centre of bolt holes in diagonals, in load direction	$[m]$
$p_{1,horizontal}$	Space between centre of bolt holes in horizontal elements, in load direction	$[m]$
$p_{1,vertical}$	Space between centre of bolt holes in vertical elements, in load direction	$[m]$
$p_{2,horizontal}$	Space between bolt holes in horizontal elements, perpendicular to load	$[m]$

q_{dist}	Distributed live load	$[\frac{N}{m^2}]$
t_{plate}	Thickness of connection plate	$[m]$

δ	Deflection	$[m]$
γ_G	Partial safety factor, permanent loads	[-]
γ_Q	Partial safety factor, variable loads	[-]
ρ	Density	$[\frac{kg}{m^3}]$
σ_{Ed}	Applied design stress	$[Pa]$
σ_{Rd}	Design stress resistance	$[Pa]$

1 Introduction

All over the world there are rural communities isolated from vital resources such as healthcare, education and employment opportunities due to dangerous river crossings. By building footbridges over these rivers and giving access to those vital resources, Bridges to Prosperity, n.d.-b states, that the quality of life of the local communities improves significantly. Many footbridges built today in industrialised parts of the world are structures that focuses on either aesthetical qualities or on pushing the limits regarding how bridges are built (Keil, 2013), and demand both technical knowledge and resources not available in rural areas. To counteract the isolation of rural communities, bridge concepts developed specifically for the demands and limitations of rural areas are needed.

1.1 Background

The modern construction industry is characterised by innovation and the usage of advanced production techniques. Over the last years these characteristics have become more and more pronounced, and Krystle Donati (2025) anticipates that this development will continue. This progression is especially evident in industrialised parts of the world, and most of these new techniques are not suitable or even possible to apply where the access to resources as well as technical knowledge is limited. Rurally isolated areas, which are characterised by these limitations, are also more or less isolated from vital resources such as healthcare and education, and lack sufficient infrastructure. Figure 1.1 describes the difference in conditions on a site in a rurally isolated area in Rwanda and a common building site in Europe.

(a) A picture showing a construction site in Rwanda. (Bridges to Prosperity, 2023a). Reprinted with permission.

(b) A picture showing a construction site in France. (Encyclopædia Britannica, n.d.).

Figure 1.1: Photos showing the differences of construction sites in Rwanda and Europe.

Rwanda is a country which, according to USAID (2024), has large areas that lack sufficient infrastructure and thus contain many villages that experience rural isolation. A deep river or valley can be an obstacle that results in total isolation or long detours to get to vital resources. Since the access to education often is limited, and the materials or tools needed to cross the obstacle in question are missing, any growth of the village is hard to obtain. The lack of infrastructure which leads to rural isolation is observed and counteracted by several organisations, one of them being Bridges to Prosperity, B2P.

Bridges to Prosperity is a non-profit organisation that aims to minimise rural isolation by building pedestrian bridges, and thus improving the quality of life for people living in these rural areas. According to Bridges to Prosperity (n.d.-a), their work have a positive effect on gender equality, economic opportunities, healthcare and education. In Rwanda, where they have one of their bases, the need for footbridges is immense (Bridges To Prosperity, n.d.). By ensuring that locals can reach vital resources and facilities, the quality of life can be greatly improved. The context of rural Rwanda, characterised by hard terrain, limited technical knowledge and a lack of infrastructure, results in difficulties regarding using the techniques that often are used to build bridges in other parts of the world.

In most places that B2P installs bridges the spans are long and, with the given context, a suspension bridge is considered to be the most suitable bridge type. Now the organisation has identified the need for a bridge concept that is more suitable for shorter spans, approximately 15-30 meters, that can be built over deep rivers or ravines (A.1). The concept must be adaptable to different site conditions, and the transportation and assembly of the bridge needs to be possible without heavy machines such as large lorry's or cranes. A desire to have a modular bridge that can be adapted to suit different sites and spans has been expressed.

This thesis explores the development of a bridge concept suitable for rurally isolated areas, with the context, needs and requirements of B2P in mind. This means that the final concept will be suitable for B2P, but can be used in other rurally isolated areas, with a similar context as Rwanda, by other organisations as well.

1.2 Aim

The aim of this thesis is to find a method to develop bridge concepts for rurally isolated parts of the world, and to then apply this method to develop a concept for a footbridge that can be built in rural areas of Rwanda. Material to communicate the concept to relevant groups should then be produced, ensuring that everyone working on the bridge gets access to the information they need.

1.3 Research questions

The background and aim of this project is summarised into the four following research questions:

- ⋆ *What are the demands on bridges built in rurally isolated areas of Eastern Africa?*
- ⋆ *How can the design process for a footbridge in isolated rural areas be structured?*
- ⋆ *What is a suitable bridge concept for shorter spans crossing deep rivers and ravines in rural parts of Rwanda?*
- ⋆ *How can a bridge concept be communicated between the designers and workers and/or locals?*

1.4 Limitations

Since no site visit is made in Rwanda, all information regarding sites and available resources is second hand knowledge from literature and correspondence with Bridges to Prosperity. There is therefore a risk that information relevant for the design process has been missed. To ensure that the bridge concept is a viable option to build in rural Rwanda a more thorough investigation of the local context should be conducted.

No evaluation between the results of different design processes will be performed. The aim of exploring how the design process can be structured is to find a process that represents the design challenges in rural areas, not necessarily a more effective process.

The aim of this thesis is not to develop a complete bridge design, but a viable design concept. Further calculations and detailing is therefore needed before a bridge can be built.

1.5 Method

This project consists of three parts. In part one, information needed to develop a design concept is gathered and documented. This information enhances the understanding and knowledge of the problem. The second part handles the conceptual design process, starting from demands and requirements and resulting in a final bridge concept. In the third and final part, a suitable way to present the results of the design process is explored.

Part I: In this part, information required to increase the knowledge and understanding of the project is gathered. This information comes from B2P as well as from existing bridges and other disciplines. Historical bridges are built with less advanced technologies and materials than most modern bridges, and is therefore a relevant source of inspiration and knowledge. Other types of structures that are hand-built or made to be easily transported, for example structures developed for the aerospace industry or military which often are modular and easily assembled, are investigated. This information gathering is mainly performed through a literature study and personal contact.

Part II: When a sufficient amount of information is gathered and documented, and a better understanding of the context is achieved, the next part is entered. In this part the conceptual design process is performed and documented. First the relevant demands are stated and described shortly. These demands are ranked against each other and an order of priority is established. The ranking is then used to decide which demands should be used as filters in the filtration process, and which should be used as soft demands for the modification phase. Six preliminary concepts are presented and evaluated against the highest prioritised demands, the filters, in the filtration process. The concepts, or concept, that pass all filters then move on to the modification phase, where they will be modified to fulfil the less prioritised demands as good as possible. The result of the modification phase is a final bridge concept that in the last phase of part two is specified further and checked against relevant capacity requirements through calculations.

Part III: When the final bridge concept is decided on, material to communicate the concept to relevant stakeholders is produced. How the design is communicated is especially important in this project since the design must be comprehensible and feasible to build for someone that lacks any theoretical knowledge of structural engineering. Different ways of communication are investigated in this last part.

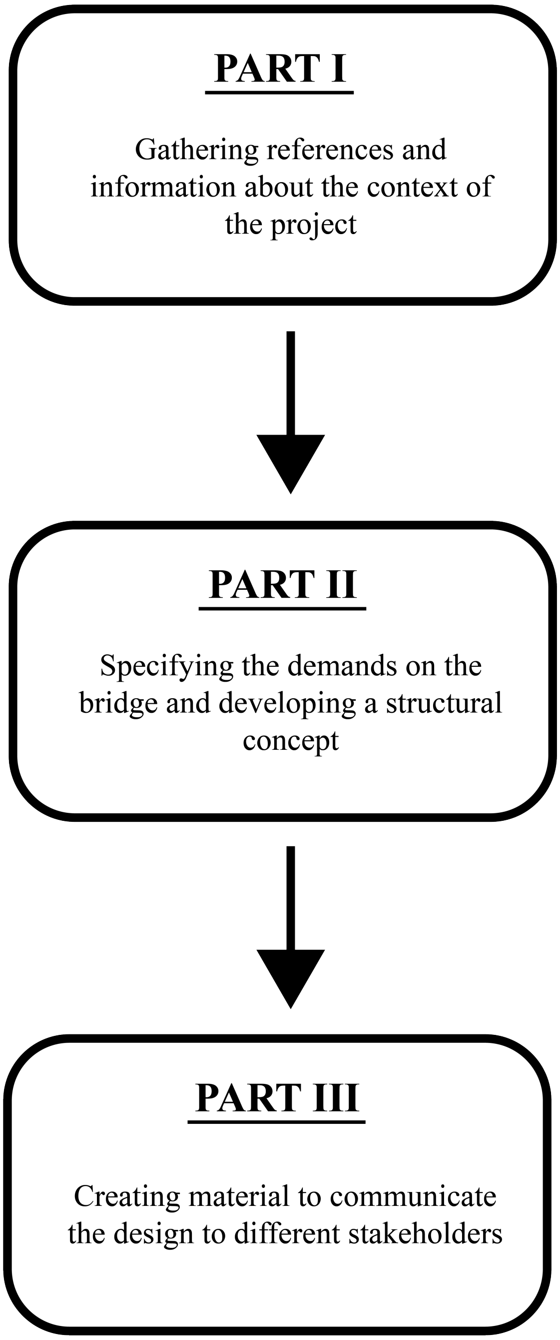


Figure 1.2: Flowchart of the method used in this thesis.

2 Part I: Literature study

This first part contains the information gathered to formulate the demands relevant for footbridges in rural parts of Rwanda. It also describes the different types of structures used as references for the design process, and how the structural integrity of the structure will be ensured.

2.1 Geography of Rwanda

Rwanda is a small country with an area of approximately 26 000 m^2, but has a high population density with most of its residents living outside of the capital Kigali (Utrikespolitiska institutet, 2023a). The country has a varied terrain with mountains, savannas and lakes, and have two rain periods every year (Utrikespolitiska institutet, 2023b). Smaller earthquakes (maximum magnitude of 5) are occurring occasionally. These geographic properties, and the weather phenomenons resulting in roads being washed away, are some of the contributing factors to the rural isolation of communities.

The western part of the country has a terrain that is mountainous and the potential bridge sites are characterised by steep hills. The ground conditions vary and can be sand, clay or solid rock. This information is provided by B2P and further information can be found in the meetings notes in Appendix A.1. A photo of the mountainous nature in Rwanda can be seen in Figure 2.1.

Figure 2.1: Photography of mountainous terrain in Rwanda. (Envision Rwanda, 2023). Reprinted with permission.

2.2 Rural context

The rural context is communicated from Bridges to Prosperity (n.d.-a) as well as through personal communication, which is noted in Appendix A.1.

The areas in need for a bridge design suitable for 15-30 meter spans are mainly located in the western part of Rwanda, which means that the surroundings are mountainous. The sites are located in areas with limited access to roads, with some sites being up to 2 kilometres from the closest road. This means that all building materials and tools must be possible to transport this distance without the help of any vehicles. In Figure 2.2, an example of a road in a rural area of Rwanda is shown.

Figure 2.2: Trail leading up to a bridge in Kayumbu, Rwanda. (Bridges to Prosperity, 2023b). Reprinted with permission.

In the building team on site there will be workers with varying backgrounds. Some might have knowledge of more advanced modern building techniques, but the biggest asset is most likely the experience from building bridges in similar contexts. Because of the high population density in Rwanda there will be many communities that benefit from a bridge being built, and therefore a lot of local residents that can help during the building process.

The main objective of the bridge is to connect isolated villages with vital resources such as water, education and healthcare. Therefore, the traffic crossing the bridge will be mainly pedestrians, and occasionally some cattle or smaller vehicles such as motorcycles.

2.3 Available materials

B2P works mostly with locally sourced material or with gifted materials, often reused or repurposed, to promote the economic sustainability. In Rwanda and the surrounding countries, building materials such as stone, steel and timber are available. Stones are collected from nearby rivers, and are currently used by B2P in their stone arch bridges designed for spans of up to 20 meters. B2P currently also builds suspension and stressed ribbon bridges, both mainly in steel, which often is reused. The cables in these bridges are normally gifted from other organisations. The decking used on the suspension bridges were, in the original design, made out of wood but due to the climate and the lack of maintenance these reached the end of their service life after only 5 years. Therefore, they are now replaced by steel plates. This experience rules out a timber construction.

This information is gathered through personal communication and a summary is found in Appendix A.1.

2.4 Footbridges

Footbridges are bridges designed primarily for pedestrians and, in some cases, emergency- or maintenance vehicles. Footbridges are naturally the oldest type of bridge, and different types have been developed all over the world depending on the local context and the available materials. For example, some of the oldest bridges found are, according to Baus et al. (2008), suspension bridges built by early civilisations in China, Mesopotamia and South America. In Europe, on the other hand, suspension bridges only started to be built many centuries later when tough steel had been developed (Keil, 2013). Instead, arch bridges have an over 2000 year long history here, and are still used today.

With the introduction of new means of transportations, beginning with trains and later cars, Baus et al. (2008) says the nature of bridge building was changed drastically. Cost-effectiveness became increasingly important, and the ethos of the structural engineers were greatly influenced by the demands put on structures by these new types of transportation. Simultaneously, the structural demands on footbridges remained the same, which means that the new materials and techniques developed for handling the heavier loads increased the freedom in designing footbridges (Baus et al., 2008). This has, according to Keil (2013), allowed footbridges to become an area with innovative structures where engineers can experiment and explore new concepts.

Most footbridges can be divided into six different types depending on the principle way that the structure carries the loads applied to the bridge. These are arch bridges, beam bridges, truss bridges, suspension bridges, stressed ribbon bridges and cable stay bridges. Elements from the different types can also be combined to create hybrid systems with new properties. Other types of footbridges also exist, but since they are not as common they will not be treated in this chapter.

2.4.1 Arch bridges

Arch bridges primarily carries loads in compression. This is made possible by the geometry of the load carrying structure. The shape needed to ensure that all parts are in compression will vary depending on the applied load. This means that a thorough understanding of how the geometry influences the structural behaviour is needed to both design and build this kind of structure. Arch bridges usually have a large self weight compared to the expected applied loads to minimise the influence of applied loads on the geometry needed for the structure to stay in equilibrium, ensuring that all parts of the structure remains in compression at all times.

The supports of an arch bridge must be able to transfer both vertical and horizontal force, which can make them large and heavy. In some cases it is possible to handle the horizontal forces by introducing a tension rod between the ends of the arch, which simplifies the design of the supports.

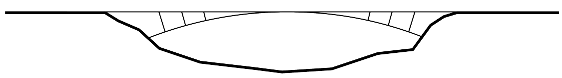


Figure 2.3: Illustration of an arch bridge.

2.4.2 Beam bridges

The load-carrying system in beam bridges consists mainly of beam elements carrying the loads applied in the span in bending to the supports. This allows for relatively simple supports since they normally do not need to transfer large horizontal forces to the ground (Allen, 2010). On the other hand, the cross sectional properties needed in the beam elements to span longer length can make them impractical and difficult to construct.

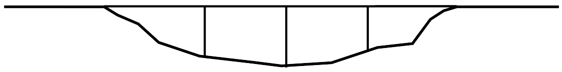


Figure 2.4: Illustration of a beam bridge.

2.4.3 Truss bridges

Truss bridges have a lot in common with beam bridges, especially regarding the demands on the supports. The main difference is that the load carrying structure consists of a truss, which has elements dedicated to carry the load in either tension or compression, instead of carrying the load in bending. This makes the structure easier to optimise compared to beam bridges with regards to the utilisation of the materials used, and it can therefore more easily be used for longer spans (Allen, 2010).

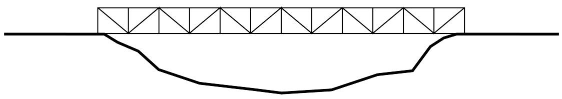


Figure 2.5: Illustration of a truss bridge.

2.4.4 Suspension bridges

In suspension bridges the bridge deck is hanging from elements in tension, normally steel cables, running along the length of the bridge. Usually, two primary cables run between pylons located at each end of the bridge. Secondary cables are then used to hang the bridge deck from the primary cables. This kind of structure makes it possible to span long distances, since the material strength of the cables can, in principle, be completely utilised. However, the supports needed to anchor tensile forces in the ground can be large and complex depending on the ground conditions.

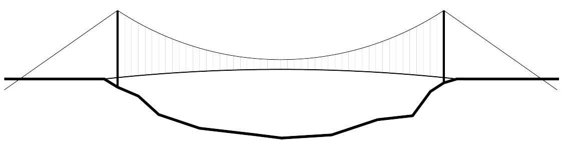


Figure 2.6: Illustration of a suspension bridge.

2.4.5 Stressed ribbon bridges

Stressed ribbon bridges have a lot in common with suspension bridges. Just as in suspension bridges, the loads applied to a stressed ribbon bridge are carried to the support through elements in tension running along the length of the bridge. The main difference is that in a stressed ribbon bridge the bridge deck is mounted on top of the tensile elements, instead of hanging from them.

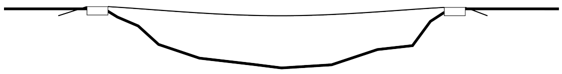


Figure 2.7: Illustration of a stressed ribbon bridge.

2.4.6 Cable stay bridges

In cable stay bridges the bridge deck is hanging directly from a pylon on angled elements in tension, usually steel cables. Keil (2013) says that cable stay bridges are much stiffer than suspension bridges because of the truss-like structure created by the cables were there are triangles of elements in either tension or compression. A consequence of the angled tension elements is that the bridge deck will always be in compression, and thus must be designed against buckling.

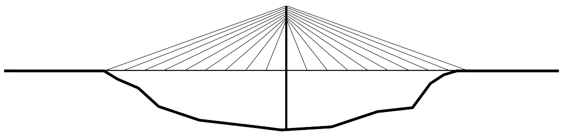


Figure 2.8: Illustration of a cable stay bridge.

2.4.7 Hybrid systems

The structural systems described in previous sections can be combined to create more complex systems where properties from one system can be used to counteract the weakness of another system. This can, according to Mostafavi and Conzett (2006), increase the load-carrying capacities of the structure, and make it possible to assemble it in several steps where one system is first put into place and then another system is added to stiffen the structure. It can also make maintenance easier by allowing some elements to be removed or changed without the need of any extra supporting structure.

The combination of different systems usually creates statically indeterminate structures, making the behaviour more complex to predict than for the original systems. Mostafavi and Conzett (2006) says that hybrid systems are therefore more common in structures designed before the middle of the nineteenth century when load-carrying systems were designed based on experience instead of calculations, allowing for more complex systems.

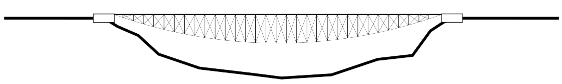


Figure 2.9: Illustration of a hybrid system.

2.5 Military structures

In the military all equipment must be robust, adaptable and transportable. This goes for rucksacks and shoes as well as vehicles or bridges and is what makes military structures a relevant source of inspiration for this project. According to Försvarsmuseum Boden (2014), one of the bridges used in Swedish military is the Bailey bridge, which is a steel truss consisting of modules that can be erected by hand.

The Bailey Bridge was designed by Sir Donald Coleman Bailey during world war II. The bridge is, according to Britannica (n.d.), designed to suit a large number of conditions, with various span lengths and support conditions, with the longest one built being 1,2 kilometres long with pontoon supports. The capacity of the bridge can be increased by adding layers of modules or panels that are connected using sprints and stabilized with a horizontal truss.

2.6 Aerospace engineering

Structures developed for use in outer space often need to be light weight, possible to transport in small spaces and easy to assemble when they have arrived at their destination. These are characteristics that would be beneficial for bridges in rural areas as well, since all parts need to be possible to transport long distances by foot and then assembled with only hand tools. But there are some key differences between the two fields which makes it difficult to use solutions developed for aerospace applications when developing bridges in rural areas.

Within aerospace engineering, solutions that demand advanced manufacturing techniques and high strength materials can be used since the organisations working in this field normally have a large budget for innovation and production of high quality components. When working with bridges in rural areas, the resources available for manufacturing and acquiring materials are much more limited. Because of this, most solutions developed for aerospace engineering are not viable to use in bridges when working within the context relevant for this thesis.

2.7 Reciprocal frame structures

Reciprocal frame structures are self supporting structures where beam elements supports each other, see Figure 2.10. This technique makes it possible to span lengths longer than the maximum length of the available elements. Historically, this has mainly been used in roof structures (Olga Popovic Larsen, 2008), but there are also examples of it being used in bridges.

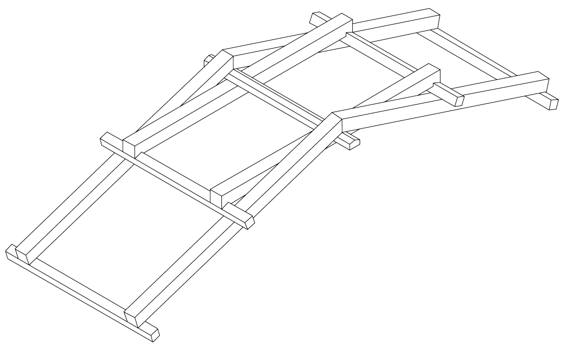


Figure 2.10: Illustration of a reciprocal frame bridge designed by Leonardo da Vinci.

2.8 Erection methods

When constructing a bridge, a crucial part is the erection. Different bridge types require different erection methods, and different sites can be more or less suitable for these methods.

There are several ways to erect a bridge, and in most cases the erection process subjects the structure to different support conditions and load cases than in the final state. Therefore, design calculation of the erection process is of as great importance as the design calculation of the final state of the bridge.

The erection methods listed in this chapter are some of the commonly used methods (Jean-Paul Lebet & Manfred A.Hirt, n.d.). In the context of rurally isolated areas with mountainous terrain, the limited space available for bridge landings and the inefficiency of temporary structures rules out some of these erection methods

2.8.1 Launching

When launching a bridge, either the whole bridge or parts of it are built on one side of the bridge span before it is pushed or pulled out into its final position. This requires space on at least one side of the bridge span to assemble the ingoing modules and to place a module behind the bridge, in line with its final position, before attaching it to the previous part.

2.8.2 Cantilever erection

Another erection method is the cantilever erection. This can be performed in a number of ways depending on the conditions on site, but all of these methods constructs the bridge from one side, or support, at a time. This means that the bridge deck, that will have supports on two sides when finished, will during construction work as a cantilever instead. In this situation the maximum moment will occur at the support and the bridge deck must thus be designed to resist different load cases during erection and usage.

This cantilever erection can also be performed using temporary cables, that lifts the end of the cantilever and therefore makes the load case during erection more similar to the one relevant during the service state.

2.8.3 Lifting into position

When constructing a bridge in tight spaces that are difficult to access, i.e. in the Alps, it might be suitable to assembly the bridge off site and use a helicopter or drones to lift the bridge into position. If it is possible to transport larger machines to the site, and there is sufficient space on at least one side of the bridge, this could also be done using cranes.

2.8.4 Temporary construction

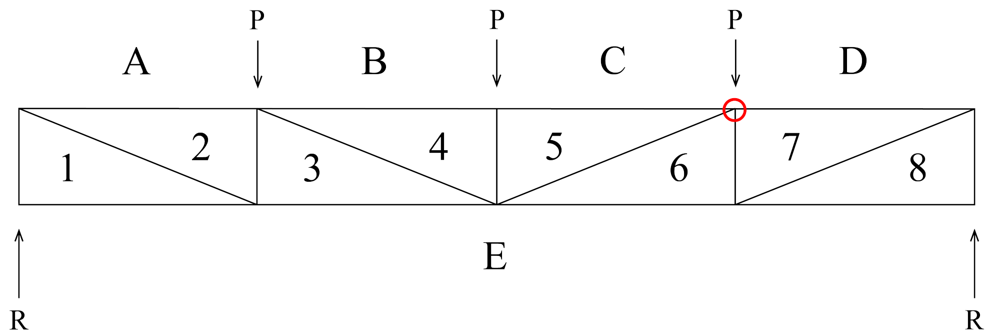
Some bridge types require temporary constructions to hold the structure in place before the construction process is finished. One example of this is the stone arch bridge that in its final state is held together by the compression forces from its self-weight, but before the arch has been completed, needs to be supported. Arches made out of other materials, for example steel, can be erected from two sides using cables, and released when they meet in the middle.

2.9 Graphic statics

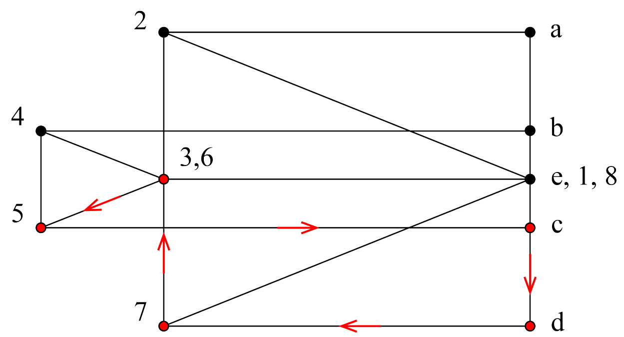
Graphical methods to describe the static equilibrium of structures, often referred to as graphic statics, can be used both as a tool for form finding and a way to calculate the internal forces in a structure. Graphic statics can, according to McRobie (2017), be traced back to the work of Varignon from the first half of the 18th century. Varignon observed that the equilibrium of a two-dimensional truss requires that the force vectors meeting in a node constructs a closed polygon, and that these polygons representing the forces in each node in the truss can be assembled into one figure describing how the forces flow through the full truss. Culmann, Maxwell, Cremona and many others then further developed the field of graphic statics during the 19th century (Kurrer, 2008). One of the results of this development is Cremona diagrams.

Cremona diagrams consists of two parts, the form diagram describing the geometry of the truss and the force diagram describing the size and sign of the forces in each element of the truss (McRobie, 2017). The size of the force in each element is described by the length of the line in the force diagram representing that element. The sign of the force is depending on the direction of the arrows in the force diagram (Kurrer, 2008). If the arrow points towards the node it represents a compressive force, and if it points away a tensile force.

In this thesis, Cremona diagrams have been used both as a tool for form finding and as a method to calculate the internal forces in structures where the load carrying elements are in pure tension or compression.



(a) Form diagram.



(b) Force diagram.

Figure 2.11: Example of Cremona diagram of a truss.

2.10 Validation of structural integrity

In Sweden the structural integrity of structures is checked using Eurocode and a national annex with additional regulations. In Rwanda no such regulations exist, but B2P is currently working on making their policies part of the governments regulations. With this as a starting point, the validation of the structure developed in this thesis will be checked using B2P's policies. But since these policies have been written focusing on B2P's existing bridges, which are mainly suspension bridges, additional checks might be needed. In these cases, relevant sections of Eurocode will be used as a complement to B2P's existing policies.

3 Part II: Conceptual design and detailing

In Part II the information gathered in Part I is used as a basis to develop bridge concepts suitable for the relevant context. The conceptual design process is documented, from compilation of demands to the final concept being presented. Finally the specification of details on the chosen concept are shown.

3.1 The process

The demands used in this project are different from the ones most often used in Sweden, and so is the way of selecting a suitable concept. A common method to compare concepts or solutions to each other among engineers is by using Kesselring or Pugh matrices. In these matrices the demands are weighted against each other depending on their importance, and then the concepts are rated by how well they fulfil the different demands. This rating system might not be the most efficient way to select a concept when the context is as demanding as it is in rurally isolated areas. Instead the viability of the concepts will be evaluated by using the demands as a series of filters. This process also makes it possible to further develop the concepts by looking at which filters they do not pass through as well as comparing them to the criteria, and adjust them accordingly.

The starting point of this process is to present six different concepts. At this stage, the concepts are not finished concepts but more of rough sketches that are one step on the way towards a final proposal. Here the only details that is decided on is the different load carrying systems, which then are refined into a suitable concept.

The demands are weighted against each other and the most important demands are made into filters. These filters are used to find which concepts fulfil most of the most important demands. The concepts that pass the most filters will then be further developed and specified to pass the filters they did not pass the first time. A second filtration is then performed to make sure that the concepts pass all filters after being developed. The concepts that pass all filter in the second filtration round move on to the modification and specification phase.

In the modification phase, the concepts that passed the filtration process are further specified and modified to fulfil the remaining demands. All concepts that passed the filtration process are evaluated against the demands and given a score based on how well they fulfil the demands. The concept with the highest score will be assumed to be the most suitable, and move on to the final phase.

In the final phase, material properties are specified and the structural integrity of the bridge is checked through calculations according to the relevant parts of Eurocode. The full process is illustrated in the flowchart in Figure 3.1.

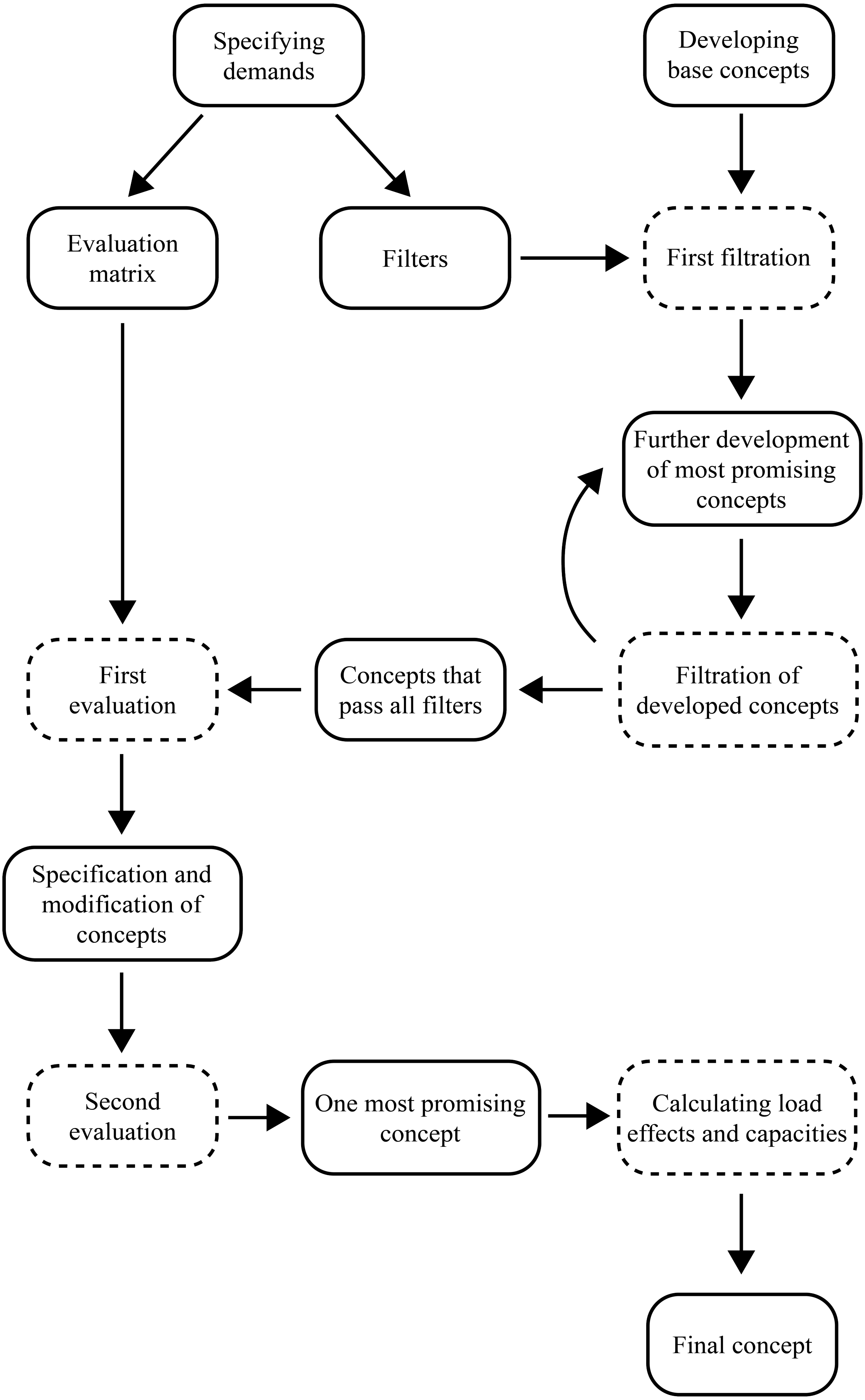


Figure 3.1: Flowchart illustrating the process implemented in Part II.

3.2 Demands

The demands on structures built in rural parts of Rwanda differs a lot from what engineers in Sweden and most of Europe are used to work with. Problems that are barely considered, or at least not focussed on, in Europe are instead crucial to make a concept viable in isolated areas.

Technical knowledge, available equipment and site accessibility is more important when designing a bridge for rural areas than the aesthetics or the exact location of the bridge. These bridges are the only reliable connection between the local communities and vital resources, not only a convenient way to save a couple of minutes on a commute.

With a perspective so far from the one usually used when building in industrialized parts of the world, a re-evaluation of the demands used to evaluate the different concepts needs to be done. In this chapter, potential demands are discussed to ensure a well founded evaluation of the concepts and thereby a suitable choice of final concept.

3.2.1 Hard and soft demands

Generally, demands can be divided into two categories, hard and soft. Hard demands are those which cannot be disregarded. They cannot be more or less fulfilled but rather they are fulfilled or not. This could for example be regulations from the organisation, Eurocode or the government. The soft demands are demands that can be rated on a scale depending on to which degree they are fulfilled. An example of a soft demands could be the time needed to build a structure.

In this thesis, the demands have been divided based on how important they are. The most important demands are made into filters for the filtration process where they are fulfilled or not fulfilled, i.e. hard demands. The demands with a lower priority is used as criteria in the evaluation matrix in the modification phase. The latter ones are divided into levels of fulfilment and can therefore be considered to be soft demands.

3.2.2 Rwanda versus Europe

When comparing the relevant demands for rurally isolated areas with demands used in projects in industrialized parts of the world, in this case mainly Europe, the large difference is clear. The initial conclusion is that the rural areas have demands that are more basic and that the soft demands are not as soft, since the option to alter things are more restricted. For example, if there are no usable roads leading up to the site, the demand regarding transport can only range from carry by hand to transportation with smaller off road vehicles and everything larger than that needs to be disregarded.

3.2.3 Definitions of demands

From the information in this chapter and the context presented in Chapter 2.2 demands are formulated. These demands are briefly described below, and will be further specified in later stages depending on if they are used as filters or as criteria in the evaluation matrix.

Sustainability

Sustainability is a broad expression that can be applied to several different perspectives. Here it will be divided into three parts: social sustainability, environmental sustainability and economic sustainability. All three of these aspects are taking off from and connects to some of the 17 sustainable development goals stated by the United Nations Development Programme, n.d. Among several is: goal number 1, no poverty and number 8, decent work and economic growth.

Social sustainability
According to UN Global Compact (n.d.), the human rights are one of the corner stones when talking about social sustainability. These rights are also the vision of B2P, "Safe access is a human right" (Bridges to Prosperity, n.d.-a), as well as the background for this project.

Therefore this demand is the most important one, but one that wont be affecting the process of choosing a final concept.

Environmental sustainability
When developing structures in Europe the environmental sustainability often is an important aspect. The environmental impact of a material or construction method can be a major reason for why it has been chosen in a project. Even if it comes with a higher cost, a material or method can be prioritised because of its lower environmental impact.

In the context of this project, the environmental sustainability is instead one of the least important factors. Because of the limited economic resources and the importance of the bridges for the local communities, other aspects will be higher prioritised. The choice of material for different concepts will be limited by what is available and possible to use within the given constraints.

The environmental sustainability will therefore not be taken into account when evaluating the different design proposals.

Economic sustainability
Economic sustainability can, according to KTH (2020), be defined in several ways, depending on which model is used. Here the three aspects of sustainability; social, environmental and economical, will be seen as individual and the definition 'economic' will regard economic growth. This means that the economic aspect is 'better' if the investment cost is lower or the return is higher.

Even if the bridge is expected to result in increased economic activity the clients, often governments, are not able or willing to pay a high price for the bridge. Therefore it is important that the bridge is cost-efficient.

Adaptability

An adaptable structure is vital to be able to ensure its efficiency at different site conditions and span lengths. It also simplifies the construction and prefabrication of the ingoing elements which is of great interest.

Simplicity

To make the most of the structure, advanced solutions are often used. These solutions can often result in less material used and/or a more aesthetically pleasing result.

In this case, the knowledge and equipment on site is limited and therefore the construction is favoured if the structure is simple.

Service life

The service life of the bridge is the time of which the bridge can be considered to be safe to use without any larger maintenance work or replacements of parts. In Sweden life span of bridges is regulated to be in the span on 40 to 120 years, depending on material. Here, other prerequisites are applied and B2P strives for a conservative lifespan of 30 years (A.1). A long technical service life is strived for.

Time

A longer construction time results in larger labour costs. In Rwanda the cost of labour is very low, especially in comparison with the cost of material, so the increase in cost that comes with a longer construction time will not affect the overall cost of the bridge significantly. Therefore, the construction time will not be taken into consideration when evaluating the different concepts.

Aesthetics

The look of the bridge can be more or less appreciated. The design might blend into the nature or it might be a statement structure. This aspect is not relevant in this case and will therefore not be evaluated.

Constructability

The bridge will consist of parts or modules that together form the bridge. Apart from the individual parts being connected somehow, the bridge also needs to be erected. The complexity of these aspects are considered here.

Transportability

The elements that the bridge consists of needs to be transported to the site. This can be more or less complicated depending on the surroundings and the equipment that can be used. A structure with parts that are easy to move, by hand and/or vehicle is preferred.

Safety

The main purpose of a bridge is to make it possible to travel from one end to the other safely. It should be safe to use the bridge even when something unexpected happens or the bridge has minor damages. Therefore, it is important that appropriate safety measures are implemented into the design, and that the load carrying structure has some redundancy to be able to carry the applied loads even if some elements are damaged.

One safety issue raised by B2P is the risk of unwanted vehicles crossing the bridge. To prevent this from happening the design of the bridge is important. B2P has solved this problem by limiting the width of the walkway to 1.5 meters in all their bridges.

Maintenance

To ensure the lifetime of a bridge it is crucial to perform maintenance work. This could include anything from removing leaves or dirt from the bridge to replacing parts that has served its time. Here the maintenance will be owned by the government and the quality of the maintenance will vary a lot. A bridge concept that requires as little maintenance as possible is aimed for.

Usage

While it is important that a bridge is safe to use, another aspect is the perceived comfort of crossing it. A wobbly bridge might result in a very uncomfortable crossing, or if the distance between the decking is too large the bridge can be perceived as unsafe.

Durability

The climate and weather on site will be very harsh and the bridge need to withstand both rain periods and smaller earthquakes over time.

Reliability

A reliable bridge means that the users can be certain that the bridge is usable at all times. This could mean that the bridge is not affected by a rain storm or a earthquake or that no maintenance problems results in a closing of the bridge.

3.3 Ranking of demands

To prioritize the demands a rating is implemented. This ranking is performed using a weighing matrix, which can be seen in Appendix B.1. In this matrix all demands are matched against each other and given a score, from 1 to 3, where 1 point means less important, 2 points equally important and 3 points more important. The scoring results in a ranking where the demand with the highest score is considered to be the most important one. The result of the weighing matrix is presented in Table 3.1.

Table 3.1: The highest ranked demands, right column representing the weighing.

Constructability	10%
Transportability	10%
Reliability	10%
Economic sustainability	8%
Adaptability	8%
Safety	8%

The ranking of demands resulted in six demands being considered the most important ones. Since the demand on safety will be evaluated through calculations when one concept has been chosen, it will not be used as a filter. The rest of the top demands are slightly modified to work as filters, and are presented below. The demand constructability has been divided into two different filters, general constructability and erection process, since the erection process has been identified as an especially challenging aspect of the building process. All filters are assumed to be equally important.

- Constructability
- Erection method
- Transportability
- Reliability
- Cost-efficiency
- Adaptability

3.3.1 Constructability

The access to, especially larger, tools are limited in the rural parts of Rwanda and to ensure that the bridge can be built in rurally isolated areas the design of the bridge needs to be made to suit this prerequisite and only require hand-held power tools.

If the bridge requires tools larger or more advanced than ordinary power tools it is sorted out in this filtration.

3.3.2 Erection method

The surroundings of the bridge sites are in most cases mountainous, as described in Chapter 2.1, and the erection of the bridge might require uncommon or extraordinary methods. Since the access to tools and heavy equipment is limited, the erection becomes even more complicated than in areas with similar terrain in Europe. The access from underneath is sometimes non-existent, the area on the sides can be steep and the regulations regarding drones are strict. Due to all this, the erection of the bridge will be used as a hard demand.

If the concept can be erected by hand, without extensive temporary structures, it will pass this filter.

3.3.3 Transportability

The distance that the material and equipment needs to be carried by hand is for some sites up to 2 km, but even in the cases where the distance is much shorter, it is necessary that the weight does not exceed the limit for manual transportation.

If the individual element weighs more than what can be expected to be carried by hand, or that the shape makes the transportation impossible, the concept is sorted out in this filtration.

3.3.4 Reliability

The bridge is used for everyday needs of the people living nearby and ensure the access for vital resources. This function must be working at all times to ensure the prosperity of the villages and therefore reliability is a necessity.

If the bridge needs to be closed off, for shorter or longer times, in the foreseeable future of the bridge's service life it is sorted out in this filter.

3.3.5 Cost-efficiency

B2P is a non-profit organization and the assets of the governments which are paying for the bridges are often limited, which results in a need for the design to be cost-efficient. This concerns both material choices and techniques, therefore for example anchors that requires a large volume of concrete is undesired.

If the bridge can not be built with mostly gifted or locally sourced parts and materials it is sorted out in this filtration.

3.3.6 Adaptability

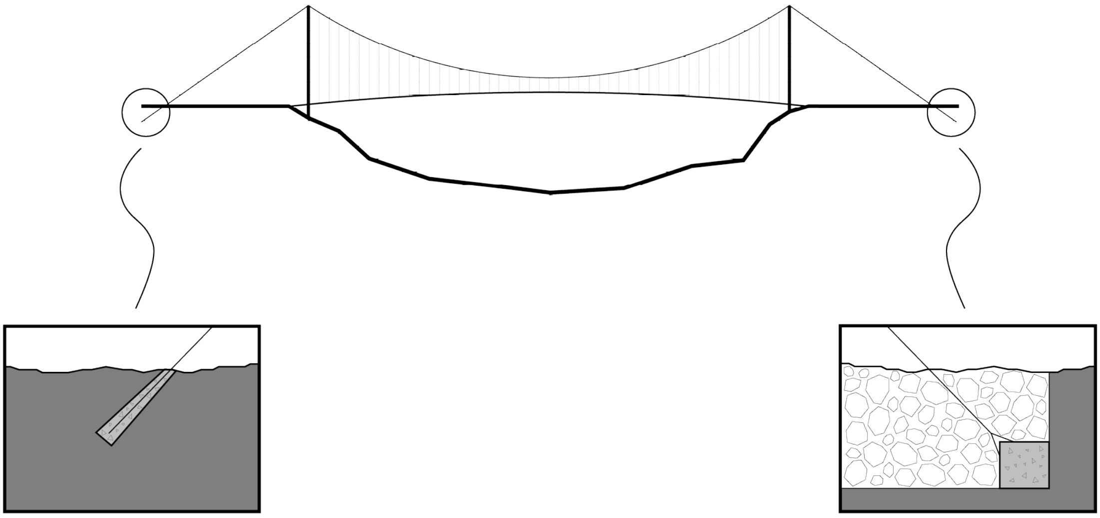
The sites that this bridge design is relevant for can differ a lot and to ensure that no redesign of geometry is needed the design itself must be easy to adapt. In addition to this the ingoing parts should be as few as possible.

If the design can be used for most sites without the need for redesign or alteration of ingoing parts, it is let through the adaptability-filter.

3.4 Initial concepts

These initial concepts have been designed based on the information presented in Chapter 2, and no detailing, apart from the load carrying system, is decided on. The concepts are introduced below, with an illustration and some quick facts.

Suspension bridge



Anchor in massive rock   Anchor in soft soil

Main structural elements:

- Primary cables in steel
- Pylons in steel
- Hangers in steel
- Cross beams for walkway in steel
- Steel plates for walkway

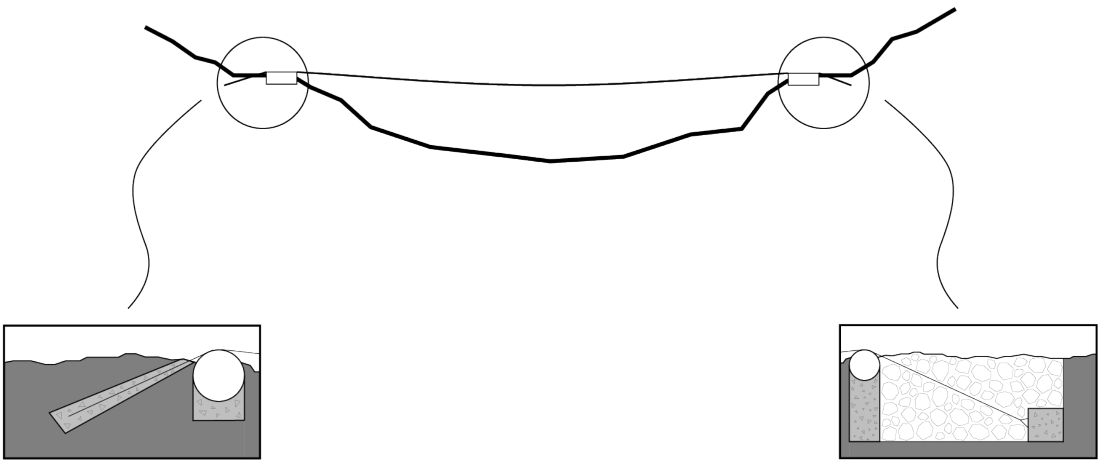
Supports:

- Concrete base acting as a pinned support for the pylons
- Anchors for cables

Other information:

- Same parts can be used for different span lengths
- High utilisation rate of all materials used in the main structural elements
- Simple connections between all structural elements
- No temporary structures needed during construction
- All main structural elements are in steel

Stressed ribbon bridge



Anchor in massive rock

Anchor in soft soil

Main structural elements:

- Cables in steel
- Cross beams for walkway in steel
- Steel plates for walkway

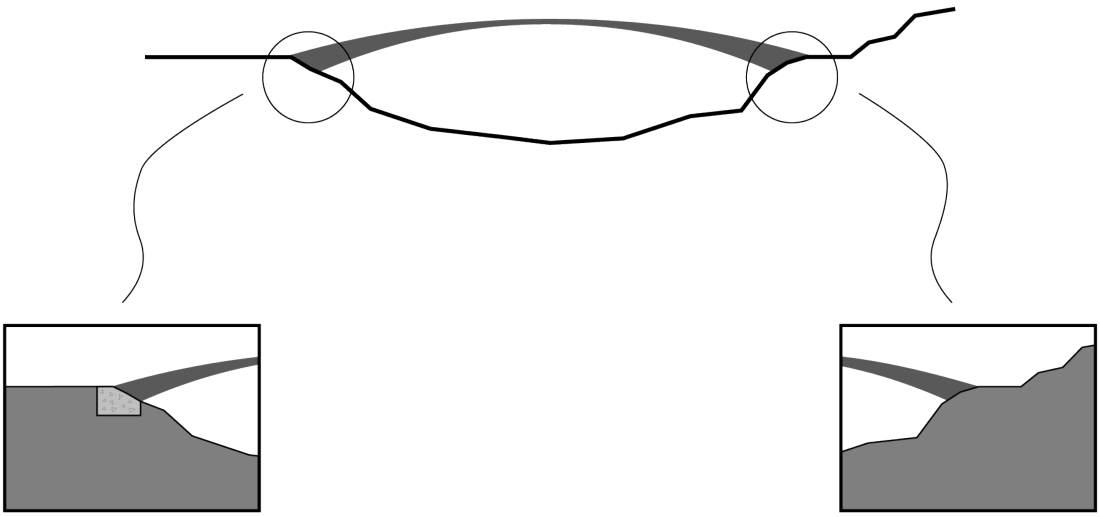
Supports:

- Anchors for cables

Other information:

- Same parts can be used for different span lengths
- High utilisation rate of all materials used in the main structural elements
- The only connection between structural elements are the connections between the walkway and the cables
- No temporary structures needed during construction
- All main structural elements are in steel
- Large horizontal forces must be tranferred into the ground at the supports, which can lead to large supports

Masonry arch bridge



Support in soft soil

Support in massive rock

Main structural elements:

- Stones or bricks
- Mortar

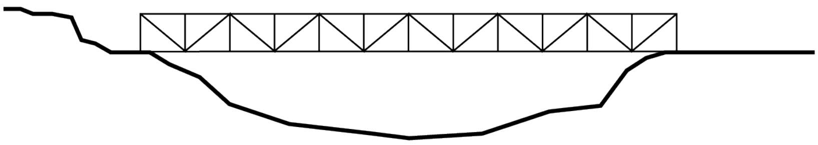
Supports:

- Stone or concrete abutments

Other information:

- Could be either an arch or a shell curved in two directions
- The geometry of the bridge might need to be changed for different spans
- Stones could be gathered locally
- High workload
- Requires skilled masons to ensure the quality of the work
- Requires falswork
- The supports must be able to transfer large forces in compression into the ground without moving over time

Steel truss bridge



Main structural elements:

- Steel elements for horizontal and vertical elements in the truss
- Steel elements for diagonals in the truss
- Cross beams in steel supporting the walkway and connecting the side trusses
- Steel plates for walkway

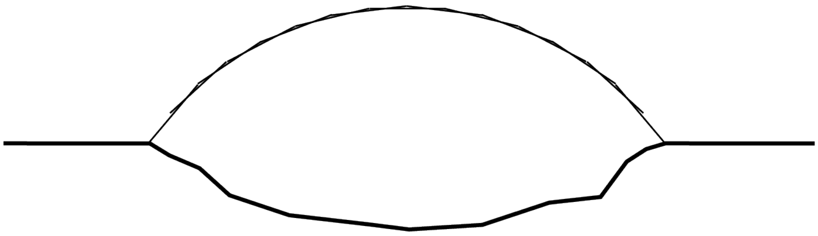
Supports:

- Must be able to transfer vertical forces in compression into the ground

Other information:

- Simple supports
- Standard elements can be used to construct the trusses
- The structure can be transported in small pieces and assembled on site
- Modular design where the span can be increased easily by adding another module
- All structural elements are in steel
- Requires many connections between different structural elements
- Depending on the site, temporary structures could be needed during construction

Reciprocal frame bridge



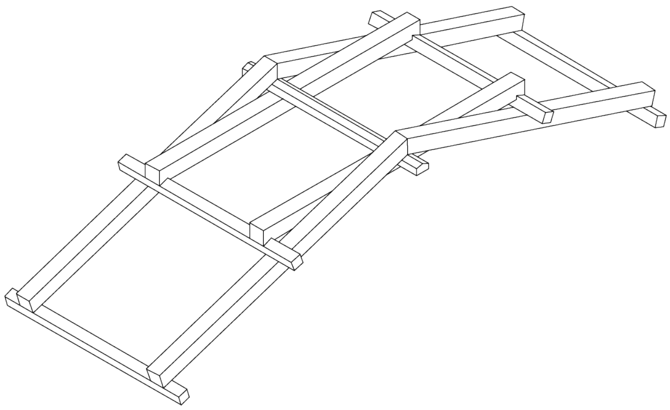


Illustration of the structural principle for the concept

Main structural elements:

- Primary steel beams
- Cross beams in steel
- Steel plates for walkway

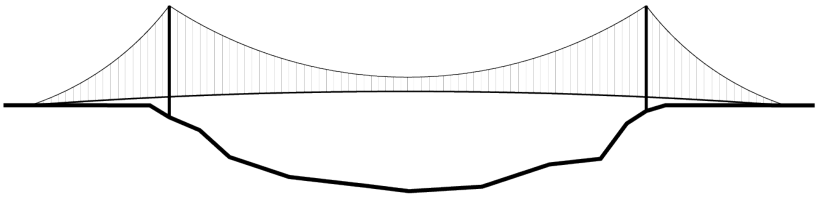
Supports:

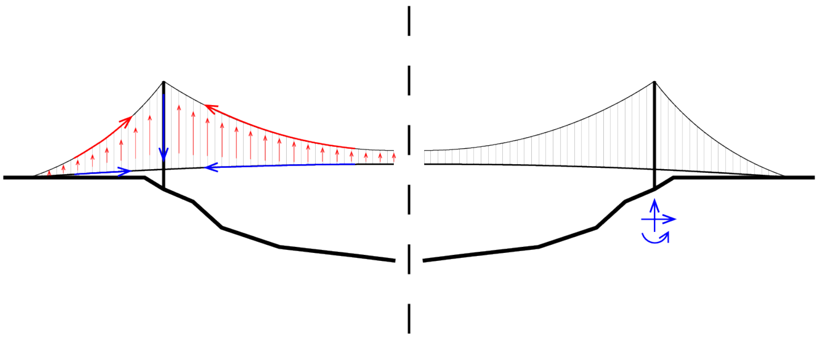
- Must be able to transfer both horizontal and vertical forces

Other information:

- Reciprocal frame structures has mainly been used in roofs before, not bridges
- Most built examples are in wood
- If the same parts are used for different spans, then the slope of the bridge will depend on the span

Self anchored suspension bridge





Main structural elements:

- Primary cables in steel
- Pylons in steel
- Hangers in steel
- Steel truss for bridge deck
- Steel plates for walkway

Supports:

- Concrete base acting as a fixed support for the pylons

Other information:

- Same parts can be used for different span lengths
- High utilisation rate of all materials used in the main structural elements
- Simple connections between all structural elements
- All main structural elements are in steel
- Temporary anchors needed for the cables during construction
- The supports for the pylons must be able to transfer moments to the ground
- Pylons must be able to carry moments
- Bridge deck must be able to carry forces in compression along the length of the bridge

3.5 The filtration process

In the filtration process the concepts are evaluated against the most important demands and the most promising ones are redeveloped to pass all filters.

In Table 3.2 the result of the first filtration can be seen. Each concept is tested against all filters and if the concept does not fulfil a filter it is marked with a cross. The number of crosses for each concept is summed up below. The background to the decisions is documented in Appendix B.2.

Table 3.2: Result of the first filtration, cross symbolizing the filter not being fulfilled.

Filter \ Concept	Suspension bridge	Stressed ribbon bridge	Masonry arch bridge	Steel truss bridge	Reciprocal frame bridge	Self anchored suspension bridge
Reliability					×	×
Transportability	×					×
Constructability						×
Erection method			×	×	×	×
Adaptability			×		×	
Cost-efficiency	×	×			×	×
SUM	2	1	2	1	4	5

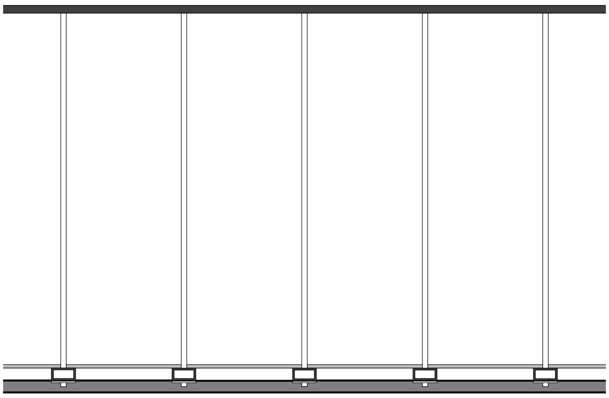
The two concepts that made it through the first round of filtration with the least number of crosses are the stressed ribbon bridge and the steel truss bridge. The stressed ribbon bridge concept is based on a design B2P already employs, but they currently do not use it for spans shorter than 30 meters due to the high cost and low utilisation of the material. The steel truss bridge is inspired by the Bailey Bridge used by the military. Since the erection methods used by the military either demand more space at the bridge landings or machines not available in this context, other ways to erect the bridge must be examined.

The two concepts are developed further to meet the filters, i.e. the anchor and cables of the stressed ribbon bridge are modified to be considered cost-efficient and suitable erection methods for the steel truss are examined.

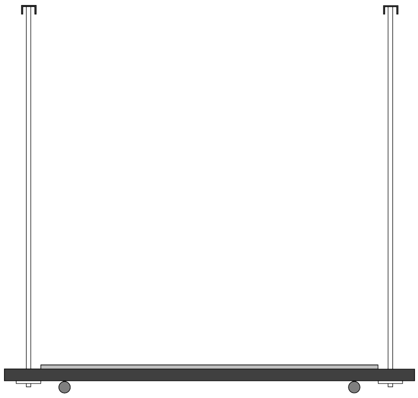
3.5.1 Development of concepts

To ensure that the final concept is as suitable as it can be and that the process to decide on a final concept is well-founded, the two concepts that made it through the filtration are developed. This development regards the erection method, anchors and cables.

For the stressed ribbon bridge, the major weakness is the cost efficiency of the design. The high cost comes from the price of cables and the large volume of concrete needed for the anchor. These problems can partly be reduced by redesign. The number of cables are reduced to two (from five, in the design B2P is currently using) by redesigning the railing, see Figure 3.2. To reduce the cost of the anchors, one option is to remove a large volume of the concrete used mainly as counterweight and instead use sand in its place.



(a) Elevation.



(b) Cross section.

Figure 3.2: Illustrations of the stressed ribbon bridge with the new rail design.

The main issue for the steel truss bridge is the erection process. The surroundings might be very steep and the space by the landings will on some sites be limited. Additionally, no heavy machines such as cranes can be used. This means that conventional erection methods, such as launching or lifting the bridge in place, will not be possible to use.

One way to solve the erection of the steel truss is to build a simple version of a crane on site. The construction would be fairly alike the top part of a tower crane with a counterweight, a tower with a cable and a horizontal part that eventually will be the bridge itself. To avoid a complex transportation of a large counterweight to site, gabions filled with rocks gathered locally could be used. The horizontal part, which will become the bridge, will be constructed by rotating new modules into position at the end of the cantilever. The rotation is controlled by the cable running from the new module over the tower to the counterweight. When the new module has reached its final position, the cable can be removed and the module becomes part of the cantilever. When the horizontal part is crossing the full span, the crane is no longer needed and is therefore disassembled and reused on the next site. An illustration of this can be seen in Figure 3.3.

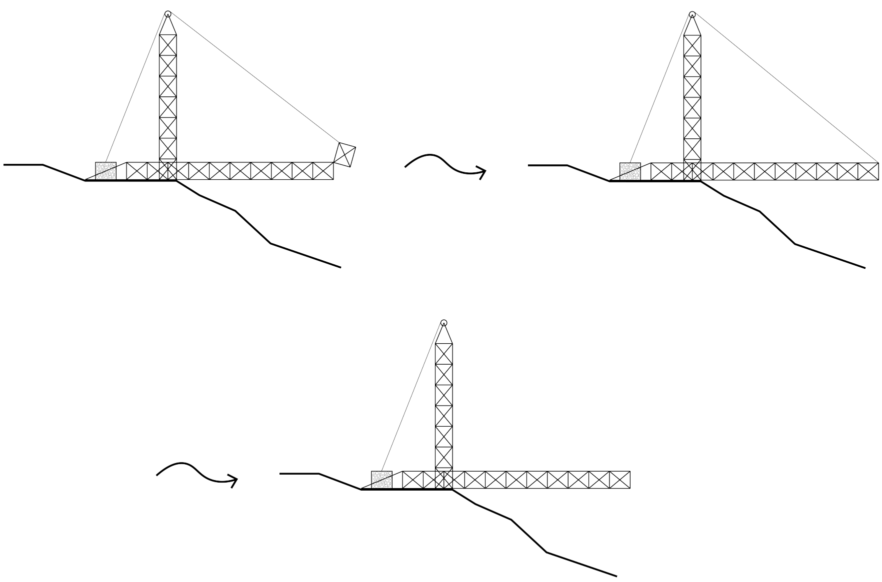


Figure 3.3: Illustration of the erection process for the steel truss bridge.

3.5.2 Second filtration

After the first filtration and development there are two relevant concepts left. The stressed ribbon bridge has been made more cost-efficient and an erection method suitable for the steel truss has been developed. These two concepts now go through a second filtration to ensure that they now pass all filters.

During this further development of the stressed ribbon bridge it became clear that the anchors demanded more space than previously anticipated. The volume of the anchors could not be reduced as much as predicted, which means that the bridge would not be as flexible as assumed. The stressed ribbon bridge did therefore not pass the adaptability filter in this second filtration, see Table 3.3. This means that the steel truss bridge was the only concept that passed all filters, and thus the only concept moving on to the modification phase.

Table 3.3: Result of second filtration, cross symbolizing the filter not being fulfilled.

Filter \ Concept	Stressed ribbon bridge	Steel truss bridge
Reliability		
Transportability		
Constructability		
Erection method		
Adaptability	×	
Cost-efficiency		
SUM	1	0

3.6 Modification phase

When one or more concepts have passed all filters, the modification phase is entered. Here the concepts will be further specified and modified to meet the demands that were not used as filters, the criteria. The concepts will be graded against the criteria based on how well they meet them. This grading process is repeated after the modifications to verify the improvements.

The only concept that passed all filters is the steel truss bridge. Therefore, this concept is the only one that will go through the modification phase.

3.6.1 Specification of remaining demands

To be able to adapt the concept to the remaining demands, these demands need to be specified. This specification is done through dividing the demands into 'levels' where 5 points is equal to high grade of fulfilment and 1 point is equivalent to non fulfilment. This specification can be seen in Appendix B.3.

3.6.2 Evaluation of initial concept

The concept is, as earlier mentioned, evaluated against the remaining demands. The scoring is based on how well the concept fulfils the demands, and how important the demand is considered to be in comparison to all other demands. Since no details are not yet decided on, and thus the characteristics of he structure unknown in many cases, several of the criteria are left without scoring for now. The result in the scoring is presented in Table 3.4.

Table 3.4: Scoring of the bridge concept for each remaining demand, before modifications.

		Steel truss	
Demand	**weight factor**	**score**	**score × factor**
Simplicity	7	3	21
Service life	7		
Safety	8		
Maintenance	7		
Usage	5		
Durability	8		
SUM	54		

3.6.3 Specifications and modifications of the chosen concept

By assessing the result in Table 3.4 the concept's weaknesses are found. The concept is modified to maximise its score, and further specified to ensure that it is possible to build the bridge the intended way.

3.6.3.1 Modifications

The temporary crane suggested for the erection process would be relatively complex to build and demands a lot of technical knowledge at the building site to be possible to build safely. Therefore, alternative solutions for how to add modules at the end of the cantilevering beam have been explored.

One alternative solution was to have a small, movable crane at the end of the cantilever, see Figure 3.4. This smaller crane would demand much less material to build, and would most likely be easier to use in the erection process because of its position closer to the end of the cantilever. On the other hand, the connections needed to secure the crane safely in the truss while still being possible to move could become complicated, or even impossible, to build using the available parts.

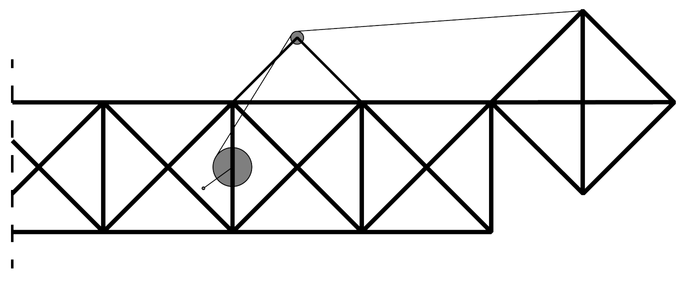


Figure 3.4: Illustration of second iteration of the erection method.

To solve these problems, a third solution was developed. In this third version a temporary tension diagonal consisting of a cable is used to fold out the horizontal elements in the bottom of the new module. By only folding out a small number of elements instead of the whole module, the weight on the cable is kept to a minimum, making it possible to control the folding without the use of a crane. The cable used control the folding is then fastened at the end of the cantilever to keep the horizontal elements in place. The rest of the module can then be assembled, making it stable without the cable acting as a diagonal. This makes it possible to remove the cable and replace it with the final piece of the new module. An illustration of this process can be seen in Figure 3.5.

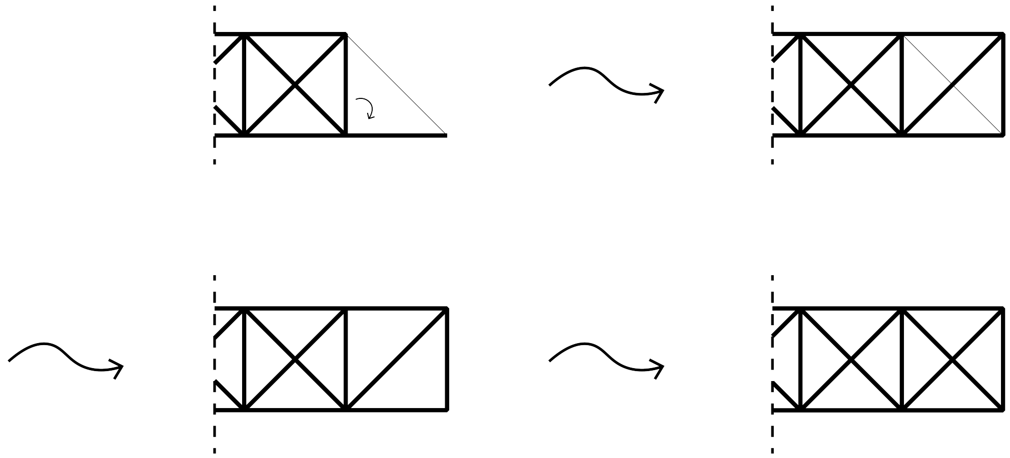


Figure 3.5: Illustration of third iteration of the erection method.

This third iteration of the erection process is more complicated to perform than the earlier iterations, but it makes the erection possible without the need for complicated special parts or large temporary structures. It is therefore the solution that has been used for the final evaluation of this design concept.

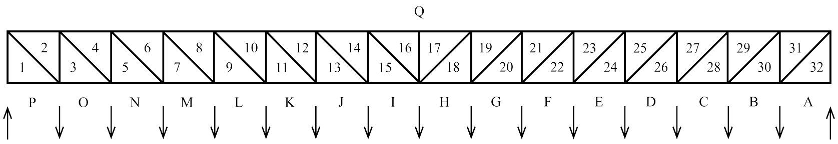
3.6.3.2 Specifications

In this section, specifications made to the concept are described together with the process of developing the final solutions.

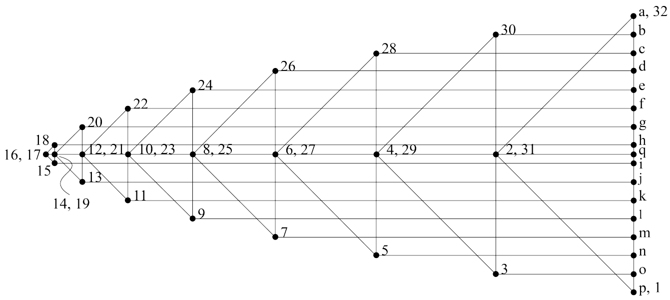
Geometry of modules and topology

The topology of the truss and the geometry of its modules are the main factors deciding how the forces flow through the structure and the size of the force in each element. To compare the behaviour of different kinds of trusses, Cremona diagrams have been used. In the Cremona diagrams presented here, the load applied in each node is assumed to be equally large for all different trusses. This assumption is made since the difference in self weight between different trusses is negligible compared to the total applied distributed load in this early design stage.

First, trusses with different height and length relations of their vertical and horizontal elements were compared. In Figure 3.6 a truss with a one to one ratio between the height and length of each module can be seen, and in Figure 3.7 a truss were the same relation is instead one to two. Here it can be seen that for the same span and applied load, the force in the diagonals and horizontal elements will be larger when the height of the truss is decreased. It can also be seen that the largest force will in both cases occur in horizontal elements in the middle of the span.

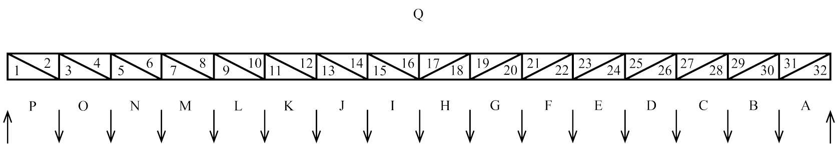


(a) Form diagram.

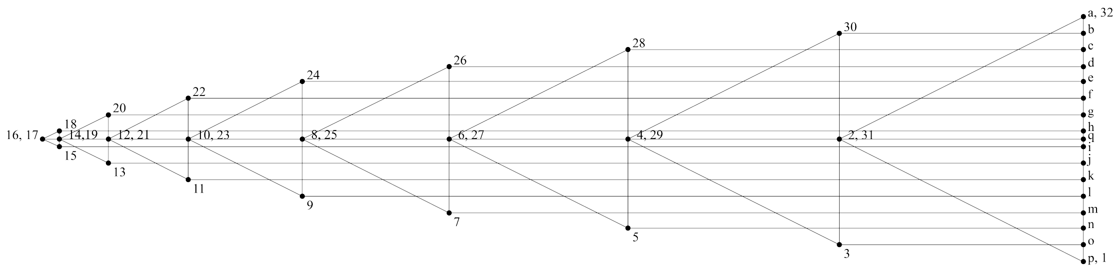


(b) Force diagram.

Figure 3.6: Cremona diagram for truss with 45 degree tension diagonals.



(a) Form diagram.

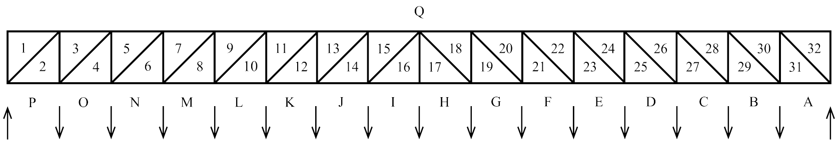


(b) Force diagram.

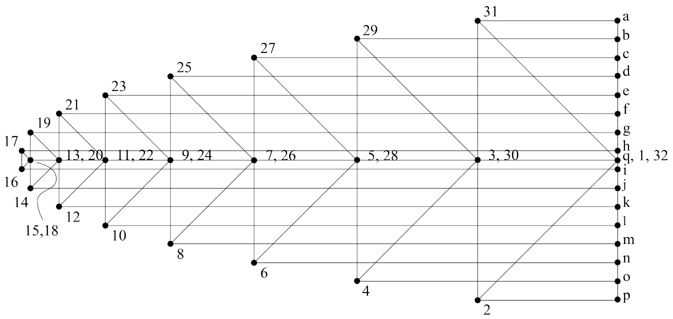
Figure 3.7: Cremona diagram for truss with 60 degree tension diagonals.

If the length of the truss is assumed to be the same for the two module alternatives, the Cremona diagrams shows that the one to one ratio between the height and length of each module minimises the force in the most critical elements. The one to one ratio between the height and length of each module could also simplify both the fabrication of elements and the assembly on site, since the same elements could potentially be used as both horizontal and vertical elements in the truss. Because of this, the modules with a ratio of one to one between the height and length of its modules was assumed to be most appropriate at this stage.

When the height to length relation of each module had been chosen, different topologies for the modules were explored. Three different topologies were identified and compared. One with only tension diagonals, Figure 3.6, one with only compression diagonals, Figure 3.8, and one with both tension and compression diagonals in a zigzag pattern, Figure 3.9.

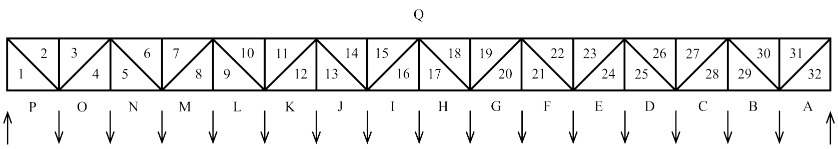


(a) Form diagram.

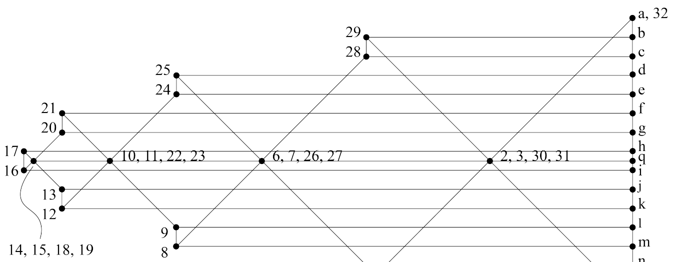


(b) Force diagram.

Figure 3.8: Cremona diagram for truss with 45 degree compression diagonals.



(a) Form diagram.



(b) Force diagram.

Figure 3.9: Cremona diagram for truss with 45 degree tension and compression diagonals.

According to the Cremona diagrams, the maximum force in the most critical element will be the same independently of which of these three topologies is chosen. The main difference between the different alternatives is if the diagonals will be loaded in compression or tension. Since the diagonals will always be the longest element in each module, it will also be the element most critical with respect to buckling if it is in compression. Therefore, having only tension diagonals could be more appropriate at this stage when the critical buckling force of the diagonals is unknown. On the other hand, if there is only one diagonal in each module, that module would become unstable if the diagonal was somehow damaged. Because of this, a fourth topology with both tension and compression diagonals in each module was added as an alternative, see Figure 3.10 for an illustration. Having both compression and tension diagonals gives the structure more redundancy, since one diagonal in each module could break without the full structure collapsing. In this context, were the quality of the elements is unknown, this redundancy could be crucial for the bridge to be safe even if it increases the self weight of the structure by doubling the amount of diagonals. Because of this, the topology with both tension and compression diagonals in each module was assumed to be most appropriate.

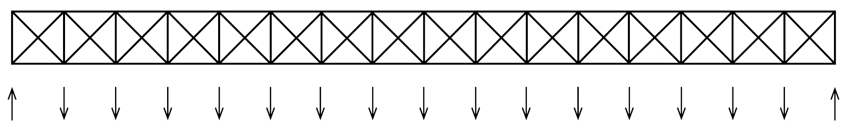


Figure 3.10: Form diagram of truss with tension and compression diagonals in each module.

The topology with both tension and compression diagonals in each module makes the truss statically indeterminate, and it can therefore not be described with Cremona diagrams. But for preliminary calculations, the worst case for this truss is assumed to be if only the compression diagonals are activated since this would create the highest risk of an element buckling. Therefore, the Cremona diagram for the truss with only compression diagonals can be used to approximate the behaviour at this stage. In later stages when more precise calculations are needed, a finite element model should be used to describe the behaviour of the structure when all diagonals are in use.

To find an appropriate height for the truss, the maximum force in the truss is calculated using the Cremona diagram. From this force a maximum stress is calculated and compared to the yield stress to determine what module height is needed to avoid yielding. Through these calculations, an appropriate module height is determined to be 2 meters.

Connection and cross section

To ensure that the bridge can carry the loads as intended, the geometry of all elements in the truss and the connections between them must be specified.

For the concept to be viable it must be possible to acquire all materials in, or in close proximity to, Rwanda for a reasonable price. To understand what materials are available, B2P was asked about which kinds of steel elements, steel plates and bolts they have access to and use in the bridges they build today.

B2P's currently uses UPE beams which have a cross section of 100x50x6 mm in their bridges. A rectangular beam with a hollow cross section is also available and have earlier been used, but due to problems with connection and difficulties painting the inside of the beam with protective paint, these are no longer used. Regarding plates and bolts, 2.4x1.2 m plates with a thickness of 3 mm, 6 mm or 8 mm, and bolts with a diameter of 10 mm are available.

Based on the information from B2P, UPE beams with a cross section of 100x50x6mm was decided to be used for all bar elements. See Figure 3.11 for an illustration of the geometry of the cross section. Since B2P already use this kind of element in their bridges, routines are in place for acquisition and maintenance of the beams. Therefore, the risk of the elements not being available or not being maintained properly was assumed to be smaller for the UPE beams than for other elements.

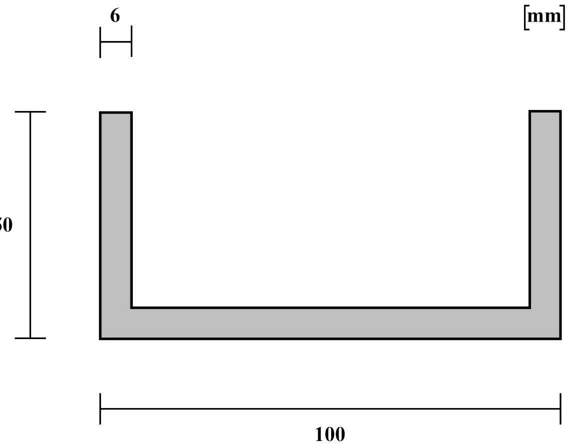
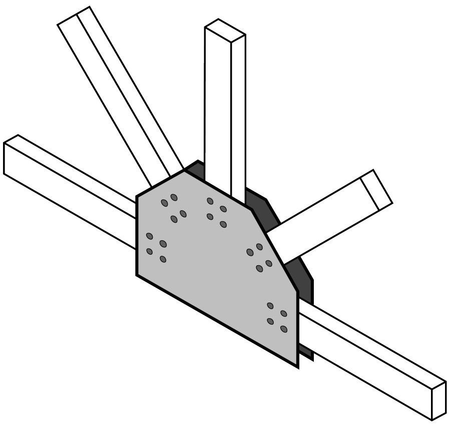


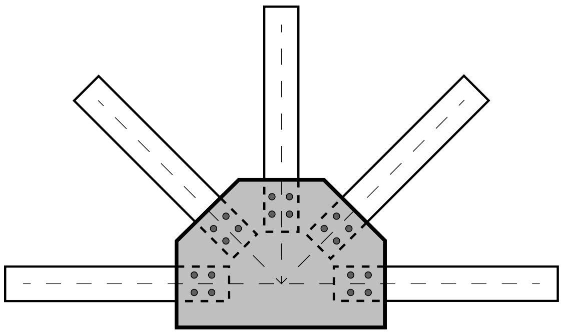
Figure 3.11: Cross section of all bar elements in the truss.

For the connections, it was decided that bolts with a diameter of 10 mm and steel plates with a thickness of 6 mm should be used. The bolt size is decided in accordance with what B2P normally use since there was no structural reason to use any other bolts, and they were available. The thickness of the steel plate did not affect the geometry of the connection significantly, and therefore a thickness of 6 mm was chosen, which also coincide with the thickness of the cross section of the beams.

Since the access to both knowledge and equipment is limited, welded connections are avoided. Instead, a bolted plate connection is designed for the truss. The first iteration of this connection has been illustrated in Figure 3.12.



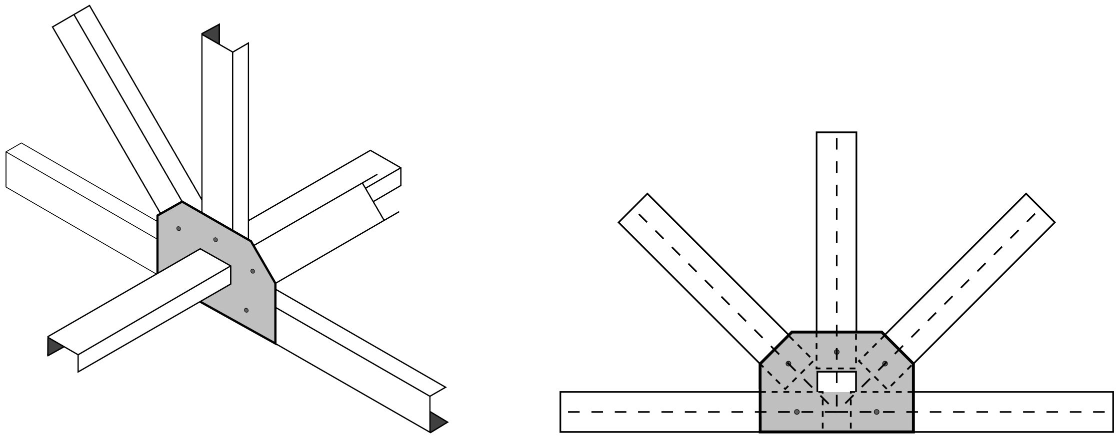
(a) Illustration of the geometry.



(b) Elevation including the position of the centre lines of the bar elements.

Figure 3.12: First iteration of the connection between bar elements in the steel truss.

When the cross section of the bar elements had been chosen, a second iteration of the connection was developed. In this second iteration, the number of plates was decreased from two to one to better fit with the cross section of the bar elements, and a hole was introduced in the middle of the plate to connect the cross beams to the trusses. An illustration of this second iteration can be seen in Figure 3.13.

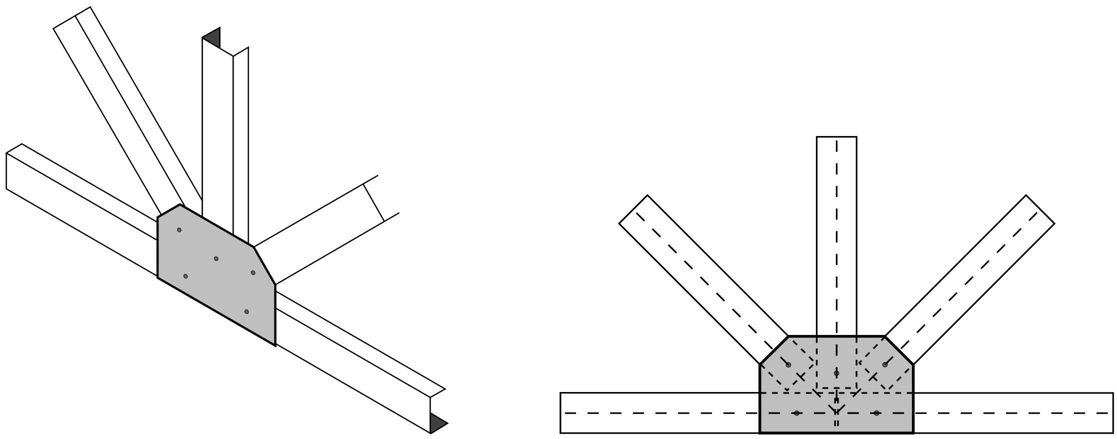


(a) Illustration of the geometry.

(b) Elevation including the position of the centre lines of the bar elements.

Figure 3.13: Second iteration of the connection between bar elements in the steel truss.

The hole introduced in the connection plate would demand a precise manufacturing process, and creates an unwanted weakness in the plate sensitive to the exact geometry of the hole. Therefore, a third iteration of the connection was developed where the connection for the cross beams was moved to another part of the truss, making it possible to remove the hole. An illustration of this third iteration of the plate can be seen in Figure 3.14. This third iteration of the connection has been used in the final evaluation of the concept.



(a) Illustration of the geometry.

(b) Elevation including the position of the centre lines of the bar elements.

Figure 3.14: Third iteration of the connection between bar elements in the steel truss.

Diagonals

Since each module has two diagonals, there will be a point where the diagonals meet. In this point, the diagonals must either be connected or be placed in such a way that they can pass each other. The first alternative considered was to have a connection with a plate, similar to the connection previously described. The downside of such a solution is that it introduces another connection, and therefore another weak point into the structure. The cost of the steel plates has also been assumed to be significantly higher than the price of the UPE beams, meaning that this solution could increase the price of the bridge significantly.

A second solution was thus developed, where one of the diagonals have been moved slightly out of the plane of the truss to make sure the diagonals could pass each other. The flanges of the diagonal still in the plane of the truss have also been removed to minimize the eccentricity of the diagonals. An illustration of the point where the two diagonals meet can be seen in Figure 3.15.

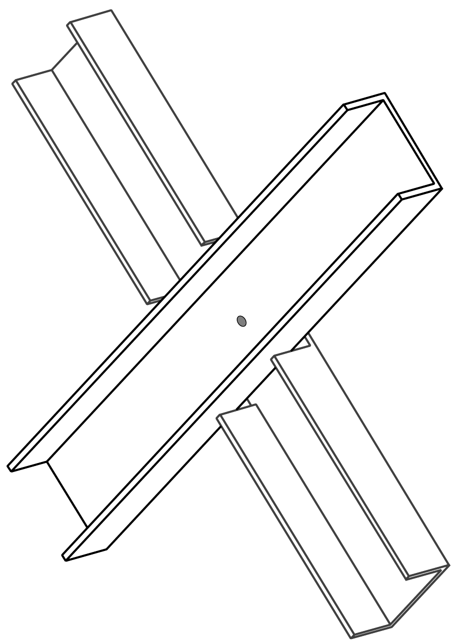


Figure 3.15: Illustration of the meeting point between the two diagonals.

Stabilising structure

For the bridge to be stable, it must be able to withstand both vertical and horizontal loads. The trusses can carry all relevant loads that are applied in the plane of the trusses, but a stabilising structure is needed between them to carry the loads applied in all other directions.

The first iteration of the stabilising structure, Figure 3.16, was design parallel to the second iteration of the connection plate. The hole in the connection plate allowed the cross beams supporting the walkway to be in the same plane as the vertical elements of the truss, making it possible to connect them with a bolted UPE beam. The primary downside with this first iteration is that the support structure is located outside the trusses, which could make it both difficult and dangerous to install and maintain.

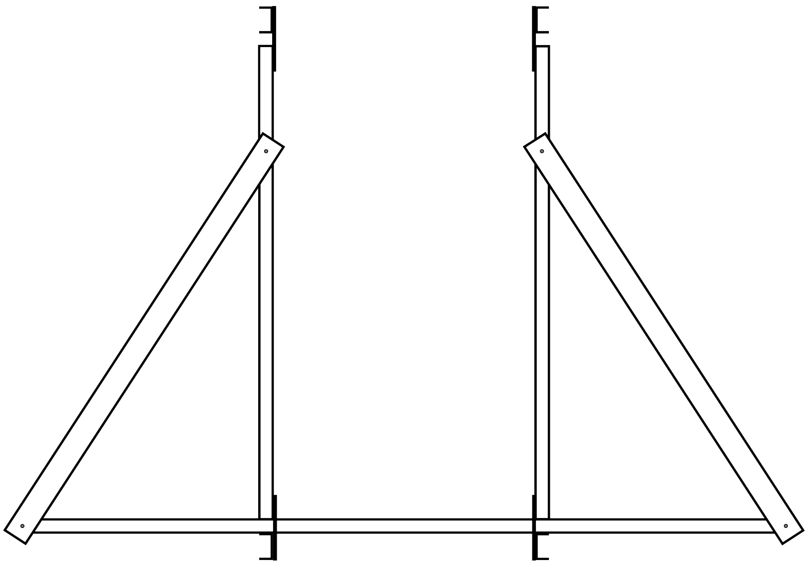


Figure 3.16: First iteration of the structure stabilising the trusses against out of plane forces.

When the second iteration of the stabilising structure was developed, the hole in the connection plate had been removed. Since all connections had to be bolted, alternative solutions which still allowed for cross beams to be in the same plane as the vertical elements of the truss were explored. The second iteration thus became a solution with cross beams on top of the trusses. These cross beams were then connected to the vertical elements of the truss with short UPE beams creating a type of frame structure, see Figure 3.17. When the cross beams are placed on top of the trusses, the free height is restricted. Since large and heavy objects often are carried on top of the head, having height restrictions could limit its positive impact on the local communities.

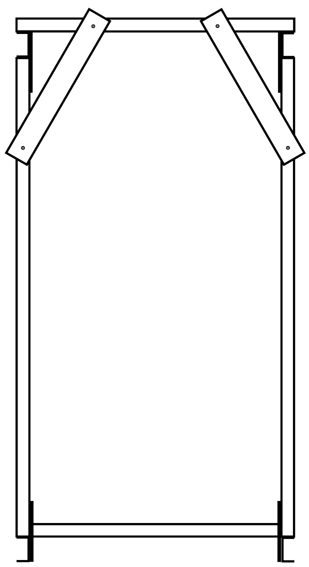


Figure 3.17: Second iteration of the structure stabilising the trusses against out of plane forces.

To avoid the height limit, a third iteration with the stabilising structure located underneath the walkway was designed. An illustration of this third iteration can be seen in

Figure 3.18. By moving up the walkway to the middle of the trusses, space is created below the walkway where diagonals connecting the two trusses can be placed. This third iteration of the stabilising structure will make the erection process more complicated, since a temporary floor must be placed at the bottom of the trusses during erection, but this is considered a minor issue compared to the problems found with earlier iterations. Therefore, this third iteration of the stabilising structure has been used in the final evaluation of the concept.

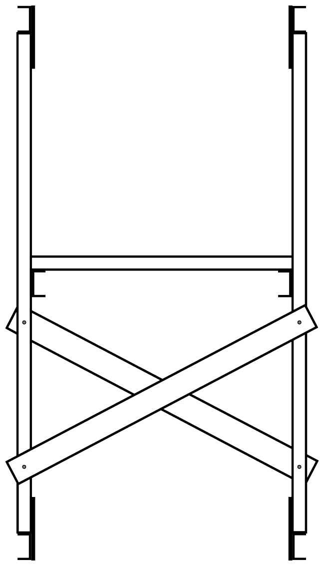


Figure 3.18: Third iteration of the structure stabilising the trusses against out of plane forces.

3.6.4 Evaluation of improved concept

When the chosen concept has been improved with respect to the remaining demands, the concept is reevaluated to present the effect of the changes made. This is presented in Table 3.5. The level of fulfilment that corresponds to the scoring can be seen in Appendix B.3.

Table 3.5: Scoring of the bridge concept for each remaining demand, after modifications.

		Steel truss	
Demand	**weight factor**	**score**	**score × factor**
Simplicity	7	5	35
Service life	7	5	35
Safety	8	5	40
Maintenance	7	5	35
Usage	5	4	20
Durability	8	4	32
SUM	46	28	197

3.7 Final concept

From the initial six concepts one has now been developed to fulfil all of the demands and has details such as topology, connections and stabilization specified. This final concept is shown below.

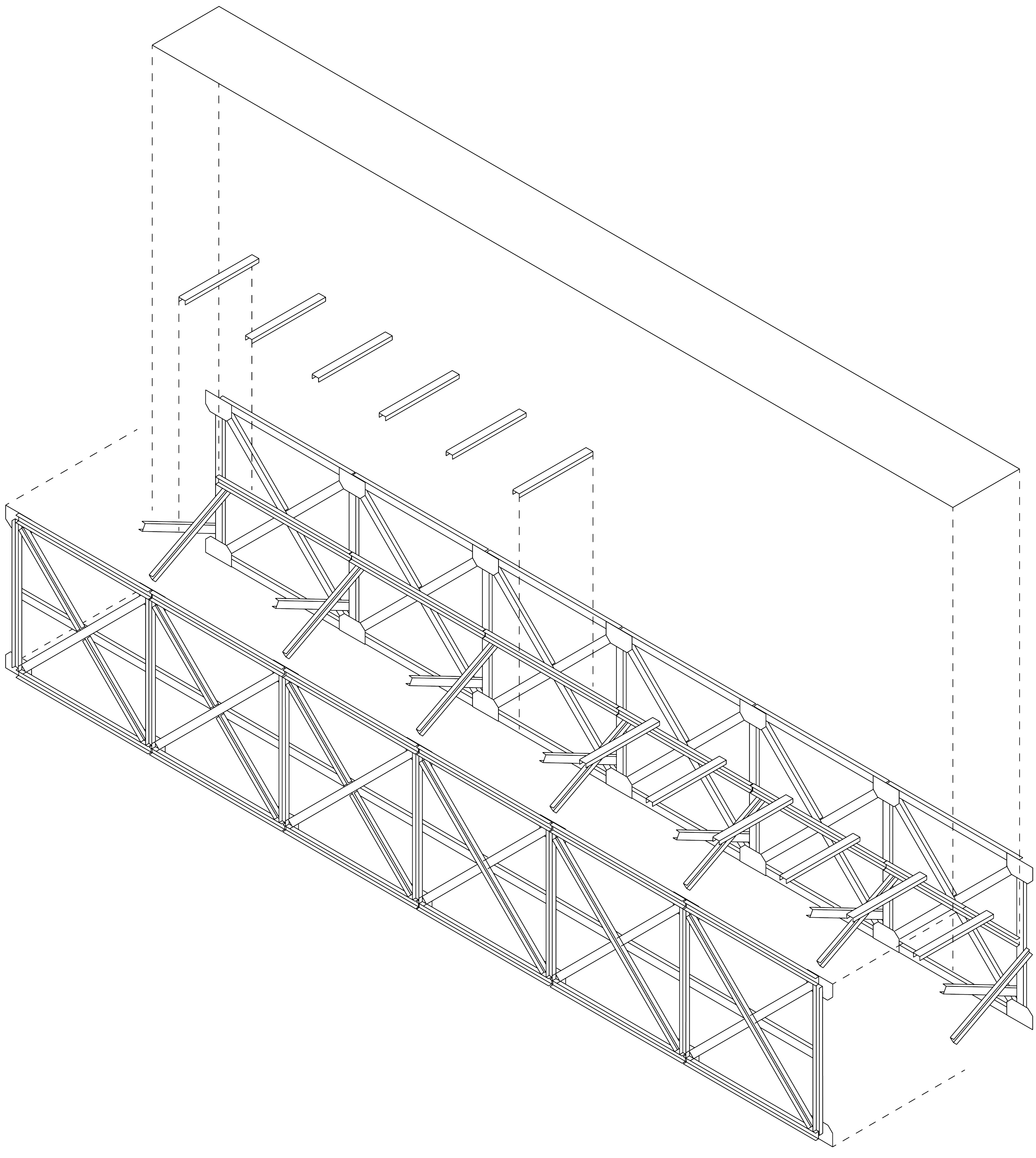


Figure 3.19: Illustration of how the different elements of the bridge are connected to each other.

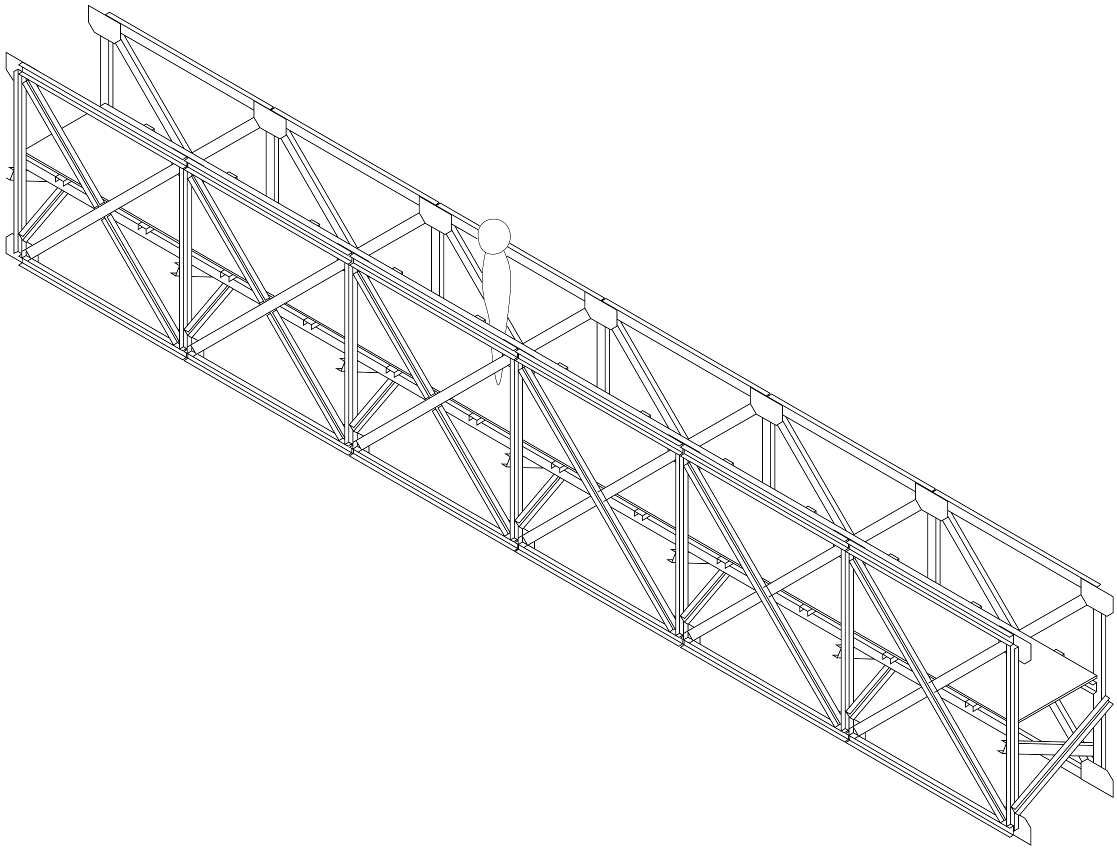


Figure 3.20: Illustration of bridge concept.

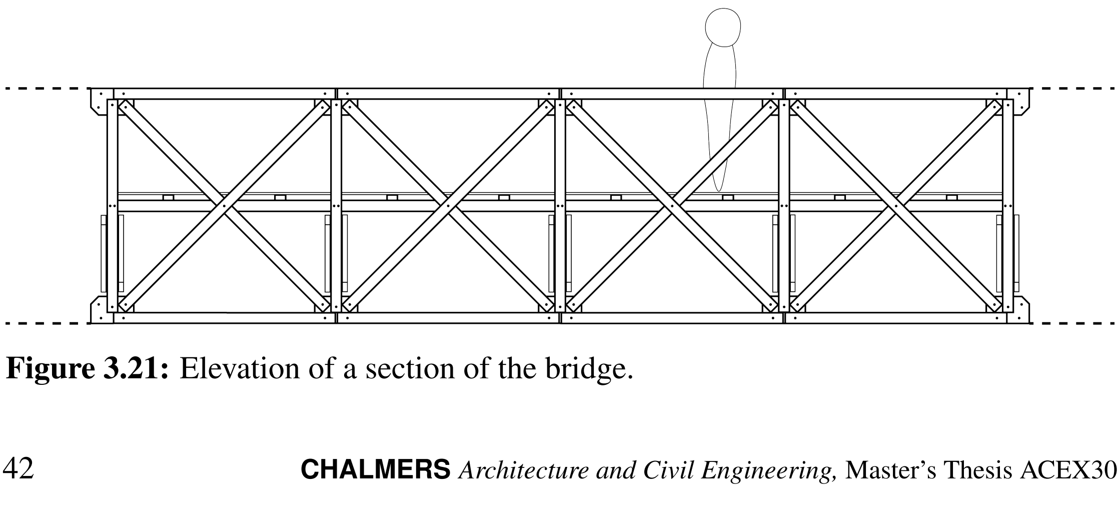


Figure 3.21: Elevation of a section of the bridge.

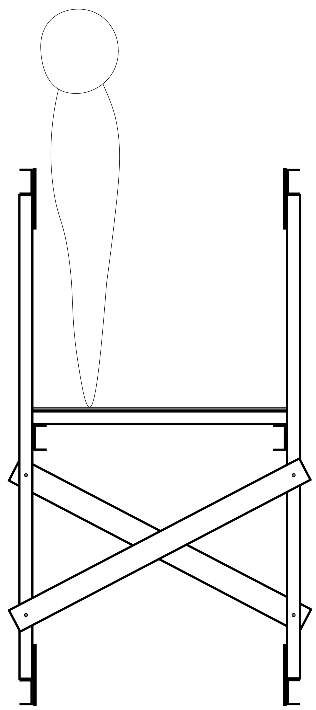


Figure 3.22: Cross section of the bridge.

The modular steel truss, with diagonals of 45 degrees, bolted plate connections and a stabilising structure consisting of crosses beneath the walkway will in the coming chapters have its details further specified according to B2P's policies and Eurocode.

3.8 Calculations according to B2P and Eurocode

As stated in Chapter 2.10 the strength and capacity of the structure will be checked against B2P's policies and calculations when applicable. When these are inadequate, Eurocode will be used instead.

Since B2P's policies are focused on calculations relevant for different kinds of suspension bridges, Eurocode will be used for the majority of the calculations. Regarding the structure as a whole, *EN1990:2002 Eurocode - Basis of structural design* will be referred to, while for detailing of the structural elements, which will be made out of steel, *EN1993 Eurocode 3 - Design of steel structures* will be used. For calculations of dead- and live loads *EN1991 Eurocode 1 - Actions on structures* will be used, and for seismic loads *EN1998 Eurocode 8 - Design of structures for earthquake resistance* will be referred to.

3.8.1 Input data

Through consultation with B2P, a list of materials that they can acquire relatively easy has been compiled. These materials will be used in the design as far as possible to ensure both access and cost-efficiency.

Chords:	**Bolts:**	**Plates:**
UPE $100 \times 50 \times 6$mm	Grade 8.8	$2.4 \times 1.2 \times 3/6/8$mm
Quality S360	M10	Quality S240

The properties of these elements can be seen in Table 3.6.

Table 3.6: Material properties.

Chords and diagonals, UPE	
Ultimate tensile strength, f_u	360 MPa
Yield strength, f_y	240 MPa
Cross sectional area, A_{chord}	1137 mm^2
Length chords, l_{chord}	2000 mm
Length diagonals, l_{diag}	2828 mm
Connection - plates, S240	
Ultimate tensile strength, f_u	360 MPa
Yield strength, f_y	240 MPa
Thickness, t_{plate}	6 mm
Connection - bolts, M10 & grade 8.8	
Ultimate tensile strength, f_{ub}	800 MPa
Yield strength, f_{yb}	640 MPa
Diameter, d_{bolt}	10 mm

3.8.2 Loads

The loads that B2P uses for stability checks on their existing bridge concepts will be used for this concept as well. Since the traffic that will cross the bridge differs a lot from most bridges in Europe, B2P's loads are assumed to be more relevant than the loads used in Eurocode. The loads B2P uses are stated in Table 3.7.

Table 3.7: Loads used by B2P, on suspension bridge.

Live load	4.07 $\frac{kN}{m^2}$
Point load (motorcycle, cattle etc.)	2.22 kN

In addition to the loads stated in Table 3.7, loads according to *EN1991 Eurocode 1 - Actions on structures* will be applied. These loads are described below.

3.8.2.1 Permanent loads

Loads applied on the bridge for a longer time period are called permanent loads. The permanent loads relevant in this design process are described below.

Dead load
The bridge structure's weight needs to be carried by the structure itself. This load is called dead load and is calculated using the volume and density of each ingoing part.

$$G_k = V \cdot \rho \cdot g$$

The load includes weight from all ingoing elements, such as chords, plates, bolts and deck. The volume and density for each element type is multiplied individually and then summarized to find the total dead load. This load differs with the span length of the bridge.

3.8.2.2 Live loads

Loads that are not permanent, i.e. that varies over time, are referred to as variable loads or live loads. These can be due to people, traffic or natural phenomenons.

Distributed live loads
A distributed live load representing a large group of people passing the bridge at the same time is applied. In this case, the same distributed live load as B2P uses on their existing bridges will be used, see Table 3.7.

$$q_{dist} = 4.07\frac{kN}{m^2}$$

Point live loads
If vehicles are able to enter the bridge the point loads coming from these needs to be considered when designing the strength of the bridge. In this case, the width of the bridge is set to one metre to ensure that no larger vehicles can cross the bridge. This results in a maximum point load coming from cattle or motorcycles crossing, which B2P considers contributes to a point load of $2.22kN$, see Table 3.7.

$$P_{live} = 2.22kN$$

Wind loads
The wind contributes to a horizontal load as well as a force lifting up or pushing down the bridge which needs to be taken into account. This load depends on the bridge area and the wind velocity. The resulting wind force is calculated in accordance with Eurocode 1, as shown in Appendix C.2.

An estimation of the ingoing parameters results in a load of a negligible magnitude both for the area on the side of the bridge and the walkway. Therefore, the wind will not be considered in further calculations.

Seismic loads

Rwanda occasionally suffers from earthquakes with a magnitude of around 5, which means that some damage to structures can be expected. The bridge needs to be designed to resist this load.

In *EN1998 Eurocode 8 - Design of structures for earthquake resistance* guidelines regarding earthquakes are presented. Many factors and coefficients that are used in these calculations are dependent on site conditions. Since this bridge concept is designed to suit several different site conditions this dependence means that a calculation for one site might not be correct for another. An estimation of factors will therefore be very unreliable and the capacity control against seismic loads will have to be performed for each individual bridge and site.

Temperature loads
Steel is a material that expands and shrinks with temperature changes. This needs to be taken into account when calculating the horizontal forces acting on the bridge (European Committee of Standardization, n.d.-a). The equation and an estimated length difference is calculated in Appendix C.1.

Since the bridge will be simply supported, and one side will be able to move horizontally, a relatively small length difference will not have a significant effect on the structure. The free degrees of freedom will enable the bridge to expand without inducing any significant stresses. The length difference must be considered when designing the steps or ramp leading up to the bridge to ensure that the bridge can expand freely.

Snow loads
A bridge in Rwanda will not be exposed to snowy weather and therefore the snow load will be neglected.

3.8.2.3 Load combinations

The loads presented above can all occur in different combinations and to account for this a load combination is done in accordance with *EN1991 Eurocode 1 - Actions on structures*.

$$F = \gamma_G \cdot G + \gamma_Q \cdot Q$$

$\gamma_G = 1.05$ partial safety factor - permanent loads
$\gamma_Q = 1.35$ partial safety factor - variable loads

3.8.3 Capacity and utilization

In the sizing phase, the capacity of the structure is calculated. Capacity checks are made for ingoing parts as well as for the structure as a whole. The capacity is then checked against the relevant applied loads and a utilization ratio is calculated. A utilization ration below 1 implies that the structure can handle the load.

To perform these calculations, a computer program called CALFEM is used. This program is a tool used to perform static and dynamic calculations (Austrell et al., 2004). A finite element model of the bridge concept is organised and is presented with the full MATLAB script in Appendix C.3.

3.8.3.1 Internal forces and stress - truss elements

All load carrying elements in the truss have to withstand the internal force resulting from the dead load and external forces during both the erection process and normal use. To calculate these internal forces, CALFEM is used. The largest forces during normal use are found in the horizontal truss elements in the middle of the span, and the utilisation ratio is presented below. The force distribution in the horizontal elements through the structure during normal use can be seen in Figure 3.23. Looking only at the diagonals, the largest forces are found in the ones closest to the supports.

$$\text{Utilisation ratio: } \frac{\sigma_{Ed}}{\sigma_{Rd}} = 88\%$$

To make sure the structure can withstand the erection process, the utilisation ratio is also calculated for the most extreme load case occurring during erection. This is assumed to be when the bridge is a 30 meter long cantilever with workers standing at the end of the cantilever. The utilisation ratio for this load case can be seen below.

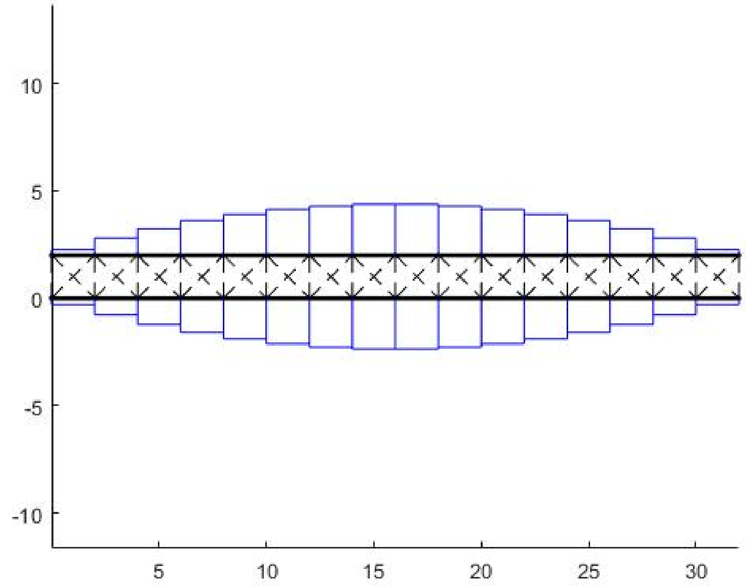


Figure 3.23: Distribution of internal forces in horizontal elements. Force magnitude illustrated in blue.

$$\text{Utilisation ratio: } \frac{\sigma_{Ed}}{\sigma_{Rd}} = 90\%$$

3.8.3.2 Connection

According to *EN1993 Eurocode 3 - Design of steel structures*, Part 1-8: Design of joints, the connections should be designed to have a resistance similar to the elements it connects, i.e. the truss elements. This is to ensure that the connection will not fail before the rest of the structure. In this case, the cost efficiency and volume of material is of great importance and by designing the connections for the maximal internal force some of this need for material can be reduced.

With the last paragraph as background, the bolted connections are designed to withstand a load that corresponds to the maximum normal force of the elements of a bridge with a 30 meter span. The calculations are presented in a Mathcad sheet, that can be modified regarding qualities, sizes and internal forces. This sheet is presented in Appendix C.4.

The connections are as mentioned designed for the longest span, so with a shorter span the connections will be stronger than what is needed. Figure 3.24 shows a drawing of the connection, with two different configurations. In Table 3.8 the distances to ends and edges as well as the distance in between the holes is listed.

(a) Design of connection with M10 bolts.

(b) Design of connection with M16 bolts.

Figure 3.24: Detailed design of bolted plate connection, measurements given in the Table 3.8.

Table 3.8: Measurements for connection, in millimetres, with M10 bolts and M16 bolts respectively.

M10		**M16**	
$e_{1.horizontal}$	30	$e_{1.horizontal}$	60
$e_{2.horizontal}$	30	$e_{2.horizontal}$	25
$p_{1.horizontal}$	40	$p_{1.horizontal}$	60
$p_{2.horizontal}$	40	$p_{2.horizontal}$	50
$e_{1.vertical}$	40	$e_{1.vertical}$	40
$e_{2.vertical}$	50	$e_{2.vertical}$	50
$p_{1.vertical}$	30	$p_{1.vertical}$	60
$e_{1.diagonal}$	20	$e_{1.diagonal}$	30
$e_{2.diagonal}$	50	$e_{2.diagonal}$	50
$p_{1.diagonal}$	30	$p_{1.diagonal}$	40

3.8.3.3 Deflection

In service limit state, SLS, the deflection of the bridge becomes relevant. In SLS, the comfort of the user is the focus and, in this case, if the deflection of the bridge is uncomfortable. According to Eurocode, this limit is set by each country. Due to the lack of a national standard for such a limit in Rwanda, a limit of $\frac{L}{250}$ is used to find the utilization ratio. According to European Committee of Standardization (2002) there is no set limit for comfort of pedestrian bridges, and therefore no set limit for deflections. This limit is instead set by the stakeholders of the project. Since no such limit has been state by any of the stakeholders, the utilisation ratio presented here only acts as a way to set the deflection in perspective.

For a bridge with a span of 30 meters, the deflection is 109 mm which results in a utilization ratio as follows.

$$\text{Utilization ratio: } \frac{\delta}{\frac{L}{250}} = 85\%$$

3.8.3.4 Eigenfrequency

The eigenfrequency of the bridge affects both the durability of the bridge, since a frequency that matches the eigenfrequency makes the bridge sway uncontrollably, and the comfort of crossing the bridge. Since most traffic will be pedestrians, an eigenfrequency above the frequency of walking is crucial.

The eigenfrequency is a dynamic problem that is solved using CALFEM. The eigenfrequencies are presented below, as well as an illustration showing the first 2 eigenmodes, Figure 3.25.

Eigenfrequency 1: $4.50 Hz$

Eigenfrequency 2: $16.46 Hz$

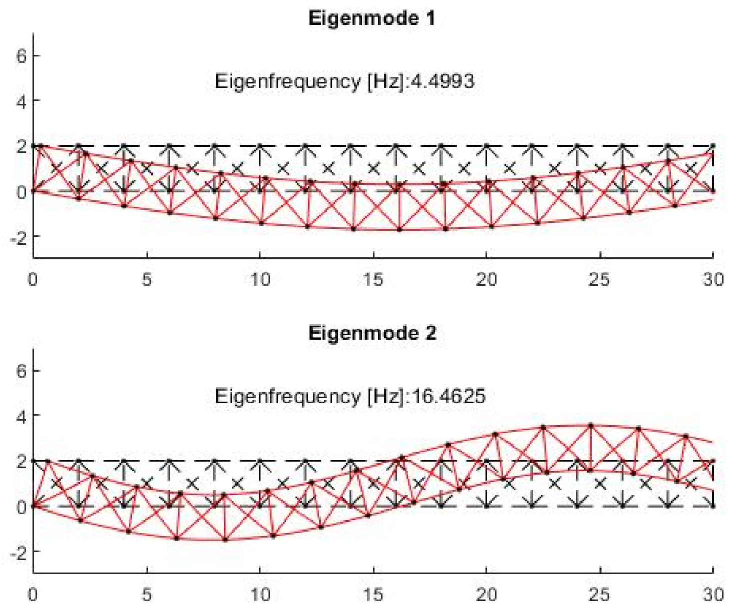


Figure 3.25: Illustration of the first two eigenmodes for a bridge spanning 30 metres.

In the *Sétra Footbridges Assessment of vibrational behaviour of footbridges under pedestrian loading* by Sétra (2006), the frequency range of pedestrians walking cross a bridge is around 2 Hz. Higher frequencies can occasionally be of interest, for example if people run over the bridge. In Table 2.3 in Sétra's Technical guide for footbridges (Sétra, 2006) an eigenfrequency above 5 Hz is considered to be in range 4, and the risk of resonance can be neglected.

Since this is a preliminary design and the vibrations investigated here are mainly an issue in SLS, it is assumed that the calculated eigenfrequency of 4.50 Hz will not cause any major problems. Therefore, no further investigations regarding the eigenfrequencies of the bridge will be conducted at this stage.

4 Part III: Communication

When communicating a design and its construction procedures, the methods used to describe the design are of great importance. This is especially important when different aspects of the design must be understood by people with varying prior knowledge. If complex calculations or text with technical language is handed to someone without the relevant prior knowledge, important information might be lost. In this third part, the research question regarding how to communicate the bridge concept to the different people working with the bridge is explored.

4.1 Target groups

To make it possible to determine what methods of communication are appropriate, different target groups have been identified. These groups have been defined based on education, technical knowledge and experience.

Senior engineers

In this context, someone is considered a senior engineer if they have an education equivalent to a Swedish bachelor's degree in civil engineering and have some experience designing bridges. This group is assumed to have some knowledge of methods and programmes commonly used for performing and presenting calculations.

Project leaders

An on site project leader is assumed to have some theoretical knowledge about the building process and experience from building several bridges in similar contexts. An understanding of drawings and some technical language is assumed.

Volunteers from the village

In addition to the two previous groups, a group of volunteers from local communities is expected to participate in the building process. It is assumed that these persons have little to no previous experience of building bridges and no relevant technical education.

4.2 Communication methods

To communicate the design concept and the erection process to the different target groups, three different methods of communication will be used. These methods are drawings, models and a construction manual.

4.2.1 Drawings

Drawings can be used to show the structure in a number of different scales and levels of detail. They are often used to show the dimensions of elements and how the different elements in the structure are located in relation to each other. Since drawings are two dimensional representations of three dimensional objects, they can sometimes be difficult to read and require the reader to implicitly understand how the information from different drawings fit together. Therefore, the drawings will mainly be used to communicate the concept to senior engineers and project leaders. Two types of drawings have been produced. Concept drawings showing an overview of the structure and detailed drawings showing the dimensions of a module and all its parts.

Concept drawings of the design can be seen in Figure 4.1 and Figure 4.2. Here the idea of the design is communicated and an understanding of the global layout of the structure is gained.

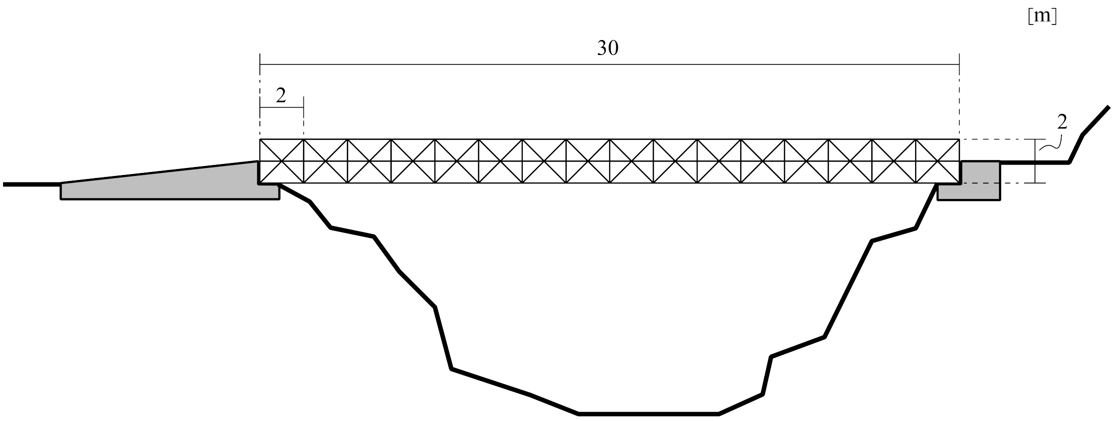


Figure 4.1: Example drawing of a bridge with a span of 30 meters.

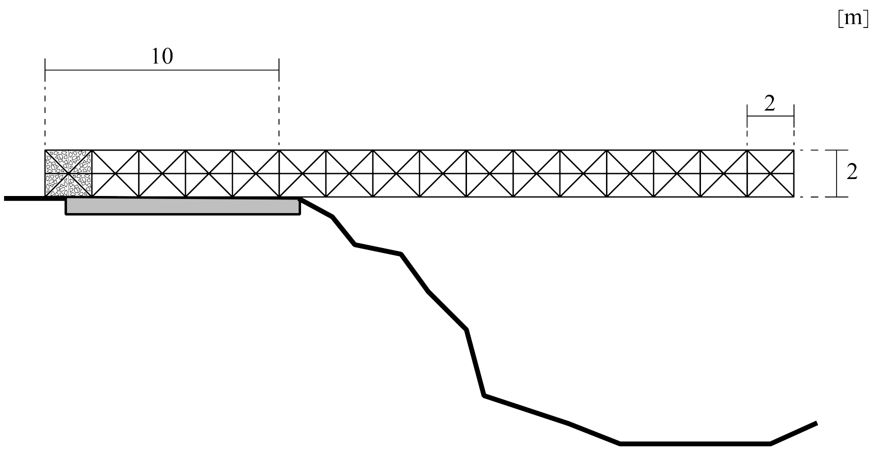


Figure 4.2: Example drawing of the erection of a 30 meter bridge.

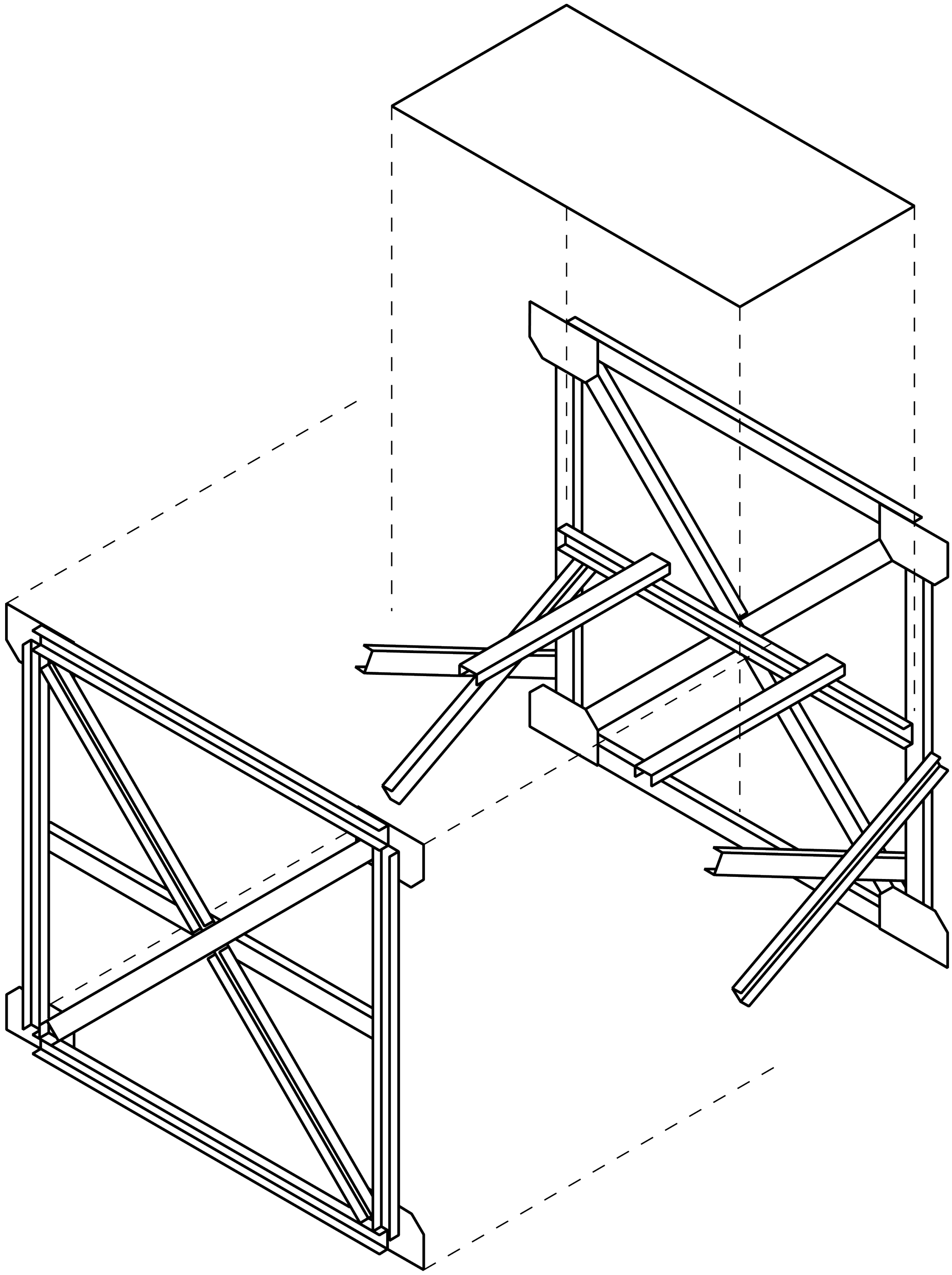


Figure 4.3: Illustration of one module showing how the different parts are connected.

To complement these conceptual drawings, detailed drawings are made. In these, length of the elements, connections and drilled holes are presented. These drawing are necessary when the bridge is to be constructed, and can be seen in Figure 4.4 to Figure 4.14.

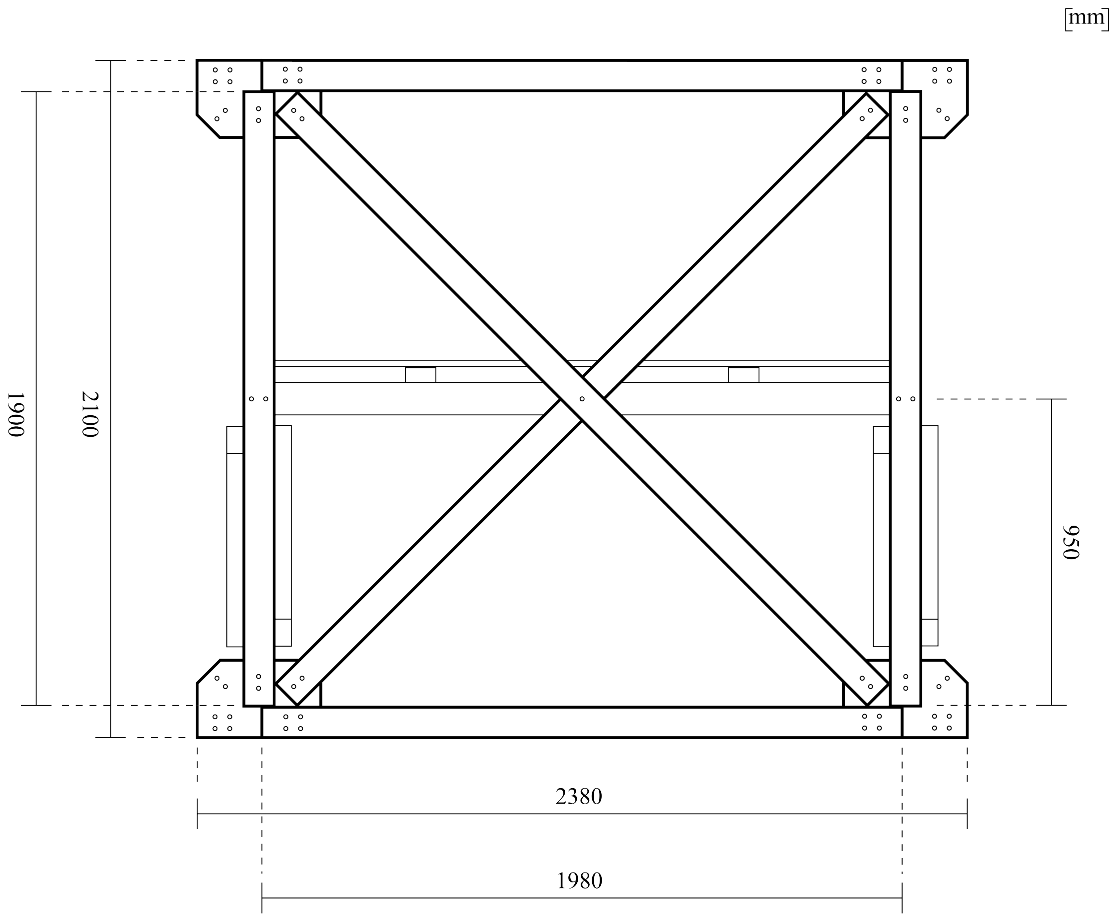


Figure 4.4: Elevation of a module with measurements.

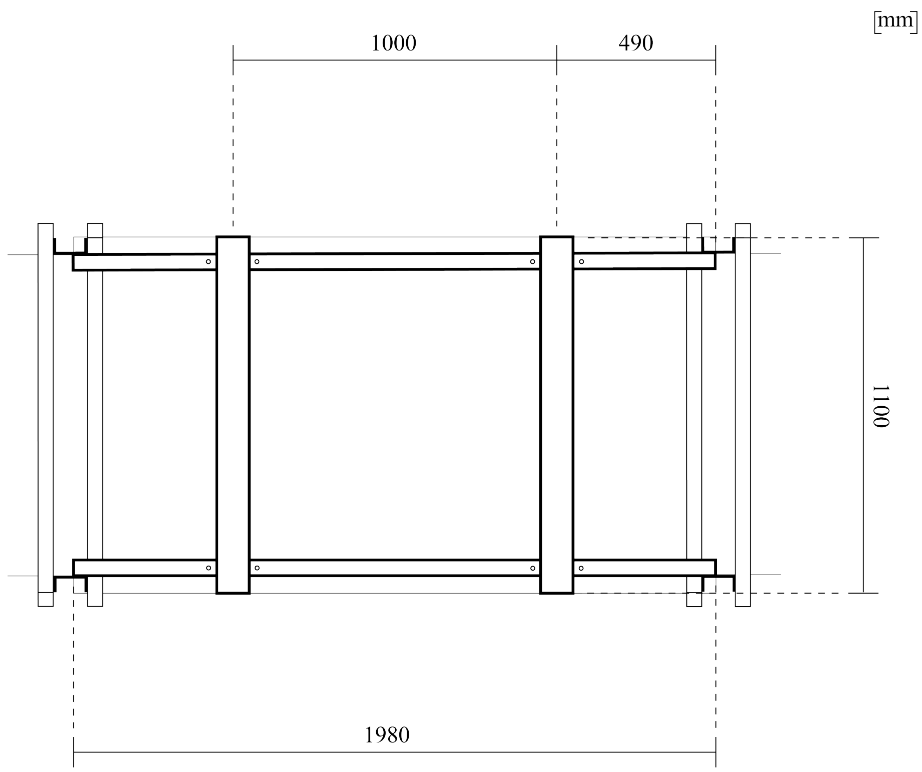


Figure 4.5: Plan of a module with measurements.

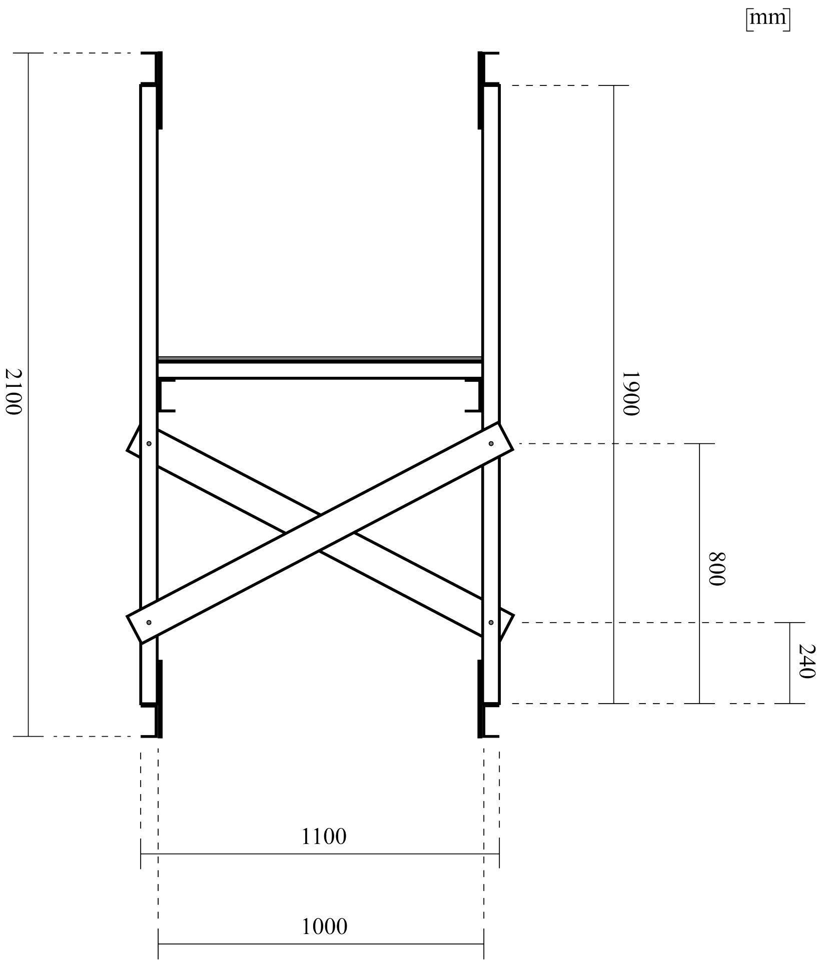


Figure 4.6: Cross section of the bridge with measurements.

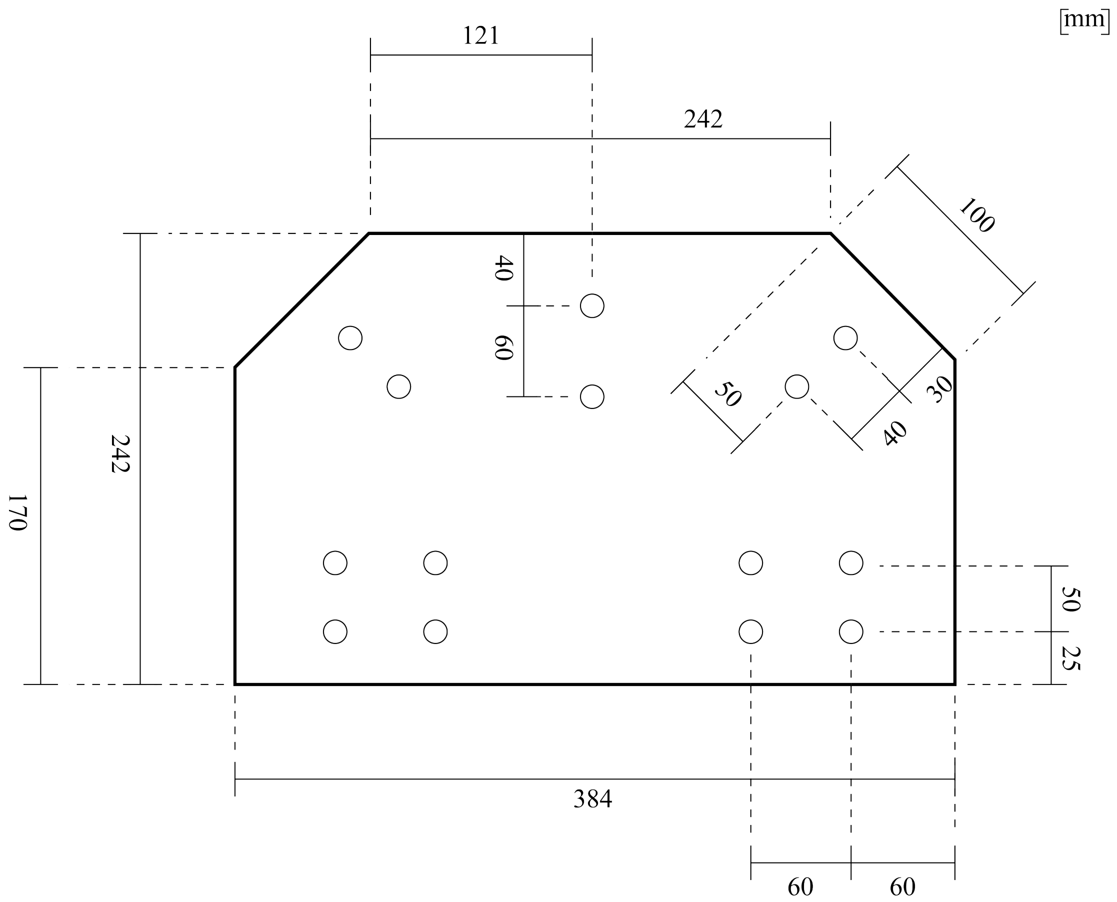


Figure 4.7: Drawing of a connection plate for M16 bolts.

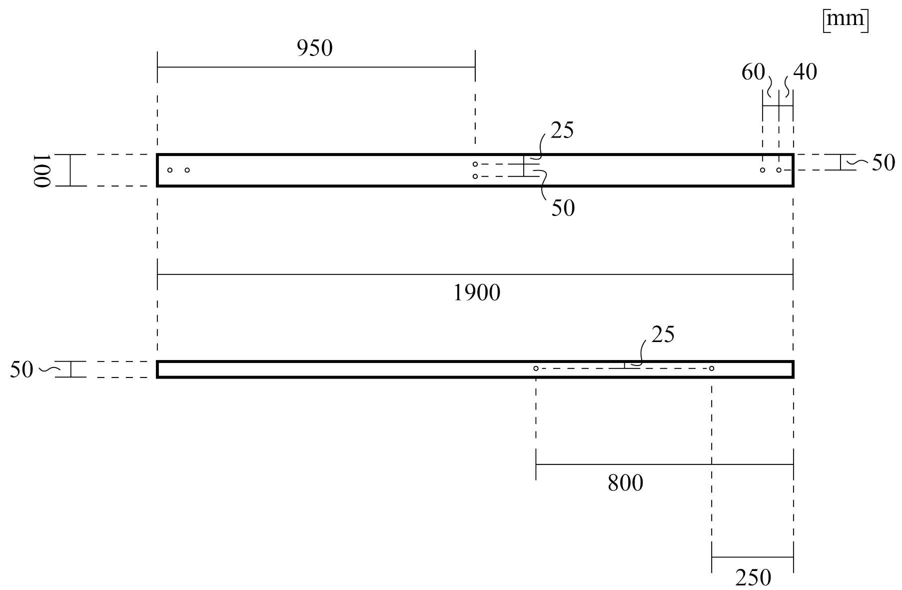


Figure 4.8: Drawing of a vertical element in the module with measurements assuming that M16 bolts are used.

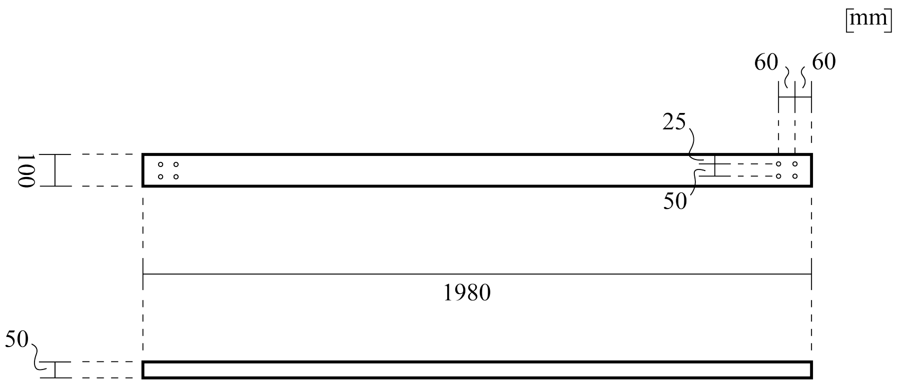


Figure 4.9: Drawing of a horizontal element in the module with measurements assuming that M16 bolts are used.

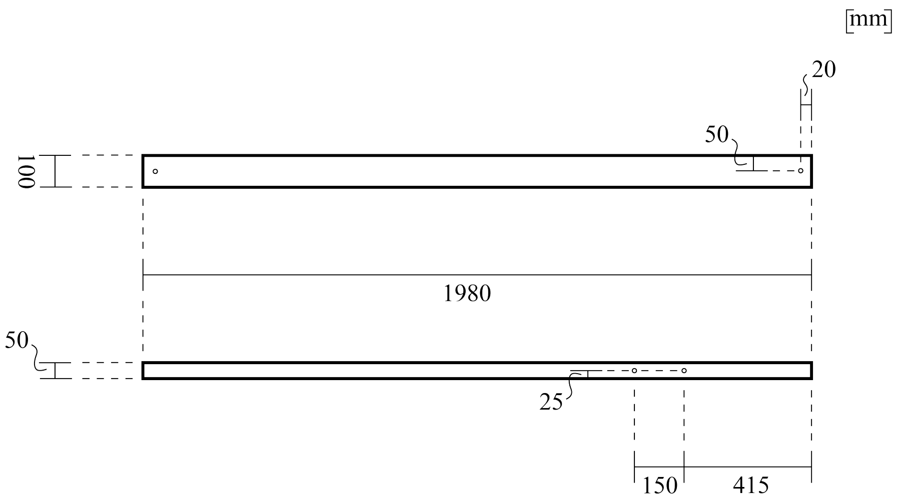


Figure 4.10: Drawing of a horizontal element in the middle of a module supporting the cross beams with measurements.

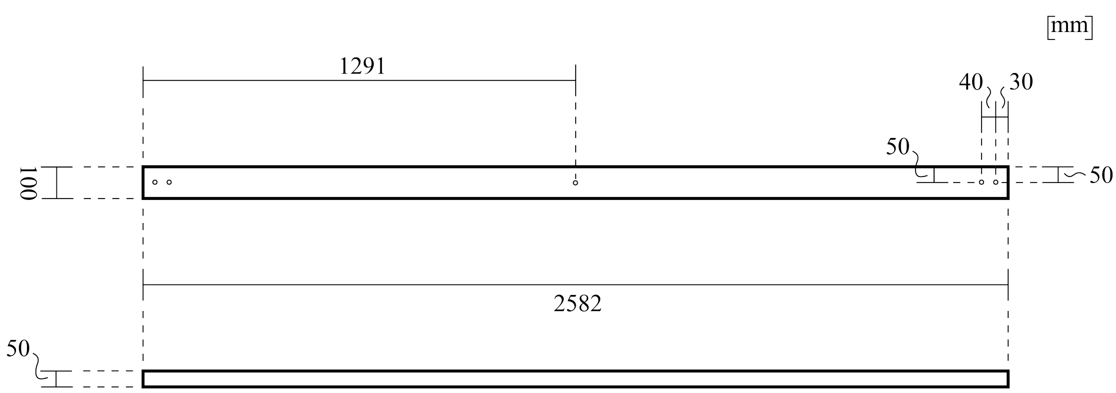


Figure 4.11: Drawing of an outer diagonal in a module with measurements assuming that M16 bolts are used.

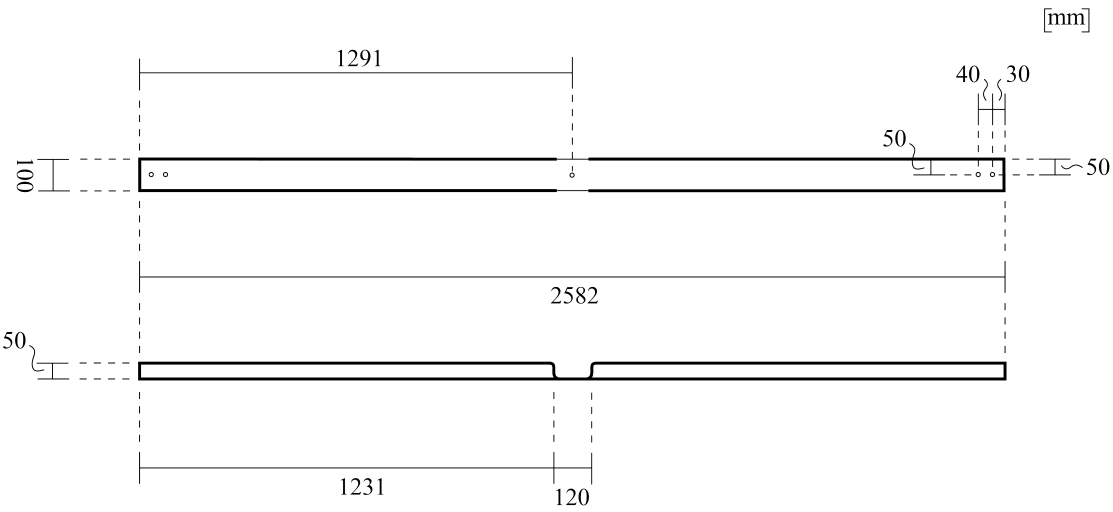


Figure 4.12: Drawing of an inner diagonal in a module with measurements assuming that M16 bolts are used.

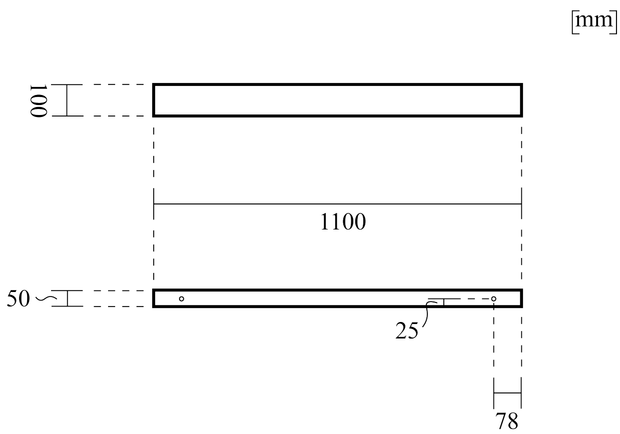


Figure 4.13: Drawing of a cross beam in a module with measurements.

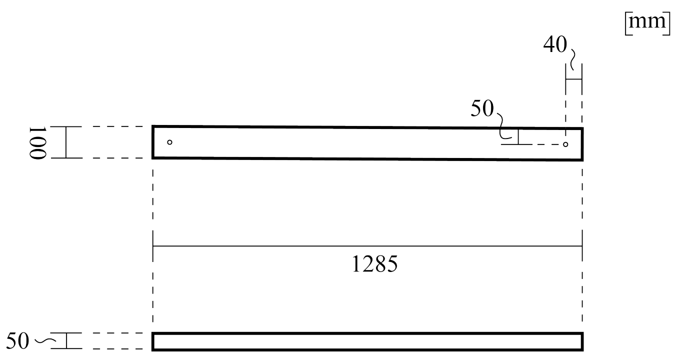


Figure 4.14: Drawing of a diagonal in the stabilising structure beneath the walkway with measurements.

4.2.2 Models

Drawings can communicate a lot about a structure, but it can sometimes be difficult to visualise how the structure looks in reality from drawings only. In these cases, models can be used to give a better understanding of how all different parts fit together.

Models can both be physical and digital. Physical models have the advantage that they are physical objects. This, among many other things, creates the possibility of touching the structure to get an intuitive understanding of how different parts interact with each other and how the structure behaves in different situations. Physical models can also be easier to understand than digital models since they can be examined without any knowledge about the specific software used to create the digital model.

Digital models, on the other hand, can be very versatile and easy to adapt to different demands if they are created in an appropriate way. They can also include more details than a physical model normally can, since they are not limited by scale in the same way. The downside with digital models is that they require access to specific computer programs, which can be both expensive and complicated to work with.

Since the qualities of both types of models are useful to communicate different aspects of the bridge concept, both will be used here.

Digital model

To give the senior engineers a simple way to visualise the bridge and get a list of all elements needed, a parametric digital model has been developed. By inputting the length of the span, a 3D model of the bridge is generated and the number of different elements needed for the bridge is calculated. In Figure 4.15 an illustration of how the parametric model works can be seen. In Figure 4.16 an example of the output from the model is shown.

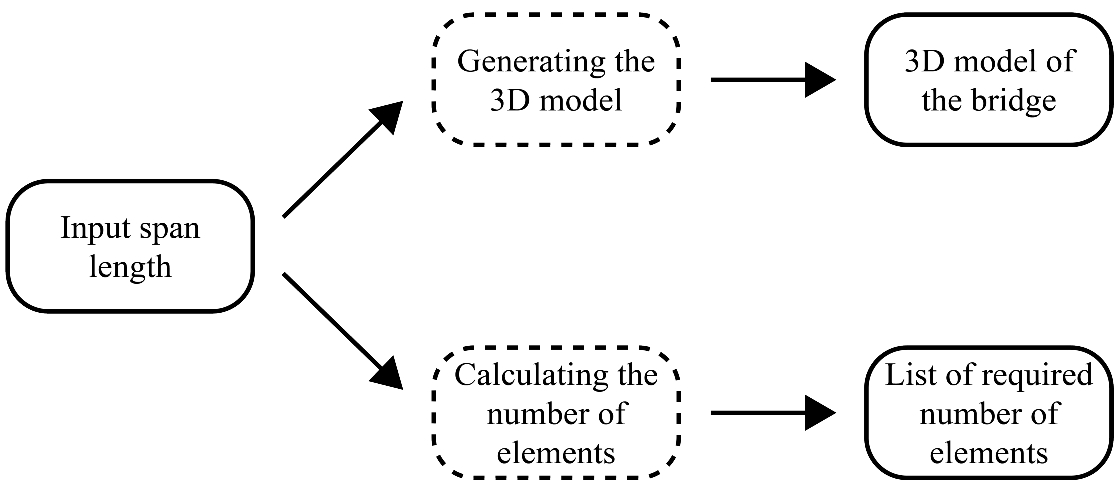


Figure 4.15: Flowchart showing how the parametric model works.

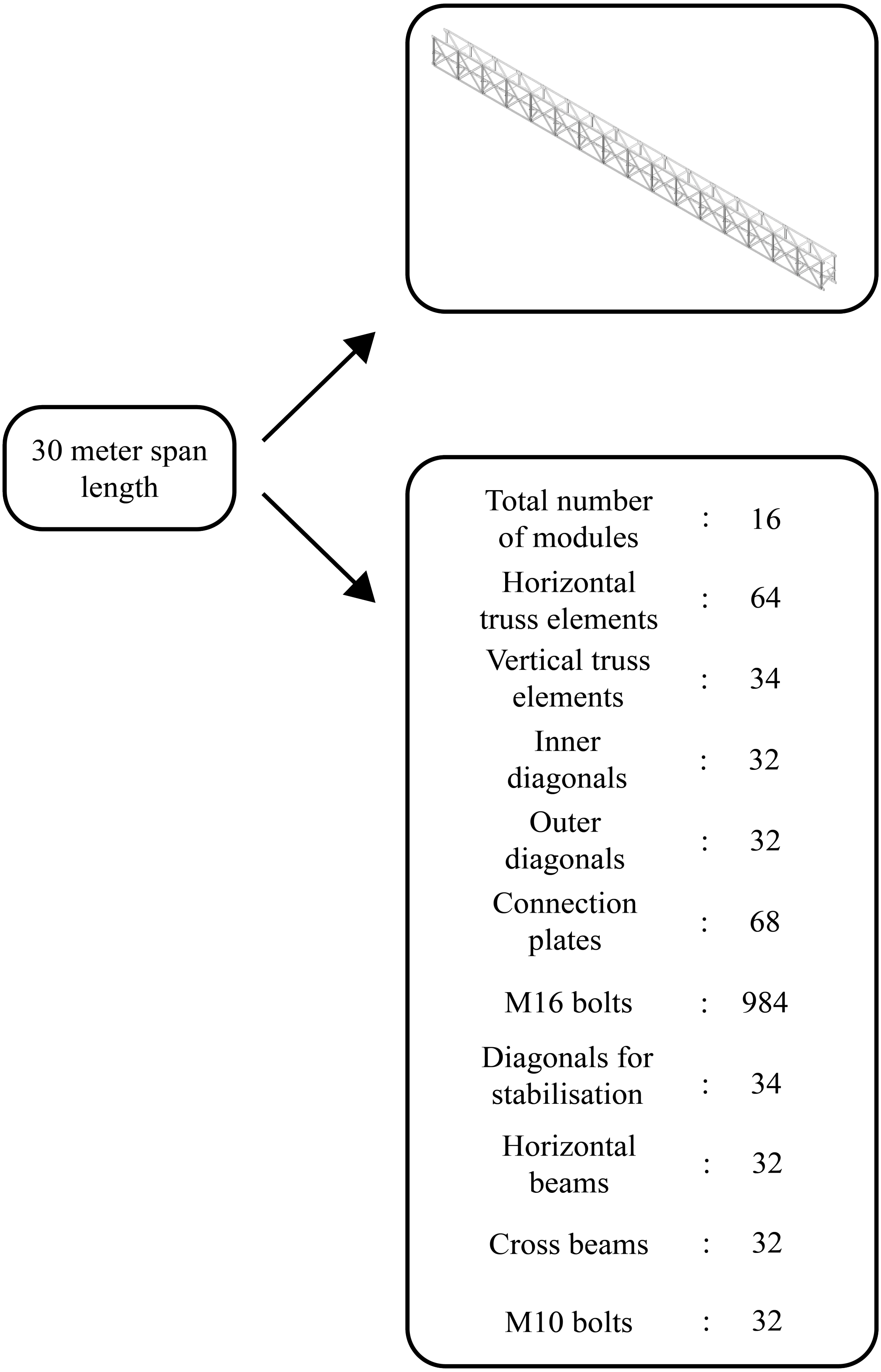


Figure 4.16: Illustration showing the output of the parametric model for a span of 30 meters.

Physical model

A physical model consisting of two modules has been built. One module has been assembled to show how a finished module looks, while the other is left in pieces so it can be used to illustrate the erection process. The primary aim of this model is to give the volunteers from the village a better understanding of the erection process by being able to go through it step by step. Pictures of the model can be seen in Figure 4.17 to Figure 4.20.

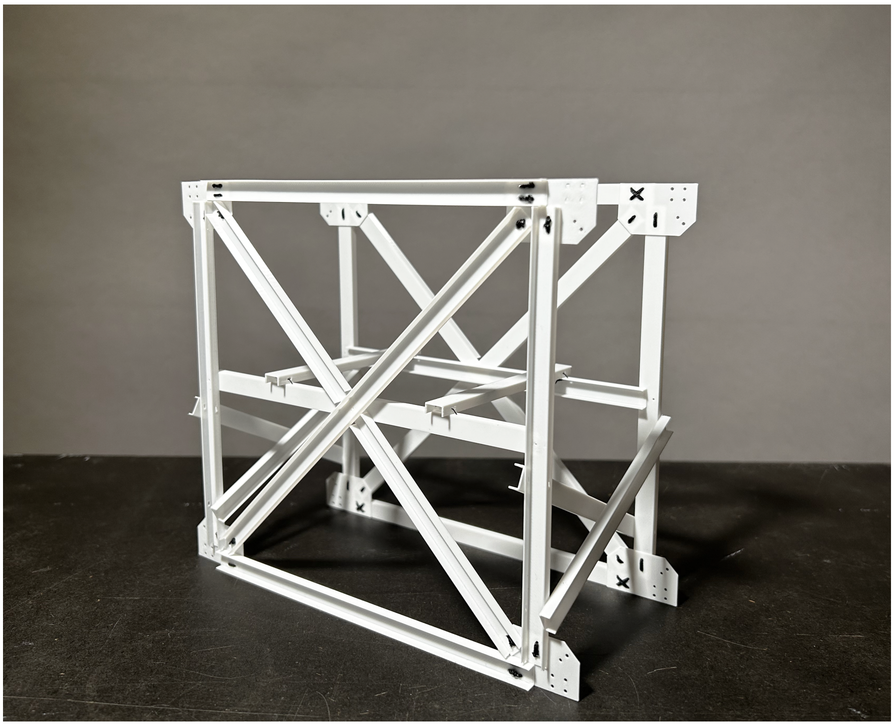
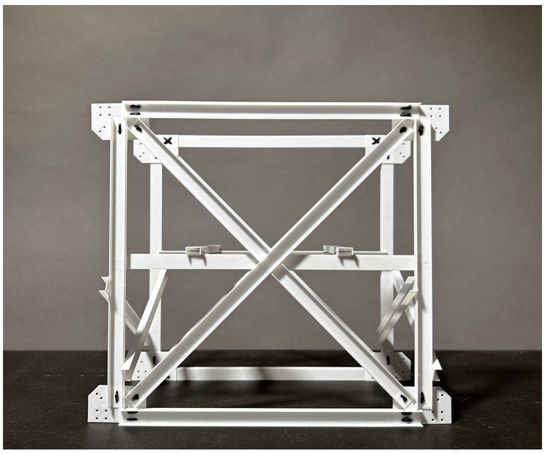


Figure 4.17: Picture of the physical model showing the finished module at an angle.



(a) Elevation.

(b) Cross section.

Figure 4.18: Pictures of the physical model showing the finished module.

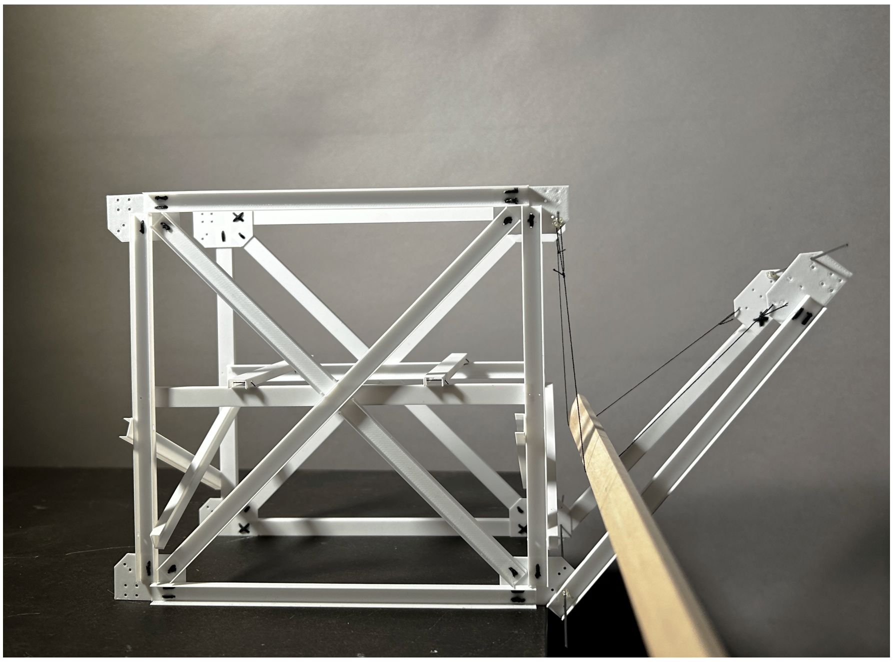


Figure 4.19: Picture of the physical model showing the lower horizontal elements being rotated into position.

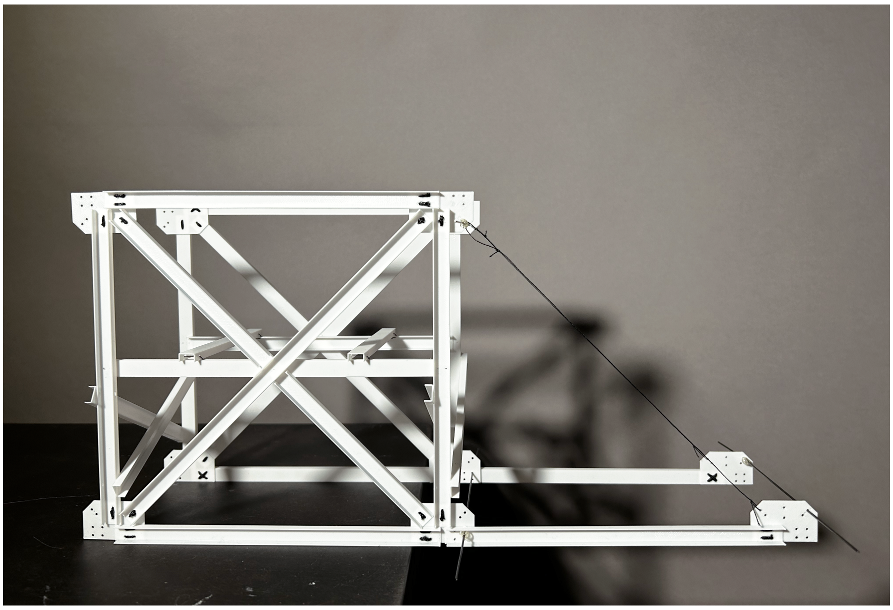
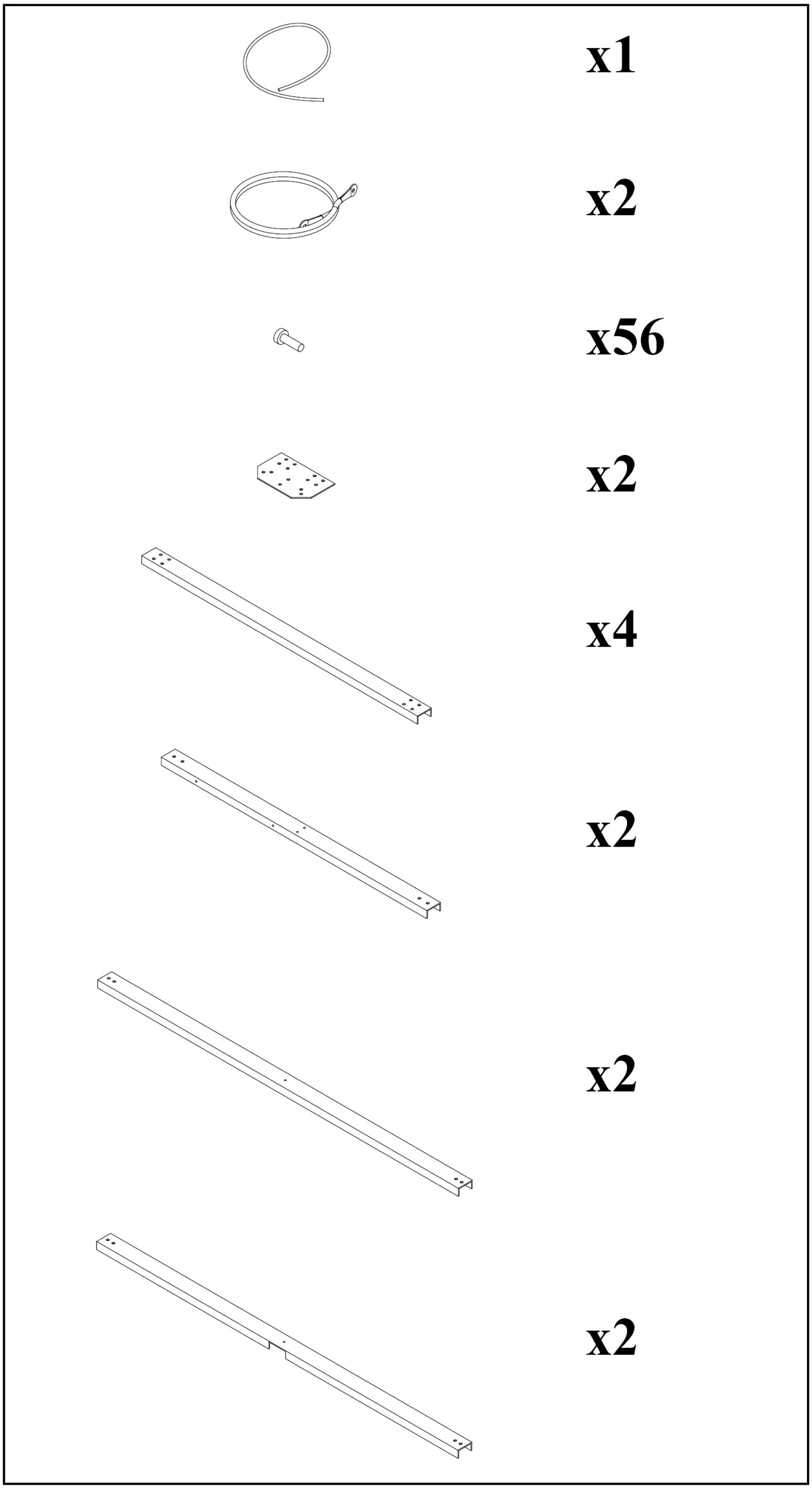


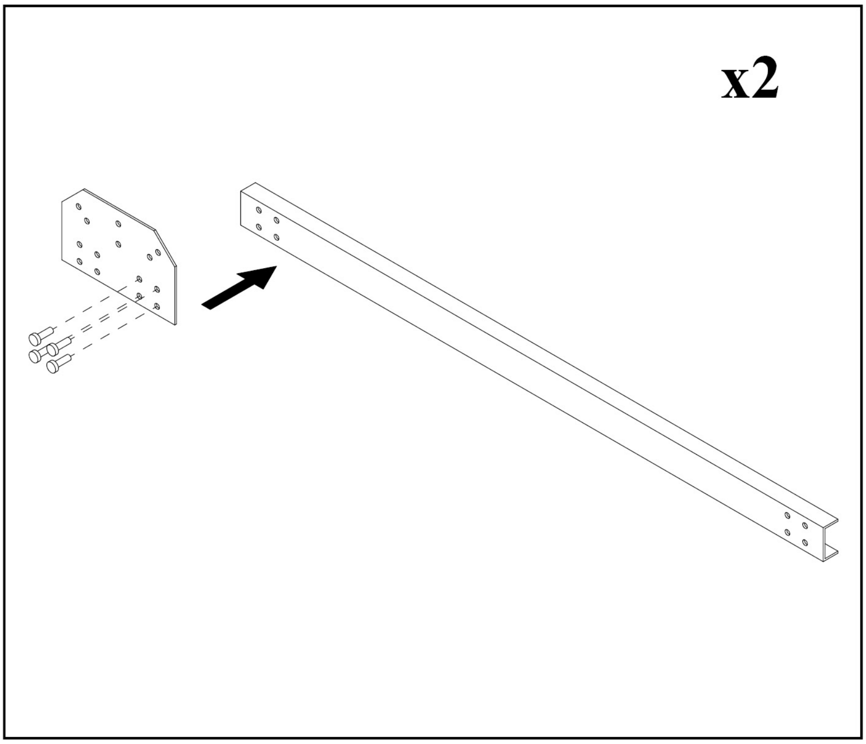
Figure 4.20: Picture of the physical model showing part of the new module hanging from the temporary diagonals.

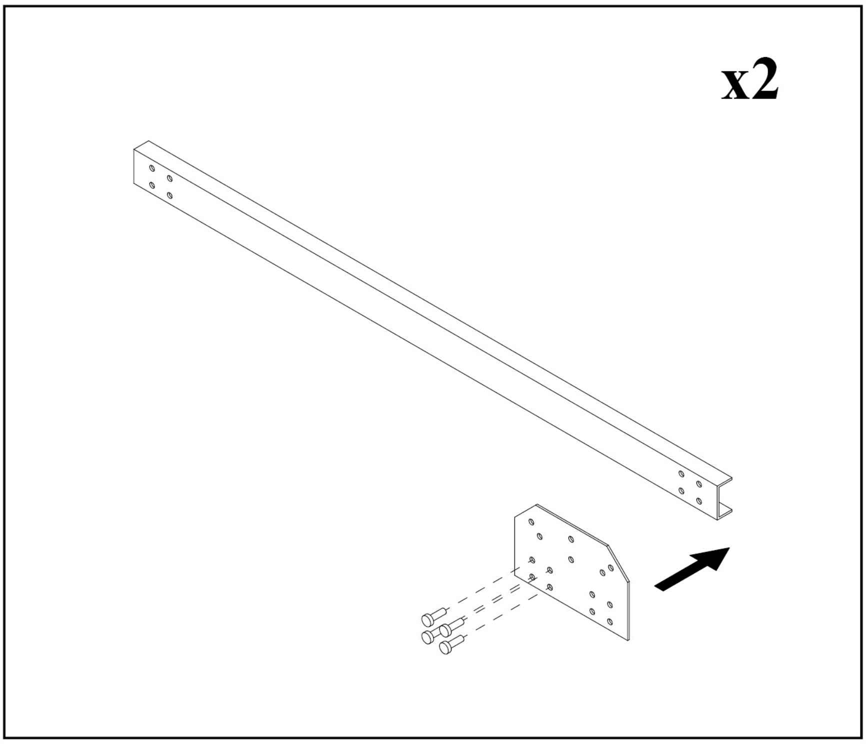
4.2.3 Building manual

By taking inspiration from the assembly manuals for IKEA furniture, a draft of a building manual is designed. The idea is, just as for IKEA's manuals, that all relevant parts are displayed at the beginning and then every step in the assembly process is illustrated to ensure that people without technical knowledge can build the structure. On the following pages, the method for adding a module at the end of the cantilever during the erection process is shown.


x1
x2
x56
x2
x4
x2
x2
x2

1.





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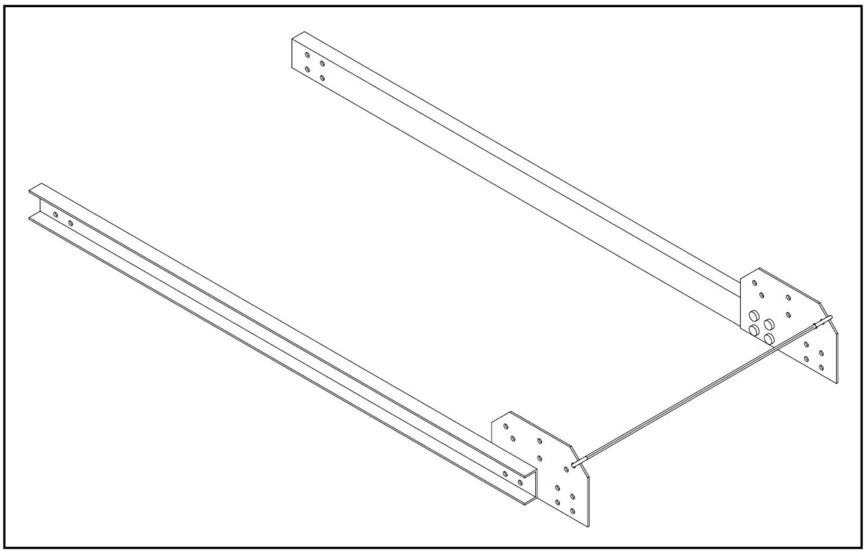

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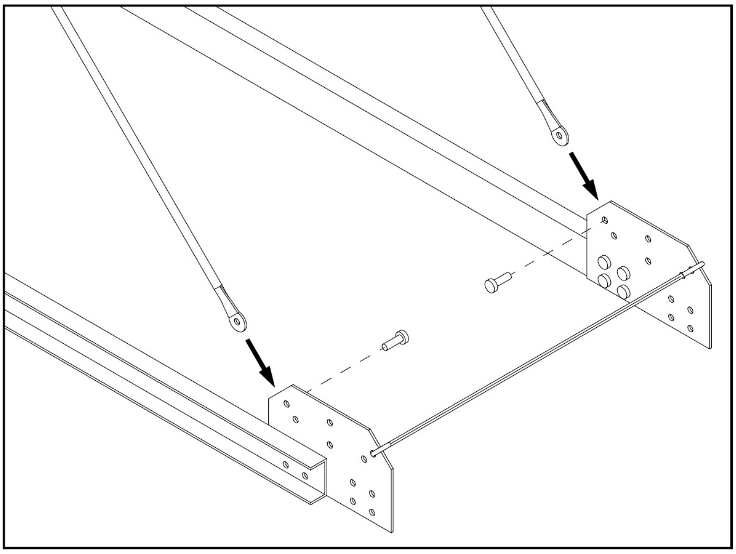

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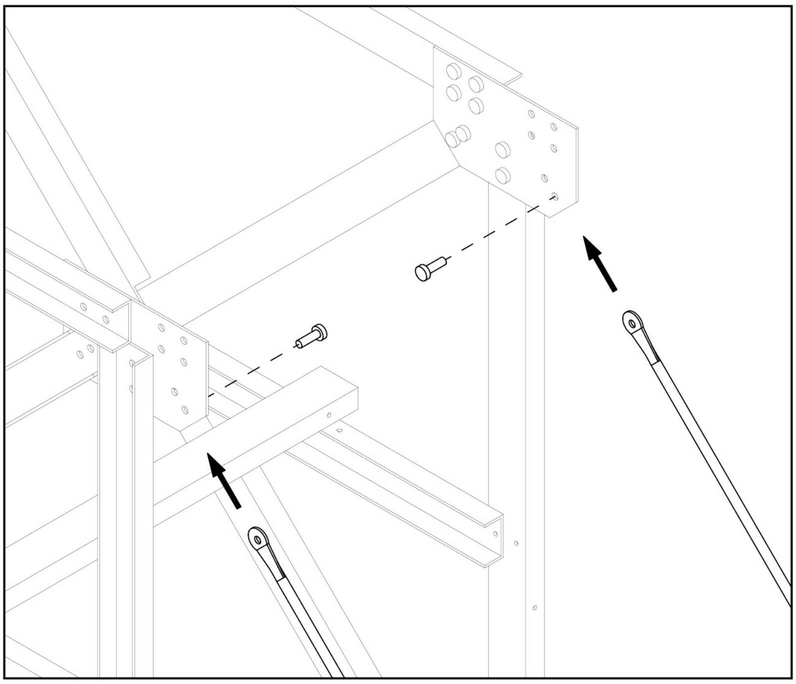

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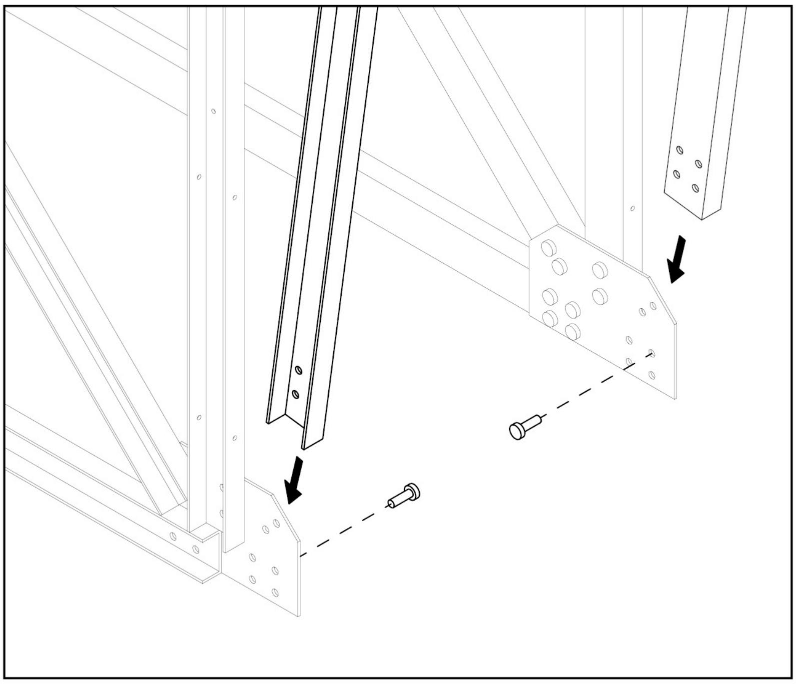

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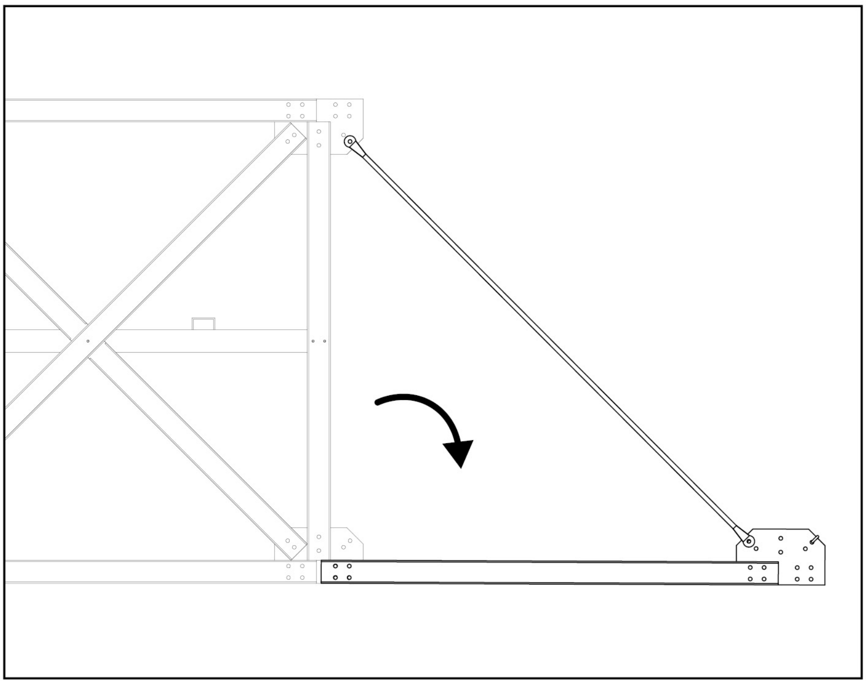

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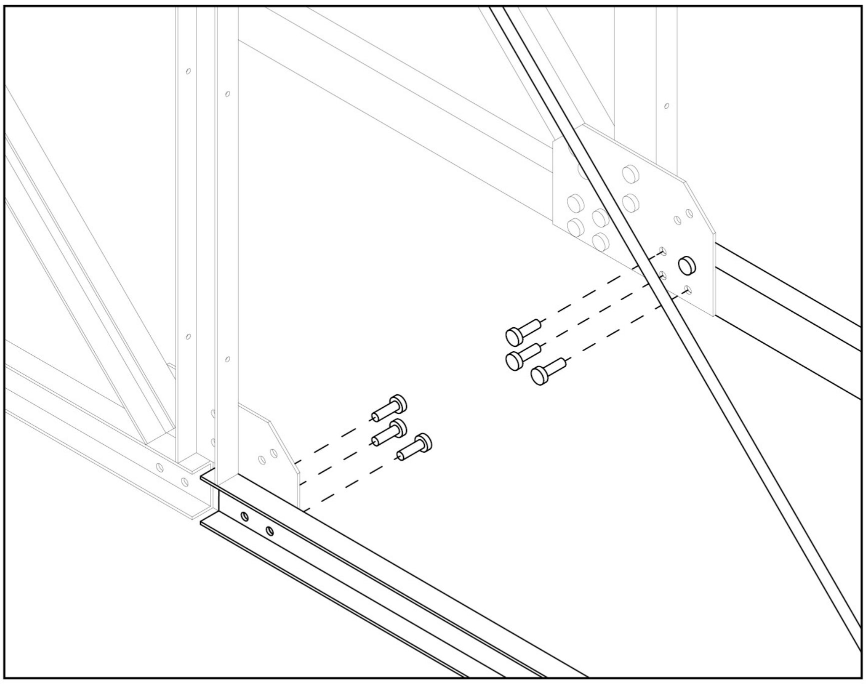

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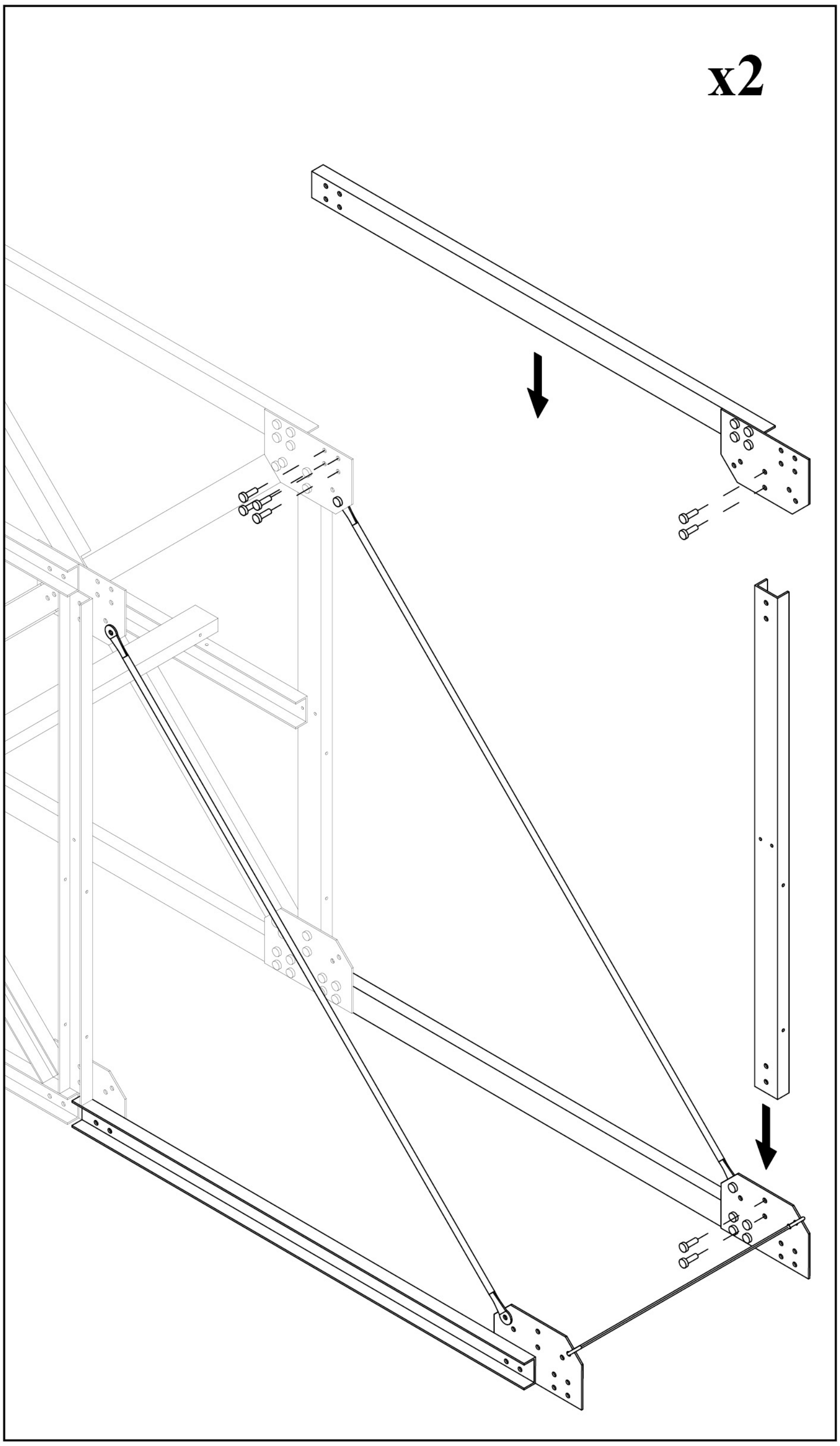

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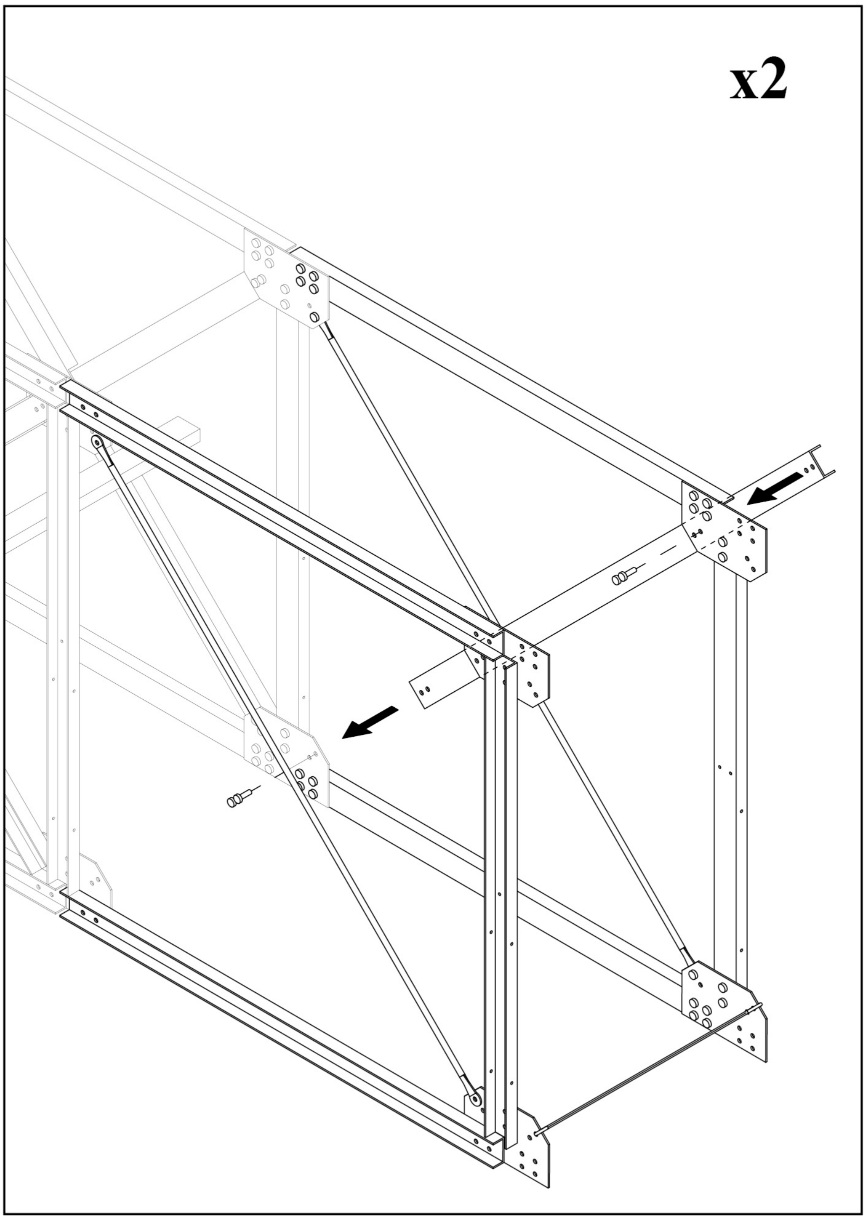

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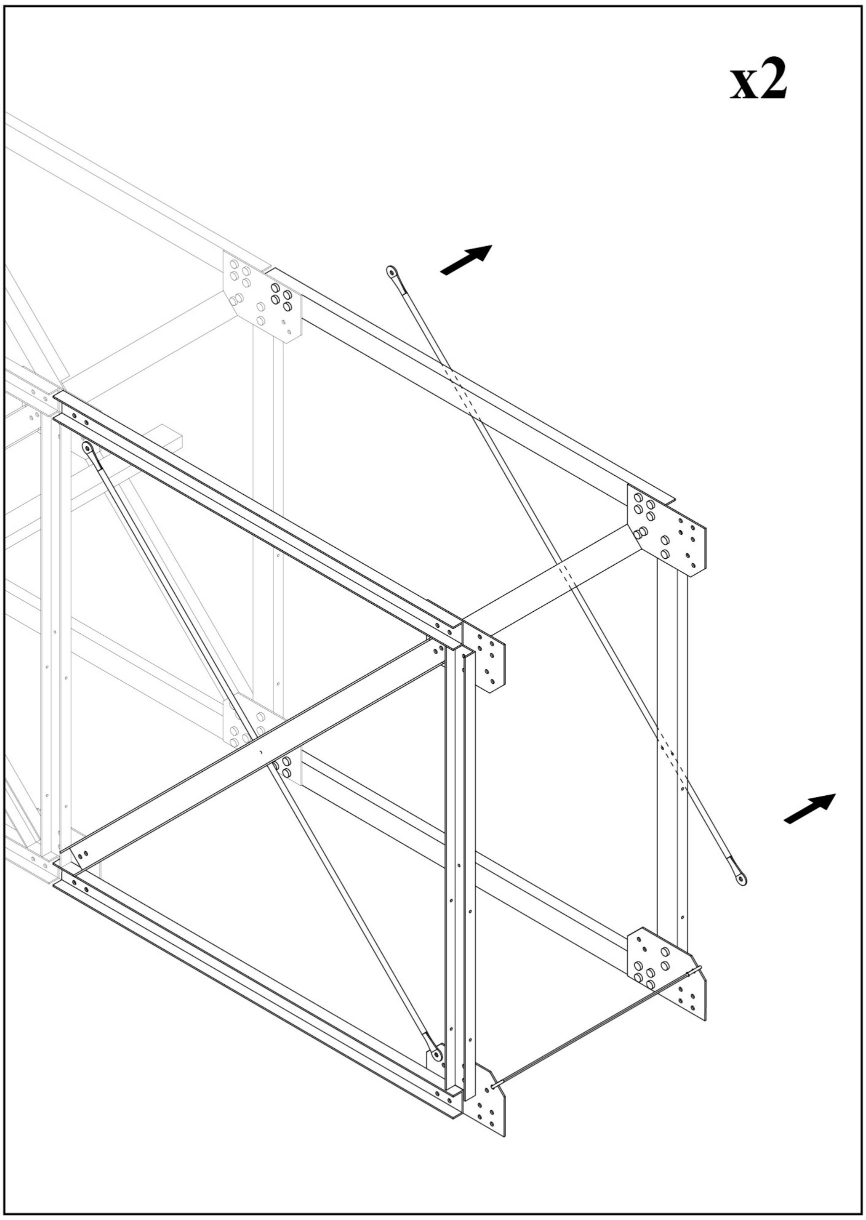

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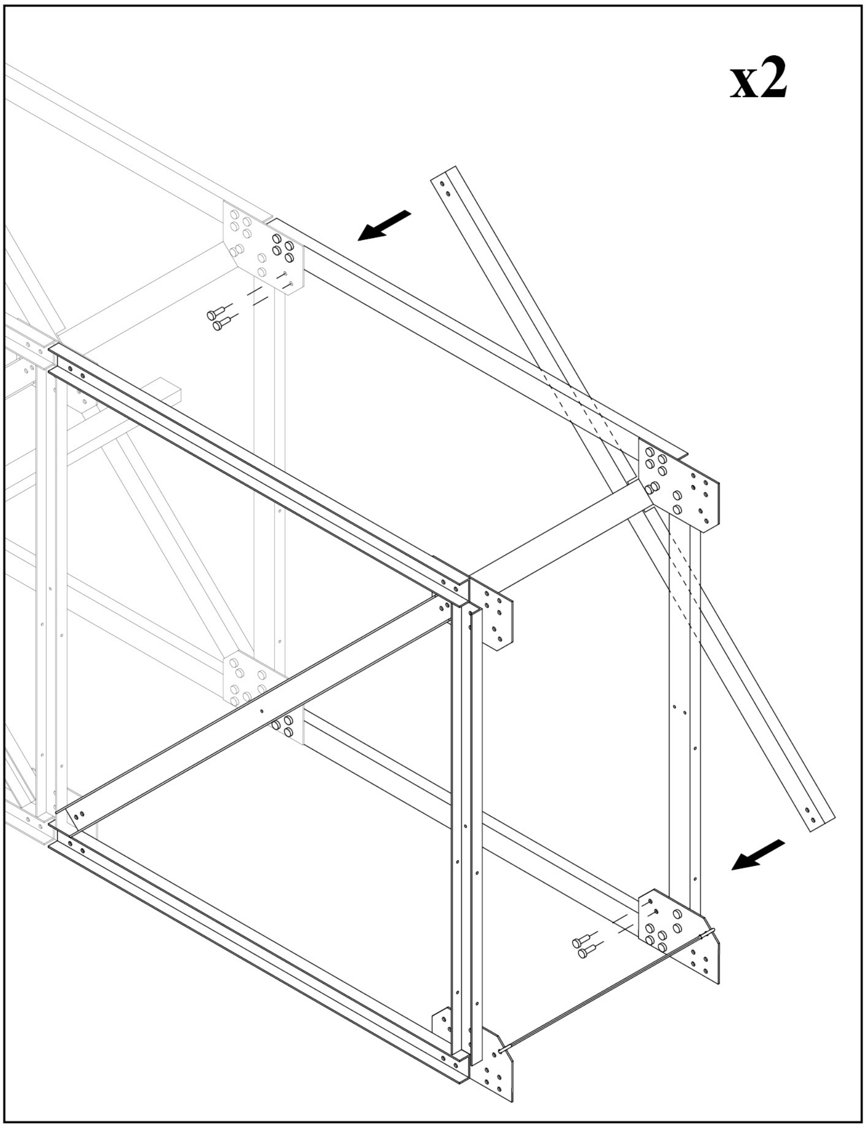

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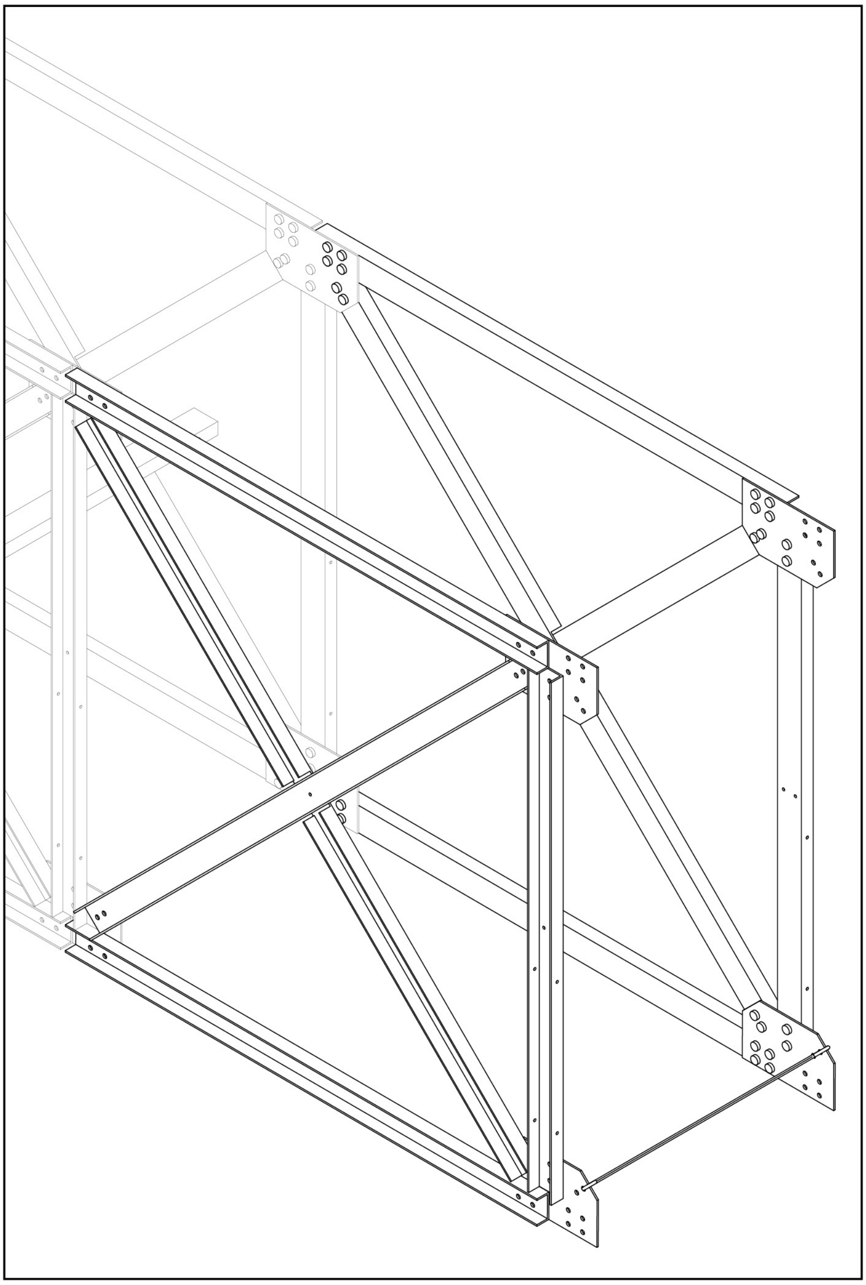

4.2.4 Risk assessment

When building a structure of this size and complexity with a large number of people involved, the safety on site must be in focus. To ensure that everybody is aware of the risks and how to prevent them, a risk analysis should be performed. In Table 4.2 an example of an outline of a risk analysis is shown. The critical events are listed and the consequences of these are described. The probability of each event and the severity of the consequence is multiplied to find the risk. In the rightmost column potential countermeasures are listed. The description for the scores are found in Table 4.1.

The same method is used to evaluate each step in the building manual. In Table 4.3 a risk analysis including the critical events associated to the steps is shown.

Table 4.1: Description of scoring used in risk analyses.

Probability	Consequence	Risk judgement
4. Almost certain	4. Very serious	10-16 High risk
3. Likely	3. Serious	6-9 Medium risk
2. Less likely	2. Small	1-5 Low risk
1. Unlikely	1. Insignificant	

Table 4.2: Example of risk analysis.

Phase	Critical event	Consequence description	Probability	Consequence	Risk (p*c)	Measures
Construction	Deviation from safety procedures	Injuries and damage to material	3	4	12	Safety brief and safety representatives on site
Usage	Heavy traffic	Potential collapse	3	4	12	Restricted width of bridge and/or Jersey barrier

Table 4.3: Risk Analysis for each step presented in the building manual.

Step (building manual)	Critical event	Consequence description	Probability	Consequence	Risk (p*c)	Measures
1	Mounting of plate	Pinching	2	1	2	Safety brief
2	Mounting of stabilizing wire					
3	Mounting cable to plate	Pinching	2	1	2	Safety brief
4	Mounting cable to end of cantilever	Sudden tug in cable	3	3	9	Safety brief
4	Mounting cable to end of cantilever	Falling off bridge	2	4	8	Safety net or harness
5	Mounting elements for rotation	Injuries from crushing	2	3	6	Clear instructions
5	Mounting elements for rotation	Falling off bridge	3	4	12	Safety net or harness
6	Uncontrolled rotation	Injuries from crushing or sudden tug	2	3	6	Clear instructions and tools for controlling the rotation from a distance
6	Uncontrolled rotation	Falling off bridge	3	4	12	Safety net or harness
7	Fastening of bottom elements	Falling off bridge	2	4	8	Safety net or harness
8	Mounting remaining elements	Injuries from crushing	2	3	6	Clear instructions
8	Mounting remaining elements	Falling off bridge	3	4	12	Safety net or harness
9	Mounting outer diagonal	Injuries from crushing	2	3	6	Clear instructions
9	Mounting outer diagonal	Falling off bridge	2	4	8	Safety net or harness
10	Removing cable	Falling off bridge	2	4	8	Safety net or harness
11	Mounting inner diagonal	Injuries from crushing	2	3	6	Clear instructions
11	Mounting inner diagonal	Falling off bridge	2	4	8	Safety net or harness

5 Results

In Chapter 1.3 four research question are stated. In Part I, II and III information is gathered, a bridge concept is developed and methods for communicating the concept are explored to find answers to these research questions. In this chapter, the results of this process are presented, and answers are given to the four research questions.

5.1 Demands on footbridges in Eastern Africa

For the first question, the demands put on a bridge in rurally isolated areas of Eastern Africa are investigated. The result in Part I and Part II implies that there are significant differences between the demands put on bridges built in industrialised parts of the world and in these isolated areas. The demands as such might be the same, but the importance each demand has in the design process is different.

The demands relevant when developing a bridge concept for rurally isolated areas of Eastern Africa, including their relative importance, are presented in Table 5.1.

Table 5.1: Description of demands, in descending priority order.

Constructability The ease to build the structure	10%
Transportability The ease of transportation of elements	10%
Reliability The trustworthiness of the bridge's cross-ability	10%
Economic sustainability The cost efficiency of the structure	8%
Adaptability The ease of adapting the structure according to site	8%
Safety The prevention of injuries, from construction to use	8%
Durability The ability to withstand hard weather	8%
Simplicity The absence of advanced techniques and equipment	7%
Service life The expected life-time of the bridge	7%
Maintenance The need for reparation and/or substitution of ingoing parts	7%
Usage The comfort of using the bridge	5%
Environmental sustainability The ecological footprint of the bridge	4%
Time The time needed to build the bridge	4%
Aesthetics The appearance of the bridge	4%

5.2 Design process

The second research question explores the design process for a bridge suitable for rurally isolated areas. With a standard engineering design process from Sweden as a starting point, an alternative design process adapted to the design challenges in rurally isolated areas has been developed.

This alternative design process starts with developing a couple of base concepts and specifying the demands on the design. The demands are then weighted against each other to divide them into two groups; filters and criteria. The most important demands becomes filters in the filtration process, and the rest becomes criteria for the evaluation matrix used in the modification phase. The filters are defined in such a way that they can be passed or not, while the criteria can be fulfilled to different levels.

In the filtration process, the base concepts are evaluated against the filters. For a concept move on from the filtration phase, it must pass all filters. The concepts that pass the filtration process are then further developed in the modification phase. They are also evaluated against each other by using an evaluation matrix with weighted criteria. The concept with the highest score at the end of the modification phase is assumed to be the most suitable concept for the given context. These load effects and capacities of this concept is finally calculated to make sure that it can withstand the relevant loads.

A flow chart describing this alternative design process can be seen in Figure 5.1.

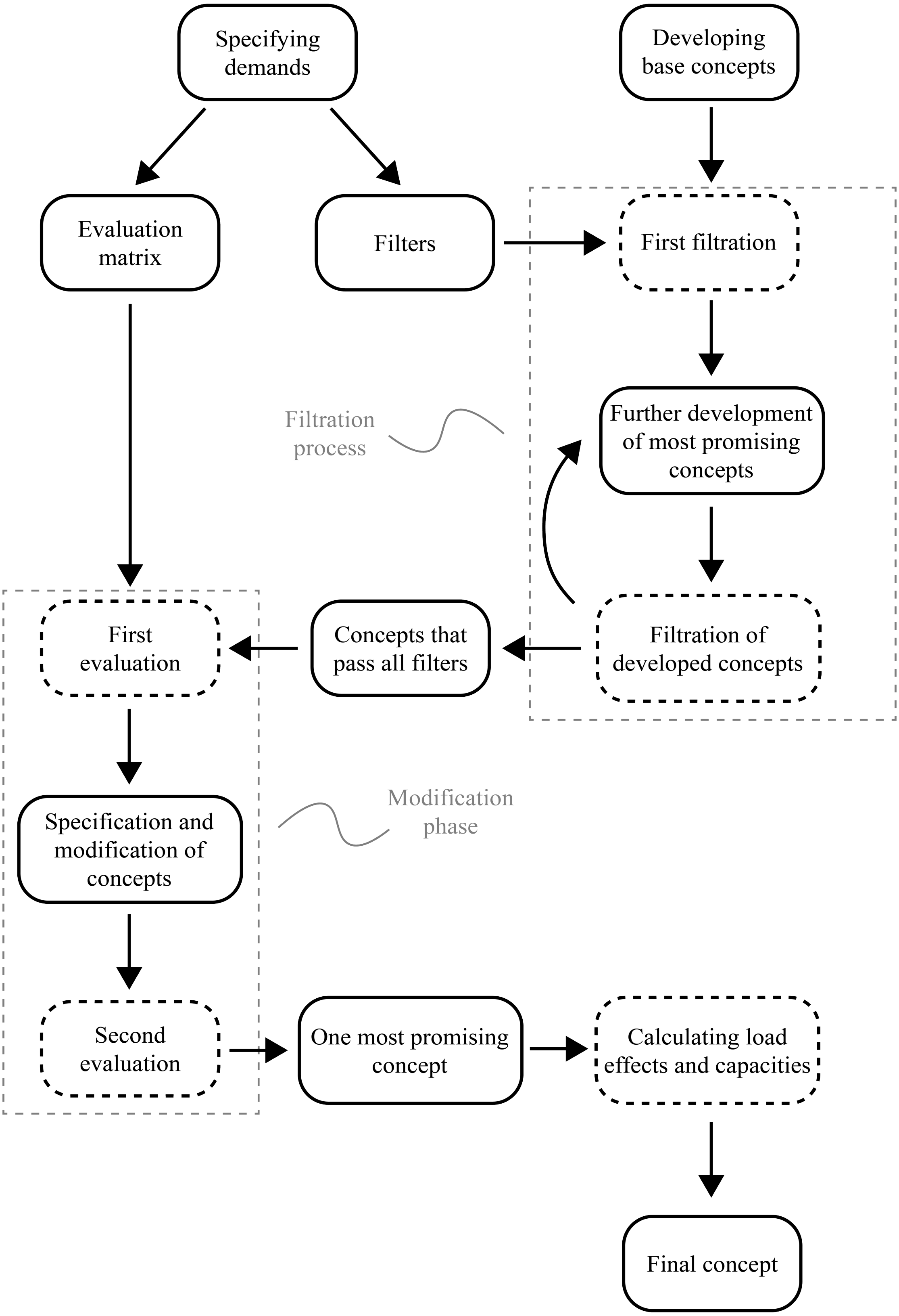

Figure 5.1: Flowchart illustrating the process implemented in Part II.

5.3 Bridge design

By using the answers to the first two questions, a bridge concept was developed to answer the third research question. The design process developed was used to find one suitable bridge concept and design some of its most important details. The final concept, a modular steel truss bridge, is found to be suitable for the context in question. The final concept can be seen in Figure 5.2 to Figure 5.6.

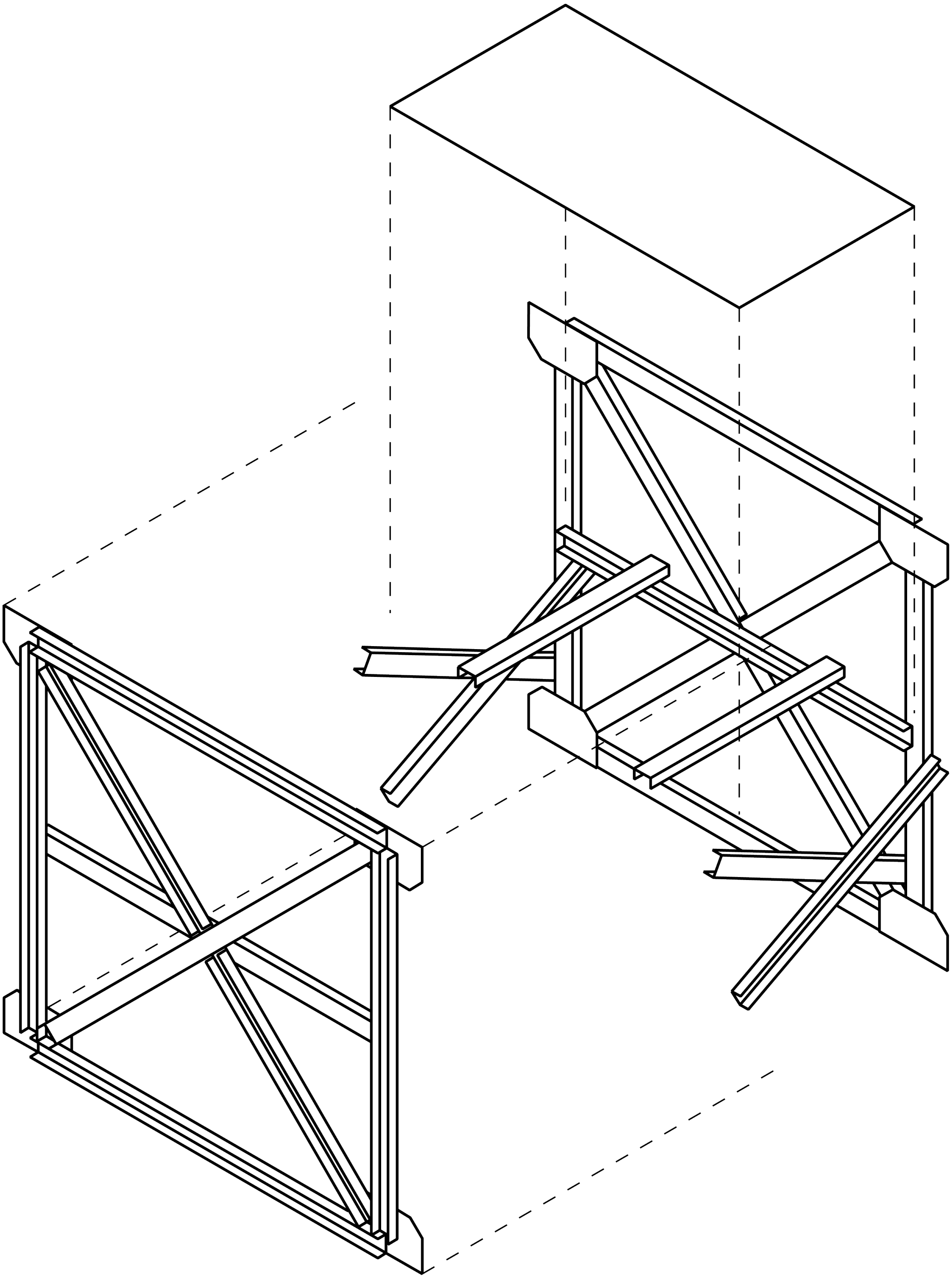

Figure 5.2: Illustration showing how the different elements in a module fit together.

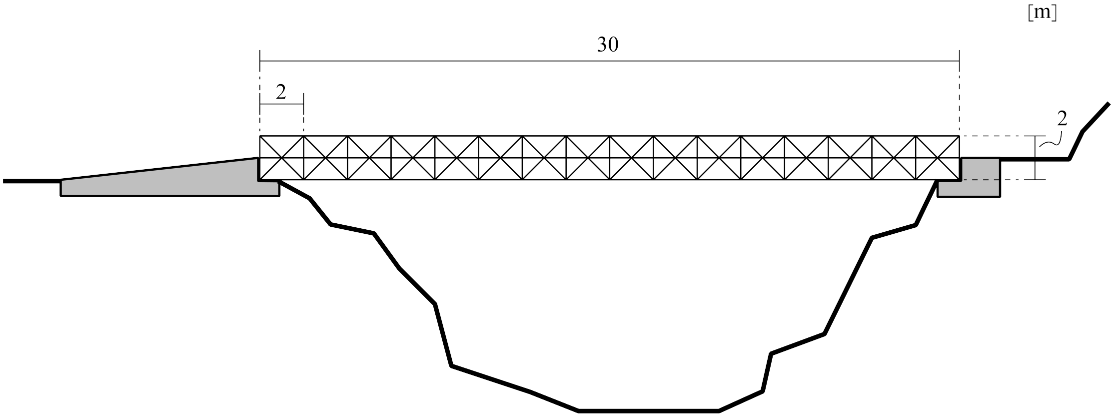

Figure 5.3: Example drawing of the bridge concept applied on a 30 meter span.

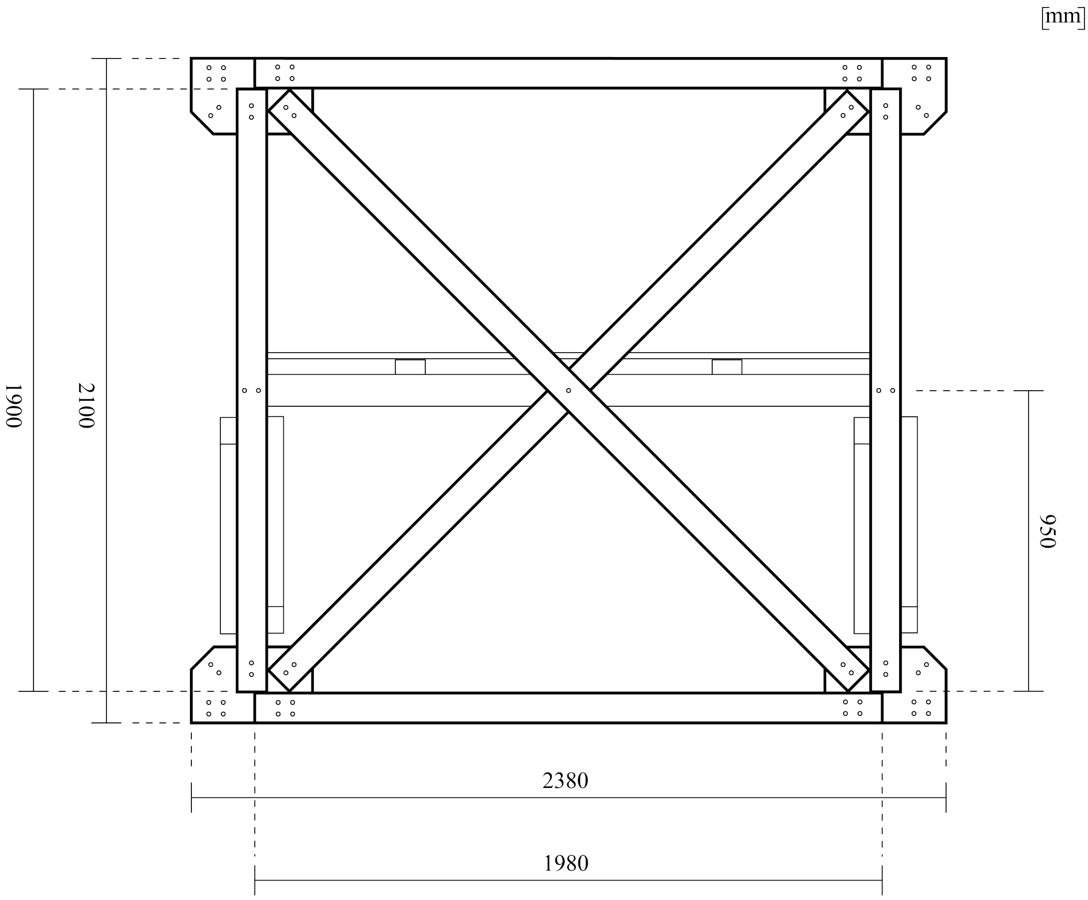

Figure 5.4: Drawing showing an elevation of a module.

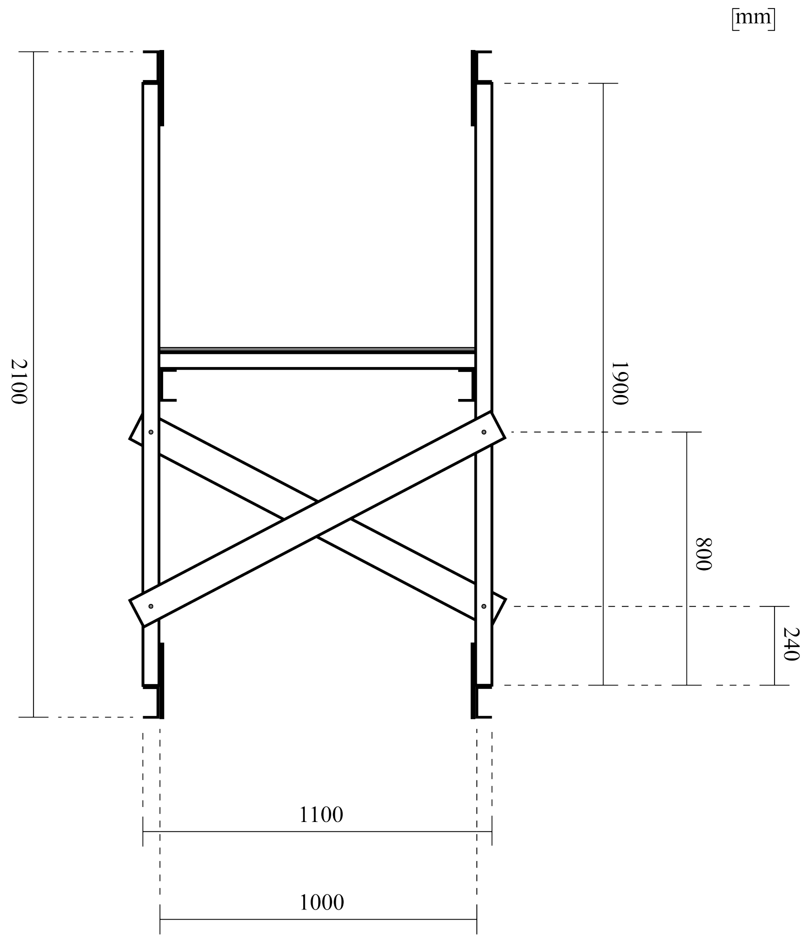

Figure 5.5: Drawing showing a section of a module.

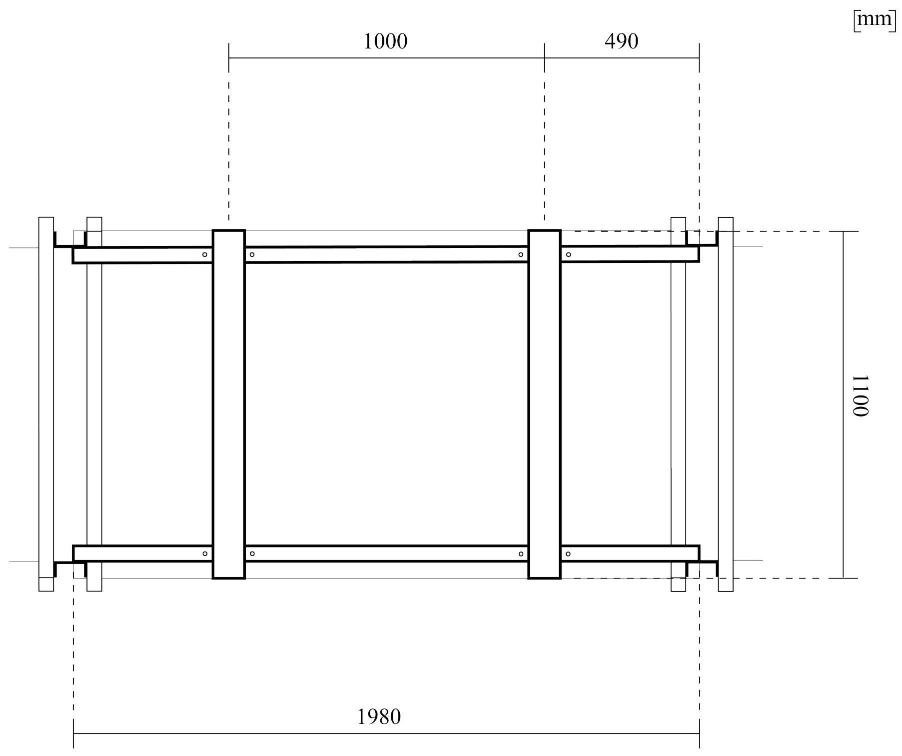

Figure 5.6: Drawing showing a plan of a module.

5.4 Communication

The final question concerns how the bridge concept can be communicated to relevant stakeholders. In B2P's case, people with a wide variety of backgrounds are involved in building the bridge, and they all need to understand different aspects of the concept for the building process to be safe and run smoothly. To ensure that everyone gets the information they need, five different methods of communication have been used. In Figure 5.7 each of the identified target groups have been paired with one or more communication methods based on their previous knowledge and experience.

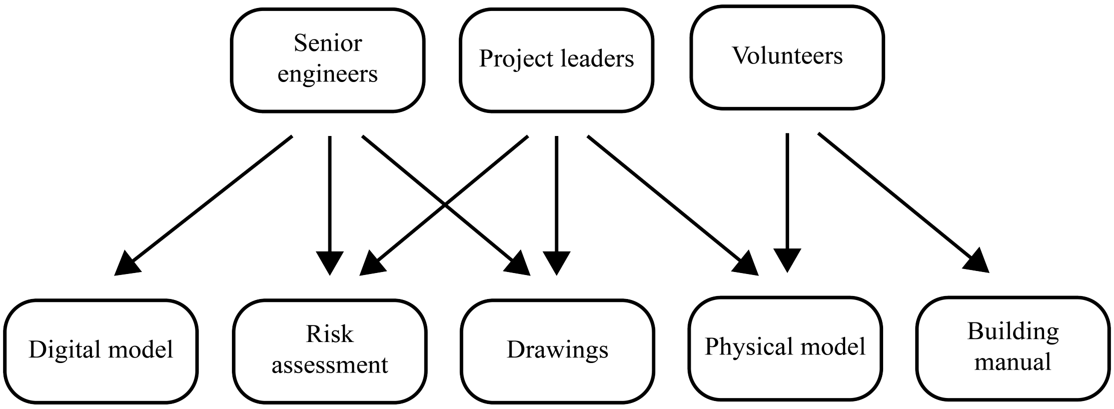

Figure 5.7: Flowchart showing which communication method is aimed at which group.

6 Discussion

In this chapter the work that has been conducted and the results of it are discussed.

6.1 Priority of demands

The demands have been prioritised in accordance with B2P's resources and with the context of Rwanda in mind. With another starting point, the demands might be prioritised different, which could result in another concept being considered more suitable.

6.2 Evolution of design process

The design process started in something very similar to the design process often used by engineers in industrialised countries: with a weighing matrix used to score and rate each concept against each other. As the work proceeded, it was discovered that this standard design process was not well equipped to deal with the design challenges of rural areas. Therefore, the process was altered to put more weight on the limited resources and specific site conditions. No investigation regarding what would be the most accurate or efficient process was conducted. The aim of the alternative process was only to better represent what had been found to be the critical challenges with building a bridge in rurally isolated areas. This resulted in the process described in 5.3. To see if this change in process actually affected the final result, further studies would need to be performed.

6.3 Other potential designs

During the process of finding a suitable concept a set of initial concept were produced. Even if these concepts were very general, a potentially suitable concept could have been missed since only a limited number of concepts were produced.

In the following steps, more and more concepts were removed. Since no concept had been designed in detail at these stages, the decisions about which concept should move on were made without knowing the full potential of each concept. To produce a detailed design would take a lot of time, and is not justifiable to do for each concept. Therefore, due to the limited amount of information available during the design process, a more suitable concept might have been missed.

One of the initial concepts was a reciprocal frame. It was filtered out due to its complexity and the lack of experience of building this type of structures as bridges in this scale. Reciprocal frame structures could have a lot of potential in this kind of context, since they make it possible to span long lengths with short elements. If more knowledge was available, or the bridge would be built in a context were it would be possible to work with more complex solutions, a reciprocal frame structure could be a very efficient solution.

In the end of this design process, the steel truss bridge was compared to the stressed ribbon bridge. The latter was discarded due to the difficulties of designing a cable anchor possible to adapt for different kinds of sites. A possible solution could be found if a more thorough investigation into possible anchor designs were performed. The result might also be different if a specific site had been decided on so that the concept would not have to suit a large variety of site conditions.

As mentioned earlier, the final concept has been designed to suit a large variety of sites. This includes the most extreme sites with steep hills on the sides, accessible only by small roads through hard terrain and with no possibility to access the bridge from underneath. If the most extreme sites were excluded, another concept might be more suitable. If a specific site had been chosen, and the site specific conditions had been known, other concepts could also have been more efficient. For example, if the ground conditions were known it might have been possible to design an anchor for the stressed ribbon concept, potentially making that a more suitable concept.

6.4 Final design

Since the design has been evaluated and developed in several stages, some assumptions made early in the process might not be correct by the end. In the case of the steel truss bridge, assumptions has been made about the cost-efficiency and safety during the construction phase that might no longer be true for the final concept.

6.4.1 Cost-efficiency

The steel truss concept was partly chosen due to its assumed cost efficiency. This assumption was made during the filtration process, but as the concept has been developed and detailed, more and more parts have been added to the structure to make it viable. To ensure that the design still is cost-efficient, a new cost analysis should be performed for the final design.

6.4.2 Potential risks during construction

When developing the design and erection method, decisions were taken to try and make the building process as safe as possible. For example, a large reason for moving on from the first iteration of the stabilising structure was that it required people working outside the trusses, which would greatly increase the risk of people falling of the bridge. In all later iteration, the stabilising structure was kept in between the trusses to avoid that risk.

Even if attempts were made to make the construction as safe as possible, some large risks are still present during the erection process. When folding out the lower truss elements of a new module, for example, someone must control the rotation and therefore stand at the end of the cantilever. If proper security equipment is not used during this stage, there is a risk of that person falling of the end of the bridge.

The bridge is also kept in place only by the counter weight during the entire erection process. It is therefore critical that this counter weight is sufficiently heavy, since otherwise the bridge will collapse. It would be preferable to have a erection process with more redundancy, which does not rely on a counter weight consisting of locally gathered stones, but with the limited resources available this was the only possible solution found.

6.5 Sizing of connections

The connections have been designed to withstand the largest internal force in a bridge with a span of 30 metres. All connections have also been assumed to be the same to ensure as few unique ingoing parts as possible. This could result in more material being used than needed since the force applied in most connections will be smaller than what the connection is designed to withstand. To minimize the number of bolts used, each connection could be designed individually with the number of bolts needed to withstand its specific force. A solution like that would reduce the volume of material used, but would induce extra work from an engineer. On top of the additional hours, an extra risk of mistakes in the construction would be introduced if there are any misunderstandings regarding which connections is which.

7 Conclusion

To build bridges in rurally isolated areas differs a lot from building bridges in industrialised parts of the world. The remote sites and limited resources creates a need for a design process focused on fulfilling a few critical demands rather than balancing several different demands against each other. A design process were more weight is put on the most important demands has therefore been developed.

The alternative design process has then been applied in the context of rural Rwanda to develop a bridge concept suitable for spans of up to 30 meters. The process resulted in a modular steel truss bridge that can be assembled completely by hand and that is adaptable to a variety of spans.

To give everyone working on the bridge access to the information they need for the building process to run smoothly, material for five different methods of communication has been produced. This includes drawings, digital and physical models, a building manual inspired by IKEA's assembly manuals and a template for risk assessment.

The need for bridges in rurally isolated areas is immense, but the conditions are difficult. The bridge concept presented in this thesis is a possible solution, but it is far from the only one. By changing the context only slightly, the final design might look completely different.

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A Appendix A

In appendix A, transcriptions of- and notes from meetings are gathered.

A.1 Meeting notes, B2P

Date: 2025-02-19

Attendees: Lisa Ryrstedt
Peter Stanek Sörner
Kyle Shirley, Director of Advisory Service, B2P
Simon Niyitegeka, Senior Design Engineer, B2P
Etienne Mutebutsi, Needs Assessment Manager, B2P

A.1.1 Questions sent in advance

Before the meeting a number of questions were gathered and sent in advance to B2P. The questions, together with answers from Kyle Shirley, can be seen below.

What are the soft and hard requirements on bridges built in rural areas of Eastern Africa?

What demands are relevant for the sites where our bridge concept might be of interest?

How long technical service life should the bridge have?

As long as reasonably possible given the cost of the bridge. Our cable bridges have a very conservative life span of 30 years.

We understand that the government is in charge of maintaining the bridges. Do you provide a plan or check list for the maintenance, or is it up to them?

Yes, it is up to them. But maintenance is very problematic and given timber decking wasn't being replaced when it was needed we moved to steel decking years ago, w/ the goal to essentially build a bridge that requires as little maintenance as possible.

Are there any demands that are 'hard'? For example, regulations or requirements that cannot be overseen or altered?

No, we're in the process of getting cable trail bridge standards and manuals adopted in Rwanda or Uganda. For rural pedestrian bridges there aren't currently regulations in place.

What materials are you comfortable working with? What materials do we have access to?

There are some limitations on certain steel parts (for example we important steel tubes for suspension bridge towers in Rwanda) and there is no hot dipped galvanization in Rwanda. Larger steel beams may have to be imported, but I my have to get Simon to weigh-in here.

Do the builders have access to any machines, such as drills, screw drivers or drones?

Drills, screw drivers, angle cutters yes, we typically have a generator at all sites if needed. Drones - no. Excavators, backhoe, etc. aren't at sites.

Do B2P have access to a workshop where specific parts can be prefabricated?

Yes, steel parts like cross beams and panels are fabricated in country.

How is the material transported to site?

Some sites can require carrying materials and tools up to 2 km to site. It's safe to assume nothing larger / heavier than our steel tubes currently used should be required in the design/construciton process.

What is the climate and surroundings like?

Rwanda climate most of the bridge sites are built next to if not within small farm plots. Rwanda is very densely populated so there's farms everywhere and typically houses not very far. It's very mountainous. Rwanda is called the land of 1,000 hills and 1,000 is a understatement.

How is a bridge concept best communicated between engineers and workers and/or locals?

How are the current solutions communicated between engineers and builders or locals?

We have forepersons on site at all times to supervise the construction. B2P currently designs all the bridges and we have 4 types. 3 cable bridges - suspended (concrete abutments w/ sagging deck), suspension (towers with arching deck) & hybrid (half suspended half suspension) minimum span of 30 meters & stone arch bridges (single arch max span of 15 meters)

Do you have any ideas on improvements?

We don't have a standard bridge type for 15-30 meters. We want something light weight, constructibility without heavy machinery, cost efficient, durable

Alan McGrane (former Director of Engineering) mentioned a steel truss concept, is there a specific reason for steel (or for truss) more than just that it might be an option?

(see comments on improvement above). We're open to other ideas they would need to address above challenges with access durability, cost and constructibility.

A.1.2 Notes from meeting

The meeting was planned around the questions presented above. The information shared during the meeting is summarized below.

Demands

- Bridge: A design suitable for spans of 15-30 meters, must be cost efficient and possible to do by hand. The width should not be more than 1 meter to ensure that no larger vehicles can enter the bridge, if some kind of obstruction is used it cannot be movable in any way.
- Site: most likely mountainous with sand, clay or rock as top layer. Up to 2 km from road, hard to get to. Steep hills or flat.

- Materials:
  - Steel: Can get some type of steel from Rwanda, South Africa, Kenya or USA. The suppliers provide quality properties, but these are unknown if collected at smaller markets or reused. Circular or rectangular cross sections available, from old cell towers (?). Some modifications can be done in workshops, but the design needs to be very simple. Some kind of protective painting can be done, but often just once, no repairs or maintenance.
  - Timber/wood: Has not been working with it more than for steps. Since the maintenance is poor, these only lasted for a couple of years. Don't seem to have any good timber suppliers close, and due to climate not really interested either.
  - Concrete: Must be carried to site and mixed by hand or by front loader and large volumes are therefore hard to produce, the quality might vary as well.
  - Stone: collected from nearby rivers.
- Codes and regulations: B2P implements their standards in Rwanda, i.e. follow their regulations. Otherwise, Eurocode can be a good alternative?
- Cost: Must be cost efficient! Labour is cheap while materials are expensive.

Bridge concepts already in use by B2P

- Stone arch bridges: Requires a lot of labour work. They have manuals for stone arch bridges (two different types) that work for spans up to 20 meters. Over 20 meters the design is advanced, and the labour is high. Not efficient.
- Suspension bridges: Requires a lot of excavation, the ropes are heavy and the transport from roads (up to 2 km) is hard. When under 30 meter span the material is not used efficiently. The cables are reused and gifted which makes the bridge type cost efficient, if the cables weren't gifted it would be a very expensive bridge. Anchoring is expensive.

General comments and conclusions

Drones are most likely not an option since the regulations of these are very strict in Rwanda.

Most importantly, others that have tried to design a new concept forgets or misunderstands that the sites are very remote and isolated which means that the design must be both CONSTRUCTABLE and TRANSPORTABLE.

B Appendix B

B.1 Weighing matrix

When relevant demands are decided on, they are weighted against each other to find their priority. Every combination are given a score that indicates if the demand is more or less important than the one it is matched against. 1 point implies less important, 2 points implies equally important and 3 points more important. The scores are then transformed to percentage to simplify the prioritization. As can be seen in Table B.1 there are three demands (constructibility, transportability and reliability) that get a score of 10 % and therefore is the highest priority.

B.2 Comments on filtration process

Suspension bridge The suspension bridge include long cables and the anchor is made out of concrete which both are hard to transport to site. The anchor would need to be very large to handle the forces and therefore require a lot of concrete. In addition to this, if the cables can not be gifted they have to be imported, both of which makes the concept costly.

Stressed ribbon bridge The stressed ribbon bridge includes both cables and anchorage, which for the same reason as the suspension bridge is costly.

Masonry arch bridge The masonry arch bridge would most likely need a temporary construction to be erected. It is also hard to adapt an arch without recalculation of the whole design which makes the masonry arch bridge being caught in the adaptability filter.

Steel truss bridge The erection of a steel truss bridge, without the space needed for launching or for an effective counterweight is complex.

Reciprocal frame bridge The reciprocal frame bridge concept is inspired by other reciprocal structures, mostly roofs. The few reciprocal bridges that has been built are made out of timber and on shorter spans, therefore the reliability can not be reassured. These types of structures are often built on the side and then lifted into place, which would be a problem in this context. If the ingoing parts were going to be the same or at least few, the adaptability would be a problem as well as the cost-efficiency.

Self anchored suspension bridge The self anchored suspension bridge is caught by the same reasons as the ordinary suspension bridge, as well as in reliability, constructibility and erection method. This is due to the unusual structure (as the reciprocal frame), its complicated construction with cables being placed at the right place at the right time which also makes the erection hard.

B.3 Specification of remaining demands

The score that corresponds to the level of fulfilment of the remaining demands are stated below. These scores are used in the evaluation in the modification process.

B.3.1 Adaptability

1p. The bridge is designed for one span length and one site

2p. The bridge can be adapted regarding length but not site type

3p. The bridge can be built on different site types but only with one span length

4p. The bridge suits most relevant spans and sites

5p. The bridge can be adapted to fit all relevant spans and is suitable for all different kinds of relevant site conditions

B.3.2 Simplicity

1p. The bridge is designed with the need for advanced techniques and solutions, and most ingoing parts needs to be prefabricated

2p. The bridge is designed with the need for advanced techniques and solutions, and some ingoing parts needs to be prefabricated

3p. The bridge is designed with some more advanced techniques or solutions, and a need fore some prefabrication

4p. The bridge is design with simple solutions and a need for some prefabrication

5p. The bridge is design with simple solutions and no need for prefabrication

B.3.3 Service life

1p. 5-9 years

2p. 10-14 years

3p. 15-19 years

4p. 20-29 years

5p. 30+ years

B.3.4 Safety

1p. The bridge is safe to use under normal circumstances

2p. The bridge is equipped with safety measures such as railings that stops users from falling of the bridge

3p. Appropriate safety measures are included into the design that stops unwanted vehicles from using the bridge

4p. The load carrying system has been designed in such a way that the risk of progressive collapse is minimized

5p. The load carrying system is designed to have enough redundancy so the bridge is safe to cross even if a major component has failed

B.3.5 Maintenance

1p. The bridge requires maintenance every year

2p. The bridge requires minor maintenance every other year

3p. Extensive maintenance planned once during the service life of the bridge

4p. Minor maintenance needed a few times during the service life of the bridge

5p. No need for planned maintenance

B.3.6 Usage

1p. It is possible to pass over the bridge

2p. The bridge feels wobbly for pedestrians

3p. There can be large deformations when passing over the bridge, but it feels stable

4p. Minor vibrations can be felt in the bridge, but over all it feels stable

5p. No vibrations can be felt under normal loading and it feels safe when passing the bridge

B.3.7 Durability

1p. The bridge does not suffer major damage from the rain periods

2p. The bridge withstands the rain periods but needs to be closed off at the time

3p. The bridge withstand normal earthquakes

4p. The bridge does not take any damage from the weather or normal earthquakes but needs to be closed off at the time

5p. The bridge withstands all types of weather and can handle unexpected types of traffic

Table B.1: Weighing matrix, high score means high priority

		1	2	3	4	5	6	7	8	9	10	11	12	13	14		
1	Environmental sustainability		1	1	1	1	2	3	1	1	1	1	1	1	1	16	4%
2	Economic sustainability	3		3	3	3	3	3	1	1	1	2	3	2	1	29	8%
3	Adaptability	3	1		3	3	3	3	1	1	2	2	3	2	2	29	8%
4	Simplicity	3	1	1		2	3	3	1	1	2	2	2	2	1	24	7%
5	Service life	3	1	1	2		3	3	1	1	1	2	3	2	1	24	7%
6	Time	2	1	1	1	1		3	1	1	1	1	1	1	1	16	4%
7	Aesthetics	1	1	1	1	1	1		1	1	1	1	1	1	1	13	4%
8	Constructibility	3	3	3	3	3	3	3		2	3	3	3	3	2	37	10%
9	Transportability	3	3	3	3	3	3	3	2		3	3	3	3	2	37	10%
10	Safety	3	3	2	2	3	3	3	1	1		2	3	1	1	28	8%
11	Maintenance	3	2	2	2	2	3	3	1	1	2		3	2	1	27	7%
12	Usage	3	1	1	2	1	3	3	1	1	1	1		1	1	20	5%
13	Durability	3	2	2	2	2	3	3	1	1	3	2	3		1	28	8%
14	Reliability	3	3	2	3	3	3	3	2	2	3	3	3	3		36	10%
																364	100 %

C Appendix C

C.1 Temperature load

The equation used for calculating the length change of an element is presented in Equation (C.1).

$$\Delta l = \alpha_T \cdot l \cdot \Delta T_1 \tag{C.1}$$

$$\begin{cases} \Delta l = \text{length difference} & \\ \alpha_{T.steel} = \dfrac{10^{-5}}{°C} & \text{(material specific, steel)} \\ l = \text{element length} & \\ \Delta T_1 = \text{uniform temperature variation} & \end{cases}$$

For a bridge that spans 30 meter (simplification: the bridge is considered to be one steel element) and the temperature on site differ 40 degrees, the length difference is 12 mm (see Equation (C.2)).

$$\frac{10^{-5}}{°C} \cdot 30000mm \cdot 40°C = 12mm \tag{C.2}$$

C.2 Wind load

The resultant wind force is calculated in accordance with Eurocode 1, as shown in Equation (C.3).

$$W = c_s c_d \cdot c_f \cdot q_p \cdot A_{ref} \tag{C.3}$$

$$\begin{cases} c_s c_d = 1 & \text{size and dynamic factor} \\ c_f = 1.3 & \text{force coefficient} \\ c_e = 1 + 7 \cdot I_v & \text{exposure factor} \\ I_v & \text{turbulence intensity} \\ q_b = \dfrac{1}{2} \cdot \rho \cdot v_b^2 & \text{reference mean (basic) velocity pressure} \\ \rho = 1.25 \dfrac{kg}{m^3} & \text{air density} \\ v_b & \text{basic wind velocity} \\ q_p = c_e \cdot q_b & \text{peak velocity pressure} \\ A_{ref} & \text{reference area} \end{cases}$$

C.3 CALFEM - analysis model

```
%% ULS calculations using CALFEM for truss bridge with 45
    degree diagonals
clear all
clc

% Input

rho_S355 = 8000;                    % Density of steel
   elements[kg/m^3]
sigma_y = 240e6;                    % Yield stress [Pa]
E = 210e9;                          % Young's modulus for
    steel [Pa]

h_truss = 2;                        % Height of truss [m]
l_module = h_truss;                 % Length of each
   modul [m]
w_bridge = 1;                       % Width of the bridge
    [m]

t = 6e-3;                           % Wall thickness of
   profiles [m]
h = 100e-3;                         % Height of web [m]
w = 50e-3;                          % Width of flanges [m
   ]

V_plates = 385*250*6*1e-9;          % Volume of
   connection plates [m^3]

q = 4.07e3/2;                       % Applied load on
   each truss [N/m]
P = 2.22e3;                         % Point load applied
   in the middle of the span [N]

l_span = 32;                        % Span length [m]

g = 9.82;                           % Gravity

gammaG = 1.05;                      % Load combination
   factor for permanent loads (EN1990, Table A2.4)
gammaQ = 1.35;                      % Load combination
   factor for variable loads (EN1990, Table A2.4)

%% Calculating the maximum stress in the truss from
   global effects during usage

A_w = h*t;                          % Area of the web [m
   ^2]
```

```
A_f = w*t - t^2;                    % Area of the flanges
    [m^2]

A = A_w + 2*A_f;                    % Total area of the
   cross section [m^2]

self_weight = rho_S355*A;           % Self weight of
   steel elements per meter [kg/m]

nmod = l_span/l_module;             % Number of modules
   in the truss

l_tot = 3*l_span + h_truss*(nmod+1) + 2*nmod*sqrt(
   l_module^2+h_truss^2) + nmod*w_bridge + nmod*sqrt(
   w_bridge^2+(h_truss/2)^2);         % Total length of
   elements [m]
l_45 = l_tot/nmod;                  % Length of elements
   in one module [m]

p_45 = gammaQ*q*l_module+gammaG*(l_45*self_weight+2*
   V_plates*rho_S355)*g;       % Load in each node of the
   bottom of the truss [N]

ep = [E A];                         % Element properties

nel = 5*nmod+1;                     % Number of elements
nodes = 2*(nmod+1);                 % Number of nodes
ndofs = 2*nodes;                    % Number of degrees
   of freedom (disp. in x and y)

Edof = zeros(nel, 5);               % Preparing the Edof
   matrix

% Creating the Edof matrix
for i = 0:nmod-1
    Edof(5*i+1,:) = [5*i+1 4*i+1 4*i+2 4*i+3 4*i+4];
    Edof(5*i+2,:) = [5*i+2 4*i+1 4*i+2 4*i+5 4*i+6];
    Edof(5*i+3,:) = [5*i+3 4*i+3 4*i+4 4*i+7 4*i+8];
    Edof(5*i+4,:) = [5*i+4 4*i+1 4*i+2 4*i+7 4*i+8];
    Edof(5*i+5,:) = [5*i+5 4*i+3 4*i+4 4*i+5 4*i+6];
end
Edof(5*nmod+1,:) = [5*nmod+1 4*nmod+1 4*nmod+2 4*nmod+3
   4*nmod+4];

% Creating the element coordinate vectors
ex = zeros(nel,2);
ey = zeros(nel,2);
```

```
for i = 0:nmod-1
    ex(5*i+1:5*i+5,:) = [i*l_module i*l_module ; i*
       l_module (i+1)*l_module ; i*l_module (i+1)*l_module
        ; i*l_module (i+1)*l_module ; i*l_module (i+1)*
       l_module];
    ey(5*i+1:5*i+5,:) = [0 l_module ; 0 0 ; l_module
       l_module ; 0 l_module ; l_module 0];
end
ex(end,:) = [nmod*l_module nmod*l_module];
ey(end,:) = [0 l_module];

% Creating the stiffness matrix
K = zeros(ndofs);

for i = 1:nel
    Ke = bar2e(ex(i,:), ey(i,:),ep);
    K = assem(Edof(i,:), K, Ke);
end

% Creating the force vector
f = zeros(ndofs,1);

% Adding the distributed load
for i = 1:nmod+1
    f(i*4-2) = -p_45;
end

% Adding the point load at the middle of the span

f((nmod/2+1)*4-2) = f((nmod/2+1)*4-2) - gammaQ*P;

% Defining the boundary conditions (simply supported)
bc = [1 0 ; 2 0 ; (nmod+1)*4-2 0];

% Solving the system and calculating the element
   displacements
[a,r] = solveq(K,f,bc);

ed = extract(Edof,a);

fprintf('Maximum deflection: %d m\n',max(abs(a)))
if max(abs(a)) < l_span/250
    fprintf('Deflection OK! Utilization rate: \n%d\n',max
       (abs(a))/(l_span/250))
else
    fprintf('Deflection NOT OK! Utilization rate: \n%d\n'
       ,max(abs(a))/(l_span/250))
end
```

```
figure(1)
title('Displacement during normal usage')
eldraw2(ex,ey,[2,1,0])
eldisp2(ex,ey,ed,[1,4,0],1e1);
text(10,5,['Max displacement [m]:', num2str(max(abs(a)))
   ])


% Calcualting the normal forces in the truss
es = zeros(nel,1);

for i = 1:nel
    es(i) = bar2s(ex(i,:), ey(i,:), ep, ed(i,:));
end

N_max = max(abs(es));
sigma_max = N_max/A;

fprintf('Maximal normal force: %d N\n', N_max)
fprintf('Maximal stress: %d Pa\n',sigma_max)
fprintf('Utilization bars: %d\n',sigma_max/sigma_y)

% Plotting internal forces in horizontal elements

figure(2)
eldraw2(ex,ey,[2,1,0]);
for i = 0:nmod-1
    eldia2(ex(5*i+2,:),ey(5*i+2,:),[es(5*i+2);es(5*i+2)
       ],[2 1],1e-5);
    eldia2(ex(5*i+3,:),ey(5*i+3,:),[es(5*i+3);es(5*i+3)
       ],[2,1],1e-5);
end

%% Calculating the maximum stress during erection
% Defining the force vector during erection

p_erection = gammaG*(l_45*self_weight+2*V_plates*rho_S355
   )*g;

f_erection = zeros(ndofs,1);

for i = 1:nmod+1
    f_erection(i*4-2) = -p_erection;
end

%f_erection((nmod+1)*4-2) = f_erection((nmod+1)*4-2)*3;
                     % Same point load as in the Cremona
```

```
   diagram
f_erection((nmod+1)*4-2) = f_erection((nmod+1)*4-2) -
   gammaQ*2*90*g;     % Point load corresponding to two
   people standing at the end of the cantilever

% Defining the boundary conditions during erection
bc_erection = [1 0 ; 2 0 ; 3 0];

% Solving the system and calculating the element
   displacements
[a_erection, r] = solveq(K, f_erection, bc_erection);

ed_erection = extract(Edof,a_erection);

fprintf('Maximum deflection during erection: %d m\n',max(
   abs(a_erection)))
if max(abs(a_erection)) < l_span/250
    fprintf('Deflection OK during erection! Utilization
       rate: \n%d\n',max(abs(a_erection))/(l_span/250))
else
    fprintf('Deflection NOT OK during erection!
       Utilization rate: \n%d\n',max(abs(a_erection))/(
       l_span/250))
end

figure(3)
title('Displacement during erection')
eldraw2(ex,ey,[2,1,0])
eldisp2(ex,ey,ed_erection,[1,4,0],1e1);
text(10,5,['Max displacement [m]:', num2str(max(abs(
   a_erection)))])

% Calcualting the normal forces in the truss
es_erection = zeros(nel,1);

for i = 1:nel
    es_erection(i) = bar2s(ex(i,:), ey(i,:), ep,
       ed_erection(i,:));
end

N_max_erection = max(abs(es_erection));
sigma_max_erection = N_max_erection/A;

fprintf('Maximal normal force: %d N\n', N_max_erection)
fprintf('Maximal stress: %d Pa\n',sigma_max_erection)
fprintf('Utilization bars: %d\n',sigma_max_erection/
   sigma_y)
```

```
%% Checking risk of buckling

z_tot = (A_w*t/2 + 2*A_f*(t+w/2))/A;
                                          % Coordinate of the
   center of gravity of the cross section [m]

I_w = h*t^3/12;      % Local moment of inertia of the web
   [m^4]
I_f = t*w^3/12;      % Local moment of inertia of the
   flanges [m^4]

I_tot = I_w + A_w*(t/2-z_tot)^2 + 2*(I_f + A_f*(t+w/2-
   z_tot)^2);     % Total moment of inertia of the cross
   section [m^4]

L_diag = sqrt(l_module^2+h_truss^2);
                                          % Length of diagonals in
    the truss [m]

P_cr = pi^2*E*I_tot/L_diag;
                                                   % Critical
   buckling load assuming pinned connections at both ends
   [N]

P_max = max([N_max_erection, N_max]);
                                         % Maximum applied normal
   force in any element in the truss [N]

fprintf('Critical buckling load: %d N\n', P_cr)

if P_cr > P_max
    fprintf('No risk for buckling! Utilization of
       buckling capacity: %d\n', P_max/P_cr)
else
    fprintf('Risk of buckling! Utilization of buckling
       capacity: %d\n', P_max/P_cr)
end

%% Calculating the eigenfrequencies of the bridge
% Calculating the moment of inertia
z_tot = (A_f*t/2 + A_w*(t+h/2) + A_f*(t+h+t/2))/(A);    %
    Coordinate of the center of gravity of the cross
   section [m]

I_w = t*h^3/12;      % Local moment of inertia of the web
   [m^4]
I_f = w*t^3/12;      % Local moment of inertia of the
   flanges [m^4]
```

```
I = I_f + A_f*(t/2-z_tot)^2 + I_w + A_w*(t+h/2-z_tot)^2 +
    I_f + A_f*(t+h+t/2-z_tot)^2;          % Total moment
   of inertia of the cross section [m^4]

epd = [E A I self_weight];       % Dynamic element
   properties

% Defining the new degrees of freedom (need beam elements
    for the dynamic analysis)
ndofsd = 3*nodes;                          % Number of degrees
   of freedom (disp. in x and y, and rotations in the xy-
   plane)

Edofd = zeros(nel, 7);                     % Preparing the Edof
    matrix

% Creating the Edof matrix
for i = 0:nmod-1
    Edofd(5*i+1,:) = [5*i+1 6*i+1 6*i+2 6*i+3 6*i+4 6*i+5
        6*i+6];
    Edofd(5*i+2,:) = [5*i+2 6*i+1 6*i+2 6*i+3 6*i+7 6*i+8
        6*i+9];
    Edofd(5*i+3,:) = [5*i+3 6*i+4 6*i+5 6*i+6 6*i+10 6*i
       +11 6*i+12];
    Edofd(5*i+4,:) = [5*i+4 6*i+1 6*i+2 6*i+3 6*i+10 6*i
       +11 6*i+12];
    Edofd(5*i+5,:) = [5*i+5 6*i+4 6*i+5 6*i+6 6*i+7 6*i+8
        6*i+9];
end
Edofd(5*nmod+1,:) = [5*nmod+1 6*nmod+1 6*nmod+2 6*nmod+3
   6*nmod+4 6*nmod+5 6*nmod+6];

% Creating the stiffness and mass matricies
Kd = zeros(ndofsd);
Md = zeros(ndofsd);

for i = 1:nel
    [Ked,Med] = beam2d(ex(i,:), ey(i,:), epd);
    Kd = assem(Edofd(i,:), Kd, Ked);
    Md = assem(Edofd(i,:), Md, Med);
end

% Defining the boundary conditions
b = [1 2 (nmod+1)*6-4];

% Calculating the eigenvalues of the SDE (Structural
   Dynamics Equation)
```

```
[eigenValues, Phi] = eigen(Kd, Md, b);

eigenFreq = sqrt(eigenValues)/(2*pi);

fprintf('First two Eigenfrequencies:\n%d Hz\n%d Hz\n',
   eigenFreq(1),eigenFreq(2))

figure(4)
for i=1:2
    subplot(2,1,i)
    title(['Eigenmode ',num2str(i)])
    eldraw2(ex,ey,[2 1 0]);
    edd=extract(Edofd,Phi(:,i));
    eldisp2(ex,ey,edd,[1 4 0],5e1);
    FreqText=num2str(eigenFreq(i));
    text(8,5,['Eigenfrequency [Hz]:',FreqText]);
    axis([0 30 -3 7])
end
```

C.4 Connection

Calculation of bolted plate connection

All calculations are performed in accordance with EN1993-1-8:2024.

User instructions:

1. Fill in required input data
2. Ensure that the distances fulfil requirements
3. Check utilization ratios, should not exceed 1

Input data

Rod size and shape	$RodType := $ UPE100
Bolt dimensions	$BoltSize := $ M16
Bolt quality	$BoltQual := $ 8.8
Number of bolts	$n_{bolts} := 4$
Number of bolt rows	$n_{rows} := 2$
Number of bolt columns	$n_{cols} := \frac{n_{bolts}}{n_{rows}} = 2$
Plate quality	$PlateQual := $ S240
Plate thickness	$PlateThick := $ 6mm
Number of shear planes	$n_{planes} := 1$

Loads

Area rods $A_{rod} := RodType_1 \cdot mm^2 = (1.128 \cdot 10^3)\ mm^2$

Maximum tensile force $N_{max} := 219\ kN$

Maximum force in bolt $F_{bolt} := \frac{N_{max}}{n_{bolts}} = 54.75\ kN$

Geometry and properties - bolt

Diameter bolt $d := BoltSize_1 = 16\ mm$

Diameter hole

$$d_0 := \begin{array}{l} \text{if } d < 16\ mm \\ \quad \| BoltSize_1 + 1\ mm \\ \text{else if } d \geq 16\ mm \\ \quad \| BoltSize_1 + 2\ mm \end{array} = 0.018\ m$$

Area bolt $A_{bolt} := BoltSize_2 \cdot mm^2 = 201\ mm^2$

Area bolt, tapped $A_s := BoltSize_3 \cdot mm^2 = 157\ mm^2$

Ultimate strength, bolt
Table 5.1 $f_{ub} := BoltQual_1 = 800\ MPa$

Yield strength, bolt
Table 5.1 $f_{yb} := BoltQual_2 = 640\ MPa$

Geometry and properties - plate

Ultimate strength, plate $f_u := PlateQual_1 = 360\ MPa$

Yield strength, plate $f_y := PlateQual_2 = 240\ MPa$

Plate thickness $t_{plate} := PlateThick = 6\ mm$

Distances

End distance Table 5.8	$e_1 := 60\ mm$
Edge distance Table 5.8	$e_2 := 25\ mm$
Distance between holes, parallel to force Table 5.8	$p_1 := 60\ mm$
Distance between holes, perpendicular to force Table 5.8	$p_2 := 50\ mm$

Functions below must all be equal to 1, otherwise the distances must be modified.

$1.2 \cdot d_0 \le e_1 \le 4 \cdot t_{plate} + 40\ mm = 1$

$2.2 \cdot d_0 \le p_1 \le min\left(14 \cdot t_{plate}, 200\ mm\right) = 1$

$1.2 \cdot d_0 \le e_2 \le 4 \cdot t_{plate} + 40\ mm = 1$

$2.4 \cdot d_0 \le p_2 \le min\left(14 \cdot t_{plate}, 200\ mm\right) = 1$

$2 \cdot e_2 + \left(n_{rows} - 1\right) \cdot p_2 = 0.1\ m$

$2 \cdot e_2 + \left(n_{rows} - 1\right) \cdot p_2 = RodType_2 = 1$

Partial safety factors

Partial safety factor for joints Table 4.1	$\gamma_{M2} := 1.25$
Partial factor, shear resistance Table 5.9	$\alpha_v := BoltQual_3 = 0.6$
Partial factors, bearing resistances Table 5.9	$\alpha_{b.end} := min\left(\frac{e_1}{d_0}, 3 \cdot \frac{f_{ub}}{f_u}, 3\right) = 3$

$$\alpha_{b.mid} := min\left(\frac{p_1}{d_0} - \frac{1}{2}, 3 \cdot \frac{f_{ub}}{f_u}, 3\right) = 2.833$$

$$k_m := \text{if } f_y < 460\ MPa \;\; \| \; 1 \;\; \text{else} \;\; \| \; 0.9 \quad = 1$$

Calculation of capacity

Shear resistance, per shear plane and bolt, Table 5.9

$$F_{vRd} := \frac{\alpha_v \cdot f_{ub} \cdot A_{bolt}}{\gamma_{M2}} = 77.184 \ kN$$

Total shear resistance Table 5.9

$$F_{vRd.tot} := F_{vRd} \cdot n_{planes} \cdot n_{bolts} = 308.736 \ kN$$

Bearing resistance eq. 5.7 Table 5.9

$$F_{bRd} := \text{if } n_{cols} = 1 \wedge n_{planes} = 1 \;\; \frac{1.5 \cdot f_u \cdot d \cdot t_{plate}}{\gamma_{M2}} \;\; \text{else} \;\; min\left(\frac{k_m \cdot \alpha_{b.end} \cdot f_u \cdot d \cdot t_{plate}}{\gamma_{M2}}, \frac{k_m \cdot \alpha_{b.mid} \cdot f_u \cdot d \cdot t_{plate}}{\gamma_{M2}}\right) = 78.336 \ kN$$

$$F_{bRd.tot} := F_{bRd} \cdot n_{bolts} = 313.344 \ kN$$

Tension resistance Table 5.9

$$F_{tRd} := \frac{0.9 \cdot f_{ub} \cdot A_s}{\gamma_{M2}} = 90.432 \ kN$$

$$F_{tRd.tot} := n_{bolts} \cdot F_{tRd} = 361.728 \ kN$$

$$F_{vRd.tot} \geq 0.8 \cdot F_{bRd} = 1$$

Utilization ratios

Shear resistance

$$\frac{N_{max}}{F_{vRd.tot}} = 0.709$$

Bearing resistance

$$\frac{N_{max}}{F_{bRd.tot}} = 0.699$$

DEPARTMENT OF ARCHITECTURE AND
CIVIL ENGINEERING
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2025
www.chalmers.se

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