Designing a Movable Bridge with Glass Structural Elements

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1 Introduction

Conservation of natural environment and historical areas, declining the environmental impact and aesthetic appearance are the most important issues in modern architecture especially in designing large structures such as bridges. Glass is the material that gives the opportunity for designing a transparent structure which may meet the aforementioned requirements. My initial concept was designing a structure which allows maximum transparency and not detracts people’s view of the space.

In addition, glass can be used for constructing the structure because of its notable compression strength, elasticity and stiffness (young’s modulus of around 70 GPa), its durability and versatility, elegance and transparency. However, structural applications of glass are restricted due to some deficiencies such as intrinsic brittleness and manufacturing limitations. Therefore, glass is usually associated with load-bearing skeletons made of metals or polymers.

As the main orientation of my project is designing a load-bearing glass structure, a main aim is to convince people that the mechanical properties of glass are comparable with conventional material such as steel and concrete and thus prove their capability to receive the loads of a structure. What is more, bridge may be the best example of engineering and structural physics which has notable role in our social life. Nowadays due to major breakthrough in the field of glass, glass has been used for constructing the bridges but regardless of having remarkable transparent structure, their load bearing capacities are again assigned to a traditional steel work. It means that using glass in a safe primary or secondary structure which still demonstrates that glass is a fragile and dangerous material.

However, it is possible to exploit glass with its unique structural behavior in a safe structural component, utilize its undoubtable beauty and offer the excellent space quality. So, in that case heavy steel supports and strong aluminum systems are replaced by glass beams and columns which lead to more structural integrity of bridge and give spectacular view to the water. Designing a movable glass bridge is chosen as my graduation topic to cover the mentioned purposes and may lead to more investigation about the movable load bearing glass structure in the future.
2 Outline of Design Task

The main goal of my thesis is to design a glass movable bridge with all glass load bearing structures, all the structural and non-structural components of bridge will be designed by using glass material unless to be impossible. Generally glass is hanged or supported by other materials because it is transparent and visually aesthetic. As a result, it does not have structural role. However, today glass is used for constructing structural elements like beams and columns and bars for the trusses based on the new technologies.

For using glass as structural elements for bearing loads it is required to have a good understanding about the material properties of glass such as its strength, rupture behavior and brittle quality and different types of connection systems.

Regarding the connection systems, nowadays there have been standard connection systems for glass structures such as gluing and connecting through reinforcement which have been proven to be reliable and best practices have been established that are applicable to the most situations. On the other hand, it is possible to insert the metal in the glass by adhesive to avoid making any hole and as a result reduce the concentrated stresses. However, special connection systems are required for some applications such as movable glass structure or glass drawbridge.

The objectives of my graduation topic is designing a movable glass bridge based on research about the material properties of glass and the available connection systems, and then the overall structural design and joint design for glass movable bridge will be done. Finite element analyses (FEM) are carried on by using software such as Diana to demonstrate the validation of proposal geometrical model. In addition, my plan is to look at the different moving systems of movable bridges as well as designing a proper one for this project.
4 Research Questions

4.1 Main Question
➢ How the glass can be applied/implemented as the structural elements in a movable bridge?

4.2 Sub Questions
1. What are the characteristics of structural glass?
2. What kind of glass should be used?
   ➢ Float glass
   ➢ Heat strengthened
   ➢ Fully tempered glass
   ➢ Steel reinforced glass
   ➢ Laminated with PVB layer or Sentry glass
3. What type of connections is reliable for having movable glass structure?
4. What are the requirements for designing a movable glass bridge compare to the fixed bridge?
5. Which moving systems are more appropriate for Glass Bridge?
6. How is it possible to avoid slipping on the glass deck?
5 Methodology

- Literature study
- Architectural design study
- Research on new technologies
- Detailing
- Validation by structural analysis
6 Intended Outcome

- Designing a movable glass bridge
- Validation by structural analysis
- Prototype
7 Graduation Planning

Planning
Methodology
Research Question
Topic Chosen

3D Geometry Modeling
Moving System
Joint Design
Component Design
Overall Bridge Design

Structural Design

Presentation
Final

P1

P2

P3

P4

P5

Literature Background
Material Properties
Available Connection Systems
Existing Movable Glass Structures
Moving System for Bridge

Detailing
Creating FEM Diana Model
Calculation and Analysis
Finishing Design
8 Site Location

My proposed site location is Koepoorbrug over the Rijn-Schiekanaal closed to the centre of delft. The Koepoorbrug has a more local function. It links the eastern districts to the city center. At the moment, it is a narrow bridge for mixed traffic and rather high car volumes: 6,000 in a 12 hours period. At the current situation the type of bridge over the water channel is a movable metal bascule bridge with a span of around 10.35 m. One of the reasons for choosing this site location is the proper channel width for designing a glass bridge in view of the fact that glass has some limitations for covering the large span yet. However, it is estimated that glass can also be applied in bridge with large span in the future due to rapid glass technology advancements.

Delft and specially its city center has historical environment which can attract many tourist during the year but at the moment the current bridge not only adds any value to the district but also interferes a view to the new church and historic part. Having a glass bridge can minimize this visual intrusion due to its material transparency.
In addition, standing and walking on a glass bridge can provide a unique experience of walking on air. Having a spectacular view to the water transforms a bridge not only as a way for simply passing but as a place for staying and pondering. In this regard a movable glass bridge can affect the social life of people in two separate areas by giving this opportunity to join together. On the other hand, using innovative mechanism for bridge movement will be appealing for people to see the glass bridge during movement. As a consequence, it can be considered as a new iconic symbol of Delft which promotes the economic situation due to more tourist attraction.

It should be stated that this project can also be applied in other site location around the Netherlands with minor modification owing to standard size of Koepoortbrug channel width.

It should be mentioned that the clearance between the bridge and water is about 2.5m in a closed position. But it required high clearance in the open position which should be considered in the design. The bridge is opened and closed approximately 30 times per day. Figure 8-6 demonstrates the old design and current situation. It is clear that upper structure and part of the foundation have been changed.
Figure 8-5 View to Koepoortbrug in open position

Figure 8-6 The past and current situation of Koepoortbrug in Delft
(Source: http://www.jeannebouwmeester.nl/)
(Source: http://commons.wikimedia.org/wiki/File)
9 Glass Overview

For designing a structure from the glass material, it is required to have a good knowledge about the properties of the glass and know all the pros and cons of this material. So, in this section the property of the glass material is reviewed and new technologies for using the glass as the structural element are discussed. In addition, the different methods for connecting the structural glass elements to each other are presented. At the end, the different ways for having anti-slip glass surface are described.

As a result, the following research sub-questions will be answered in this section:

- What are the characteristics/behaviors of structural glass?
- What kind of glass should be used?
- What type of connections is reliable for having movable glass structure?
- How is it possible to avoid slipping on the glass deck?

9.1 Material Property of Glass

“Amorphous silica is the basis of almost all glasses; it is mixed with Na2O to make soda glass, and with B2O5 to make borosilicate glasses, but it is the silica that gives the structure. It is for this reason that the structure itself is called glassy, a term interchangeable with amorphous.” (V J Ortiz, 2013)

Glass is made of sand, soda and chalk. Materials that exist in big amounts in Earth, and is 100% recycled. It behaves better than concrete at compression and can be reinforced as concrete. In theory “glass is an homogeneous and isotropic solid material displaying ideal, perfectly elastic behavior up to very high stresses, but in reality its usable strength is governed by fracture mechanics and is determined by the presence of microscopic cracks in the glass surface.” (Smith Anthony, 2005)

The negative outside of the pyramid in Figure 9-1 is responsible for the little gaps in the material allowing light (photons) to pass but also responsible for the quick cracking of glass.” (Nijsse Rob, 2003)

The main reason that glass is often perceived as dangerous is because it shows no warning signs before failure. This is due solely to the lack of elasticity in glass. (R. L. White, 2007)
Figure 9-1 The basic molecule of glass: SiO4
(Source: http://www.substech.com/)

Figure 9-2 Defect in the edge of glass
(Veer F.A, 2014)

Figure 9-3 Comparing stress behaviour of three materials (Loughran, 2007)

Figure 9-3 shows the stress-strain curves for three structural materials, steel, glass, and wood. It can be observed that unlike steel, glass does not yield before failure. This is because of the brittle nature of glass (R. L. White, 2007)

9.1.1 Strength of Glass
- Surface strength 100 MPa scratched
- Surface strength 150 MPa factory fresh surface
- Edge strength 20-80 MPa depending on thickness, quality, etc (Veer, F.A., 2014)

As it is shown in Figure 9-5 the compressive strength of glass materials is good enough compare to concrete and metal while the density of glass materials is not too high.
Figure 9-4 Surface and edge strength of glass (Veer, F.A., 2014)

Cut, ground, polished surface
Strength 20-80 MPa

Smooth surface
Strength 100-150MPa

Figure 9-5 Compressive strength of glass compare to the other materials (Graph created by CES software)
9.1.2 Conclusion
The general properties of glass can be described as the following:
- Amorphous Silica is the basis of almost all glasses
- It can be recycled 100%
- It is homogeneous and isotropic material
- It behaves better than concrete at compression and can be reinforced similar to concrete
- It is a brittle material
- Its usable strength is governed by fracture mechanics

9.2 Glass size
The typical size of jumbo glass is 3.21m*6m but nowadays special glass sizes up to 3.30m x 8-17m can be ordered. However, size more than 12 m long only produced in 15 mm or thicker because otherwise the panel is too fragile

The standard glass thicknesses are: 2, 3, 4, 5, 6, 8, 10, 12, 15, 19 and 22 mm, and usually glass is made to the minimum tolerance but for 15, 19 and 22 mm special order with higher cost is required.

9.3 Glass Production
9.3.1 Float Glass
Glass is normally produced by the float process. The product obtained is annealed or float glass.

The float glass can be toughened by heating it to about 700 degrees centigrade, then depending on fast cooling or slow cooling the fully tempered or heat strengthen glass respectively can be produced at the end.

9.3.2 Fully Tempered Glass
“During the thermal tempering process, float glass is heated to approximately 620–675 °C (approximately 100 °C above the transformation temperature) in a furnace and then quenched (cooled rapidly) by jets of cold air.” (Haldimann, M., 2006) As a result, the surfaces are cooling rapidly while the center is still viscous. The surfaces are then put into compression as the center cools and contract. The high surface
compressive stresses are equilibrated by smaller tensile stresses acting over a greater proportion of the cross sectional area.”(Rice, Peter. 1995) “The typical residual compressive surface stress varies between 80MPa and 150MPa for fully tempered soda lime silica glass.”

![Figure 9-6 Compression in Surface of fully tempered glass](http://www.constructionspecifier.com/) and (http://www.glazette.com/)

For the reasons of having high tensile strength and the characteristic of failing into millions of small pieces, the fully tempered glass can be the safest option for constructing something above people’s head. But, if the glass panels (composed of multi-layers glass) fail at too high a failure stress, so many cracks form simultaneously that the stress cannot go from one layer to another layer.”(Veer F.A, 2005)

So, it is not common to use fully tempered glass in multi-layers glass due to safety issue.

9.3.3 Heat strengthened glass

“Heat strengthened glass is produced using the same process as for fully tempered glass, but with a lower cooling rate. The residual stress and therefore the tensile strength are lower. The fracture pattern of heat strengthened glass is similar to annealed glass, with much bigger fragments than for fully tempered glass. Used in laminated glass elements, this large fracture pattern results in a significant post-breakage structural capacity. (Veer, F.A. 2014)
Figure 9-7 Breakage pattern in two different glass types (Source: http://bearglass.com/)

Figure 9-8 Breakage patterns and characteristics of three different glass types (Ph. Oikonomopoulou, 2012)

### 9.3.4 Conclusion
The heat strengthened glass will be the first option for multilayers structural glass in my project according to have proper tensile bending strength around 70MPa and its failure behavior.
9.4 Glass cutting
Glass has to be cut before processing it. It can’t be cut after tempering or heat strengthening.

![Different types of edge grounding and polishing](http://www.adonispauli.com/)

**Figure 9-9 Different types of edge grounding and polishing** (Source: http://www.adonispauli.com/)

9.4.1 Drilling
If glass holes are cut by drilling, it has to be drilled simultaneously from both sides. “If the drill bits are not perfectly coaxial the hole will have a shoulder.”(Rice, Peter. 1995)

9.4.2 Water jet cutting
Water jet cutting for glass consists of a machine that cuts glass through applying at the same time an abrasive element as sand with a very high pressure of water. Through this invention glass can be cut without creating too much damage to the glass surface, and provides a sanded finish at the same time. (V J Ortiz, 2013)
9.5 Glass as Structural Element

9.5.1 Laminated PVB and Sentry Glass

A laminated glass is made of 2 or more glass planes (annealed, heat strengthened or floated) which are welded together with a sheet of PVB or Sentry Glass or a resin. Sentry Glass is resistant to higher temperatures than PVB. What is more, Sentry Glass is recommended when the glass will be where the temperatures are higher than 30 degrees Celsius. According to the design and availability, different combination of thicknesses can be used. Figure 9-11 shows the attachment of the glass fragments to the adhesive layer in a laminated fully tempered glass after failure.
SGP compared to PVB:
- Has 5 times higher tear strength
- Makes the laminated component 100 times more rigid
- Easily conforms to dimensional inaccuracies
- Excellent Weather and Edge Stability
- Much less vulnerable to moisture exposure or yellowing over time (www2.dupont.com)

But SGP is more expensive than PVB. As a result, it is only used for structural load bearing elements.
9.5.2 Armored Laminated Glass

The most common method for increasing the residual stability is to make armored laminated glass. This is done by adding a layer of armor between the glass layers. Figure 9-13 shows the composition of an armored laminated glass structure. The armor is needed because of the low bending strength and load-bearing capacity of the broken glass pieces. Although a high tensile stress is required of the armored elements, it is also important that they are very thin so as not to disrupt the transparency of the object. Research has found that the best reinforcing elements are meshes made of stainless steel wire or high-strength springs. Another option is embedding glass-fiber or carbon-fiber products into the PVB layers (Kaltenbach, 2004).

However, it should be mentioned that this method can be useful for the situation that loads are applying perpendicular to the surface of the glass.

![Figure 9-13 Armored Laminated glass (Kaltenbach, 2004)](image)

9.5.3 Steel reinforced glass

At Tu Delft several tests have been performed incorporating a steel reinforcement at the top and bottom of laminated glass beams. The latest test was done with an eight meter long beam consisting of two panels of 2*12 mm heat strengthened PVB laminated glass, with a 20 mm square hollow stainless steel profile at the edges in between (Figure 9-14).
9.5.4 Glass Beams
Laminated glass beams can be manufactured to meet nearly any size required. Because the use of such beams is rare, there are no standard sizes that designers must use. The limiting factor on size of a beam is the limitations of the manufacturer’s equipment, such as their autoclave, which is used in the laminating process. Typically, beams are made no longer than 6m, but if the owner is willing to pay more, lengths up to 7m are possible.

9.5.5 Glass Columns
Although glass works well under compression, it is difficult to prevent a glass column from buckling. When a column buckles, tension forces are introduced into the glass, which eventually breaks. Laminated glass principles can be used to reduce the likelihood of buckling in columns. In laminated columns, each layer acts as a lateral support for the others and the slenderness ratio is decreased (Nijssse, 2003). Figure 9-16 shows four different types of creating glass columns.
Figure 9-16 Different Types of Glass Column (Nijssse, 2003)

1-Gluing bundle of massive glass bars
2-Gluing cylindrical glass together
3-Laminating rectangular glass panels
4-Cross shaped Column

9.5.6 Conclusion (proposed type of glass (as structural elements) in this project)
- Using different layers of heat strengthened glass with thickness of 10mm
- Using Sentry Glass interlayer
- Using stainless steel hollow profile at the edges in the middle layer
9.6 Glass Connection

Glass connections are the main important part of the design because the loads should be gently transferred to the glass at the location of connections.

For designing a connection used in a glass structure, the following functional demands and criteria are to be considered.

- Appearance
- Easy in construction
- Weather conditions
- Long term aspects
- Repair work and maintenance
**Appearance:** The appearance of the connection is of great importance. A slender and light connection emphasize the lightness of the overall structure and more important the structural principle that the facets are the structure. (Hansen. J. Z, 2010)

**Construction:** Assembling must be as simple as possible which for an adhesive connection might be difficult if performed on site. This is due to the fact that optimal bonding quality can be difficult to achieve due to humidity, temperature and cleanness which all influence the final result. (Hansen. J. Z, 2010)

**Weather Conditions:** All kinds of climatic conditions such as rain, sunlight, ice and temperature changes affect the connection. Movements in the structure as a result of climatic changes should not induce significant stress concentrations in the glass or the connection. (Hansen. J. Z, 2010)

**Long Term Aspects:** If one or more materials in the connection show time dependent properties such as creep it is very important to investigate the consequence. Creep behavior has an influence on the stress distribution and can be influenced by external effects such as temperature and moisture. (Hansen. J. Z, 2010)

**Repair Work and Maintenance** In case of failure in one of the facets it should remain in one piece. This it achieved using laminated glass panes. Furthermore the connection should remain intact so the facet will be kept in place. In order to avoid a total collapse of the structure a certain yielding capacity of the connections enables the forces to be redistributed and thereby sustain the loads in an alternative way until the broken facet is replaced or repaired. When a broken facet is repaired an alternative connection might be necessary in order to fasten the new facet.

In case of failure in the connection the connected facets should balance against each other still held together by the broken connection.

Damages in the structure should be visible by simple inspection. (Hansen. J. Z, 2010)

Additionally, it should be possible to replace the broken parts easily.

The main four different types of glass connections are:

- Making holes in glass
- Clamping
- Gluing
- Glass inserts

**9.6.1 Making holes**

Making holes in the glass for connections cannot be a good option because of:
- Creating high local stresses
- Difficulty in tempering the inside of a hole
- Difficulty in accurate lamination of multi-layers glass with the holes

**Figure 9-18 Hole connection and high local stresses around the holes** (Source: http://thane.all.biz/)

### 9.6.2 Clamping
This option cannot be completely reliable due to sliding of glass at the location of connection when the loads are applied parallel to the surface of glass.
9.6.3 Glass Gluing

The quality of the bonding which is created by gluing can be so high that this option can be considered as a better solution compare to clamping and making hole. However, special care must be taken in the selection of the glue, according to the design requirements, and the site’s characteristics. In addition, the following requirements should be considered as minimum:

- Selecting right thickness for the gluing layer to achieve optimum strength
- Special care is required to make sure that the surfaces are matching
- The surfaces should be cleaned precisely before applying the glue
Figure 9-20 A sample of adhesive connection in glass structural elements (Nijssse, 2014)

Figure 9-21 Comparing tensile strength of different types of adhesives (V J Ortiz, 2013)
9.6.4 Glass Inserts Used for Connections

Inserts with the material of stainless steel, Aluminum and titanium can be embedded in the laminates glass for using as connection. This recent development has proved to be a better solution to making holes in the glass since in case of failure only one of the interlayer will break. Figure 9-22 shows the glass inserts in Apple store and Figure 9-23 shows a hinge connection for glass by using inserts.
Figure 9-22 Glass insert connections for apple store (Veer F.A, 2014)
Figure 9-23 Glass Plates Hinge Detail (V J Ortiz, 2013)

1. 6mm HS Laminated Sentry Glass
2. 12mm HS Laminated Sentry Glass
3. 180mm diam. Titanium connector inserted between laminates
4. 2.5mm soft aluminum ring
5. Titanium 6/8” nut
6. Titanium 6/8” spacer
7. White anodized aluminum 6/8” bolt

9.6.5 Connection to Hollow Profile (Metal Reinforcement) of Glass

For the glass reinforce by hollow profile, it is possible to make the connection to the metal reinforcement part. Figure 9-24 and Figure 9-25 show some samples for this option.
Figure 9-24 Sample of connections to the metal reinforcement
9.6.6 Special Glass Connections

Figure 9-26 shows a proposal connection for a movable glass canopy. According to the rotation of glass structure in horizontal plane, a stainless steel ball bearing is proposed in the connection system for reducing the friction during rotation.
Figure 9-26 Connection in a movable glass structure (V J Ortiz, 2013)

1. Borosilicate Glass Cap
2. White anodized aluminum 6” tube
3. Stainless Steel clamp
4. Stainless Steel Thrust 8”diam Ball Bearing
5. Steel u profile beam reinforcement
6. 6-12-12-6mm HS Laminated Sentry curved Glass
7. 200mm Duran Schott glass tube
8. 180mm Duran Schott glass tube
9. 180mm Titanium connector inserted between glass tube laminates
10. Stainless Steel Thrust 8”diam Ball Bearing
11. Soft aluminum ring glass column connector
12. Soft aluminum cross spacer column connector
13. 300mm & 304mm Duran Schott glass tube laminated column.
**9.6.7 Conclusion (glass connection)**
Making hole in the glass will be avoided in this project as much as possible. It will be tried to use the glass insert or connection will be made by using the hollow square profile.

**9.7 Safety Factor in Design of Glass Structure**
Using a proper safety factor in the design of a glass structure is another important requirement. Generally, safety factor of 5 to 7 is usually used for glass but there is no reason to treat glass differently from other materials. A safety factor of two should be enough, as we know more about the strength of glass than 20 years ago and the risk of failure can be reduced by using proper reinforcement and the right connections (Veer F.A, 2014)

**9.8 Psychology Consideration**
Strength and stability calculations are not the only element that needs attention during the design of a glass structure. The psychological effects must be considered. Because people perceive glass as a fragile material, it can be difficult for them to accept that a completely transparent floor is going to carry their weight safely (Nijsse, 2003). For this reason, a part of glass deck can be opaque for offering a feeling that the glass bridge is strong enough.

**9.9 Slipping**
Another important consideration of glass walkways is that manufactured glass has a naturally smooth surface, which can be detrimental when specified for walkways. When a smooth surface, such as glass, gets wet it becomes very slippery. This is a hazard that must be avoided in construction. To prevent glass from becoming slick, it must be specially treated before installation. Making a rougher and more durable surface is a simple process surface (Nijsse, 2013).

To avoid slipping on the glass deck, the different options are:
- **Using grain of sand or small pieces of broken glass:**
  In this method, one face of the glass is melted until it is of a syrupy consistency, and then grains of sand or small pieces of broken glass are sprinkled onto it. The pieces that are dropped onto the glass will sink until the glass is no longer molten enough. After this the glass is allowed to return to a normal temperature, and the surface hardens. Aside from making a rough, non-slip surface, this process also slows the wear process of the glass because the sand grains or glass pieces are very well connected to the original glass surface (Nijsse, 2013).
- **Acid-etched anti-slip glass** (Figure 9-27)
- Anti-slip Coating (Figure 9-28)
- Contour Glass
- Gluing clear rubber
- Sandblasted anti-slip glass (dots or pattern)

Figure 9-27 Acid-etched glass for avoiding slipping (Source: http://walkerglass.com/)

Figure 9-28 A sample of glass with anti-slip coating (Source: http://p3surfacesolutions.com/)
Figure 9-29 Samples of couture glass (Source: http://finishboard.com/wp content/uploads/2013/01/collage_corrugated.jpg)

Figure 9-30 Gluing clear rubber (Source: http://www.amazon.com/Self-Adhesive-Rubber-Large-Square-Bumpers/)

Figure 9-31 Sandblasted anti-slip glass (dots) (Source:https://www.facebook.com/AboutLondonLaura/photos/a.10153345463418625.1073741890.82057278624/10153345463603625/?type=3&theater)
Conclusion:
The option of using grain of sand or small pieces of broken glass for producing anti-slip glass could be complicated process. Additionally, in the option of contour glass, the empty space of contour glass will be filled with water due to rain and create slippery surface. On the other hand, rubber is subjected to the wearing. So, it should be replaced in a short period. Therefore, the other options of anti-slip coating, sandblasted or acid-etched anti-slip glass are recommended for this project to provide slip resistance for the glass deck in the both situations of wet and dry. It should be mentioned that sandblasted anti slip glass is used in this project as incorporating a top ‘sacrificial’ layer of glass into the panels by gluing to laminated glass. So, it can be quickly and easily replaced due to any damage without affecting the structural integrity of the deck.
10 Movable Bridge Overview

In this section, the following questions will be discussed:

- Which moving systems are more appropriate for Glass Bridge?
- What are the requirements for designing a movable glass bridge compare to fixed bridge?

10.1 Different types of movable bridge

The motions of all movable bridge can be provided by combination of rotation and translation; the differences between various types are due to the axes selected for these displacements. In terms of primary displacement and axes of displacement, movable spans are usually categorized as follows: (C. Birnstiel, 2008)

- rotation about a fixed transverse horizontal axis (trunnion bascule)
- rotation about a transverse horizontal axis that simultaneously translates longitudinally (rolling bascule)
- rotation about a fixed vertical axis (swing)
- translation along a fixed vertical axis (vertical lift)
- translation along a fixed horizontal axis (retractile and transporter)
- rotation about a fixed longitudinal axis (Tilting)
- rotation about multiple transverse horizontal axes (folding) (Manual-Movable bridges-Birnstiel Consulting Engineer)

10.1.1 Bascule Bridge

A bascule bridge (commonly referred to as a drawbridge) is a moveable bridge with a counterweight that continuously balances a span which can be located either above or below the bridge deck. About the deck, there is possibility to have one leaf or double leafs for providing clearance for boat traffic.

Generally speaking, there are two types of bascule bridge designs which are fixed trunnion and rolling Bascule Bridge. The fixed-trunnion (sometimes a "Chicago" bascule) rotates around a large axle that raises the span(s). The Chicago bascule name derives from the location where it is widely used, and is a refinement by Joseph Strauss of the fixed-trunnion. The rolling lift trunnion raises the span by rolling on a track resembling a rocking chair base. The "Scherzer" rolling lift is a patented refinement by the American engineer William Donald Scherzer. (Wikipedia)

Advantages:
- Quick opening and closing
- Requiring low force for operating due to having counterweight
- Providing unlimited vertical clearance for passage of the vessels

**Disadvantages:**
- Having high dead load due to counterweights and it means high costs for constructing the counterweight and abutments
- Being visually intrusive in the option of overhead counterweight (e.g. Mystic River bridge in Figure 10-3)

Fixed-trunnion Bascule Bridge can be recommended in this project:
- with under deck counterweight
- without counterweight and relying only on hydraulic force

![Figure 10-1 Fixed-trunnion and rolling bascule bridges](https://www.deldot.gov)
10.1.2 Folding Bridge

A folding bridge is a type of movable bridge which is designed to fold up and the movement is produced by rotating a deck about multiple transverse horizontal axes.

**Advantages** of this type of bridge are:
- Having the opportunity to use light weight members according to have less bending moment in members
- Providing unlimited vertical clearance

**Disadvantages:**
- Normally, a complicated moving system is required to be designed for transferring the loads during folding of bridge. In addition, the different segments of the bridge should be supported carefully for having allowable stresses in both cases of folded and unfolded.

Figure 10-4 shows HÖrn Bridge in Kiel, Germany which is a three-segment folding bridge with the following technical data (http://www.sbp.de):
• One sided cable-stayed folding bridge
• 26 m span (total length of the three folding segments)
• Weight of folding part equal to 54 t
• Deck width around 5 m
• Folding time (opening or closing) is 2 minutes approximately

This alternative can be a good option for this project because it is attractive visually and less glass is required for members. As a result, light weight structure can be achieved.

10.1.3 Swing bridges
A swing bridge is a movable bridge which has a turning span that rotates in a horizontal plate around a vertical axis. Generally, it can be categorized in two types of Center pivot and Edge pivot. Most swing bridges are built as symmetrical structures with a central pillar so that two shipping lanes with unlimited headroom are available, one on either side of the pillar. Like all movable bridge systems, swing bridges must function quickly and efficiently to ensure an uninterrupted flow of traffic. If the pivot axis is at mid-length of the draw, the draw is said to have equal-length arms or be symmetrical. Sometimes, the arms are not of equal length and the draw is termed unequal-armed or bobtailed. The dead load (self-weight) of a swing span is usually balanced about
the pivot. Hence, bobtailed spans require counterweights at the ends of the shorter arms for balance. However, short span swing bridges were built with only one arm and no counterweight, but special pivots were required for stability.

**Advantages:**
- As this type requires no counterweights, its total weight is reduced dramatically in compared to other moveable bridges.
- According to the fact that there is individual traffic direction in sufficient channel, the vessel to vessel collision will be reduced.
- The central support is often mounted on a berm along the axis of the watercourse to protect the bridge from watercraft. What is more, this artificial island forms an excellent construction area for building the movable span because the construction will not impede channel traffic. (Wikipedia)

**Disadvantages:**
- For a symmetrical bridge, the central pier forms a hazard to navigation. As a result, asymmetrical bridges may place the pivot near one side of the channel.
- Where a wide channel is not available, a large portion of the bridge may be over an area that would be easily spanned by other means.
- A wide channel will be reduced by the center pivot and foundation.
- Owing to the fact that there is difference in a structural behavior of bridge in open and closed positions, additional stiffness is required for some members which are alternately in compression or tension due to live load in a closed condition. While, when bridge is open the bridge keeps its own weight as a balanced double cantilever.
- It may have unintended rotation due to struck from the water near the edge which resulted in safety problem (Wikipedia).

This movable bridge type is not recommended for the proposed site location because of limited channel width.
Figure 10-7 Swing bridge (Scale Lane bridge) (Source: http://www.architectsjournal.co.uk)
A vertical-lift bridge or lift bridge is a type of movable bridge in which a span is lifted vertically along a fixed axis while remaining parallel with the deck. The vertical lift bridge has several benefits compared to other movable bridges, such as:

- Its cost for building a long span is lower than the others
- The counterweights are only required to be equal to the weight of the deck whereas bascule bridge counterweights must weigh several times as much as the span being lifted
- As a result of these advantages, heavier material can be used in the deck, and so this type of bridge is especially suited for heavy railroad use. (Wikipedia)

Disadvantages of this type are as follows:

- Its height restriction is the main disadvantage because the deck remains suspended above the passageway (Wikipedia)
- The cables linking the bridge and the counterweights are subject to wearing
- Being visually intrusive in both open and closed situations because of having large towers.
This movable bridge type is not recommended for this project because of:

- Requiring too much glass material for the towers
- Disturbing the glass transparency by towers

Figure 10-9 A sample of vertical lift bridge (Gustave Flaubert Bridge) (Source: http://www.vijaybisht.in)
10.1.5 Submersible bridge
A submersible bridge is a type of movable bridge that the bridge deck goes down below the water level along a fixed vertical axis instead of raising.
Advantages of this type of movable bridge are:
- Lack of an above-deck structure is considered aesthetically pleasing
- No height limitation on ship traffic

Disadvantages:
- The draft of vessels become limited due to submerge bridge structure

Figure 10-12 shows submersible bridge exists across the Corinth Canal in Greece. The bridge deck is lowered to 8 meters below water level for allowing ship passage.

This movable bridge type is not recommended for this project because of the corrosion risk for the glass connections.
10.1.6 Tilt Bridge

A tilt bridge which has a curved deck that rotates at an angle about fixed endpoints (Figure 10-13) rather than lifting or folding.

**Advantages:**
- Less energy is required for operating because the structural arch and pathway counterbalancing each other

**Disadvantages:**
- It is not suitable for vehicular traffic due to deck with curved shape
- Height limitation specially in short span

This movable bridge type is not recommended for the proposed site location because of limited channel width.
Figure 10-13 Gateshead Millennium tilt bridge
Source: (http://en.wikipedia.org) and (http://www.slideshare.net/DhruvSeth/gateshead-dhruv)
<table>
<thead>
<tr>
<th><strong>Bascule bridge</strong></th>
<th><strong>Pro</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Leaf</td>
<td>1. Quick opening and closing</td>
</tr>
<tr>
<td>Leaf</td>
<td></td>
</tr>
<tr>
<td>Counterweight</td>
<td></td>
</tr>
<tr>
<td>Trunnion</td>
<td></td>
</tr>
<tr>
<td>Leaf</td>
<td></td>
</tr>
</tbody>
</table>

1. Quick opening and closing
2. Requiring low force for operating

3. Providing unlimited vertical clearance for passage of the vessels
<table>
<thead>
<tr>
<th><strong>Bascule bridge conclusion</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. High dead load due to counterweights</strong></td>
<td><img src="image" alt="Diagram showing high dead load due to counterweights" /></td>
</tr>
<tr>
<td><strong>2. Being visually intrusive in the case of having overhead counterweight</strong></td>
<td><img src="image" alt="Diagram showing visual intrusion" /></td>
</tr>
</tbody>
</table>

**Fixed-Trunnion Bascule bridge can be recommended in this project:**
1. with under deck counterweight
2. without counterweight, relying on applying force by the hydraulic system
Swing bridge

1. As this type requires no counterweights, the complete weight is significantly reduced as compared to other moveable bridges.

2. Where sufficient channel width is available to have individual traffic directions on each side, the likelihood of vessel-to-vessel collisions is reduced.
3. The central support is often mounted upon a berm along the axis of the watercourse, intended to protect the bridge from watercraft collisions when it is opened.

Swing bridge cons-

1. For a symmetrical bridge, the central pier forms a hazard to navigation. Asymmetrical bridges may place the pivot near one side of the channel.
2. A wide channel will be reduced by the center pivot and foundation.
3. When open, the bridge will have to maintain its own weight as a balanced double cantilever, while when closed and in use for traffic, the live loads will be distributed as in a pair of conventional, which may require additional stiffness in some members whose loading will be alternately in compression or tension.
4. Safety problem due to unintended rotation if struck from the water near the edge

Swing bridge conclusion

This movable bridge type is not recommended for the proposed site location because of limited channel width.

Lift bridges

[Diagram of Lift bridges]
1. Its cost for building a long span is lower than the others.

2. The counterweights are only required to be equal to the weight of the deck whereas bascule bridge counterweights must weigh several times as much as the span being lifted.
3. As a result of above advantage, heavier material can be used in the deck, and so this type of bridge is especially suited for heavy railroad use.
<table>
<thead>
<tr>
<th>Lift bridge cons-</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Its height restriction is the main disadvantage because the deck remains suspended above the passageway</td>
</tr>
<tr>
<td>2. The cables linking the bridge and the counterweights are subject to wearing</td>
</tr>
</tbody>
</table>
3. Being visually intrusive in both open and closed situations because of having large towers.

Lift bridge

Conclusion

This movable bridge type is not recommended for this project because of:
1. Requiring too much glass material for the towers
2. Disturbing the glass transparency by towers
Submersible bridge

1. Lack of an above-deck structure is considered aesthetically pleasing
2. No height limitation on ship traffic

3. The presence of the submerged bridge structure limits the draft of vessels in the waterway and it can be considered as its disadvantage.
This movable bridge type is not recommended for this project because of the corrosion risk for the glass connections.
### Tilt Bridge

<table>
<thead>
<tr>
<th>Pros+</th>
<th>Cons-</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Less energy is required for opening because the structural arch and pathway counterbalancing each other.</td>
<td>2. Height limitation specially in short span.</td>
</tr>
</tbody>
</table>

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**Diagram:**

1. Less energy is required for opening because the structural arch and pathway counterbalancing each other.

2. Height limitation specially in short span.
3. It is not suitable for vehicular traffic because of deck with curved shape

<table>
<thead>
<tr>
<th>Tilt bridge Conclusion</th>
<th>This movable bridge type is not recommended for the proposed site location because of limited channel width.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Folding Bridge</td>
<td>A mast portal connected rigidly to the deck. Both mast portals have hinged joints at their bases.</td>
</tr>
</tbody>
</table>
1. Having the opportunity to use light weight members

2. Unlimited vertical clearance
3. Normally, a complicated moving system is required to be designed for transferring the loads during folding of bridge. In addition, the different segments of the bridge should be supported carefully for having allowable stresses when the bridge is closed, being folded and during folding operation.

This alternative can be a good option for this project because:
1. It is attractive visually
2. Less glass is required for members. As a result, light weight structure can be achieved.

Figure 10-14 Comparing the pros and cons of different movable bridge

10.1.7 Conclusion (type of movable bridge)
Based on analyzing and evaluating the pros and cons of different types of movable bridge and also considering the proposed site location it can be come to conclusion that two types of simple trunnion bridge and folding bridge can be a good option for my project.

10.2 The requirements for designing a movable bridge compare to fixed bridge
According to the fact that the applied loads to a movable bridge are different in close and open situation, the resulted stresses are changing in different situations. As a consequence, the analyses for checking the stresses of bridge should be done for the following situations:
- When the bridge is closed, the stress analyses of movable bridge are similar to fixed bridge.
- During the movement
- When the bridge is fully opened

What is more, the glass is more susceptible to failure due to stress concentration. So, the bridge loads should be transferred to the supports in a way to avoid high local stresses and bending moments.

It should be mentioned that these requirements will be discussed more during the design and analyses tasks.
11 Reference Projects
As there has not been any movable glass bridge yet. The following projects are selected to be reviewed more:

- A proposal for an arch footbridge in Venice made of structural glass masonry
- An icicle bridge
- Hörn Bridge

11.1 A proposal for an arch footbridge in Venice made of structural glass masonry (Gianni Royer-Carfagni, Mirko Silvestri)

11.1.1 The arch footbridge design
The proposal consists of a fixed-arch deck bridge with 48 m span and 6 m rise (rise to span ratio 1:8). The supporting structure is composed of two twin arches made of glass masonry, whereas the balustrade, the floor and the piers are all made of laminated glass, with just a few metal parts, mainly used for connection. In proximity of the abutments the deck and stairways are sustained by two concrete cantilever arches, fixed to the arch footings. The pillars are not vertical but almost orthogonal to the arch centroid line in order to center the line of thrust inside the core of the arch cross sectional area. (Gianni Royer-Carfagni, 2007)

![Figure 11-1 Visual rendering of the glass bridge](Gianni Royer-Carfagni, 2007)

![Figure 11-2 Visual rendering of the glass pillars connecting the arches to the deck](Gianni Royer-Carfagni, 2007)
11.1.2 The deck

The deck is formed by two 19.5 m-long, 6%-inclined ramps and a 6 m-long horizontal central portion. It is 5.25 m-wide and composed of 30 laminated glass modules, each one formed by three PVB laminated panels, whose size is $150 \times 100$ cm for the central one, and $150 \times 200$ cm for the lateral ones. Each panel is composed of three 12 mm plies and an 8 mm topping ply, forming the deck floor, with anti-slip surface treatment. The panels are supported by a frame composed of steel beams and laminated glass beams (Figure 11-1). The steel part of the frame consists in two longitudinal steel beams, placed at the edge of the deck, welded to 2 m-spaced transversal steel beams, all of them having a $150 \times 150 \times 5$ mm box transversal section. The longitudinal skeleton is completed by two, 1.5 m spaced, rows of glass beams, obtained by laminating four glass plies with a $60 \times 15$ mm cross section with PVB inter layers.

The longitudinal glass beams are pinned at the ends to stainless steel bearings, directly welded to the transversal steel beams. The visual aspect of the assembly will thus be similar to that of Fig. 12. The 1.35 m-high balustrades is formed by 16 mm thick laminated glass panels, directly fixed to the lateral steel beams.

The deck is directly supported by the arches in proximity of the central horizontal portion, whereas the lateral ramps are connected to the arches through four colonnades of laminated glass pillars. Each pillar is connected to the arch and deck through stainless hinge supports (Figure 11-2). The lower hinges, made of stainless steel, are connected to the glass arches by pins, fitting in holes and successively sealed. The upper hinges are directly welded to the transversal steel beams. The whole system is conceived of to allow for thermal expansions. (Gianni Royer-Carfagni, 2007)

![Figure 11-3 Details of transversal and longitudinal sections of the bridge](Gianni Royer-Carfagni, 2007)
11.1.3 The arch

The bridge main structure consists in two twin arches, 2 m wide and placed at a distance of 1 m one from the other, with a free span of 48 m and a rise to span ratio of 1:8.

Each arch, 200 cm wide and with height varying from 150 cm at the springings to 100 cm at the crown, is formed by 98 glass voussoirs of thickness approximately 50 cm. Each voussoir, weighting about 15 kN, is composed of \(200 \times 400 \times 15\) mm glass tiles, shop-assembled as a glass masonry, with shift joints filled with plastic acrylic resins that polymerize under the action of UV rays. The system is analogous to the one referred to as “epoxy cubes”. In order to give a proper wedge shape to the voussoirs, the bed joints are slightly thicker at the extrados than at the intrados.

For avoiding possible stress concentrations due to contact forces, neoprene bearings will be interposed at the arch springing, where the first glass voussoir meets the concrete abutment.

Once completed, the glass arches will exhibit quite an unusual visual sensation. Evidently, due to the glass thickness a total transparency will not be achieved, but the multiple diffraction of light will produce a rather sophisticated kaleidoscopic effect. (Gianni Royer-Carfagni, 2007)

![Figure 11-4 Assembly of the voussoirs to form the arch](Gianni Royer-Carfagni, 2007)
Figure 11-5 Control joints at the crown and at the springing of the main arches (Gianni Royer-Carfagni, 2007)

Figure 11-6 Visual renderings of the glass bridge (Gianni Royer-Carfagni, 2007)
11.2 An icicle bridge

This bridge is spanning 20 meter of Dutch canal and it composed of 5 big beams and 300 small ones perpendicular to main beams. Each big beam composed of 3 laminated panels which are connected to each other by the metal Z shape connection. This type of connection of two glass panels transfers axial forces, bending moment and shear force.

Figure 11-7 Different views of the icicle glass bridge (Nijss, 2014)
Figure 11-8 Connection of glass panels in main beams (Nijssse, 2014)
11.3 Hörn Bridge – Kiel, Germany

- Total Length: 105m
- Main Span: 26 m (total length of the three folding segments)
- Deck Width: 5m
- Weight of Folding Part: 54 t
- Folding Time: open/close in approx. 2 minutes each

The Hörn Bridge is a three segment folding bridge in Kiel (Germany) and it is completed in 1997. Designed by Hamburg-based architecture firm Gerkan, Marg and Partners, the bridge enables pedestrians to cross over from the Norwegian ferry terminal to the city’s primary railroad station.

The Hörn Bridge retracts into an “N” shape, generally once every hour, allowing ships to pass through. The deck of the bridge is drawn back by two hydraulic drives together with winches while the moving system is not hidden. (http://www.sbp.de)
The sea jetty made of girder grids with rolled steel profiles reflects the industrial surrounding with ships and cranes. At the points marking its thirds, the folding part of the deck is subdivided by hinges. The deck is borne on both sides by two cables that are deviated via two mast portals and are anchored in the foundation of the jetty. One mast portal is connected rigidly with the deck; both portals have hinged joints at their bases (see Figure 11-12). In this way, not only does an eye catching movement unfold, but the surface area exposed to wind is also reduced. In all positions and under all loads the cable system is statically determinate (http://www.sbp.de).
Figure 11-11 view to the Hörn Bridge during movement (Source: http://www.gmp-architekten.com)

Figure 11-12 Structure of Hörn Bridge (Source: http://www.gmp-architekten.com/)
Figure 11-13 view to the Hörn Bridge in a closed position (Source: http://www.gmp-architekten.com/)
12 Preliminary Design

12.1 Alternative- 1
My first proposed alternative is double leaf Bascule Bridge with combination of under deck counterweight and hydraulic system which can support each other. Most of structural and nonstructural parts are designed from glass. The counterweight can be constructed from other material like metal according to the fact that it is located inside the pits which are not seeable from outside. The deck of each leaf has triangular configuration to distribute the load on the bridge in a way to have less bending moment at the end supports. What is more, the longitudinal beams for supporting the deck load have higher depth near the supports owing to having more bending moment.

In compared to common double leaf deck which is composed of two cantilevered deck, it has the benefit of supporting from both side, one side as a pin and the other side as a fixed.

Figure 12-1 Visual rendering of the glass bridge in a closed position
Figure 12-2 Visual rendering of the glass bridge in an open position
Figure 12-3 Visual rendering of the glass bridge in an open position

Figure 12-4 Visual rendering of hydraulic system
12.2 Alternative -2
The second proposed alternative is folding bridge with two separate lanes for both traffic directions. The deck of bridge is composed of two segments which are connected to each other by hinge connection. The longitudinal arch beams are proposed for supporting the deck loads in view of the fact that it is subjected to more bending moment in the middle of span in the closed position. A cable system is proposed for distributing the force and it has constant length in both open and closed situations. As a result, the concentration stresses can be avoided specially during movement.

Figure 12-5 Visual rendering of bridge in closed position
Figure 12-6 Visual rendering of bridge during closing
Figure 12-7 Visual rendering of hydraulic systems in closed position

Figure 12-8 Visual rendering of bridge during closing

Figure 12-9 Visual rendering of hydraulic systems during closing
12.2.1 Moving system for second alternative

The movement of this bridge is provided by two separate hydraulic systems which are located at the support and in the middle of span. For moving mechanism, five options are proposed and option 5 is considered as applicable solution for this folding glass bridge.

Figure 12-10 Option 1 for folding- Using cables and tower

Figure 12-11 Option 2 for folding- Using hydraulic from one side to the other side of the bridge
Figure 12-12 Option 3 for folding- Using hydraulic from middle of one segment to middle of other segment

Figure 12-13 Option 4 for folding- Using vertical hydraulic in the middle of the span
12.3 Final Alternative:
The final alternative will be chosen by analyzing and evaluating the pros and cons of two proposed alternatives based on the following criteria:

- Load bearing capacity
- The required energy and hydraulic force
- Efficient use of material
- Aesthetic
- Innovative Components
- Maintenance

After comparing the bending stress diagrams of two alternatives (see Appendix), it can be said that the maximum bending stress in folding bridge has less magnitude in compared to Bascule Bridge. What is more, the bending moment is less along the longitudinal beams in proposed
folding bridge. In other words, folding bridge has better load bearing capacity. As a result, lighter members with less glass and metal materials can be used which leads to have lighter and more transparent bridge. Besides, less energy and hydraulic force is required for opening and closing the bridge because of having lighter bridge with better configuration. Moreover, it should be stated that having less bending moment in glass beams can lead to have wider span. So, it is possible to propose glass folding bridge with the span larger than our proposed site location. In addition, it is feasible to have more efficient folding bridge with finding the proper location and dimension of hydraulic and other moving components. So, it will be investigated more in the next steps to find the best optimum configuration of moving systems. Additionally, from aesthetic point of view folding bridge is more attractive. For example in Horn Bridge, which is chosen as my reference project, a lot of people have been attracted every day to see the bridge during the movement. As a result, folding bridge can be considered as modern monumental element in historical city of Delft. On the other hand, glass folding bridge requires designing innovative components and joints for having precise and reliable operation. So, this alternative is chosen to have more creative and innovative bridge which can lead to more investigation about movable glass bridge in the future. However it should not be neglected that a complicated system with more challenges is needed for folding bridge which is very new in compared to Bascule Bridge which has long history and proved to be reliable option from structural point of view. Furthermore, Bascule Bridge requires less maintenance owing to the fact that it has less movable components with simple moving system in compared to folding bridge with more hinge connections. Finally, folding bridge is chosen after evaluating the pros and cons of each alternative based on the above mentioned criteria.
Load bearing capacity

The required energy and hydraulic force
Figure 12-15 Comparing two proposed alternatives based on different aspects
13 Structural design

Figure 13-1 Visual rendering of the bridge
13.1 Component design

13.1.1 Beams configuration

As mentioned before, the folding bridge has two separate lanes with two longitudinal beams in each lane. According to the fact that the proposed longitudinal beams have crucial role in supporting the deck load including the dead and live load, their precise shape and dimension can help to have reliable movable structure. As a result, the optimum shape is found based on the bending moment diagram in both close and open conditions. As discussed before, the bridge has maximum bending moment at the location of the side hydraulic during movement. In the closed condition the maximum bending moment is in the middle of the bridge and also at the location of side hydraulic. So, the beams have more depth in these locations.

Furthermore, secondary beams are proposed in lateral direction to strengthen our structure. For improving the structural strength, these lateral beams are designed in a way to be perpendicular to bridge deck for having the loads in the plane of beams. Furthermore, the shape of cantilevered secondary beams is also proposed based on the bending moment stress. Consequently, it has more depth in its supports (close to the connection to longitudinal beam) (Figure 13-2 and Figure 13-3).
13.1.2 Dimensions of beams:
As discussed before, each longitudinal beam composed of two segments with hinge connection in the middle. Owing to the fact that the dimension of each segment is less than the size of jumbo glass, it is possible to have main beams of each segment in one piece with lamination of five glass panes with thickness of 0.01m and interlayer of sentry glass (5*0.01m).
However, after IDiana analysis seven glass panes (7*0.01m) are proposed for the first segment of main beams for the redundancy (Figure 13-4). What is more, each main beam is reinforced by stainless steel hollow square profile (0.01m *0.01m) that is located in the middle layer. As a result, this inserting hollow profile allowing the bolt connections to them for preventing making holes on the glass beams (Figure 13-5). Additionally, the secondary beams are constructed with lamination of three glass panes with thickness of 0.01m and interlayer of sentry glass and similar to longitudinal beams, they have also hollow profile insert (Figure 13-5).

![Figure 13-4 Dimensions of main beam](image)
Figure 13-5 Composition of main beam after Idiana analysis

Figure 13-6 Composition of secondary beams
13.1.3 Deck configuration
The bridge deck has a grid of 1.25m*3m (the dimension of glass panels of bridge deck). Each panel is constructed by lamination of three glass panes with PVB interlayer. What is more, another sacrificial glass pane (sandblasted anti slip glass) with thickness of 0.01m is glued to previous layers for the purpose of quickly and easily replacement due to any damage without affecting the structural integrity of the bridge deck (Figure 13-7 and Figure 13-8).
Figure 13-8 Composition of glass panel of the deck

3 glass panes (3 x 0.01m)
Sacrificial layer (1 x 0.01m)
sandblasted anti-slip glass
13.2 Connection design

13.2.1 Connection of secondary beams to main beams:
As can be seen from the Figure 13-10, rectangular metal plate is inserted on top part of the middle layer of lateral beams for reinforcement. In addition a metal bar is also connected to hollow profile. Besides, the metal connection blocks are rested on top of the main beams by bolting to the aforementioned insert hollow profile. As a result, the secondary beams are hanged on the longitudinal beams by locating the metal bars of lateral beams inside the space of connection blocks on the main beam (Figure 13-11 and Figure 13-12).
Figure 13-10 Resting the metal connection block on the main beam

Figure 13-11 Hanging the secondary beams on the main beam
Additionally, the connection of bottom of secondary beams to main beams is demonstrated in Figure 13-13. As can be seen, part 1 is inserted in the middle layer of secondary beam. Then part 2, which has empty space for accommodating part 3, is bolted to part 1. Part 3 (washer) is fastened to the threads of part 4. On the other side, part 4 is bolted to the insert of main beams. After assembling of secondary beam to the main beam at the bottom, the part 5 is bolted to part 2 to prevent downward displacement of secondary beam.

This system allows the adjustment of horizontal clearance between main and secondary beams. What is more, the secondary beams can be fitted in the place easier due to circular shape of part 3.
Figure 13-13 General view to bottom connections of beams

Figure 13-14 Part-1 and part-2 in bottom connections of beams
Figure 13-18 Horizontal section of secondary beams to main beam connection
13.2.2 Connection of deck to beams:
As can be seen from Figure 13-19 the glass deck is supported by beams through inserting rectangular metal plate in the middle layer of glass panel of deck. This proposed metal insert has circular space to accommodate the metal propeller. The fixation of metal propeller will be provided by bolting it to hollow profile at the center (Figure 13-20 and Figure 13-21).

Figure 13-19 General view to the deck connections

Figure 13-20 Connection of deck to beam

Figure 13-21 Connection of deck to beam
Figure 13-22 Horizontal section of deck to beam connection

Figure 13-23 Vertical section of deck to beam connection
13.3.1.1 Modifications:
Each connection is made by 3D printing to have better overview of assembling. What is more, to be sure that its components can be assemble and disassemble very easily and have adjustable, integrated and strong connection systems. From this point of view, almost all connections work proper. However, in the case of connecting the deck to beams on top a minor modification is proposed. In that case rectangular metal insert in the middle layer of the deck will extended a little bit more than the finished surface of glass and sit on the metal connection block on the beams. As a result, there will be more uniform load distribution on top of beams in compared to previous concept (Figure 13-25).
13.3.2 Moving system

As mentioned before, the proposed moving system is composed of three elements, two elements with constant lengths and one element with adjustable length which can be achieved by jack. In this regard, one of the main challenges is the proper length of elements which let the system to be folded precisely. From Figure 13-26, it can be seen that elements with constant lengths should have rotation around circles with the center of their connections to the main beams and radius of their lengths. These two mentioned circles should have always intersection during folding. However, at the first step the lengths of elements were specified inaccurate which causes that the system cannot be folded (Figure 13-27). So, the lengths of them were modified to have almost equal length and similar distance to the middle hinge connection for the purpose of having intersection between two circles in a reasonable location (Figure 13-28)
Figure 13-26 Preliminary design of moving elements
Connection of each segment of beam at hinge location is composed of triangular plate which is inserted in the laminated glass. As a result, the two segments of span are connecting to each other and holding in a place by locating single bolt into corresponding holes (Figure 13-29).

13.3.3 Support and hydraulic connections

In addition, the glass longitudinal beams are reinforced by inserting triangular metal plates at locations of moving elements. The plates are connected to sleeve for passing and assembling on the cylindrical beams. It should be mentioned that, these cylindrical beams are used for structural improvement at the locations of moving parts and support according to having high load on the support and applying high force by hydraulic. Moreover, the dimensions of cylinders are found based on the applied load and calculating the resulted maximum bending stress in the cylinder beams and comparing it with the allowable stress of steel. The Figure 13-31 demonstrates the connection of main beams to the support and side hydraulic. As can be seen the sleeve of plates have some grooves which mating to the teeth of the hollow cylindrical beam to prevent rotation.
13.3.4 Simple end support (Rest support)

The simple end support for the main beams is created by inserting metal plates in the second and fourth layers of the main beams at the end. So, in open position these plates are located in the gap inside the base support to avoid lateral movement of beams. However, the beams are free in axial movement due to expansion and contraction.

Furthermore, the restrain of the beams in downward direction is provided by seating the T-shape plate on the support. It should be mentioned that these T-shape plates are welded to the plates of the beams before glass lamination. In addition, for reinforcement curved shape plates are welded to the bottom of T-plate web for reinforcement and having a soft movement and preventing any erosion during opening/closing of bridge (Figure 13-33). Moreover, when the bridge is seated the motor driven lock bars are proposed at the bottom of main beams to lock them to the rest support and prevent the upward movement of span due to wind load (Figure 13-34).
Figure 13-32 View to the simple supports

Figure 13-33 Resting the beam on the support

Figure 13-34 Motor driven lock bar
13.4 Handrail

As can be seen from Figure 13-36, the vertical hand rail is connected to the secondary beams by pin connection. This proposed handrail can be folded during bridge movement for occupying less space. To achieve this purpose, two segments of handrail are connected to each other by two glass columns in the middle with considering the distance of two segments of deck during folding. As a result, this system provides the rotation of handrail during the bridge movement (Figure 13-37).

The vertical components of hand rail consist of Duran Schott glass tubes with soft aluminum cross spacer inside them at top and bottom for allowing pin connection to secondary beams and horizontal glass handrail. The horizontal glass handrail composed of three glass panes with hollow profile insert in the middle layer which pinned to cross spacer. What is more, glass tube is located inside the U-shape support in unfolded condition to improve the load bearing capacity of handrail (Figure 13-36).
Figure 13-36 Connections of glass tubes to secondary beams and horizontal glass handrail
Besides, two cables in addition to horizontal handrail are used along the bridge which are connected to glass tubes.

For strengthening the handrail and glass columns in the middle of bridge, the glass tube are pinned to T-shape structural element which is supported by two U-shape elements on the secondary beams in unfolded situation (Figure 13-38).
Figure 13-38 Connection of two segments of handrails in the middle

Figure 13-39 Connection of cables to glass tube
Figure 13-40 View to the physical model of handrail
13.6 Assembling:

Figure 13-41 Step-1: Visual rendering of the bridge
Step-1: Lamination of Glass Panes and inserting metal and hollow profile inside the beams
Step-2: Connection of main beams to support and side hydraulic
Step-3: Connection of two segments of main beams to each other
Step-4: Connection of moving elements to the main beams
Step-5: Connecting the secondary beams to main beams at the bottom and top
Step-6: Installing the glass deck on the main and secondary beams
Step-7: Connecting the vertical glass tubes of handrail to the deck
Step-8: Connecting the horizontal handrail to the glass tubes
Step-9: Gluing the sacrificial anti slip glass panes on the deck (This step can also be done as prefab in shop)
Figure 13-43 Step-2: Connection of main beams to support and side hydraulic

Figure 13-44 Step-3: Connection of two segments of main beams to each other
Figure 13-45 Step-4: Connection of moving elements to the main beams

Figure 13-46 Step-5: Connecting the secondary beams to main beams at the bottom and top
Figure 13-47 Step-6: Installing the glass deck on the main and secondary beams
Figure 13-48 Step-7: Connecting the vertical glass tubes of handrail to the deck

Figure 13-49 Step-8: Connecting the horizontal handrail to the glass tubes
Figure 13-50 Step-9: Gluing the sacrificial anti-slip glass panes on the deck
14 Diana analysis

14.1 Full bridge model
At the first step, the general model was simplified to a 3d drawing for analyzing. So, the glass beams, including the main and secondary beams, and deck are considered as surface with disregarding the metal connections. For connecting the deck segments to glass beams and also secondary beams to main beams the command of MPC Rbody is used for defining the pin connections. Furthermore, the movable mechanism in the side and middle were drawn as truss elements. It should be stated that the model is analyzed in two conditions of:
- Unfolded situation
- Folded situation: At the beginning of the movement( when the bridge is lifted a little bit and is not supported from one side)

14.1.1 Input for the Calculation (Modeling in Femgen)

14.1.1.1 Mesh type:
The element type which was used for the glass beams and deck is CQ48S. CQ48S is a curved shell element with 8 nodes loaded in and out-off plane. Additionally, CL18B as a beam element was used for the side cylindrical beams and moving elements were modeled by using L2TRU truss element.

![Figure 14-1 General view of meshing](image)
14.1.1.2 Section Properties of the Glass Beams

At this stage the material properties of glass and Stainless Steel were determined. The Young modulus (E) of 70 and 200 (GPa) and Poisson’s ratio of 0.2 and 0.3 are considered for glass and Stainless Steel respectively. Besides, the mass density of glass and steel are given 2400kg/m³ and 7800 kg/m³ respectively.

Furthermore, physical properties are specified for different considered sets. Thickness and dimension of each set is proposed due to approximate size found by hand calculations in previous steps. As a result thickness of 0.05m, 0.03m and 0.03 is considered for the main beams, secondary beams and deck respectively. In addition, two layers with thickness of 0.01m are added to the main glass beam close to the support for redundancy and due to having high stress here based on finite element analyses.

Additionally, the side cylindrical beams are steel pipes with diameter of 0.3m and wall thickness of 0.02m.

14.1.1.3 Loads

**Unfolded condition:** Six kinds of load case are determined for modeling and analyzing the bridge structure in IDiana.

Three of them are single load cases which are:

1. LC1-Dead weight of the bridge (gravity)
2. LC2-Uniform live load due to traffic
3. LC3-Snow load: Uniform snow load of 0.7(kN/m²) is considered on the deck
4. LC4- Wind load: Uniform wind load of 861(N/m²) is considered on the main beam due to following assumption:
   - Wind velocity pressure: q=861(N/m²)
   - External pressure coefficient for bridge: Cp=1

   The distributed load is applied on the main glass beams and it is:
   \[ q \times Cp = 861(N/m²) \times 1 = 861N/m² \]

Furthermore, different loads are combined in one single load case for checking the structure in the serviceability limit state and ultimate limit state:

5. LC5 (SLS): (Gravity + 0.4 Uniform live load + 0.5 Wind load + 0.5 Snow load) (Sanpaolesi.2005)
6. LC6 (ULS): (1.35 Gravity + 1.35 Uniform live load + 1.5 Wind load + 1.5 Snow load) (Sanpaolesi.2005)

It is obvious that structure must not collapse when subjected to the peak design load for which it was designed. Therefore, the maximum stresses should not exceed the ultimate stress.
**Folded condition:** In this situation, five load cases are considered as following:
1. LC1: Dead weight of the bridge (gravity)
2. LC2: Snow load
3. LC3: Wind load
4. LC4 (SLS): (Gravity + 0.5 Wind load + 0.5 Snow load)
5. LC5 (ULS): (1.35 Gravity + 1.5 Wind load+ 1.5 Snow load) (Sanpaolesi.2005)

14.1.1.4 **Boundary conditions:**

**Unfolded condition:** The pin connection is considered for side support and hydraulic which imposes vertical and horizontal force to the structure for avoiding translation in three directions (X,Y,Z) and let the structure to rotate (so the moment in supports is zero). The simple support is constraint in Z and X directions (vertical and lateral directions). The components of deck, main and secondary beams are connected (pinned) to each other by the command of MPC.
**Folded condition:** In this situation, the simple support is eliminated and the other boundary conditions are similar to the unfolded condition.

14.1.1.5 Analysis type

In Diana, a linear static analysis type is selected and the following specific output on the output tab is specified:

- DISPLA TOTAL TRANSL GLOBAL
- FORCE REACTI TRANSL GLOBAL
- STRESS TOTAL DISFOR LOCAL
- STRESSES TOTAL DISMOM LOCAL
- STRESS TOTAL CAUCHY LOCAL
- STRESS TOTAL CAUCHY PRINCI

14.1.2 Analysis results

The results are given in specified tables and compared in a graph for the different load cases. What is more, the stresses results are obtained for top, middle and bottom surfaces.

The allowable tensile strength of glass with considering the safety factor of 1.75 is 40 (MPa). So, the stresses results will be compared with the allowable stresses which are presented in Table 14-1. All IDiana results are presented in appendix.

<table>
<thead>
<tr>
<th>Mechanical Properties of Heat strengthened Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength (MPa)</td>
</tr>
<tr>
<td>Compressive strength (MPa)</td>
</tr>
<tr>
<td>Allowable tensile stress SLS (MPa)</td>
</tr>
<tr>
<td>Allowable Compressive stress SLS (MPa)</td>
</tr>
<tr>
<td>Allowable tensile stress ULS (MPa)</td>
</tr>
<tr>
<td>Allowable Compressive stress ULS (MPa)</td>
</tr>
</tbody>
</table>

Table 14-1 Allowable stresses for glass in different load cases
14.1.2.1 Stress results of main beams in unfolded condition

From Table 14-2 and Figure 14-3, it can be seen that the maximum principle stress of main beam (tensile stress) is around 20 (MPa) and as a result it is less than allowable stress.

<table>
<thead>
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<th>Main Beams (Unfolded)</th>
<th>LC1</th>
<th>LC2</th>
<th>LC3</th>
<th>LC4</th>
<th>LC5</th>
<th>LC6</th>
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<tr>
<td></td>
<td>Top</td>
<td>Mid</td>
<td>Bot</td>
<td>Top</td>
<td>Mid</td>
<td>Bot</td>
</tr>
<tr>
<td>S1 (MPa) Max</td>
<td>4.6</td>
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<td>4.8</td>
<td>14.4</td>
<td>14.1</td>
<td>20.8</td>
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<tr>
<td>S1 (MPa) Min</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S2 (MPa) Max</td>
<td>0.5</td>
<td>0.3</td>
<td>1.3</td>
<td>2.6</td>
<td>1.2</td>
<td>5.4</td>
</tr>
<tr>
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<td>-0.3</td>
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<td>-1.4</td>
<td>-1.4</td>
<td>-1.9</td>
</tr>
<tr>
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<td>0</td>
<td>0</td>
</tr>
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<td>-7.4</td>
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<td>3.3</td>
<td>5.3</td>
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<td>-11.2</td>
<td>-4.7</td>
<td>-4.6</td>
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<tr>
<td>Syy (MPa) Max</td>
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<td>3.3</td>
<td>15.3</td>
<td>9.2</td>
<td>9.2</td>
</tr>
<tr>
<td>Syy (MPa) Min</td>
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<td>-1.8</td>
<td>-7.9</td>
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<td>3.9</td>
<td>2.3</td>
<td>2.7</td>
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<td>-1.8</td>
<td>-7</td>
<td>-4.1</td>
<td>-3.7</td>
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<td>-2.8</td>
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<tr>
<td>Syz (MPa) Max</td>
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<td>Syz (MPa) Min</td>
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<td>-1.3</td>
<td>-5.1</td>
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</tr>
</tbody>
</table>

Table 14-2 Stresses in main beams due to different load cases in unfolded condition
Figure 14-3 Principal stresses in main beams due to different loadcases in unfolded condition

Figure 14-4 Unfolded- Principle stress S1(global) in main beams due to loadcase LC2 (top surface)

Figure 14-5 Unfolded- Principle stress S3 (global) in main beams due to loadcase LC2 (top surface)
Additionally, the maximum normal stresses $S_{xx}$ and $S_{yy}$ are in load combination LC5 and LC6 which are lower than acceptable stresses. It should be mentioned that these maximum stresses are locally and mostly close to the support points and connection points. However, in reality the support and connections are not in one point. What is more, Stainless steel is proposed as inserts in these locations. So, the loads will be distributed and the stresses will be lower in the connections and supports.

Figure 14-6 Normal stresses in main beams due to different loadcases in unfolded condition
Figure 14-7 Unfolded - Normal stress SYY (Local) in main beams due to loadcase LC6 (top surface)

Figure 14-8 Unfolded - Shear stress SXY (Local) in main beams due to loadcase LC6 (top surface)
14.1.2.2 Stress results of secondary beams in unfolded condition

As can be seen from Table 14-3 and Figure 14-9, the maximum principle stress in secondary beams is around 13 MPa. And similar to the main beams is in allowable range. What is more, the maximum normal stress $S_{xx}$ is approximately 30 MPa which is acceptable.

<table>
<thead>
<tr>
<th>Secondary Beams (unfolded)</th>
<th>LC1</th>
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<th>LC3</th>
<th>LC4</th>
<th>LC5</th>
<th>LC6</th>
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<tbody>
<tr>
<td><strong>S1 (MPa)</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
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<td>7</td>
<td>11.4</td>
<td>11.9</td>
<td>13.6</td>
</tr>
<tr>
<td>Min</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>S2 (MPa)</strong></td>
<td></td>
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<td></td>
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<tr>
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<tr>
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<tr>
<td><strong>S_{yz} (MPa)</strong></td>
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</tbody>
</table>

Table 14-3 Stresses in secondary beams due to different loadcases in unfolded condition
Figure 14-9 Principal stresses in secondary beams due to different loadcases in unfolded condition

Figure 14-10 Unfolded- Principle stress S1 in secondary beams due to loadcase LC2 (top surface)
Figure 14-11 Normal stresses in secondary beams due to different loadcases in unfolded condition
Figure 14-12 Unfolded- Normal stress SXX (Local) in secondary beams due to loadcase LC6 (top surface)

Figure 14-13 Unfolded- Shear stress SXY (Local) in main beams due to loadcase LC6 (top surface)
Stress results of deck in unfolded condition

Table 14-4 and Figure 14-14 show that the maximum principle stress in deck beams is approximately 18 MPa and similar to the main beams is in allowable range. What is more, the maximum normal stress $S_{xx}$ is approximately 30 MPa which is acceptable.

<table>
<thead>
<tr>
<th>Deck (Unfolded)</th>
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<th>LC3</th>
<th>LC4</th>
<th>LC5</th>
<th>LC6</th>
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</thead>
<tbody>
<tr>
<td></td>
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<td>Top</td>
<td>Mid</td>
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<tr>
<td>$S_1$ (MPa)</td>
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<td>6.3</td>
<td>4.5</td>
<td>2.6</td>
</tr>
<tr>
<td>Min</td>
<td>-2.5</td>
<td>-2.8</td>
<td>-3.1</td>
<td>-6.3</td>
<td>-7.6</td>
<td>-9.2</td>
</tr>
<tr>
<td>$S_{xy}$ (MPa)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>2.8</td>
<td>3</td>
<td>3.3</td>
<td>5.6</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Min</td>
<td>-3.3</td>
<td>-3.2</td>
<td>-3.2</td>
<td>-7.2</td>
<td>-6.2</td>
<td>-6.7</td>
</tr>
</tbody>
</table>

Table 14-4  Unfolded- Stresses in deck due to different loadcases in unfolded condition
Figure 14-14 Unfolded- Principal stresses in deck due to different loadcases in unfolded condition

Figure 14-15 Unfolded- Principle stress $S_1$ (global) in deck due to loadcase LC2 (top surface)
Figure 14-16 Unfolded- Local stresses in deck due to different loadcases in unfolded condition
Figure 14-17 Unfolded- Normal stress SXX (Local) in deck due to loadcase LC6 (bottom surface)
14.1.2.4 Displacement of main beams in unfolded condition

The maximum displacement of the main beam is presented in the following table (Table 14-5).

<table>
<thead>
<tr>
<th>Main Beams (unfolded)</th>
<th>LC1</th>
<th>LC2</th>
<th>LC3</th>
<th>LC4</th>
<th>LC5</th>
<th>LC6</th>
</tr>
</thead>
<tbody>
<tr>
<td>DTX (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Min</td>
<td>-0.1</td>
<td>-0.3</td>
<td>0</td>
<td>-0.1</td>
<td>-0.3</td>
<td>-0.8</td>
</tr>
<tr>
<td>DTY (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>0.1</td>
<td>0.25</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>0.6</td>
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<tr>
<td>Min</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DTZ (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Min</td>
<td>-0.2</td>
<td>-0.4</td>
<td>0</td>
<td>0</td>
<td>-0.4</td>
<td>-0.8</td>
</tr>
<tr>
<td>RESDTX (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>0.2</td>
<td>0.4</td>
<td>0.1</td>
<td>0.4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table 14-5 Unfolded- Displacement of main beams due to different load cases

Figure 14-18 Unfolded- Result displacement (global) of main beams due to loadcase LC6
14.1.2.5 Displacement of secondary beams in unfolded condition

<table>
<thead>
<tr>
<th>Secondary Beams (unfolded)</th>
<th>LC1</th>
<th>LC2</th>
<th>LC3</th>
<th>LC4</th>
<th>LC5</th>
<th>LC6</th>
</tr>
</thead>
<tbody>
<tr>
<td>DTX (mm)</td>
<td>Max</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>0</td>
<td>-0.3</td>
<td>0</td>
<td>-0.1</td>
<td>-0.2</td>
</tr>
<tr>
<td>DTY (mm)</td>
<td>Max</td>
<td>0.1</td>
<td>0.3</td>
<td>0</td>
<td>0.3</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>0</td>
<td>-0.4</td>
<td>0</td>
<td>-0.3</td>
<td>-0.8</td>
</tr>
<tr>
<td>DTZ (mm)</td>
<td>Max</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-0.2</td>
<td>-0.4</td>
<td>0</td>
<td>-0.4</td>
<td>-0.9</td>
</tr>
<tr>
<td>RESDTX (mm)</td>
<td>Max</td>
<td>0.2</td>
<td>0.5</td>
<td>0</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 14-6 Unfolded- Displacement of secondary beams due to different load cases

Figure 14-19 Unfolded- Displacement of secondary beams in Z direction (global) due to loadcase LC6
14.1.2.6 Displacement of deck in unfolded condition

<table>
<thead>
<tr>
<th>Deck (unfolded)</th>
<th>LC1</th>
<th>LC2</th>
<th>LC3</th>
<th>LC4</th>
<th>LC5</th>
<th>LC6</th>
</tr>
</thead>
<tbody>
<tr>
<td>DTX (mm)</td>
<td>Max</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>0</td>
<td>-0.3</td>
<td>0</td>
<td>-0.1</td>
<td>-0.2</td>
</tr>
<tr>
<td>DTY (mm)</td>
<td>Max</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>0</td>
<td>-0.3</td>
<td>0</td>
<td>0</td>
<td>-0.7</td>
</tr>
<tr>
<td>DTZ (mm)</td>
<td>Max</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-0.3</td>
<td>-1.2</td>
<td>-0.2</td>
<td>0</td>
<td>-0</td>
</tr>
<tr>
<td>RESDTX (mm)</td>
<td>Max</td>
<td>0.3</td>
<td>1.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.9</td>
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<tr>
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<td>Min</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table 14-7 Unfolded- Displacement of deck due to different load cases

Figure 14-20 Unfolded- Displacement of deck in Z direction (global) due to loadcase LC6
14.1.2.7 Moment of main beams in unfolded condition

<table>
<thead>
<tr>
<th>Main Beams (Unfolded)</th>
<th>LC1</th>
<th>LC2</th>
<th>LC3</th>
<th>LC4</th>
<th>LC5</th>
<th>LC6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mxx (N.m)</td>
<td>Max</td>
<td>459</td>
<td>2140</td>
<td>368</td>
<td>350</td>
<td>1670</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-3870</td>
<td>-15400</td>
<td>-2640</td>
<td>-2840</td>
<td>-12800</td>
</tr>
<tr>
<td>Myy (N.m)</td>
<td>Max</td>
<td>2190</td>
<td>8520</td>
<td>1460</td>
<td>1550</td>
<td>7100</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-568</td>
<td>-2170</td>
<td>-374</td>
<td>-847</td>
<td>-1770</td>
</tr>
<tr>
<td>Mxy (N.m)</td>
<td>Max</td>
<td>821</td>
<td>2850</td>
<td>490</td>
<td>529</td>
<td>2390</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-1280</td>
<td>-5420</td>
<td>-933</td>
<td>-1050</td>
<td>-4440</td>
</tr>
</tbody>
</table>

Table 14-8 Unfolded- Moment of main beams due to different load cases

Figure 14-21 Unfolded- Bending moment MY (Local) in main beams due to load case LC6
14.1.2.8  Moment of secondary beams in unfolded condition

<table>
<thead>
<tr>
<th>Secondary Beams (Unfolded)</th>
<th>LC1</th>
<th>LC2</th>
<th>LC3</th>
<th>LC4</th>
<th>LC5</th>
<th>LC6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mxx (N.m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>14.8</td>
<td>17.2</td>
<td>2.96</td>
<td>2.33</td>
<td>13.3</td>
<td>32.1</td>
</tr>
<tr>
<td>Min</td>
<td>-234</td>
<td>-708</td>
<td>-122</td>
<td>-107</td>
<td>-631</td>
<td>-1610</td>
</tr>
<tr>
<td>Myy (N.m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>30.1</td>
<td>91.1</td>
<td>15.7</td>
<td>14.2</td>
<td>81.3</td>
<td>208</td>
</tr>
<tr>
<td>Min</td>
<td>-21.7</td>
<td>-62.8</td>
<td>-10.8</td>
<td>-10.6</td>
<td>-57.2</td>
<td>-145</td>
</tr>
<tr>
<td>Mxy (N.m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>77.1</td>
<td>235</td>
<td>40.4</td>
<td>39.1</td>
<td>211</td>
<td>541</td>
</tr>
<tr>
<td>Min</td>
<td>-76.6</td>
<td>-230</td>
<td>-39.5</td>
<td>-32.5</td>
<td>-204</td>
<td>-519</td>
</tr>
</tbody>
</table>

Table 14-9 Unfolded- Moment of secondary beams due to different load cases

Figure 14-22 Unfolded- Bending moment MXX(Local) in secondary beams due to loadcase LC6
14.1.2.9  Moment of deck in unfolded condition

<table>
<thead>
<tr>
<th>Deck (Unfolded)</th>
<th>LC1</th>
<th>LC2</th>
<th>LC3</th>
<th>LC4</th>
<th>LC5</th>
<th>LC6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mxx (N.m)</td>
<td>Max</td>
<td>95.5</td>
<td>390</td>
<td>67.2</td>
<td>184</td>
<td>247</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-485</td>
<td>-1510</td>
<td>-260</td>
<td>-197</td>
<td>-1040</td>
</tr>
<tr>
<td>Myy (N.m)</td>
<td>Max</td>
<td>144</td>
<td>818</td>
<td>141</td>
<td>31.4</td>
<td>536</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-18.1</td>
<td>-68.3</td>
<td>-11.8</td>
<td>-26.2</td>
<td>-47.4</td>
</tr>
<tr>
<td>Mxy (N.m)</td>
<td>Max</td>
<td>113</td>
<td>558</td>
<td>96</td>
<td>48.2</td>
<td>357</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-111</td>
<td>-554</td>
<td>-95.3</td>
<td>-44.3</td>
<td>-344</td>
</tr>
</tbody>
</table>

Table 14-10 Unfolded- Moment of deck due to different load cases

Figure 14-23 Unfolded- Bending moment MYY(Local) in deck due to loadcase LC6
14.1.2.10 Support reaction force

<table>
<thead>
<tr>
<th>Support Reaction (unfolded)</th>
<th>LC1</th>
<th>LC2</th>
<th>LC3</th>
<th>LC4</th>
<th>LC5</th>
<th>LC6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FBX (N)</strong></td>
<td>Max</td>
<td>339</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-5140</td>
<td>-20000</td>
<td>-3440</td>
<td>-3730</td>
<td>-16700</td>
</tr>
<tr>
<td><strong>FBY(N)</strong></td>
<td>Max</td>
<td>16000</td>
<td>21600</td>
<td>3720</td>
<td>0</td>
<td>25900</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-2120</td>
<td>-3610</td>
<td>-620</td>
<td>-1790</td>
<td>-3880</td>
</tr>
<tr>
<td><strong>FBZ (N)</strong></td>
<td>Max</td>
<td>-1800</td>
<td>-3060</td>
<td>-3060</td>
<td>1590</td>
<td>-3300</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-5710</td>
<td>-16300</td>
<td>-16300</td>
<td>-2540</td>
<td>-14400</td>
</tr>
<tr>
<td><strong>RESFBX (N)</strong></td>
<td>Max</td>
<td>17200</td>
<td>32300</td>
<td>5560</td>
<td>4680</td>
<td>32800</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>2790</td>
<td>4730</td>
<td>814</td>
<td>15.5</td>
<td>5090</td>
</tr>
</tbody>
</table>

Table 14-11 Unfolded- support reaction force due to different load cases

Figure 14-24 Unfolded- Support reaction force in Z direction (global) due to loadcase LC6
14.1.2.11 Stress results of main beams in folded condition

As can be seen from Table 14-12 and Figure 14-25, the maximum principle stress of main beam (tensile stress) is around 22 (MPa) due to dead weight of the bridge. Furthermore, in ultimate limit state condition there is maximum normal stress of Syy with magnitude of about 53 MPa. As a result, in all load cases the stresses are in allowable range.

<table>
<thead>
<tr>
<th>Main Beams (folded)</th>
<th>LC1</th>
<th>LC2</th>
<th>LC3</th>
<th>LC4</th>
<th>LC5</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1 (MPa)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>21.5</td>
<td>21.3</td>
<td>21.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S2 (MPa)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>3.1</td>
<td>3.1</td>
<td>3.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>-1.3</td>
<td>-1.4</td>
<td>-1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S3 (MPa)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>-24.1</td>
<td>-24.2</td>
<td>-24.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sxx (MPa)</td>
<td>Max</td>
<td>7.7</td>
<td>7.7</td>
<td>7.7</td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>-8</td>
<td>-8</td>
<td>-8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Syy (MPa)</td>
<td>Max</td>
<td>20.7</td>
<td>20.4</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>-15.9</td>
<td>-15.6</td>
<td>-15.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sxy (MPa)</td>
<td>Max</td>
<td>10.8</td>
<td>10.8</td>
<td>10.8</td>
<td></td>
</tr>
<tr>
<td>Sxz (MPa)</td>
<td>Max</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>-0.9</td>
<td>-0.9</td>
<td>-0.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Syz (MPa)</td>
<td>Max</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>-1.6</td>
<td>-1.6</td>
<td>-1.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 14-12 Folded- stresses of main beams due to different load cases
Figure 14-25 Folded- Principal stresses of main beams due to different load cases
Figure 14-26 Folded- Principle stress S1 (global) in main beams due to loadcase LC1 (top surface)

Figure 14-27 Folded- Principle stress S3 (global) in main beams due to loadcase LC1 (top surface)
Figure 14-28 Folded - Local stresses of main beams due to different load cases
Figure 14-29 Folded- Normal stress SYY (Local) in main beams due to loadcase LC5 (top surface)
Figure 14-30 Folded- Shear stress SXY (Local) in main beams due to loadcase LC5 (top surface)
14.1.2.12 Stress results of secondary beams in folded condition
Similar to the unfolded condition, the maximum principle stress of secondary beams is less than allowable stress of glass (40 MPa) and mostly is located close to the support and connections.

<table>
<thead>
<tr>
<th>Secondary Beams (folded)</th>
<th>LC1</th>
<th>LC2</th>
<th>LC3</th>
<th>LC4</th>
<th>LC5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Top</td>
<td>Mid</td>
<td>Bot</td>
<td>Top</td>
<td>Mid</td>
</tr>
<tr>
<td>S1 (MPa)</td>
<td>Max</td>
<td>15.8</td>
<td>16.3</td>
<td>17.6</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S2 (MPa)</td>
<td>Max</td>
<td>2.4</td>
<td>2.2</td>
<td>2.1</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-2.2</td>
<td>-2.2</td>
<td>-2.3</td>
<td>-0.9</td>
</tr>
<tr>
<td>S3 (MPa)</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
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<td>-16.7</td>
<td>-15.4</td>
<td>-14.1</td>
<td>-7.5</td>
</tr>
<tr>
<td>Sxx (MPa)</td>
<td>Max</td>
<td>13.2</td>
<td>13.4</td>
<td>14.1</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-13.6</td>
<td>-11.8</td>
<td>-11.6</td>
<td>-6.1</td>
</tr>
<tr>
<td>Syy (MPa)</td>
<td>Max</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-8.8</td>
<td>-8.8</td>
<td>-8.8</td>
<td>-4.3</td>
</tr>
<tr>
<td>Sxy (MPa)</td>
<td>Max</td>
<td>7.1</td>
<td>7</td>
<td>6.9</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-5.9</td>
<td>-6.2</td>
<td>-6.5</td>
<td>-2.5</td>
</tr>
<tr>
<td>Sxz (MPa)</td>
<td>Max</td>
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<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-0.1</td>
<td>-0.1</td>
<td>-0.1</td>
<td>-0.1</td>
</tr>
<tr>
<td>Syz (MPa)</td>
<td>Max</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-1.5</td>
<td>-1.5</td>
<td>-1.5</td>
<td>-0.1</td>
</tr>
</tbody>
</table>

Table 14-13 Folded- stresses of secondary beams due to different load cases
Figure 14-31 Folded- Principal stresses of secondary beams due to different load cases

Figure 14-32 Folded- Principle stress S1 (global) in secondary beams due to loadcase LC1 (top surface)
Figure 14-33 Folded- Local stresses of secondary beams due to different load cases
Figure 14-34 Folded- Normal stress $S_{XX}$ (Local) in secondary beams due to loadcase LC4 (top surface)

Figure 14-35 Folded- Shear stress $S_{XY}$ (Local) in secondary beams due to loadcase LC5 (top surface)
Stress results of deck in folded condition

<table>
<thead>
<tr>
<th>Deck (folded)</th>
<th>LC1</th>
<th>LC2</th>
<th>LC3</th>
<th>LC4</th>
<th>LC5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Top</td>
<td>Mid</td>
<td>Bot</td>
<td>Top</td>
<td>Mid</td>
</tr>
<tr>
<td>S1 (MPa)</td>
<td>Max</td>
<td>15.3</td>
<td>16.0</td>
<td>18.1</td>
<td>6.1</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S2 (MPa)</td>
<td>Max</td>
<td>2.1</td>
<td>1.8</td>
<td>3</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-2.1</td>
<td>-1.9</td>
<td>-2.3</td>
<td>-1.0</td>
</tr>
<tr>
<td>S3 (MPa)</td>
<td>Max</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-15.9</td>
<td>-16.2</td>
<td>-17.9</td>
<td>-7</td>
</tr>
<tr>
<td>Sxx (MPa)</td>
<td>Max</td>
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<td>10.6</td>
<td>13.6</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-13.5</td>
<td>-11.6</td>
<td>-14.2</td>
<td>-5.9</td>
</tr>
<tr>
<td>Syy (MPa)</td>
<td>Max</td>
<td>8.8</td>
<td>8.1</td>
<td>7.4</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-7</td>
<td>-6.8</td>
<td>-6.6</td>
<td>-2.6</td>
</tr>
<tr>
<td>Sxy (MPa)</td>
<td>Max</td>
<td>7.2</td>
<td>7</td>
<td>6.9</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-7.6</td>
<td>-7.3</td>
<td>-7.1</td>
<td>-3.2</td>
</tr>
<tr>
<td>Szx (MPa)</td>
<td>Max</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-0.5</td>
<td>-0.5</td>
<td>-0.5</td>
<td>-0.3</td>
</tr>
<tr>
<td>Syz (MPa)</td>
<td>Max</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
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<td></td>
<td>Min</td>
<td>-0.3</td>
<td>-0.3</td>
<td>-0.3</td>
<td>-0.2</td>
</tr>
</tbody>
</table>

Table 14-14 Folded- stresses of deck due to different load cases
Figure 14-36 Folded- Principal stresses of deck due to different load cases

Figure 14-37 Folded- Principle stress $S_1$ (global) in deck due to loadcase LC1 (bottom surface)
Figure 14-38 Folded- Normal stresses of deck due to different load cases
Figure 14-39 Folded- Normal stress SXX (Local) in deck due to loadcase LC5 (bottom surface)
14.1.2.13 Displacement of main beams in folded condition

<table>
<thead>
<tr>
<th>Main Beams (folded)</th>
<th>LC1</th>
<th>LC2</th>
<th>LC3</th>
<th>LC4</th>
<th>LC5</th>
</tr>
</thead>
<tbody>
<tr>
<td>DTX (mm)</td>
<td>Max</td>
<td>0.1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-0.2</td>
<td>-0.1</td>
<td>-4.9</td>
<td>-2.7</td>
</tr>
<tr>
<td>DTY (mm)</td>
<td>Max</td>
<td>4.4</td>
<td>1.9</td>
<td>0.5</td>
<td>5.6</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>0</td>
<td>0</td>
<td>-0.5</td>
<td>0</td>
</tr>
<tr>
<td>DTZ (mm)</td>
<td>Max</td>
<td>0.6</td>
<td>0.3</td>
<td>2.1</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-20.6</td>
<td>-9.2</td>
<td>2.2</td>
<td>-26.3</td>
</tr>
<tr>
<td>RESDTX (mm)</td>
<td>Max</td>
<td>20.7</td>
<td>9.2</td>
<td>5.4</td>
<td>26.5</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 14-15 Folded- displacement of main beams due to different load cases

Figure 14-40 Folded- Displacement of main beams in Z direction (global) due to loadcase LC5
14.1.2.14 Displacement of deck in folded condition

<table>
<thead>
<tr>
<th>Deck (folded)</th>
<th>LC1</th>
<th>LC2</th>
<th>LC3</th>
<th>LC4</th>
<th>LC5</th>
</tr>
</thead>
<tbody>
<tr>
<td>DTX (mm)</td>
<td>Max</td>
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<td>0</td>
<td>-0.1</td>
<td>-0.1</td>
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<tr>
<td></td>
<td>Min</td>
<td>-0.2</td>
<td>-0.1</td>
<td>-3.7</td>
<td>-2</td>
</tr>
<tr>
<td>DTY (mm)</td>
<td>Max</td>
<td>4.4</td>
<td>1.9</td>
<td>1</td>
<td>5.8</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-0.1</td>
<td>-0.1</td>
<td>-1</td>
<td>-0.1</td>
</tr>
<tr>
<td>DTZ (mm)</td>
<td>Max</td>
<td>0.6</td>
<td>0.3</td>
<td>4.2</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-21</td>
<td>-9.2</td>
<td>-4.3</td>
<td>-27</td>
</tr>
<tr>
<td>RESDTX (mm)</td>
<td>Max</td>
<td>20</td>
<td>9.2</td>
<td>5.7</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>Min</td>
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<td>0</td>
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</tr>
</tbody>
</table>

Table 14-16 Folded- Displacement of main beams in Z direction (global) due to loadcase LC5

Figure 14-41 Folded- Result displacement (global) of deck due to loadcase LC5
14.1.2.15 Moment of main beams in folded condition

<table>
<thead>
<tr>
<th>Main Beams (folded)</th>
<th>LC1</th>
<th>LC2</th>
<th>LC3</th>
<th>LC4</th>
<th>LC5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mxx (N.m)</td>
<td>Max</td>
<td>510</td>
<td>326</td>
<td>1330</td>
<td>907</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-5050</td>
<td>-3210</td>
<td>-4230</td>
<td>-8380</td>
</tr>
<tr>
<td>Myy (N.m)</td>
<td>Max</td>
<td>2710</td>
<td>1720</td>
<td>5020</td>
<td>4620</td>
</tr>
<tr>
<td></td>
<td>Min</td>
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<td>-5118</td>
<td>-4770</td>
<td>-2010</td>
</tr>
<tr>
<td>Mxy (N.m)</td>
<td>Max</td>
<td>925</td>
<td>541</td>
<td>3210</td>
<td>1580</td>
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<tr>
<td></td>
<td>Min</td>
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<td>-1160</td>
<td>-2100</td>
<td>-3010</td>
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</table>

Table 14-17 Folded- Moment of main beams due to different loadcases

Figure 14-42 Folded- Bending moment MYY (Local) in main beams due to loadcase LC5

Figure 14-43 Folded- Torsional moment MXY (Local) in main beams due to loadcase LC5
### 14.1.2.16 Moment of secondary beams in folded condition

<table>
<thead>
<tr>
<th>Secondary Beams (folded)</th>
<th>LC1</th>
<th>LC2</th>
<th>LC3</th>
<th>LC4</th>
<th>LC5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mxx (N.m)</td>
<td>Max</td>
<td>15.8</td>
<td>4.6</td>
<td>44.4</td>
<td>29.4</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-384</td>
<td>-202</td>
<td>-152</td>
<td>-548</td>
</tr>
<tr>
<td>Myy (N.m)</td>
<td>Max</td>
<td>46.7</td>
<td>27.1</td>
<td>41.5</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-41.4</td>
<td>-19.7</td>
<td>-41.5</td>
<td>-58.7</td>
</tr>
<tr>
<td>Mxy (N.m)</td>
<td>Max</td>
<td>128</td>
<td>66.1</td>
<td>151</td>
<td>187</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-127</td>
<td>-66.6</td>
<td>-58.5</td>
<td>-181</td>
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</tbody>
</table>

Table 14-18 Folded- Moment of secondary beams due to different loadcases

![Figure 14-44 Folded- Bending moment MXX (Local) in secondary beams due to loadcase LC5](image)

Figure 14-44 Folded- Bending moment MXX (Local) in secondary beams due to loadcase LC5
14.1.2.17 Moment of deck in folded condition

<table>
<thead>
<tr>
<th>Deck (folded)</th>
<th>LC1</th>
<th>LC2</th>
<th>LC3</th>
<th>LC4</th>
<th>LC5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mxx (N.m)</td>
<td>Max</td>
<td>525</td>
<td>74.9</td>
<td>300</td>
<td>409</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-883</td>
<td>-428</td>
<td>-302</td>
<td>-1020</td>
</tr>
<tr>
<td>Myy (N.m)</td>
<td>Max</td>
<td>171</td>
<td>143</td>
<td>48.2</td>
<td>238</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-55.8</td>
<td>-16.4</td>
<td>-42.2</td>
<td>-34.7</td>
</tr>
<tr>
<td>Mxy (N.m)</td>
<td>Max</td>
<td>208</td>
<td>135</td>
<td>140</td>
<td>235</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-209</td>
<td>-126</td>
<td>-71.6</td>
<td>-238</td>
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</table>

Table 14-19 Folded- Moment of deck due to different loadcases

Figure 14-45 Folded- Bending moment MXX (Local) in deck due to loadcase LC5
14.1.2.18 Support reaction force

<table>
<thead>
<tr>
<th>Support Reaction (folded)</th>
<th>LC1</th>
<th>LC2</th>
<th>LC3</th>
<th>LC4</th>
<th>LC5</th>
</tr>
</thead>
<tbody>
<tr>
<td>FBX (N)</td>
<td>Max</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-6250</td>
<td>-4000</td>
<td>-5480</td>
<td>-10900</td>
</tr>
<tr>
<td>FBY(N)</td>
<td>Max</td>
<td>24900</td>
<td>7320</td>
<td>2790</td>
<td>30000</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>8780</td>
<td>4210</td>
<td>-7300</td>
<td>10800</td>
</tr>
<tr>
<td>FBZ (N)</td>
<td>Max</td>
<td>24900</td>
<td>7320</td>
<td>2790</td>
<td>30000</td>
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<tr>
<td></td>
<td>Min</td>
<td>8780</td>
<td>4210</td>
<td>-7300</td>
<td>10800</td>
</tr>
<tr>
<td>RESFBX (N)</td>
<td>Max</td>
<td>25900</td>
<td>8330</td>
<td>11100</td>
<td>32100</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>11500</td>
<td>5530</td>
<td>272</td>
<td>14100</td>
</tr>
</tbody>
</table>

Table 14-20 Folded- support reaction force due to different load cases

Figure 14-46 Folded- Support reaction force in Z direction (global) due to loadcase LC5
14.2 Modeling the bottom connection of secondary beam to main beam

14.2.1 Input for the Calculation (Modeling in Femgen)
The bottom connection of the main beam was simplified to 2d drawing of cross section of main beam at the bottom with proposing different set of the glass, SGP interlayer, metal insert and metal rod (Figure 14-48). The analysis of this connection is important to check the stresses especially shear stress in SGP interlayer. As a result, a cross section at the bottom of main beam was modelled and the element type of plane strain was chosen.

![Figure 14-47 View to the bottom connection of secondary beams to main beam](image)

14.2.1.1 Mesh type:
The meshing type, which is proposed for created set, is CQ16E. CQ16E is an eight node quadrilateral isoperimetric plane strain element. As can be seen from Figure 14-48, the SGP, glass, metal insert and bar elements are shown by red, green, yellow and blue colours respectively.
14.2.1.2 Section Properties of the Glass Beams
SGP is considered as isotropic material with Young modulus of 200 (MPa) and poison’s ratio of around 0.48. Besides, the material properties including the Young modulus (E) of 70 and 200 (GPa) and Poisson’s ratio of 0.2 and 0.3 are proposed for glass and Stainless Steel respectively.

14.2.1.3 Loads and boundary conditions
Two nodal loads of 1500(N) in vertical direction (Y-axis) and two distributed loads of 1950 (N) in axial direction (X-axis) are applied to the ends of rods. These loads are found based on the gravity of the bridge, live load and snow load on the deck.

The model is extended far from the connection area and then is fully restrained in directions of X and Y (Pined) to have minimum consequence on the results of glass connection.
14.2.2 IDiana results

The proposed allowable stresses for glass, stainless steel and SGP interlayer are provided in Table 14-21.

<table>
<thead>
<tr>
<th>Mechanical Properties</th>
<th>Glass (Heat Strengthened glass)</th>
<th>Stainless Steel (Austentic Stainless Steel grade 304)</th>
<th>SGP Interlayer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allowable tensile stress (MPa)</td>
<td>Allowable Compressive stress (MPa)</td>
<td>Yield strength (MPa)</td>
<td>Allowable stress (MPa)</td>
</tr>
<tr>
<td>40</td>
<td>100</td>
<td>230</td>
<td>115</td>
</tr>
</tbody>
</table>

Table 14-21 Assumed allowable stress of glass, stainless Steel and Sentry Glass (SGP data from www2.dupont.com)
As can be seen from Error! Reference source not found. and Figure 14-51, the principal stresses in SGP interlayer and glass are very low and less than 1 (MPa). What is more, the maximum principal stress in Steel bar and Steel insert are around 1.5 (MPa) and 1 (MPa) respectively. The general low stresses in the model can prove that the glass connection at the bottom has appropriate size and can distribute the load properly. As a consequence, the local stresses, which were found in the full bridge IDiana analysis, can distribute properly by metal connection and impose low stresses on the glass panes.
The Figure 14-54 demonstrates that the maximum shear stress in the SGP is approximately 1(MPa) which is too lower than allowable shear stress of SGP.
From Figure 14-55 and Figure 14-56, it can be found that the maximum tensile and compressive strain in Sentry glass in the bottom connection is even less than 0.1%. However, the SGP has high elongation of 400% (www2.dupont.com). As a result, SGP has allowable strain in this proposed connection.
Figure 14-55 Tensile Strain E1

Figure 14-56 Compressive Strain E2
Figure 14-57 Displacement in x direction

Figure 14-58 Displacement in y direction
14.3 Modeling the top connection of secondary beam to main beam

14.3.1 Input for the Calculation (Modeling in Femgen)
The top connection of the main beam is also converted to simple 2d drawing of cross section. So, different sets are specified for the surfaces of glass, hollow profile, and metal connection block. The resulting stresses on the connection block can demonstrate that the considered size for connection is defined well or not.

![View to the top connection](image)

**Figure 14-59 View to the top connection**

14.3.1.1 Mesh type
The mesh element of CQ16E, which is plane strain element, is specified for created geometry.
14.3.1.2 Section Properties of the Glass Beams
The aforementioned material properties of Steel and glass including Young modulus and Poisonous ratio are specified here.

14.3.1.3 Loads and boundary conditions:
Two nodal loads of 1400(N) in vertical direction (Y-axis) and two distributed loads of 1950 (N) in axial direction (X-axis) are applied to the ends of bars. Moreover, a concentrated load of 2800(N) is applied on the top middle of connection block due to deck force. These loads are found based on the gravity of the bridge, live load and snow load on the deck.

The model is extended far from the connection area and then is fully restrained in directions of X and Y (Pined) to have minimum consequence on the results of glass connection.
14.3.2 IDiana results
The maximum principal stress $S_1$ in the glass is less than 5(MPa). What is more, the maximum principal stress in Steel connection is approximately 21.5 (MPa) As a result, top connection has also proper size similar to the bottom connection which was analyzed before.
Figure 14-62 Principle Stress S1

Figure 14-63 Principle Stress S2
Figure 14-66 Shear stress $S_{xy}$
Figure 14-67 Displacement in X direction

Model: TOP_CONNECTION
LC1: Load Case 1
Nodal DTX....G DTX
Max = .243E-4
Min = -.243E-4
Factor = 120

Figure 14-68 Displacement in Y direction

Model: TOP_CONNECTION
LC1: Load Case 1
Nodal DTX....G DTY
Max = .503E-5
Min = -.153E-5
Factor = 500
14.4 Buckling

For checking the buckling of the bridge, Euler stability analysis is done in IDiana. This type of analysis gives the information whether solutions from linear elastic analysis are stable or small disturbances to those solutions exist requiring no extra external energy. With this method it is possible to get an impression of structure’s buckling mode (Diana User’s Manual, 2008).

In this project the lowest buckling values or most critical buckling values are presented. This factor demonstrates that if the external load $f$ (the applied load on the bridge) is multiplied by the buckling value, then the buckling will be occurred. It means that:

$$\frac{\text{Critical load} (f_{\text{crit}})}{\text{Applied load}} = \text{buckling value}$$

14.4.1 Checking the full model

According to the fact that the bridge and specially its main beams might be subjected to the buckling, the bridge is analysed for the following conditions:

- The bridge is in the start of the folding
- The bridge is folded

![Mesh view when the bridge is folded](image)
The results of buckling analyses are presented in the following figures and it shows that:

- The buckling value is -1.23, which will be happened in Z-direction, when the bridge starts to be folded
- The buckling value is 2, which will be happened in Y-direction, when the bridge is folded.

**Figure 14-70** Buckling mode of the bridge in the start of folding - normalised translation in X direction

**Figure 14-71** Buckling mode of the bridge in the start of folding - normalised translation in Y direction
Figure 14-72 Buckling mode of the bridge in the start of folding - normalised translation in Z direction
Figure 14-73 Buckling mode of the bridge in folded situation- normalised translation in X direction

Figure 14-74 Buckling mode of the bridge in folded situation- normalised translation in Y direction
It should be mentioned that negative buckling value indicates that buckling occurs if the direction of external loads is switched. Hence, the direction of external loads on the bridge (gravity) cannot be changed; such modes of buckling will not be occurred. So, it can be concluded that the bridge will not be susceptible to buckling.

14.4.2 Checking the first segment of main beam

As mentioned before, the first segment of main beam is more subjected to buckling. As a result, separate models are created for checking the buckling in more depth with applying conservative loads. Furthermore, it should be noted that the presence of the secondary beams and deck, which can improve the resistance of the structure against buckling, are not taking into account conservatively.

For the situation of starting the movement of the bridge, two models are created. In the first model, two distributed loads are applied on the first segment of the main beam including vertical load due to weight and a conservative axial load. The second model is also similar to the first model while the applied loads are different. In this case, the distributed load on top of the main beam is only due to weight of the first segment of the bridge. Besides, three concentrated loads are applied due to imposed loads from second segment of the bridge.
Figure 14-76 Applied loads for checking the buckling of first segment of main beam (Case-1)

Figure 14-77 Applied loads for checking the buckling of first segment of main beam (Case-2)
Figure 14-78 Buckling mode of first segment of the main beam in the start of bridge folding - normalised translation in X direction (Case-1)

Figure 14-79 Buckling mode of first segment of the main beam in the start of bridge folding - normalised translation in Y direction (Case-1)
Figure 14-80 Buckling mode of first segment of the main beam in the start of bridge folding - normalised translation in Z direction (Case-1)

Figure 14-81 Buckling mode of first segment of the main beam in the start of bridge folding - normalised translation in X direction (Case-2)
Figure 14-82 Buckling mode of first segment of the main beam in the start of bridge folding - normalised translation in Y direction (Case-2)

Figure 14-83 Buckling mode of first segment of the main beam in the start of bridge folding - normalised translation in Z direction (Case-2)
The folded bridge is the other situation which is considered. In this model, the first segment of the main beam is oriented vertically and it is assumed that the whole weight of the bridge is applied as a distributed load on the depth of the beam.

Figure 14-84 Applied loads for checking the buckling of first segment of main beam when the bridge is folded
Figure 14-85 Buckling mode of first segment of the main beam when the bridge is folded - normalised translation in X direction

Figure 14-86 Buckling mode of first segment of the main beam when the bridge is folded - normalised translation in Y direction
Based on the results of analyses, it can be come to this conclusion that the main beam is stable and will not be subjected to buckling.
15 Final Architectural Design
Figure 15-2 Top view of the bridge
Figure 15-3 Bird view to the bridge
Figure 15-4 View to the South-East side of the bridge
Figure 15-5 View to the North-West side of the bridge
Figure 15-6 Visual rendering of the bridge
Figure 15-7 View to the bridge and New Church in Delft
Figure 15-8 Visual rendering of the bridge
Figure 15-9 View to the North-West side of the bridge in proposed site
Figure 15-10 View to the South-East side of the bridge in proposed site
16 Conclusion and Recommendations

After answering the sub questions in previous sections, and making the connections and general model, answering the research problem and main question in this project is now possible. The results from IDiana analysis and physical model all demonstrate that it is possible to have movable glass bridge where glass is used as structural load bearing elements. However, Steel was proposed for moving elements in a middle and side of span but in compared to the amount of glass used in the bridge, this amount of metal is negligible. On the other hand, it would be possible to replace some moving elements such as moving part with constant length in the second segment with glass material owing to the fact that they are taking the compression force.

In addition, according to the fact that a glass bridge is susceptible to the damage by ship and people accidents, some safety consideration should be considered to minimize this risk as much as possible. For example a movable barrier can be proposed in both side of the bridge. Furthermore, considering armored laminated glass by using a metal wire mesh in the middle layer of deck can improve the structural strength of deck against bending. However, in minimum damage such as breaking one glass pane of deck or beam the results from IDiana prove that the stresses are generally low enough to have some margins for these unexpected damages without collapsing the bridge.

It should be mentioned that different challenges tried to be solved in this project and according to have limited time, several aspects are not considered and need to be investigated in more depth for the final evaluation and improvement. For example, the optimum shape and dimension of moving elements can be looked in more detail. What is more, the geometry of bridge is simplified in IDiana and there was not any option for modeling the jack hydraulic in detail and apply force from it. As a result, analyzing such a complicated system dynamically can be recommended for the future developments.

Additionally, the proposed design proves that achieving a movable glass bridge with negligible metal use for the span of approximately 11m can be possible. But for longer span with more optimum shape, more investigations and also experimental tests will be required.
17 References

- Professor Fred Veer,” AR105 Technoledge Lectures”, TU Delft, 2014
- Professor Nijsse. Rob,” AR105 Technoledge Lectures”, TU Delft, 2014
- RICE PETER, ”Structural glass”, 1995
- Ate SNIJDER , Fred VEER , Rob NIJSSE , Kees BAARDOLF , Ton ROMEIN “Designing and testing an eight meter span glass portal frame”, International Conference at glasstec, Düsseldorf, Germany, October 2014
- TNO DIANA BV, ”Diana User’s Manual”, 2008

Web Adresses:
- http://www. novumstructures.com/
- http://en.wikipedia.org/wiki/Moveable_bridge
• http://en.wikipedia.org/wiki/Submersible_bridge
• http://en.wikipedia.org/wiki/Swing_bridge
• http://www.sbp.de/
• www2.dupont.com/Building_Innovations/zh_CN/.../SGPintro_E.pdf
18 Appendix

18.1 Alternative 1- Bascule bridge- during movement

\[ a := \sqrt{c^2 + b^2 - 2 \cdot c \cdot b \cdot \cos(90\text{deg} + \theta)} \]

Where:

\[
\frac{a}{\sin(A)} = \frac{c}{\sin(C)}
\]

\[
\sin(90\text{deg} - \alpha) = \frac{c}{a}
\]

\[
\sin(90\text{deg} + \theta)
\]

\[
\alpha := 90\text{deg} - \arcsin\left(\frac{c}{a} \cdot \sin(90\text{deg} + \theta)\right)
\]

\[ \alpha = 32.723\text{deg} \]

L1 := 0.8m
L2 := 10.2m
L := 11m
l1 := L1 \cdot \cos(\theta)
l2 := L2 \cdot \cos(\theta)

\[ \theta := 1\text{deg} \]

\[ e_n := 0.8\text{m} \]

b := 0.5m
18.1.1 Deck Load

![Diagram of Deck Load]

18.1.2 Longitudinal Beam Load

Width := 6m
Length := 11m
Thickness := 0.04m
Density := 2500 $\text{kg/m}^3$

$$W_{\text{Deck}} := \left( 9.8 \frac{\text{m}}{\text{s}^2} \right) \text{Width} \times \text{Length} \times \text{Thickness} \times \text{Density}$$

$$W_{\text{Deck}} = 6.468 \times 10^4 \text{ N}$$

$$W_{\text{deck}} := \frac{W_{\text{Deck}}}{4 \times \text{Length}}$$

$$W_{\text{deck}} = 1.47 \times 10^3 \frac{\text{N}}{\text{m}}$$
length := 11m
depth_{avT} := 0.65m
thickness := 0.05m
density := 2500 \text{ kg/m}^3

W_{beam} := \left( 9.8 \frac{m}{s^2} \right) \cdot \text{depth}_{avT} \cdot \text{thickness} \cdot \text{density}

W_{beam} = 796.25 \text{ N/m}

W = 2.266 \times 10^3 \text{ N/m}
\[ \Sigma M := 0 \]
\[ -W \cdot L_1 \cdot \frac{L_1 \cdot \cos(\theta)}{2} + P \cdot \sin(\alpha) \cdot L_1 \cdot \cos(\theta) - P \cdot \cos(\alpha) \cdot L_1 \cdot \sin(\theta) - L_2 \cdot W \left( L_1 \cdot \cos(\theta) + \frac{L_2 \cdot \cos(\theta)}{2} \right)^2 = 0 \]

\[ P := \frac{W \cdot (L_1 + L_2)^2 \cdot \cos(\theta)}{2 \cdot L_1 \cdot (\sin(\alpha) \cdot \cos(\theta) - \cos(\alpha) \cdot \sin(\theta))} \]

\[ P = 3.259 \times 10^5 \text{ N} \]

\[ \Sigma F_x := 0 \]
\[ F_{XA} + P \cdot \cos(\alpha) := 0 \]

\[ F_{XA} := -P \cdot \cos(\alpha) \]

\[ F_{XA} = -2.742 \times 10^5 \text{ N} \]

\[ \Sigma F_y := 0 \]
\[ F_{YA} + P \cdot \sin(\alpha) - W (L_1 + L_2) := 0 \]

\[ F_{YA} := W (L_1 + L_2) - P \cdot \sin(\alpha) \]

\[ F_{YA} = -1.512 \times 10^5 \text{ N} \]
\[ F_{X_A} \cdot X \cdot \tan \theta - F_{Y_A} \cdot X + \frac{W \cdot X^2}{2 \cdot \cos \theta} + M_1 := 0 \]

\[ M_1(X) := F_{Y_A} \cdot X - F_{X_A} \cdot X \cdot \tan(\theta) - \frac{W \cdot X^2}{2 \cdot \cos(\theta)} \]

\[ \Sigma F_X := 0 \]

\[ F_{X_A} + N_{\text{prim}_1} := 0 \]

\[ N_{\text{prim}_1} := -F_{X_A} \]

\[ \Sigma F_Y := 0 \]

\[ F_{Y_A} - \frac{W \cdot X}{\cos(\theta)} - V_{\text{prim}_1} := 0 \]

\[ V_{\text{prim}_1}(X) := F_{Y_A} - \frac{W \cdot X}{\cos(\theta)} \]

\[ N_1(X) := N_{\text{prim}_1} \cdot \cos(\theta) - V_{\text{prim}_1}(X) \cdot \sin(\theta) \]

\[ V_1(X) := V_{\text{prim}_1}(X) \cdot \cos(\theta) + N_{\text{prim}_1} \cdot \sin(\theta) \]
18.1.4 Part 2

\[ L_1 \leq X \leq L_1 + L_2 \]
\[ \sum F_X = 0 \]
\[ F_{xA} + P \cos \alpha + N_{\text{prim}_2} = 0 \]

\[ N_{\text{prim}_2} := -P \cos (\alpha) - F_{xA} \]

\[ \sum F_Y = 0 \]
\[ F_{YA} + P \sin (\alpha) - \frac{W \cdot X}{\cos (\theta)} - V_{\text{prim}_2} = 0 \]

\[ V_{\text{prim}_2}(X) := F_{YA} + P \sin (\alpha) - \frac{W \cdot X}{\cos (\theta)} \]

\[ \sum M = 0 \]
\[ F_{xA} X \tan \theta - F_{YA} X + \frac{W \cdot X^2}{2 \cos \theta} + P \cos (\alpha) \left( X \tan (\theta) - L_1 \sin (\theta) \right) - P \sin (\alpha) \left( X - L_1 \cos (\theta) \right) + M_2 := 0 \]

\[ M_2(X) := F_{YA} X + P \sin (\alpha) - F_{xA} X \tan (\theta) - P L_1 \sin (\alpha) \cos (\theta) - \frac{W \cdot X^2}{2 \cos (\theta)} - P X \cos (\alpha) \tan (\theta) + P \cos (\alpha) L_1 \sin (\theta) \]

\[ N_2(X) := N_{\text{prim}_2} \cos (\theta) - V_{\text{prim}_2}(X) \sin (\theta) \]

\[ V_2(X) := V_{\text{prim}_2}(X) \cos (\theta) + N_{\text{prim}_2} \sin (\theta) \]
\[ M(X) := \begin{cases} M_1(X) & \text{if } 0 \leq X < L_1 \\ M_2(X) & \text{if } L_1 \leq X \leq L_1 + L_2 \end{cases} \]
thickness of beam \( \text{bb} := 0.05 \text{m} \)

Height of beam

\[
\text{hh}(X) := \begin{cases} 
0.9 \text{m} & \text{if } 0 \leq X \leq L_1 \\
0.9 \text{m} - 0.5 \text{m} \frac{(X - 0.8 \text{m})}{10.2 \text{m}} & \text{otherwise}
\end{cases}
\]

\[
I(X) := \frac{\text{bb} \cdot \text{hh}(X)^3}{12}
\]

\[
\sigma(X) := \frac{M(X) \cdot \text{hh}(X)}{I(X)}
\]
18.2 Alternative 2- folding Bridge during movement

\[
\begin{align*}
\theta_1 &= 1 \text{deg} \\
\theta_2 &= 1 \text{deg} \\
L_1 &= 0.8 \text{m} \\
L_2 &= 5.2 \text{m} \\
L_5 &= 1.54 \text{m} \\
L_6 &= 3.5 \text{m} \\
\theta_2 &= 1 \text{deg} \\
\cos(\theta_2) &= 1.586 \text{m} \\
\cos(\theta_2) &= 1.514 \text{m} \\
a &= 1.482 \text{m} \\
b &= 1.54 \text{m} \\
c &= 0.645 \text{m} \\
W &= 2.266 \times 10^3 \frac{\text{N}}{\text{m}} \\
W &= 2.266 \times 10^3 \frac{\text{N}}{\text{m}}
\end{align*}
\]
Where:

\[ D_{\text{angle}} := 180 \text{deg} - (B_{\text{angle}} + A_{\text{angle}}) \]

\[ B_{\text{angle}} + A_{\text{angle}} := \theta_1 + \theta_2 \]

\[ a := \sqrt{e^2 + c^2 - 2 \cdot e \cdot c \cdot \cos(A_{\text{angle}})} \]

\[ d := \sqrt{e^2 + c^2 - 2 \cdot e \cdot c \cdot \cos(A_{\text{angle}})} \]

\[ e := \frac{\sqrt{a^2 + b^2 - 2 \cdot a \cdot b \cdot \cos(180 \text{deg} - \theta_1 - \theta_2)}}{2 \cdot a} \]

\[ e = 3.022 \text{m} \]

\[ A_{\text{angle}} := \acos\left(\frac{c^2 + e^2 - d^2}{2 \cdot e \cdot c}\right) \]

\[ A_{\text{angle}} = 13.227 \text{deg} \]

\[ A_{\text{angle}} := \acos\left(\frac{b^2 + c^2 - a^2}{2 \cdot b \cdot e}\right) \]

\[ A_{\text{angle}} = 0.981 \text{deg} \]

Where:

\[ \alpha_2 + \theta_2 := (A_{\text{angle}} + A_{\text{angle}}) \]

\[ \alpha_2 := A_{\text{angle}} + A_{\text{angle}} - \theta_2 \]

\[ \alpha_2 = 13.208 \text{deg} \]
18.2.1 Segment 2

$$\Sigma M := 0$$

$$P \cdot \sin(\alpha_2) \cdot L_5 \cdot \cos(\theta_2) + P \cdot \cos(\alpha_2) \cdot L_5 \cdot \sin(\theta_2) = \frac{W \cdot (L_5 + L_6)^2 \cdot \cos(\theta_2)}{2}$$

$$P := \frac{W \cdot (L_5 + L_6)^2 \cdot \cos(\theta_2)}{2 \cdot L_5 \cdot \sin(\alpha_2) \cdot \cos(\theta_2) + \cos(\alpha_2) \cdot \sin(\theta_2)}$$

$$P = 7.613 \times 10^4 \text{ N}$$

$$\Sigma F_x := 0$$

$$F_{x2} + P \cdot \cos(\alpha_2) := 0$$

$$F_{x2} := -P \cdot \cos(\alpha_2)$$

$$F_{x2} = -7.412 \times 10^4 \text{ N}$$

$$\Sigma F_y := 0$$

$$F_{y2} + P \cdot \sin(\alpha_2) - W \cdot (L_5 + L_6) := 0$$

$$F_{y2} := W \cdot (L_5 + L_6) - P \cdot \sin(\alpha_2)$$

$$F_{y2} = -5.974 \times 10^3 \text{ N}$$
\[
f := \sqrt{b^2 + c^2 - 2 \cdot b \cdot c \cdot \cos(\alpha_2 + \theta_2)}
\]
\[
f := a^2 + d^2 - 2 \cdot a \cdot d \cdot \cos(\gamma_1)
\]
\[
\gamma_1 := \arccos \left( \frac{(a^2 + d^2 - f^2)}{(2 \cdot a \cdot d)} \right)
\]
\[
\gamma_2 := 180 \text{deg} - \gamma_1
\]
\[
g := \sqrt{h^2 + i^2 - 2 \cdot h \cdot \cos(\gamma_2)}
\]
\[
\frac{i}{\sin(\gamma_3)} = \frac{g}{\sin(\gamma_2)}
\]
\[
\gamma_3 := \arcsin \left( \frac{i \cdot \sin(\gamma_2)}{g} \right)
\]
\[
\gamma_4 := 180 \text{deg} - (\gamma_3 + \gamma_2)
\]
\[
\gamma_{\text{prim}_2} := 180 \text{deg} - (\theta_1 + \gamma_2)
\]
\[
\gamma_{\text{prim}_4} := (\gamma_{\text{prim}_2} - \gamma_4)
\]
\[
f = 0.379 \text{m}
\]
\[
\gamma_1 = 13.636 \text{deg}
\]
\[
\gamma_2 = 166.364 \text{deg}
\]
\[
g = 2.509 \text{m}
\]
\[
\gamma_3 = 3.474 \text{deg}
\]
\[
\gamma_4 = 10.162 \text{deg}
\]
\[
\gamma_{\text{prim}_2} = 12.636 \text{deg}
\]
\[
\gamma_{\text{prim}_4} = 2.474 \text{deg}
\]
\[ \sum F_x := 0 \]
\[-P_3 \cdot \cos(\gamma_{prim2}) + P_2 \cdot \cos(\gamma_{prim4}) - P \cdot \cos(\alpha_2) := 0 \]

\[ \sum F_y := 0 \]
\[ P_2 \cdot \sin(\gamma_{prim2}) - P_2 \cdot \sin(\gamma_{prim4}) - P \cdot \sin(\alpha_2) := 0 \]

\[ P_2 := \frac{(P \cdot \sin(\alpha_2) + P \cdot \cos(\alpha_2) \cdot \tan(\gamma_{prim2}))}{\cos(\gamma_{prim4}) \cdot \tan(\gamma_{prim2}) - \sin(\gamma_{prim4})} \]
\[ P_2 = 1.881 \times 10^5 \text{ N} \]

\[ P_3 := \frac{(P_2 \cdot \cos(\gamma_{prim4}) - P \cdot \cos(\alpha_2))}{\cos(\gamma_{prim2})} \]
\[ P_3 = 1.166 \times 10^5 \text{ N} \]
18.2.2 Segment-1

\[ \alpha_1 := 90 \text{deg} - \sin \left( \frac{0.8 \sin(90 \text{deg} + \theta_1)}{\sqrt{0.8^2 + 0.3^2 - 2 \cdot 0.8 \cdot 0.5 \cos(90 \text{deg} + \theta_1)}} \right) \]

\[ \alpha_1 = 32.723 \text{deg} \]

\[ \Sigma M := 0 \]

\[ P_1 \cdot \sin(\alpha_1) \cdot L_1 \cdot \cos(\theta_1) - P_1 \cdot \cos(\alpha_1) \cdot L_1 \cdot \sin(\theta_1) - W \cdot (L_1 + L_2) \cdot \left( \frac{L_1 + L_2}{2} \right) \cdot \cos(\theta_1) \]

\[ + P_2 \cdot \cos(\gamma_{\text{prim}}) \cdot (L_2 + L_1 - h - a) \cdot \sin(\theta_1) + P_2 \cdot \sin(\gamma_{\text{prim}}) \cdot (L_2 + L_1 - h - a) \cdot \cos(\theta_1) \]

\[ - P_3 \cdot \cos(\gamma_{\text{prim}}) \cdot (L_2 + L_1 - a) \cdot \sin(\theta_1) - P_3 \cdot \sin(\gamma_{\text{prim}}) \cdot (L_2 + L_1 - a) \cdot \cos(\theta_1) \]

\[ + F_{x_2} \cdot (L_1 + L_2) \cdot \sin(\theta_1) - F_{y_2} \cdot (L_1 + L_2) \cdot \cos(\theta_1) = 0 \]
\[ P_1 := \frac{-W \left( \frac{L_1 + L_2}{2} \right)^2 \cos(\gamma)}{2} + P_2 \cos(\gamma_{prim_2}) \left( L_2 + L_1 - h - a \right) \sin(\alpha_1) + P_2 \sin(\gamma_{prim_2}) \left( L_2 + L_1 - h - a \right) \cos(\alpha_1) \]

\[ + \left( -P_3 \cos(\gamma_{prim_3}) \left( L_2 + L_1 - a \right) \sin(\alpha_1) - P_3 \sin(\gamma_{prim_3}) \left( L_2 + L_1 - a \right) \cos(\alpha_1) \right) \]

\[ \frac{F_{x_2} \left( L_1 + L_2 \right) \sin(\theta_1) - F_{y_2} \left( L_1 + L_2 \right) \cos(\theta_1)}{L_1 \left( \cos(\alpha_1) \sin(\theta_1) - \sin(\alpha_1) \cos(\theta_1) \right)} \]

\[ \Sigma F_x := 0 \]

\[ F_{x_1} + P_1 \cos(\alpha_1) - P_2 \cos(\gamma_{prim_4}) + P_2 \cos(\gamma_{prim_2}) - F_{x_2} := 0 \]

\[ F_{x_1} := P_2 \cos(\gamma_{prim_4}) - P_1 \cos(\alpha_1) - P_2 \cos(\gamma_{prim_2}) + F_{x_2} \]

\[ F_{x_1} = -2.13 \times 10^5 \text{ N} \]

\[ \Sigma F_y := 0 \]

\[ F_{y_1} + P_1 \sin(\alpha_1) + P_2 \sin(\gamma_{prim_4}) - P_2 \sin(\gamma_{prim_2}) - W \left( L_1 + L_2 \right) := 0 \]

\[ F_{y_1} := P_2 \sin(\gamma_{prim_2}) + W \left( L_1 + L_2 \right) - P_1 \sin(\alpha_1) - P_2 \sin(\gamma_{prim_4}) + F_{y_2} \]

\[ F_{y_1} = -1.123 \times 10^5 \text{ N} \]

\[ P_1 = 2.54 \times 10^5 \text{ N} \]
18.2.3 Segment-1 Part 1

\[ 0 \leq X < L_1 \]
\[ \sum M := 0^\circ \]

\[ F_{x1} \cdot X \cdot \tan \theta_1 - F_{y1} \cdot X + \frac{W \cdot X^2}{2 \cdot \cos \theta_1} + M := 0 \]

\[ M_{1,1}(X) := F_{y1} \cdot X - F_{x1} \cdot X \cdot \tan(\theta_1) - \frac{W \cdot X^2}{2 \cdot \cos(\theta_1)} \]

\[ \sum F_x := 0^\circ \]
\[ F_{x1} + N_{\text{prim}} := 0 \]
\[ N_{\text{prim}_{1,1}} := -F_{x1} \]

\[ \sum F_y := 0^\circ \]
\[ F_{y1} - \frac{W \cdot X}{\cos(\theta_1)} - V_{\text{prim}} := 0 \]
\[ V_{\text{prim}_{1,1}}(X) := F_{y1} - \frac{W \cdot X}{\cos(\theta_1)} \]

\[ N_{1,1}(X) := N_{\text{prim}_{1,1}} \cdot \cos(\theta_1) - V_{\text{prim}_{1,1}}(X) \cdot \sin(\theta_1) \]
\[ V_{1,1}(X) := V_{\text{prim}_{1,1}}(X) \cdot \cos(\theta_1) + N_{\text{prim}_{1,1}} \cdot \sin(\theta_1) \]
18.2.4 Segment-1 Part 2

\[ L_1 \leq X < L_1 + L_2 - h - a \]
\[ \sum F_x := 0 \]
\[ F_{x1} + P_1 \cos \alpha_1 + N_{\text{prim}} := C \]
\[ N_{\text{prim}_1,2} := -P_1 \cos (\alpha_1) - F_{x1} \]
\[ \sum F_y := 0 \]
\[ F_{y1} + P_1 \sin (\alpha_1) - \frac{W \times X}{\cos (\theta_1)} - V_{\text{prim}_1,2} := \]
\[ V_{\text{prim}_1,2}(X) := F_{y1} + P_1 \sin (\alpha_1) - \frac{W \times X}{\cos (\theta_1)} \]
\[ \sum M := 0 \]
\[ F_{x1} X \tan \theta_1 - F_{y1} X + \frac{W \times X^2}{2 \cos \theta_1} + P_1 \cos (\alpha_1) \tan \theta_1 \left( X - L_1 \cos (\theta_1) \right) - P_1 \sin (\alpha_1) \left( X - L_1 \cos (\theta_1) \right) + M_{1,2} := \]
\[ M_{1,2}(X) := -F_{x1} X \tan (\theta_1) + F_{y1} X - \frac{W \times X^2}{2 \cos (\theta_1)} - P_1 \cos (\alpha_1) \tan (\theta_1) \left( X - L_1 \cos (\theta_1) \right) - P_1 \sin (\alpha_1) \left( X - L_1 \cos (\theta_1) \right) \]
\[ N_{1,2}(X) := N_{\text{prim}_1,2} \cos (\theta_1) - V_{\text{prim}_1,2}(X) \sin (\theta_1) \]
\[ V_{1,2}(X) := V_{\text{prim}_1,2}(X) \cos (\theta_1) + N_{\text{prim}_1,2} \sin (\theta_1) \]
\[ L_1 + L_2 - h - a \leq X \leq L_1 + L_2 - a \]

\[ \Sigma F_x = 0 \]

\[ F_{x1} + P_1 \cos \alpha_1 - P_2 \cos (\gamma_{prim4}) + N_{prim} := N_{prim1,3} := -P_1 \cos (\alpha_1) - F_{x1} + P_2 \cos (\gamma_{prim4}) \]

\[ \Sigma F_y = 0 \]

\[ F_{y1} + P_1 \sin (\alpha_1) - \frac{W \cdot X}{\cos (\alpha_1)} + P_2 \sin (\gamma_{prim4}) - V_{prim1,3} := V_{prim1,3}(X) := F_{y1} + P_1 \sin (\alpha_1) + P_2 \sin (\gamma_{prim4}) - \frac{W \cdot X}{\cos (\alpha_1)} \]

\[ \Sigma M = 0 \]

\[ F_{x1} X \tan \alpha_1 - F_{y1} X + \frac{W \cdot X^2}{2 \cos \alpha_1} + P_1 \cos (\alpha_1) \tan \alpha_1 (X - L_1 \cos (\alpha_1)) - P_1 \sin (\alpha_1) (X - L_1 \cos (\alpha_1)) \ldots \]

\[ + (-P_2) \cos (\gamma_{prim4}) \tan (\alpha_1) \left[ X - \cos (\alpha_1) \left( L_1 + L_2 - h - a \right) \right] - P_2 \sin (\gamma_{prim4}) \left[ X - \cos (\alpha_1) \left( L_1 + L_2 - h - a \right) \right] + M_{1,3} \]

\[ M_{1,3}(X) := -F_{x1} X \tan (\alpha_1) + F_{y1} X - \frac{W \cdot X^2}{2 \cos (\alpha_1)} - P_1 \cos (\alpha_1) \tan (\alpha_1) (X - L_1 \cos (\alpha_1)) + P_1 \sin (\alpha_1) (X - L_1 \cos (\alpha_1)) \ldots \]

\[ + P_2 \cos (\gamma_{prim4}) \tan (\alpha_1) \left[ X - \cos (\alpha_1) \left( L_1 + L_2 - h - a \right) \right] + P_2 \sin (\gamma_{prim4}) \left[ X - \cos (\alpha_1) \left( L_1 + L_2 - h - a \right) \right] \]

\[ N_{1,3}(X) := N_{prim1,3} \cos (\alpha_1) - V_{prim1,3}(X) \sin (\alpha_1) \]

\[ V_{1,3}(X) := V_{prim1,3}(X) \cos (\alpha_1) + N_{prim1,3} \sin (\alpha_1) \]
18.2.2 Segment-1 Part 4

\[ L_1 + L_2 - a \leq X \leq L_1 + L_2 \]

\[ \Sigma F_x := 0 \]

\[ F_{x1} + P_1 \cos \alpha_1 - P_2 \cos(\gamma_{prim_4}) + P_3 \cos(\gamma_{prim_2}) + N_{prim} := \]

\[ N_{prim_{1,4}} := -P_1 \cos(\alpha_1) - F_{x1} + P_2 \cos(\gamma_{prim_4}) - P_3 \cos(\gamma_{prim_2}) \]

\[ \Sigma F_y := 0 \]

\[ F_{y1} + P_1 \sin(\alpha_1) - \frac{W \cdot X}{\cos(\theta_1)} + P_2 \sin(\gamma_{prim_4}) - P_3 \sin(\gamma_{prim_2}) - V_{prim_{1,3}} := \]

\[ V_{prim_{1,4}}(X) := F_{y1} + P_1 \sin(\alpha_1) + P_2 \sin(\gamma_{prim_4}) - P_3 \sin(\gamma_{prim_2}) - \frac{W \cdot X}{\cos(\theta_1)} \]

\[ \Sigma M := 0 \]

\[ F_{x1} \cdot \tan \theta_1 - F_{y1} \cdot X + \frac{W \cdot X^2}{2 \cdot \cos \theta_1} + P_1 \cdot \cos(\alpha_1) \cdot \tan \theta_1 \cdot (X - L_1 \cdot \cos(\theta_1)) - P_1 \sin(\alpha_1) \cdot (X - L_1 \cdot \cos(\theta_1)) \]

\[ + \left( -P_2 \cos(\gamma_{prim_4}) \tan(\theta_1) \cdot \left[ X - \cos(\theta_1) \left( L_1 + L_2 - h - a \right) \right] - P_2 \sin(\gamma_{prim_4}) \left[ X - \cos(\theta_1) \left( L_1 + L_2 - h - a \right) \right] \right) \]

\[ + P_3 \sin(\gamma_{prim_2}) \left[ X - \cos(\theta_1) \left( L_1 + L_2 - a \right) \right] + P_3 \cos(\gamma_{prim_2}) \left[ X - \cos(\theta_1) \left( L_1 + L_2 - a \right) \right] \tan(\theta_1) + M_{1,4} \]
\[ M_{1,4}(X) := -F_{x1} \cdot X \cdot \tan(\theta_1) + F_{y1} \cdot X - \frac{W \cdot X^2}{2 \cdot \cos(\theta_1)} - P_1 \cdot \cos(\theta_1) \cdot \tan(\theta_1) \cdot (X - L_1 \cdot \cos(\theta_1)) + P_1 \cdot \sin(\theta_1) \cdot (X - L_1 \cdot \cos(\theta_1)) \cdots \]
\[ + P_2 \cdot \cos(\gamma_{prim4}) \cdot \tan(\theta_1) \cdot (X - \cos(\theta_1) \cdot (L_1 + L_2 - h - a)) + P_2 \cdot \sin(\gamma_{prim4}) \cdot (X - \cos(\theta_1) \cdot (L_1 + L_2 - h - a)) \cdots \]
\[ + (-P_3) \cdot \sin(\gamma_{prim3}) \cdot (X - \cos(\theta_1) \cdot (L_1 + L_2 - a)) - P_3 \cdot \cos(\gamma_{prim3}) \cdot (X - \cos(\theta_1) \cdot (L_1 + L_2 - a)) \cdot \tan(\theta_1) \]

\[ N_{1,4}(X) := N_{prim1,4} \cdot \cos(\theta_1) - V_{prim1,4}(X) \cdot \sin(\theta_1) \]

\[ V_{1,4}(X) := V_{prim1,4}(X) \cdot \cos(\theta_1) + N_{prim1,4} \cdot \sin(\theta_1) \]

\[ M_1(X) := \begin{cases} M_{1,1}(X) & \text{if } 0 \leq X < L_1 \\ M_{1,2}(X) & \text{if } L_1 \leq X < L_1 + L_2 - h - a \\ M_{1,3}(X) & \text{if } L_1 + L_2 - h - a \leq X < L_1 + L_2 - a \\ M_{1,4}(X) & \text{if } L_1 + L_2 - a \leq X \leq L_1 + L_2 \end{cases} \]
thickness of beam

\[ bb := 0.05 \text{m} \]

Height of beam in segment-1

\[ h_1(X) := \begin{cases} 
(0.9 \text{m}) & \text{if } 0 \leq X \leq L_1 \\
0.9 \text{m} - 0.5 \frac{(X - 0.8 \text{m})}{10.2 \text{m}} & \text{otherwise}
\end{cases} \]

\[ I_1(X) := \frac{bb \cdot h_1(X)^3}{12} \]

\[ M_1(X) = \frac{h_1(X)}{I_1(X)} \]

\[ \sigma_1(X) := \frac{M_1(X)}{I_1(X)} \]
18.2.3 Segment-2 Part 1

\[0 \leq X < L_2 \]
\[\Sigma F_x := 0\]
\[F_{x2} + N_{\text{prim}_{2,1}} := 0\]
\[N_{\text{prim}_{2,1}} := -F_{x2}\]

\[\Sigma F_y := 0\]
\[F_{y2} - \frac{W \cdot X}{\cos(\theta_2)} - V_{\text{prim}_{2,1}} := 0\]
\[V_{\text{prim}_{2,1}}(X) := F_{y2} - \frac{W \cdot X}{\cos(\theta_2)}\]

\[\Sigma M := 0\]
\[-F_{x2} \cdot X \cdot \tan(\theta_2) - F_{y2} \cdot X + \frac{W \cdot X^2}{2 \cdot \cos(\theta_2)} + M_{2,1} := 0\]
\[M_{2,1}(X) := F_{y2} \cdot X + F_{x2} \cdot X \cdot \tan(\theta_2) - \frac{W \cdot X^2}{2 \cdot \cos(\theta_2)}\]
\[N_{2,1}(X) := N_{\text{prim}_{2,1}} \cdot \cos(\theta_2) - V_{\text{prim}_{2,1}}(X) \cdot \sin(\theta_2)\]
\[V_{2,1}(X) := V_{\text{prim}_{2,1}}(X) \cdot \cos(\theta_2) + N_{\text{prim}_{2,1}} \cdot \sin(\theta_2)\]
18.2.4 Segment-2 Part 2

\[ L_4 \leq X \leq L_4 + L_6 \]
\[ \Sigma F_x = 0 \]
\[ F_{x_2} + P \cos(\alpha_2) + N_{\text{prim}_{2,2}} = 0 \]
\[ N_{\text{prim}_{2,2}} := -F_{x_2} - P \cos(\alpha_2) \]

\[ \Sigma F_y = 0 \]
\[ F_{y_2} + P \sin(\alpha_2) - \frac{W \cdot X}{\cos(\alpha_2)} - V_{\text{prim}_{2,2}} = 0 \]
\[ V_{\text{prim}_{2,2}} := F_{y_2} + P \sin(\alpha_2) - \frac{W \cdot X}{\cos(\alpha_2)} \]

\[ \Sigma M = 0 \]
\[ -F_{x_2} \cdot X \cdot \tan(\alpha_2) - F_{y_2} \cdot X - P \cdot \sin(\alpha_2) \left( X - L_5 \cdot \cos(\alpha_2) \right) - P \cdot \cos(\alpha_2) \left( X - L_5 \cdot \cos(\alpha_2) \right) \cdot \tan(\alpha_2) + \frac{W \cdot X^2}{\gamma \cdot \cos(\alpha_2)} + M_{2,2} = 0 \]
\[ M_{2,2}(X) := F_{x_2} \cdot X + F_{y_2} \cdot X \cdot \tan(\alpha_2) + P \cdot \sin(\alpha_2) \left( X - L_5 \cdot \cos(\alpha_2) \right) + P \cdot \cos(\alpha_2) \left( X - L_5 \cdot \cos(\alpha_2) \right) \cdot \tan(\alpha_2) - \frac{W \cdot X^2}{2 \cdot \cos(\alpha_2)} \]
\[ N_{2,2}(X) := N_{\text{prim}_{2,2}} \cdot \cos(\alpha_2) - V_{\text{prim}_{2,2}} \cdot \sin(\alpha_2) \]
\[ V_{2,2}(X) := V_{\text{prim}_{2,2}} \cdot \cos(\alpha_2) + N_{\text{prim}_{2,2}} \cdot \sin(\alpha_2) \]
\[ M_2(X) := \begin{cases} 
M_{2.1}(X) & \text{if } 0 \leq X < L_5 \\
M_{2.2}(X) & \text{if } L_5 \leq X < L_5 + L_6 
\end{cases} \]
thicknes of beam $b_0 = 0.05 m$

Height of beam $h(x) = \begin{cases} 0.9m - 0.5m & \frac{(X + L_1 + L_2) - 0.8m}{10.2m} \quad \text{if } 0 \leq X \leq L_5 + L_6 \\ 0 & \text{otherwise} \end{cases}$

$I_2(x) := \frac{bb \cdot h(x)^3}{12}$

$
\sigma(x) := \frac{M_2(x)}{I_2(x)}$

$M(x)$
18.3 Alternative 1- Bascule bridge-Close condition

\[ \begin{align*}
L_1 & := 0.8 \text{m} \\
L_2 & := 10.2 \text{m} \\
L & := 11 \text{m} \\
W & := P \sin(\alpha) \\
\theta & := 0 \text{deg} \\
\alpha & := 26.565 \text{ deg} \\
R_A & := \frac{W}{L}(L - a) \\
R_B & := \frac{W}{L}a \\
\theta_A & := \frac{W}{6E1L}(2L - a)(L - a) \\
y_A & := 0 \\
M_A & := 0 \\
y(X) & := y_A + \theta_A X + \frac{M_A X^2}{2E1} + \frac{R_A X^3}{6E1} + \frac{W}{6E1} < X - L_1 >^3
\end{align*} \]
\[ x_1 = L_1^* \]

\[ y_1(L_1) := \frac{W L_1^2 (2L - L_1)(L - L_1) + W L_1^3 (L - L_1)^*}{6EI\cdot L} \]

\[ y_1(L_1) := \frac{P \sin(\alpha) L_1^2 (2L - L_1)(L - L_1) + P \sin(\alpha) L_1^3 (L - L_1)^*}{6EI\cdot L} \]
L := L_1 + L_2
a := 0
R_{Ao} := \frac{W_0 L}{2}
\theta_{Ao} := \frac{-W_0 L^2}{24EI}
y(X) := \theta_{Ao} X + \frac{R_A X^3}{6EI} - \frac{W_0 X^4}{24EI}
y_2(L_1) := \frac{W_0 \left[ (-L)^3 L_1 + 2L L_1^3 - L_1^4 \right]}{24EI}
y_1(L_1) - y_2(L_1) := 0
P := \frac{W_0 L \left[ (-L)^3 L_1 + 2L L_1^3 - L_1^4 \right]}{4 \sin(\alpha) \left( L - L_1 \right) \left[ L_1^3 - L_1^2 (2L - L_1) \right]} \quad P = 2.971 \times 10^5 \text{ N}
\[ \sum F_x := 0 \]
\[ F_{xA} := -P \cos(\alpha) \]
\[ F_{xA} + P \cos(\alpha) := 0 \]
\[ F_{xA} = -2.657 \times 10^5 \text{ N} \]

\[ \Sigma M_0 := 0 \]
\[ P \sin(\alpha) L_1 - \frac{W_0 (L_1 + L_2)^2}{2} + F_{yB} (L_1 + L_2) := 0 \]
\[ F_{yB} := \frac{W_0 (L_1 + L_2)^2 - 2 \cdot P \sin(\alpha) L_1}{2 / (L_1 + L_2)} \]
\[ F_{yB} = 2.391 \times 10^4 \text{ N} \]

\[ \Sigma F_y := 0 \]
\[ F_{yA} + P \sin(\alpha) + F_{yB} - W_0 (L_1 + L_2) := 0 \]
\[ F_{yA} := \frac{W_0 (L_1 + L_2)^2 - 2 \cdot P \sin(\alpha) L_2}{2 / (L_1 + L_2)} \]
\[ F_{yA} = -8.963 \times 10^4 \text{ N} \]
18.3.1 Part 1

\[
0 \leq X < L_1
\]
\[
\Sigma M := 0
\]
\[
F_{xA} \cdot X \cdot \tan(\theta) - F_{yA} \cdot X + \frac{W \cdot X^2}{2 \cdot \cos(\theta)} + M_1 := 0
\]
\[
\Sigma F_x := 0
\]
\[
F_{xA} + N_1 := 0
\]
\[
\Sigma F_y := 0
\]
\[
F_{yA} - \frac{W_0 \cdot X}{\cos(\theta)} - V_1 := 0
\]
\[
V_1(X) := F_{yB} - \frac{W_0 \cdot X}{\cos(\theta)}
\]

\[
M_1(X) := F_{yA} \cdot X - F_{xA} \cdot X \cdot \tan(\theta) - \frac{W_0 \cdot X^2}{2 \cdot \cos(\theta)}
\]

\[b = 0.5m\]
\[L_1 = 0.8m\]
18.3.2 Part 2

\[ L_1 \leq X \leq L_1 + L_2 \]

\[ \Sigma F_x := 0 \]

\[ F_{xA} + P \cos \alpha + N_{prim2} := 0 \]

\[ N_2 := -P \cos \alpha - F_{xA} \]

\[ \Sigma F_y := 0 \]

\[ F_{yA} + P \sin \alpha - \frac{W \cdot X}{\cos \theta} - V_{prim2} := 0 \]

\[ V_2(X) := F_{yA} + P \sin \alpha - \frac{W_0 \cdot X}{\cos \theta} \]

\[ \Sigma M := 0 \]

\[ F_{xA} \cdot X \cdot \tan \theta - F_{yA} \cdot X + \frac{W \cdot X^2}{2 \cdot \cos \theta_1} + P \cos \alpha \cdot \left( X \cdot \tan \theta - L_1 \cdot \sin \theta \right) - P \sin \alpha \cdot \left( X - L_1 \cdot \cos \theta \right) + M_2 := \]

\[ M_2(X) := -F_{xA} \cdot X \cdot \tan \theta + F_{yA} \cdot X + P \cdot X \sin \alpha - F_{xA} \cdot X \cdot \tan \theta - P \cdot L_1 \sin \alpha \cdot \cos \theta - \frac{W_0 \cdot X^2}{2 \cdot \cos \theta} - P \cdot X \cdot \cos \alpha \cdot \tan \theta + P \cos \alpha \cdot L_1 \cdot \sin \theta \]

\[ M(X) := \begin{cases} M_1(X) & \text{if } 0 \leq X < L_1 \\ M_2(X) & \text{if } L_1 \leq X \leq L_1 + L_2 \end{cases} \]
thickness of beam \( b_b := 0.05 \text{m} \)

Height of beam
\[
\begin{align*}
\text{hh}(X) := \begin{cases} 
0.9 \text{m} & \text{if } 0 \leq X \leq L_1 \\
0.9 \text{m} & \text{otherwise}
\end{cases} \\
0.9 \text{m} - 0.5 \frac{(X - 0.8 \text{m})}{10.2 \text{m}} & \text{otherwise}
\end{align*}
\]

\[ I(X) := \frac{b_b \cdot \text{hh}(X)}{12} \]

\[ M(X) := \frac{\text{hh}(X)}{2} \]

\[ o(X) := \frac{M(X)}{I(X)} \]
18.4 IDiana results

View to the Diana model
Unfolded-Normal stress $S_{XX}$ (Local) in main beams due to loadcase LC5 (bottom surface)

Unfolded-Normal stress $S_{YY}$ (Local) in main beams due to loadcase LC5 (top surface)

Unfolded-Shear stress $S_{XY}$ (Local) in main beams due to loadcase LC5 (top surface)

Unfolded-Shear stress $S_{ZX}$ (Local) in main beams due to loadcase LC5 (top surface)
Unfolded- Normal stress $S_{XX}$ (Local) in main beams due to loadcase LC6 (bottom surface)

Unfolded- Shear stress $S_{ZX}$ (Local) in main beams due to loadcase LC6 (top surface)
Unfolded- Principle stress S3 (global) in secondary beams due to loadcase LC2 (top surface)

Unfolded- Normal stress SXX (Local) in main beams due to loadcase LC5 (top surface)
Unfolded- Principle stress S3 (global) in deck due to loadcase LC2 (top surface)

Unfolded- Normal stress SXX (Local) in deck due to loadcase LC5 (bottom surface)
Unfolded - Displacement of bridge in Z direction (global) due to loadcase LC6

Unfolded - Torsional moment MXY (Local) in main beams due to loadcase LC6

Unfolded - Torsional moment MXY (Local) in deck due to loadcase LC6
Unfolded- Support reaction force in X direction (global) due to loadcase LC6

Folded- Normal stress SYY (Local) in main beams due to loadcase LC4 (top surface)
Folded- Principle stress S3 (global) in main beams due to loadcase LC1 (top surface)

Folded- Shear stress SXY (Local) in secondary beams due to loadcase LC5 (top surface)
Folded- Principle stress S3 (global) in deck due to loadcase LC1 (bottom surface)

Folded- Normal stress SXX (Local) in deck due to loadcase LC4 (bottom surface)
Folded- Shear stress SXY (Local) in deck beams due to loadcase LC5 (bottom surface)

Folded- Displacement of bridge in Z direction (global) due to loadcase LC5
Folded- Torsional moment MXY (Local) in deck due to loadcase LC5

Folded- Support reaction force in Y direction (global) due to loadcase LC5