Structural Analysis and Design of Movable Bridges

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Table of Contents

List of figures

List of Tables

1. Definition of Movable Bridges & Icons Movable Bridges Around the World

Movable bridges are designed and constructed to change its position and occasionally its shapes to permit the passage of vessels and boats in the waterway. This type of bridge is generally cost effective since the utilization of long approaches and high piers are not required. When the waterway is opened to vessels and ships, traffics over the bridge would be stopped and vice-versa. There are different types of movable bridges and many of them are not construct nowadays while some of them are still considered as a movable bridge. Different types of movable bridges which are still desirable and applicable are discussed in this course. Table 1 shows some of the Important Movable bridges around the world.

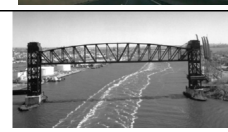
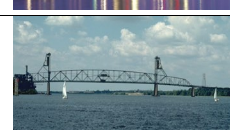
#	Name / Country	Photo	Main Span
1	El Ferdan Swing Bridge / Egypt		340 m
2	Erasmus Bridge/ Netherlands		280 m
3	Melville Bridge / USA		236.52 m
4	Merwede Bridge/ Netherlands		202.80 m
5	Arthur Kill Vertical Lift Bridge / USA		170 m
6	Cape Cod Canal Railroad Bridge/ USA		166 m
7	Delair Bridge / USA		165.20m
8	Marine Parkway Gil Hodges Memorial Bridge / USA		164.60 m
9	Burlington-Bristol Bridge / USA		164.60 m
10	Interstate Bridge / USA		161.80 m

Table 1. Some of the icons movable bridges around the world

1.1 Types of Movable Bridges

Various types of movable bridge are available, but three of them are significantly desirable and practical are discussed in the following sections and number of special types of movable bridge will be discussed as well:

1) Bascule bridge
2) Swing bridge
3) Vertical lifting bridge
4) Special types of movable bridge

1.1.1 Bascule Bridge

Bascule bridge, which is also called as drawbridge, is fixed and supported on an axis which is perpendicular to the bridge longitudinal centerline axis. The horizontal line on which the bridge is pivoted is commonly located at the center of gravity of the bridge to create a balance between the weight of the bridge on either side of the horizontal pivotal axis. It should be known that the weight balance is not accurate and slight inaccuracies are provided based on the future utilization of the bridge, for example, if the tendency is to open the waterway, then the weight is distributed to help opening the bridge and this weight distribution is termed as counterweight heavy, but if the trend is to employ the weight for closing the bridge, then it is called heavy span. There are two major types of bascule bridges including single leaf and double leaf bascule bridge (Fig. 1 & 2). In addition to triple and quadruple types which are occasionally constructed. The term leaf is used for the part of the bridge that moves and opens the waterway consequently.

Figure 1. Single Leaf Bascule Bridge

Figure 2. Double Leaf Bascule Bridge

Bascule bridge is a suitable type of movable bridge for most situations. Not only does it structurally sound and reliable but also both construction and operation can be carried out economically.

Advantages and Disadvantages of Bascule Bridge

Advantages of Bascule Bridge

- It opens the water way for ships and vessels with considerable speed and it permits the passage of small size boats to pass through even if the passage is not opened completely.
- It is reported that, the passage of small boat through partially opened bascule bridge is safer compare with partial opening of vertical lift bridge and swing bridge, especially if the bascule bridge is double leaf.
- Whether fully or partially opened, most of bascule superstructure bridge is out of vessel reach during collision, so it would not suffer considerable damage.
- The time required to pass vessels through bascule bridge is smaller than that of vertical lifting bridge and swing bridge. This is because vessels may come closer to the partially opened bascule than partially opened swing or vertical lifting bridge.
- Both single leaf and double leaf bascule bridge provide obstacles for the cars, but single leaf provides barrier at one side of the road.
- Double leaf bascule bridge offers the broadest spaces for vessels compared with other types of movable bridges.
- The depth of the span that extended from the pier to the center of the bridge can be decreased.

Disadvantages of Bascule Bridge

- Bascule bridge is subjected to considerable wind load especially when it is opened. So, this should be accounted for during the design of bascule bridge.
- The machinery used to control bascule bridge should be crucially strong and robust compared to the case where wind load is not present.
- In the double leaf bascule bridge where the behavior of each leaf is similar to that of cantilever in carrying live loads, shear locks are provided at the location where the end of each leaf meet which normally at the center of the channel. These shear locks are likely to suffer from wearing. This is because road dirt and other detrimental material would pollute lubricant material, and heavy traffics will impose serious shocks on the

locks. The shocks will be greater as the locks are getting weaker and consequently the locks would not be suitable to perform their tasks.

- The stability of double leaf bascule bridge is based on the adequate seating of leaves on their live load shoe, alignment of the leaves, and fitting the end of each leaf by their locks. Any damages of these components due to differential temperature or wearing on the aligning components will lead to improper seating of bridge, and consequently the leaves will jump up and down under traffics which is not desirable.

1.1.2 Swing Bridge

Swing bridge (Fig. 3 & 4) is fixed on horizontal plane that turns around vertical axis to provide ways for vessels and ships to travel through the bridge. The horizontal plane is on a bearing installed on a pier which is termed as pivotal pier. When the swing bridge is closed, the end of the span should be supported by resting piers or abutments if the total length of the bridge span is not very long. Machineries used to open and close swing bridge is more complicated compared to other types of movable bridges. The end of its span should be free during opening and closing that is why retractable rollers, wedges, shoe or jacks are introduced to lift the end of swing span. Therefore, swing bridge moves horizontally around vertical axis to provide water way and vertical movement is not involved whereas other types of movable bridges need to move vertically to provide passage spaces for vessels. From this discussion, one can conclude that the influence of wind force in swing bridge is less than that of bascule and vertical lifting bridge. However, the effect of wind force cannot be neglected since it can increase overturning moment significantly especially if the bridge is fixed on a bearing at its center. The swing bridge should be supported both horizontally and vertically to carry traffics and prevent overstressing. This is because bridge stabilization due to gravity is not available as in the case of bascule and vertical lifting bridges The span of swing bridge can be either truss or plate girder which is developed in latter times. The latter is more desired to be used since it is cost effective.

Figure 3. Swing Bridge

Figure 4. Swing Bridge

Advantages and Disadvantages of Swing Bridges

Advantage of Swing Bridges

- Wind load on swing bridge is minimum compared with other types of movable bridges.
- Since swing span moves horizontally during opening of the bridge, the moment generated by wind force is smaller compared with other movable bridge types (bascule and vertical lifting bridge).
- Two movable spans in one moving structure can be achieved in symmetrical swing bridge. This would be greatly advantageous to manage busy water way properly.
- It is a desirable option for locations where aesthetic play significant role in the construction of movable bridge because swing bridge does not move up to open so aesthetic of the bridge would not be affected as the bridge is opened for ships to pass through.
- Sizable piers are not required to support swing bridge because it neither lift during opening nor need counterweight as it is the case in bascule and vertical lift bridge.
- It is possible to construct double deck swing bridge because it does not lift into air to open.

Disadvantages of Swing Bridge

- It requires considerable maintenance because of large number of moving elements. So, this factor would make this type of bridge undesirable option when there is shortage of labor force.
- It needs longer times to operate compared to other types of moving bridge because it has larger number of main mechanical functions to undergo during opening and closing. Therefore, longer times will be needed to open and close the water way.
- Generally, it is assumed that wind load does not affect swing bridge considerably, but this statement is not entirely true and wind load may impose noticeable effect on the bridge for example it may exert shocking load on machinery of the bridge and as result machineries might fail to operate.
- Swing bridge needs more machinery to open and close the water way compared to bascule and vertical lifting bridge.

- The construction of supporting piers at the center of the channel provides two-way marine traffic, but this makes the bridge vulnerable to bridge collision and the size of vessel that can travel though the bridge may be decreased.
- Tools or devices used to detach swing railroad bridges is considerably expensive and fragile. That is why numerous undesired events occurred due to malfunction of such devices.

1.1.3 Vertical Lifting Bridge

It is one of the most widely constructed and used type of movable bridge. It is composed of a span commonly truss type span which is supported by towers at the end of the span or at each corner of the span (Fig. 5 & 6). Counterweight is usually used to balance the weight of the span. Ropes, which travels over counterweight rotating sheaves fixed on towers, are utilized to connect the end of the span to the counter weight. Added to that, waterway is opened by moving the span up exactly in vertical direction. Types of vertical lifting bridge includes double, triple and quadrable and the last two types are suitable for crowded areas such as in front of terminals. If the machinery used to open and close the water way is fixed on the span, then the bridge is called span drive vertical lift bridge, whereas the bridge is termed as tower drive vertical lift bridge if machineries applied to lift and down the lift span is fixed on towers, in addition to many other variations of vertical lift bridges. This type of bridge is considerably suitable for locations or cases where long spans are required because vertical lift bridges are substantially stable.

Figure 5. Vertical Lifting Bridge

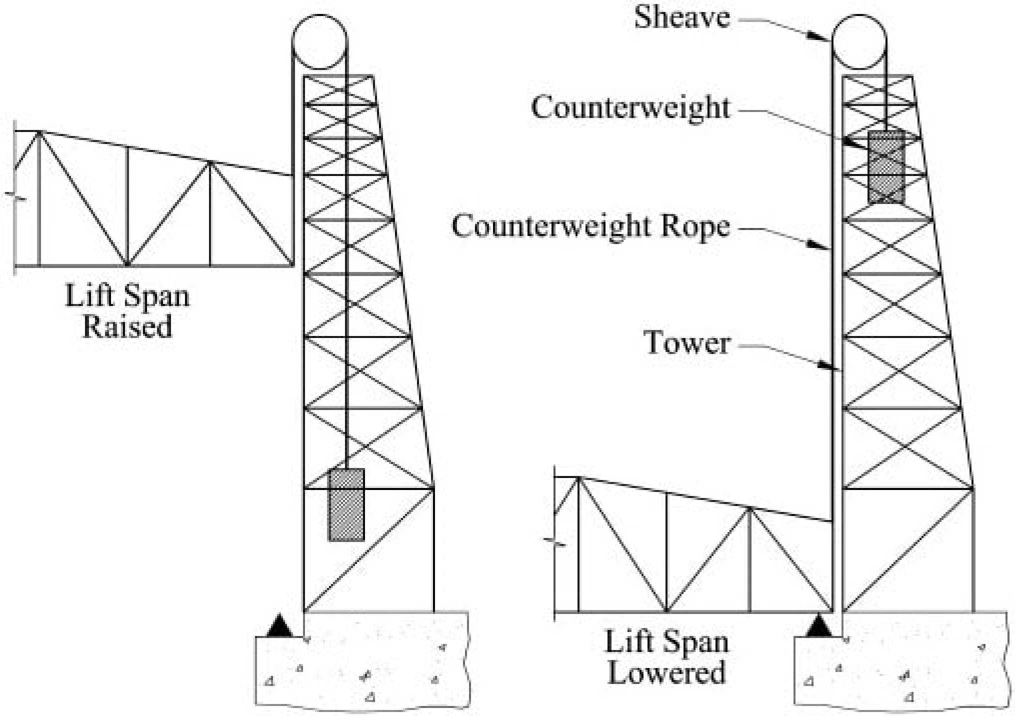


Figure 6. Details of Lifting Bridges

Vertical Lifting Bridge Advantages and Disadvantages

Advantages of Vertical Lifting Bridge

- Vertical lifting angle can be built approximately with any length that is required according to the project location and it is only restricted by ultimate simple span.
- The design and construction of vertical lifting bridge is easier compared with swing and bascule bridges.
- It is suitable to support heavy load structures like railroad bridge since vertical lifting bridge spans are approximately fixed.
- There is no restriction on the width and the number of trusses or main girders of vertical lifting bridge.
- Since vertical lifting bridge does not turn around in relation with railroads, double deck vertical lifting bridge is possible to construct and upper and lower decks can be moved up or down disregard of each other. Therefore, traffic of cars or trains need not to be blocked completely during the passage of small vessels that only lower deck required to be lifted.

Disadvantages of Vertical Lifting Bridge

- The most outstanding disadvantage of vertical lifting bridge is the restricted vertical space offered for the vessel passage. However, this has rarely caused undesired events.
- The entire width navigation channel cannot be used due to hinders posed by vertical lifting bridges even when the bridge is completely opened.
- The construction of vertical lifting towers is expensive. This is because towers should be at least 18m taller than required vertical space due to machineries and rope connection and as the height of towers increase the influence of wind load increases and consequently the construction cost rockets disproportionately.
- Vertical lifting bridges do not demonstrate satisfactory aesthetic appearance.

1.1.4 Special Types of Movable Bridge

Bridges that fall into this category are rarely constructed and uncommon. The decline in the application of such movable bridges is due to some factors such as the increase of applied loads, newly developed materials and safety precautions and concerns. Retractile, pontoon retractile, pontoon swing, shear pole swing, Folding, Curling, removable spans, Submersible bridge, Tilt bridge, Transporter bridge, Jet bridge etc. are the special types of movable bridges (Fig. 7, 8 & 9).

Figure 7. Folding Bridge

Figure 8. Transporter Bridge

Figure 9. Pontoon Bridge

2. Structural Design of Movable Bridge

2.1 Design Criteria

The design of movable bridges require much more effort than for the design of fixed bridges, for the reason that it must take into account the various position configurations of the leaf bridges and corresponding loads changes. So, it has to be considered two different approaches, when in closed position, which movable bridges are designed for the same design conditions and procedures as fixed bridges, and when in open position, which are designed following some specific conditions:

- inertia forces of the moving span due to acceleration and deceleration during the operation;
- frictional resistance of the machinery;
- malfunction and failure of the electro-mechanical devices;
- Impact of vessel.

In addition, there is a number of elements details and issues that have to be considered, such as the interaction of the structure and machinery, like locks, bearings and others. These will be detailed along the present course.

2.2 Standards and Specifications

Apart from the adapted codes from the Dutch (Nederlands Normaisatie Instituut, NEN) and the Germans (Deutsches Institute fur Normung, DIN), currently there are no specifications for movable bridge design outside the United States of America, in English (AASHTO standards and AREMA). Although is commonly good practice to use the Eurocodes and/or design standards, these are incomplete in the detailed issues regarding the mechanical and electrical design. (Birnstiel, Bowden, & Foerster, 2015) Hence it is up to every project owner to commend if the necessity for such codes is needed.

2.3 Constructive Materials

Structural and mechanisms material properties comprise one of the key points that have to be carefully considered because these are directly connected with durability and safety of the bridge.

In the past, the most common materials used for structural elements in movable bridges were wrought iron and steel. In the past few years some innovative movable bridges have been developed with aluminum and FRP (fiber-reinforced polymers).

The main aspects that the materials are required to have are:

- Hardness
- Fracture
- Tensile properties
- Residual stresses
- Corrosion

- Hydrogen embrittlement

Different materials are used for structural and mechanical elements and are going to be described in the respective chapters, though that sometimes they can be the same.

2.4 Balance

Regardless of the type of movable bridge, the balance of the bridge is a key issue to be addressed. Typically, to answer this problem, all vertical lift and bascule bridges are counterweighted. This is because it can minimize the size and power requirement for the machinery to maneuver the bridge, only needing to overcome inertia, friction, wind loads, imbalances and ice loads if it is the case.

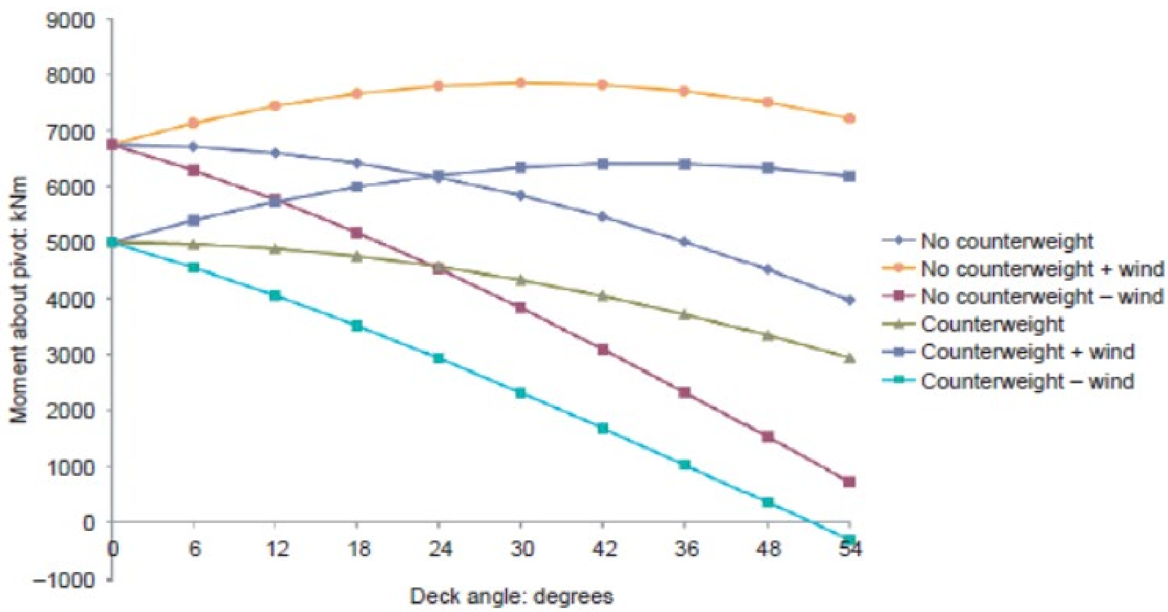


Figure 10. Graph of moment about pivot compared with angle of deck inclination (Thorogood, 2011)

It should be known that the wind loads can change to a direction that helps the lifting of the bridge bringing the moment close to zero with 50 degrees inclinations (see Figure 10). This brings a load reversal (from compressive to tensile load) in the lifting mechanism. Although not a major problem, this can pose some issues to the control and support of the bridge in closed position which has to be considered in the design stage.

It has to be noted as well, that the counterweight has to be designed to allow for adjustment of the bridge balance, as with time the weight and weight distribution can change, due to repairs, paint, replacement of locks, etc. This can be supported by having balance checks during construction or using detailed calculations comprising every structural element as well as coatings and paintings that contribute to the weight of the moving span. For more detailed balance calculations see the paper of Giernacky and Tosolt (2010).

There are primary values that can be used in the early stage of the design, which for vertical lift bridges is every kilogram of the total weight is balanced by a kilogram of the counterweight, 1:1 ratio. And for bascule bridges the counterweights normally weight three to four times more than the weight of the movable span.

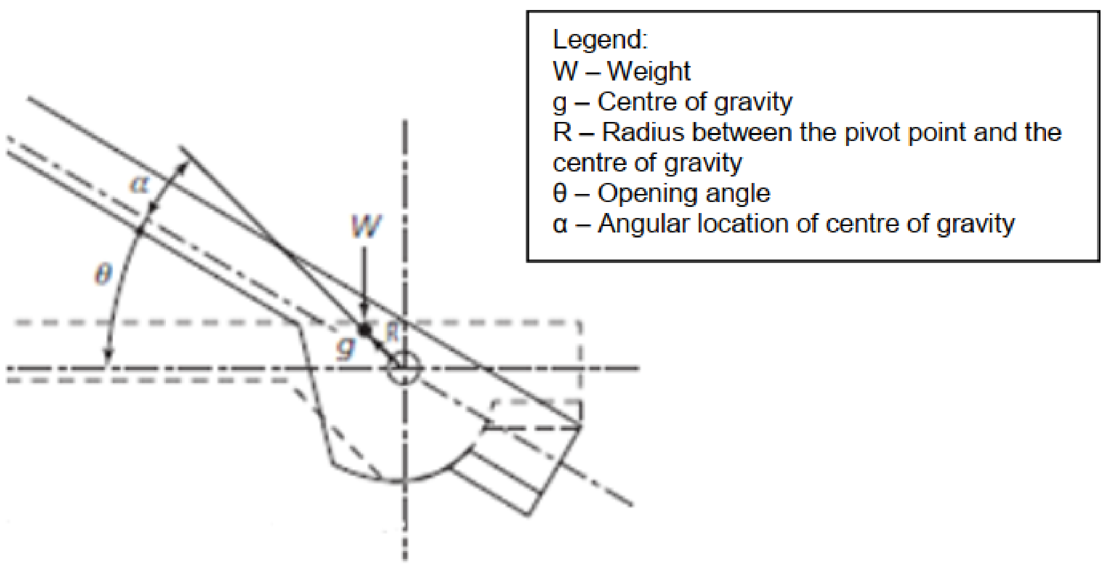


Figure 11. Balance bascule leaf (adapted Birnstiel, Bowden, & Foerster, 2015)

Note: Valid for trunnion and rolling bascules, for more information about other types see (Hool & Kinne, 1943)

There are various views about balancing a movable bridge. Balancing bascule bridges is particularly more difficult as it has to consider both the vertical and horizontal location of the center of gravity of the leaf. It is, commonly, considered a slightly "span-heavy" condition to create a tendency for the moving span to stay in closed position without needing machinery. This corresponds to a center of gravity towards the navigation channel. For vertical lift bridges

this is easier, only needing to consider the horizontal location of the center of gravity of the leaf and a slightly overall heavy span. (Coates & Bluni, 2004).
Hence, the moment needed to overcome imbalance, M_b, is given by the fundamental balance equation:

$$M_b = W.R.\cos(\theta + \alpha)$$

A "span-heavy" condition is given when a positive value of M_b, i.e. the moment necessary to open the leaf in this condition. With this, usually is applied a force to the toe of the leaf (termed Toe Reaction, T_r) that is equivalent to the imbalance moment:

$$T_r = M_b.L$$

It is exemplified, afterwards, by means of movable bridge balance tests, the different cases of torque and consequently balance/imbalance of the bascule bridge in Merritt Island, FL. (see work paper Susoy, Zaurin & Catbas, 2007)

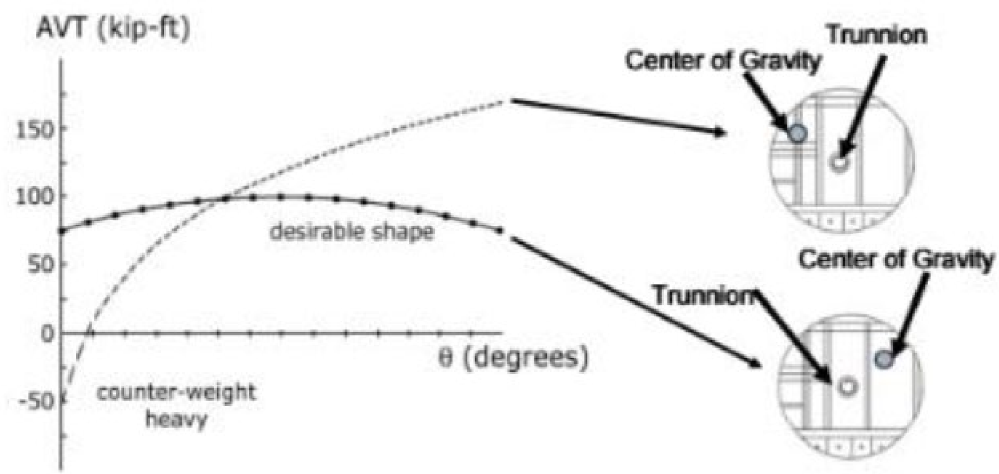


Figure 12. Comparison of different torque during operation of a bascule bridge (Susoy, Zaurin, & Catbas, 2007)

Comparison between the different motions of two bascule bridges is demonstrate below:

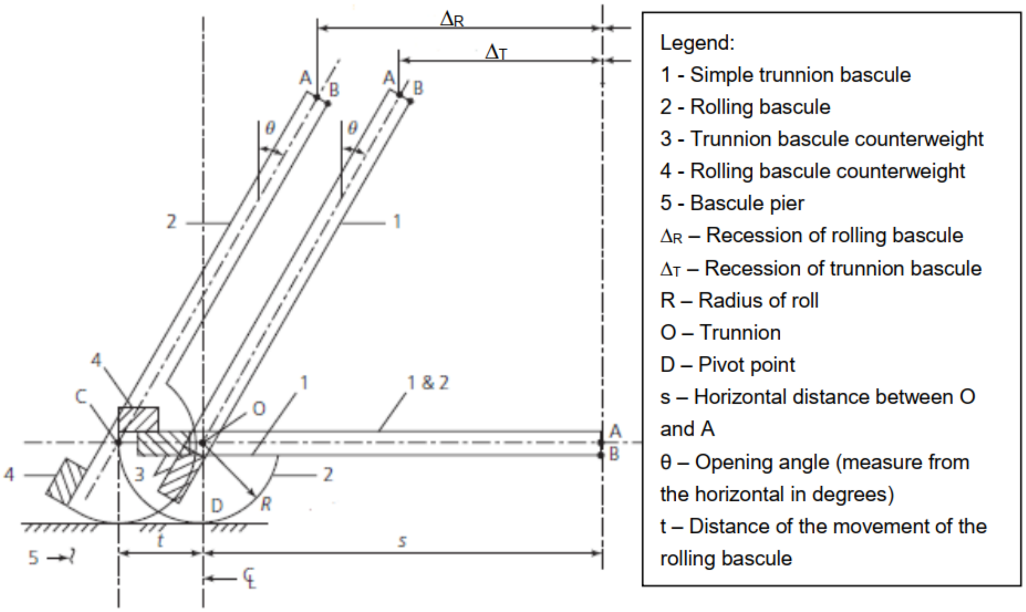


Figure 13. Comparison motions between trunnion and rolling bascules bridges (adapted Birnstiel, Bowden, & Foerster, 2015)

It can be seen thru figure 13 that the trajectories of the movement of bridge opening of the trunnion and rolling bascule bridges are different. Though the position in closed position is the same, when it starts to rotate about the same opening angle, the bridges rotate from a different motion. The trunnion rotates through a fixed point (pivot point called trunnion) proving a recession inferior to that of a rolling bascule that rotates through a rolling track.

This proves to be a very important feature when it comes to navigation channel with height ship traffic, attesting that a rolling bascule (Scherzer) is a better option for these cases.

3. Superstructure Forms

3.1 Geometry vs. Materials

One of the most important matters in movable bridge decks is the reduction of self-weight, because not only it is easy for operation purposes of the lift machinery, as it gives more support capacity for live and seismic loads.

When it comes to choose the right kind of deck form, various matters have to be considered regarding:

- Bridge settings (locality, water level)
- Buildability
- Traffic Load
- Type of maintenance required
- Costs

The most common in the present days are described below:

3.1.1 Steel grid deck - Open grid deck

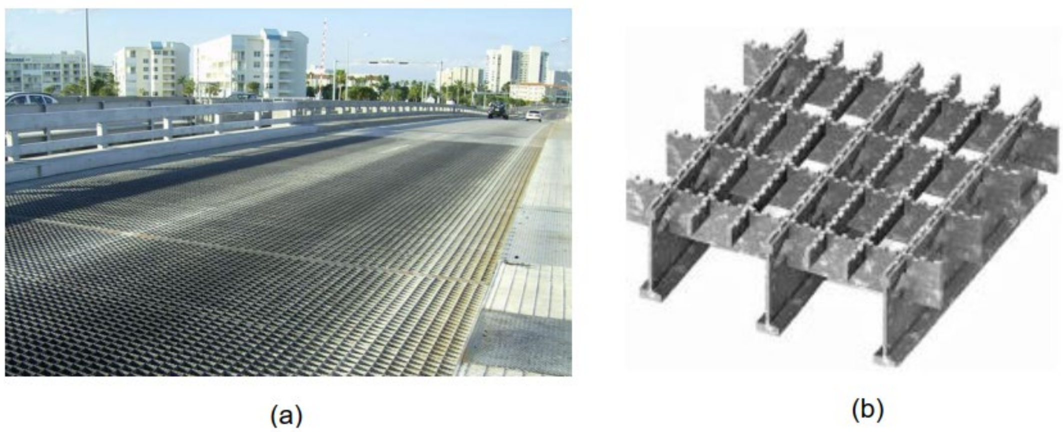


Figure 14. (a) Bridge Corey Causeway (Unknown, DrawBridgeAhead.com, n.d.) (b) Rectangular open grid (Birnstiel, Bowden, & Foerster, 2015)

Open grid steel decks have the lightest weight of all type of decks and particularly for bascule bridges reduces exposed wind area significantly when in open position. However, it increases the number of accidents with traffic high speeds and congestion, it is noisy and it can accumulate debris and rain water which leads to corrosion.

3.1.2 Exodermic and Concrete filled grid deck

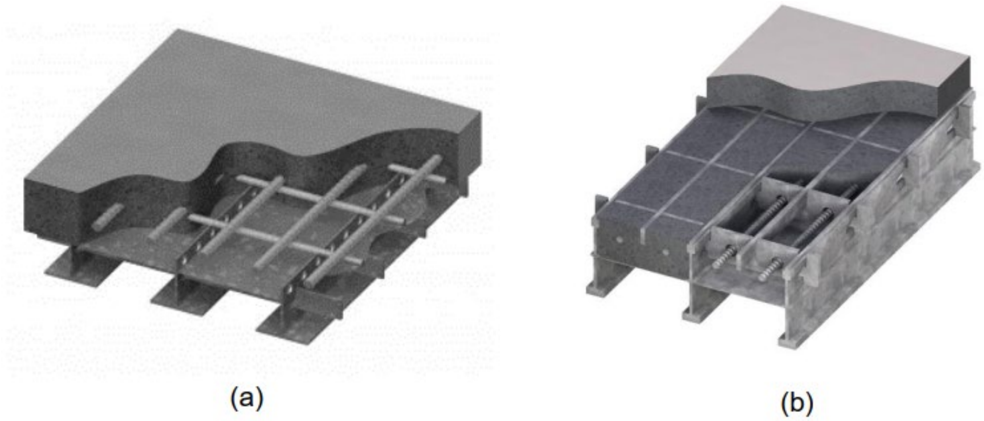


Figure 15. (a) Exodermic deck; (b) Half-filled concrete grid deck (Birnstiel, Bowden, & Foerster, 2015)

Exodermic and concrete filled grid decks (full or partial filled) have the advantage of not needing welding to supports and the possibility of construct larger spans.

3.1.3 Orthotropic steel deck

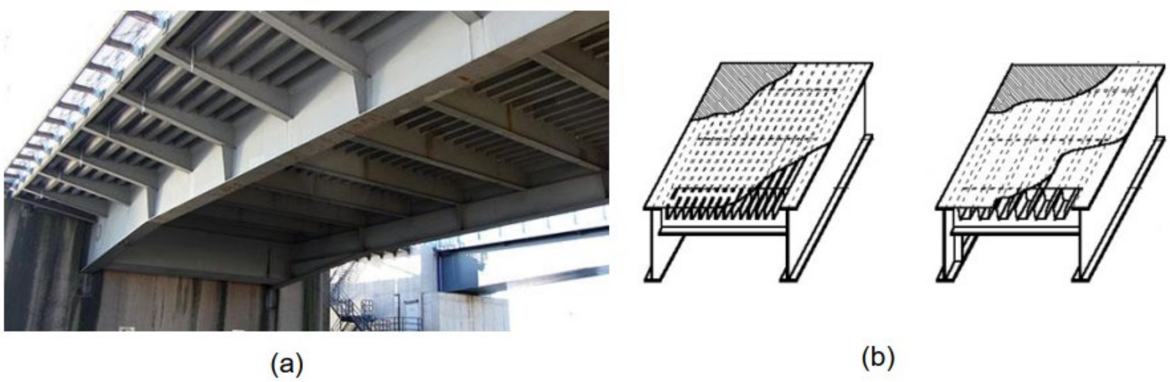
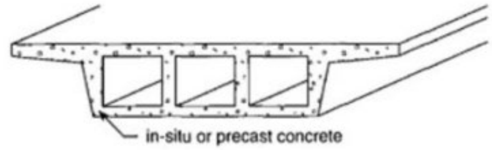


Figure 16. (a) Movable bridge across Hartelkanaal (Royal HaskoningDHV, 2014) (b) Orthotropic plate decks (Unknown, ESDEP Course)

Orthotropic steel deck gives a light weighted solution which has a beneficial interact with the remainder of the bridge structure. This causes a really good seismic performance.
The main issue that has to be overcome is the wearing surfacing of this deck types which has to be light weighted, durable and particularly in bascule bridges has to be adhesive due to the lifting operation. It is more expensive than open grid steel decks.

3.1.4 Concrete deck (Light-weight concrete)

(a)



(b)

Figure 17. (a) Spokane Street Swing Bridge (Yashinsky, 2010) (b) Concrete deck (O'Brien & Keogh, 1999)

When using concrete deck, it is required stainless steel reinforced bars and lightweight concrete to allow a minimum cover and hence control the deck weight.

3.1.5 Aluminum

(a)

(b)

Figure 18. (a) Bridge Han Lammersbrug (Koutsarsky, 2012) (b) Aluminium deck (Aluminium Association of Canada, n.d.)

Aluminum decks are recently being developed, as well as FRP decks, for being light weighted, durable, low in maintenance and having high fatigue strength.

3.2 Properties

For purposes of conception and initial sizing, some basic “rules” are acknowledged for economic strategy and are summarized afterwards.

Double leaves swing bridges proportions in comparison with front and back span comprises usually a ratio of 1/2 of the total length. For single leaf swing bridges the tail or back span are typically 30 – 40% of the main span. For bascule bridges usually around 1/3 of the total length but depends a lot on the counterweight’s layout and type of bascule bridge.

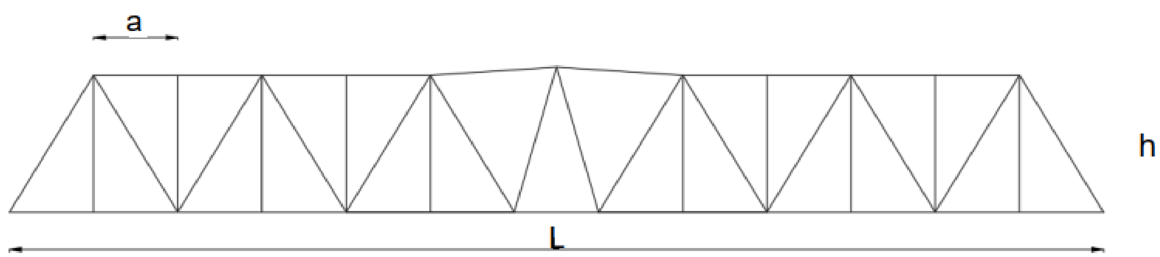


Figure 19. Initial sizing - truss (not at scale)

The section depth is typically between $a/20$ and $a/25$ in steel elements in general, being the major element.

The height of the truss is normally in the range of L /11 ratio.

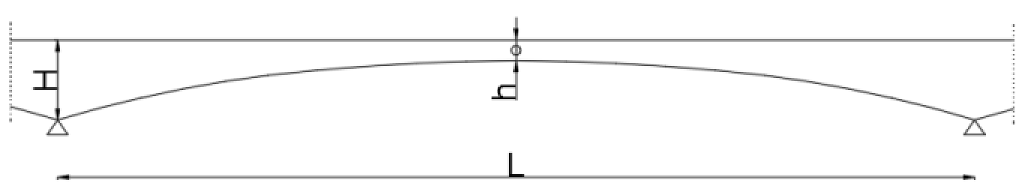


Figure 20. Initial sizing – haunch deck (not at scale)

When the section varies depth along its length, usually for bascule bridges, the typical ratio of the height of the support (H) is between $L/16$ and $L/20$ whereas in the mid-span (h) is between $L/40$ and L/50.

4. Structural Behavior and Load Paths

The main structural members of the bridge condition the entire structure due to their own weight and aerodynamic unique characteristics. A good understanding of the load paths is needed, as well as the behavior of support conditions and the interaction between the different moving elements of the movable bridge.

4.1 Bascule Bridge

The main structural members of bascule bridges can be either trusses or girders. For purposes of simplified analysis of the structural behaviour and load paths of bascule bridges, it is only considered trunnion bascule bridges, as these are the most general case. For a detailed analysis see Hool and Kinne, 1943.

Rotation of the span is supported by the drive mechanism and when it comes up to the open position the span weight is supported by the trunnions. These trunnions are subjected to lateral loads which are resisted by the piers. In the leaf these lateral loads should be resisted by a lateral bracing system.

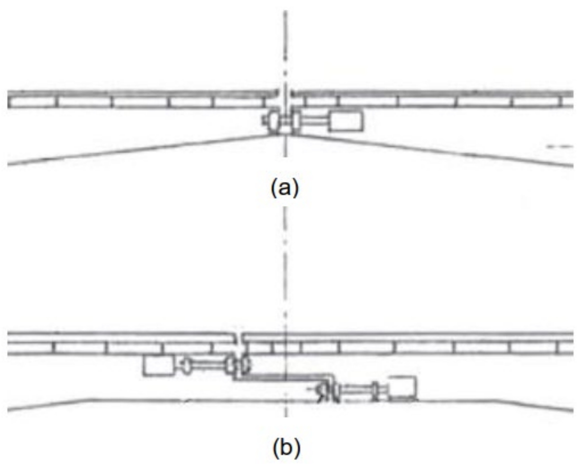


Figure 21. Shear and moment locks arrangements: (a) shear lock; (b) moment lock (adapted Birnstiel, Bowden, & Foerster, 2015

When in closed position, the center locks and devices usually only offer limited lateral resistance and nearly no longitudinal resistance. However, this can be improved with the application of tail locks which transfer the longitudinal resistance to the trunnions. For the structural analysis of these bridges, it has to be knowledgeable the behavior of this distinctive points and how it affects the overall structure. When modeling single leaf bascule bridges the behavior rolls up to a cantilever for dead loads and a simple span for live loads. In the case of double leaf bascule bridges modeling, the behavior rolls up to a cantilever for dead loads and for live loads depends on the type of connection made in the junction of the leaves.

If the connection is made with shear locks which transfer shear forces, the girder behaves like an elastic propped cantilever and if is made with moment locks, that transfer both shear and bending moments, it behaves like a continuous girder, theoretically, because the deflections on the mid span reduce the effectiveness of the system.

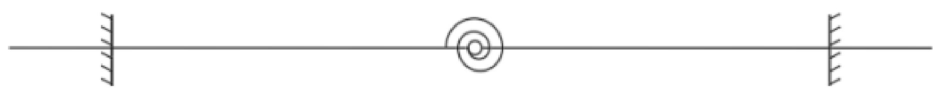


Figure 22. Schematization of real behavior double leaf Bascule Bridge with active mid-span shear locks

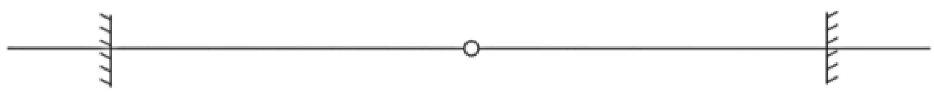


Figure 23. Analogy schematization of double leaf Bascule Bridge with active mid-span shear locks

The usual analogy that is considered for conservatism reasons when modeling the leaves for the shear lock system in a double leaf bascule is a hinged point. This because it provides the ability of transferring shear loads and it allows a leaf-tip rotation at the connecting point and expansion and contraction between the leaves due to temperature effects. This can be simplified by modeling only half of the bascule bridge considering k as the stiffness of the spring as much as the bending stiffness of the adjacent cantilever leaf.

Figure 24. Simplified schematization of double leaf Bascule Bridge with active mid-span shear locks

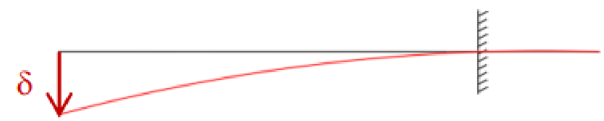


Figure 25. Displacement of adjacent cantilever leaf

$$\delta_{max} = \frac{P.l^3}{3.EI}$$

$$k = \frac{P}{\delta max} = \frac{3\ EI}{l^3}$$

It has to be noted that this type of lock system is not suitable for heavy rail traffic due to the sudden change of profile so it is usually employed moment locks.

The usual analogy that is considered when modeling the leaves for the moment lock system in double leaf bascule bridges is two point supports.

Figure 26. Analogy schematization of double leaf Bascule Bridge with active mid-span moment locks

Moment locks can reduce the expected deflections by more than half when compared with shear locks.

4.2 Swing Bridge

The main structural members of swing bridges can be also either trusses or girders. As the structural behavior of the trusses or girders changes among the different positions of the bridge moving spans, the deflected shapes due to the self-weight are different. So, the analysis of swing bridges has to consider the following requirements for both the superstructure and machinery. It is considered in the present study the load paths for double-arm swing bridges comprising trusses.

In open position, the weight of the span is supported by the center bearing in center bearing swing bridges, and by rollers in rim bearing swing bridges. In both cases the swing spans work as a double cantilever, balanced on the pivot point. On the process of opening the bride, tilting can occur so it must be resisted by the balance wheels assembly in center bearing bridges and by the rim bearing assembly in rim bearing bridges.

In closed position, the swing span is supported by three points in center bearing swing bridges, the center bearing point and two rest piers, one at each side, and by four points in rim bearing swing bridges, two points in the rim bearing assembly and two rest piers.

Swing bridges can have various structural forms depending on the designer choice as long as the stiffness and strength required for this type of bridges is achieved.

For purposes of a stiffer span and to restrain the compression chord, the common layout is the through truss which provides bracing between the two upper chords. Horizontal loading is transferred through the lateral bracing system.

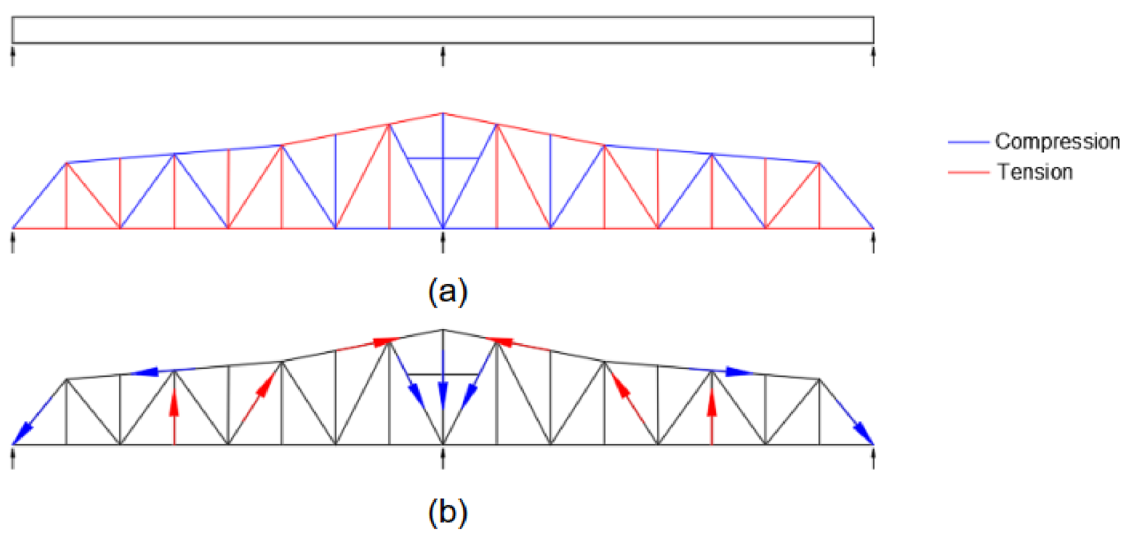


Figure 27. (a) Stresses diagram of center bearing Swing bridge (b) Load Paths of center bearing Swing Bridge closed position (not at scale)

In open position the stress in the bottom chords, close to the middle of the arm, due to dead load is compression and in closed position this stress is tension. Normally near the center support there is a truss arrangement more detailed with the purpose of not transmitting much vertical shear and a reinforced bracing since this space is subjected to greater forces.

This arrangement helps to uniform the loads going to the pivot pier, proving it to be the best solution for minimizing the possibility of uplift of the one of the center points due to live loads placed on the opposing span.

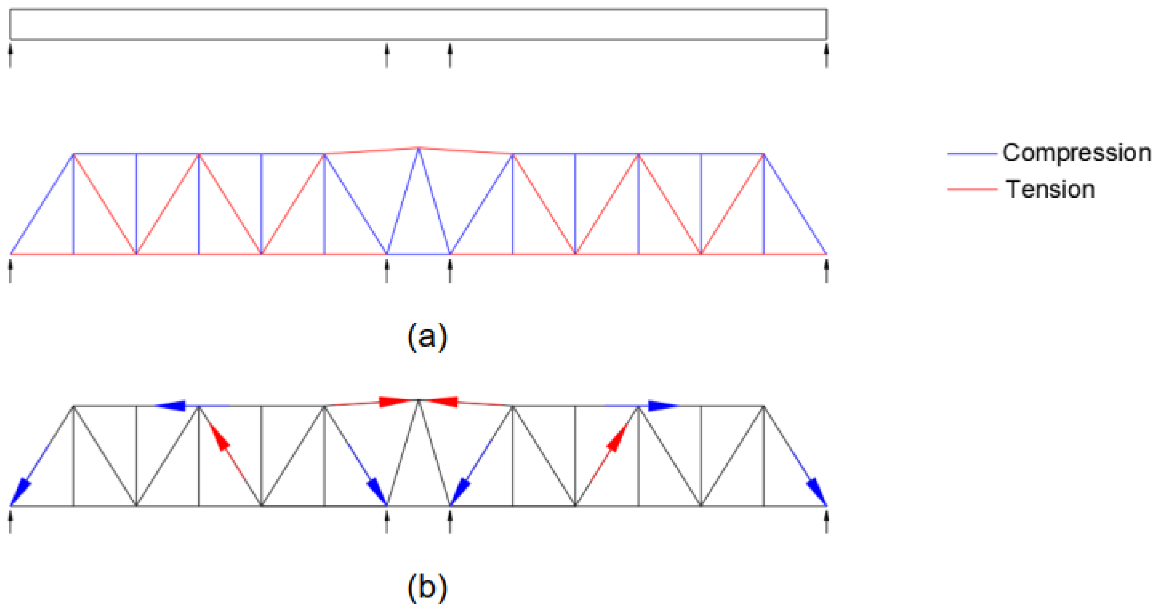


Figure 28. (a) Stresses diagram of rim bearing Swing bridge (b) Load Paths of rim bearing Swing Bridge closed position (not at scale).

In symmetrical swing bridges, the ends are lifted (with devices) when the rotation for closing the bridge is completed, providing a preload reaction into the swing span. This has the purpose of supporting additional traffic loads and avoid the uplift due to the case when the swing span is only loaded in the opposite side.

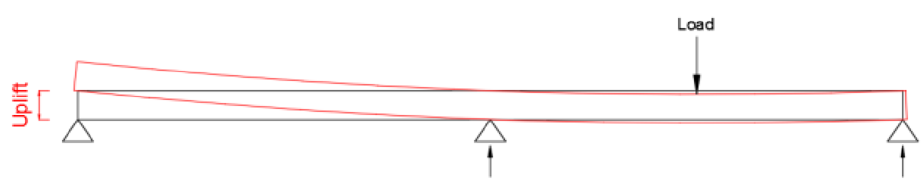


Figure 29. Deflection diagram of center bearing swing bridge (not to scale)

In the case of cable-stayed swing bridges, the orthotropic deck is in compression and cables in tension. Cable-stayed swing bridges are basically the combination of two types of bridges: swing and cable-stayed bridges. This arrangement was with the purpose of reducing the bending moment of the main pier (termed pylon) base.

The moment depends on the stiffness of the deck which in turn depends on the cable arrangement and shape of the deck.

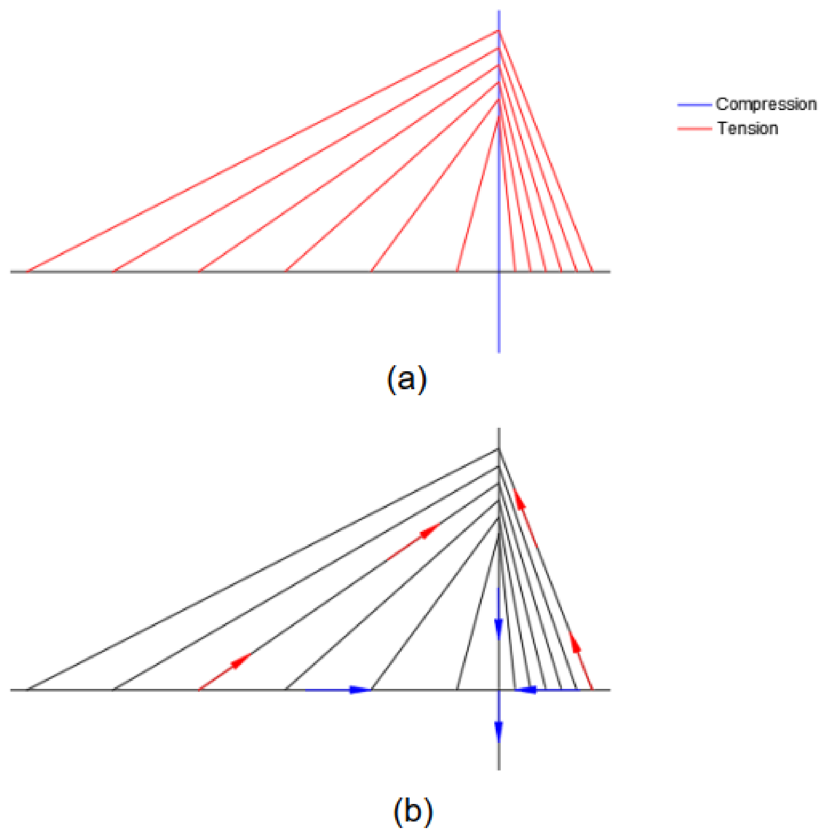


Figure 30. (a) Stresses diagram of Cable-stayed Swing bridge (b) Load Paths of Cable-stayed Swing Bridge (not at scale)

4.3 Vertical Lift Bridge

Again, the main structural members of the span of vertical lift bridges can be either trusses or girders and the main structural members of the lift towers can be trusses or reinforced concrete.

The weight and both longitudinal and lateral loadings of the moving span are all supported by the lift towers and counterweights system. It is imperative that the towers offer a reasonable resistance so it can withstand all forces.

The movement of each point where the span connects to the lift tower has to be synchronized in order to reduce the kinematic system to only one global movement, avoiding sway motions of the deck. This is the most important aspect to consider in designing a vertical lift bridge. To answer this problem, it is provided alignment and guidance devices for the lift span, counterweights and drive mechanisms.

There are some other aspects that need to be considered in motion analysis, in different positions of the bridge.

1. ***When the bridge is in open position:***

- High shear, torsion and bending moment on the towers provided from lateral reactions from the lift span and counterweights;
- The base tower connection resists the tower loading by means of anchor bolts.

2. ***When the bridge is in closed position:***

- The ends of the span are restrained by span locks and guides, and centering devices as it will be described in detail in the next chapter;
- The moving span has to be well braced transversely to be able to transfer the loads that are subjected to the towers.

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