Analysis of the force distribution on operating mechanisms in a bascule bridge

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Cover photo
Erasmusbrug in Rotterdam. The largest and heaviest bascule bridge in Western Europe.
Photo by Maarten van Dam.

ANALYSIS OF THE FORCE DISTRIBUTION ON OPERATING MECHANISMS IN A BASCULE BRIDGE

By

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in partial fulfilment of the requirements for the degree of

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PREFACE

This thesis was written as part of the Civil Engineering master curriculum at the Delft University of Technology. The research was carried out in cooperation with the Faculty of Civil Engineering and Geosciences and the Dutch engineering company *Movares*.

During my bachelor I have developed an special interest in bridges. After graduating for the bachelor Mechanical Engineering the choice was made to continue with the master track Structural Engineering with specialisation Structural Mechanics. This study combined with my background of Mechanical Engineering and interest in bridges resulted in a topic for my thesis with movable bridges.

First of all I would like to thank my daily supervisor Bert Hesselink of Movares. His expertise on movable bridges and guidance during graduation was helpful in finalising my thesis. Further my gratitude goes out to Jan Rots, Pierre Hoogenboom and Henk Kolstein for participating in my graduation committee. Their feedback during the meetings was useful to improve the thesis.

My appreciation goes out to the colleagues at Movares who helped me with specific questions and handing information and resources required for my thesis. Besides, a special thanks goes out to Hillebrand, Jansen-Venneboer and Rijkswaterstaat for their time and providing valuable information on the subject.

Finally I would like to thank my family and friends who supported and motivated me throughout my entire studies.

P.S. van Zantvliet
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ABSTRACT

The focus of this thesis is on the force distribution between operating systems in a bascule bridge. According to the code a bascule bridge with two panama crank mechanisms has to be designed that the required operating force is distributed over the two mechanisms with a ratio of 1/3 – 2/3. There are doubts if this ratio is correct in case both the leaf and operating system have a high rigidity, which is the case for a project at Gouda which is used as reference. This thesis will show if this distribution is acceptable and which factors have an influence on this ratio.

The main focus will be on the influence of offsets during manufacturing and installation of the four rod mechanism. Although manufacturing and installation has a high accuracy, small offsets already have a large impact on the four rod mechanisms. The two mechanisms can undergo a different rotation, and therefore force a deformation upon the leaf. The deformation introduces additional forces on the operating mechanism as the leaf will restrain the deformation. The additional forces will counterwork each operating mechanism, and therefore affecting the force distribution.

Although the forced deformation is only a few millimetre that occurs due to the offsets, the additional forces in the mechanism are large due to the stiffness of the leaf. Analysis shows that a few factors have a main influence on the development of the axial force in the push-pull rods. Stiffness of the leaf, stiffness of the spring inside the push-pull rod, the prestress of the spring and external operating force all have influence the axial force. Besides, the angle of the push-pull rod is of importance as well, since this will determine the stiffness of the leaf with respect to the spring. As the angle of the rod changes, the stiffness of one component to the other changes as well.

Further shows the analysis that the installation method of the push-pull rod has an impact on the required forced displacement due to offsets. Adaptation of the push-pull rod length during the installation is recommended in order to reduce the required forced displacement. At the point of installation no forced deformation is needed. Before or after this point this deformation does develop gradually, and therefore the distribution between the two mechanisms develop also gradually.

Large bridges where both the leaf and the operating mechanism are rather stiff, the distribution of 1/3 – 2/3 cannot be safely applied. Due to the offsets, the two operating mechanisms can counterwork each other. The external force, and wind load specifically, has a large impact on this distribution per operation. During heavy wind load one operating mechanism is doing all the work, while the other operating mechanism does not contribute to the operation. No wind load means a low external force, but the two operating mechanisms are counterworking each other. The magnitude of the force acting on the operating mechanism is of the same magnitude as with heavy wind. The conclusion can be drawn that the occurring distribution due to offsets are more likely to be 0.0 – 1.0 instead of the 1/3 – 2/3.

Contents

1 INTRODUCTION

1.1 PROBLEM DEFINITION

Traffic flow is often subject of discussion for improvement. Congestion of the roads in and around cities is a daily problem. In motorways congestion mostly occur around junction points and sections where local traffic merges in and out. By use of parallel roads this issue can be mitigated. Separation of local and non-local traffic beforehand at a city will increase the traffic flow. Non-local traffic has the normal flow as no vehicles have to merge in or out, while local traffic is not hindered by non-local traffic during merging.

Construction of these parallel roads is not an uncommon practice in The Netherlands. Waterways can cause an issue with the construction of parallel roads. Movable bridges are normally avoided in main roads and motorways as traffic is hindered, but sometimes it is the only option. Different types of movable bridges are applicable. In main roads the leaf has a significant size as it often spans a main waterway and therefore needs a certain width of passage, and must carry multiple lanes. A common used bridge type in these cases is a bascule bridge. The application of bascule bridges in larger movable bridges is mainly due to a few advantages it holds over other types; vertical lifting bridge and swing bridge.

- They are easier to blend in with the environment as the counterweight is situated in the basement at the abutment or pier.
- No obstruction in the waterway
- Unlimited clearance

The design of the operating system, and the operating mechanism in particular, is rather important in the design of a movable bridge. Several factors play a role in the choice of the operating mechanism, which can either be hydraulically or mechanically. Most important for the design are the applicable loads. Beside the regular loads which apply to almost every stages during operating, each stage has its own additional loads. The additional loads are caused by the behaviour of the bridge and operating mechanism. Therefore it is important to understand the behaviour of both the static and dynamic structure, and which components influence the behaviour.

1.2 SCOPE

Settings, rigidity, offsets due to tolerances and other factors all play a role in the behaviour. According to the Dutch design code for movable bridges, VOBB, for multiple operating mechanisms per bridge the load per operating mechanism should be taken as 2/3 of the total load. The Dutch code states:

> *"Due to spacings, a movable bridge driven by two engines could sway between the operating mechanisms. This problem occurs mostly when the coupling between the operating mechanism is relatively stiff. Result is an increase in loads on the operating mechanism. For rather stiff bridges in which both operating mechanisms are driven by a single engine, higher loads occur in each operating mechanism as well."*

So due to spacings and settings the load might be distributed between the two operating mechanisms with a distribution of one third - two third. The scope of this thesis is related to the lack of clarity in the choice of this load distribution. Although the code states the use of this distribution, and therefore each operating mechanisms is designed on a two third of the total load, in some cases it is questioned if this distribution is not too favourable and the actual load distribution is larger. Use of models should provide a clarification of the load distribution between the two operating mechanisms and how the load distribution can be influenced.

1.2.1 REFERENCE PROJECT

A parallel road will be constructed next to the A12 near Gouda to mitigate traffic congestion. The parallel road crosses a main waterway and a tunnel is not economically justified. Therefore a significant bascule bridge is designed, i.e. a deck of 23.5 by 26.5 meters. The load distribution according to the VOBB has been applied in this bridge. A single engine is used to drive the two operating mechanisms. The operating mechanisms are panama crank mechanisms, which are connected to the counterweight via a pull-push rod with a spring buffer. This project will be used as a reference project and the models will be based on this movable bridge.

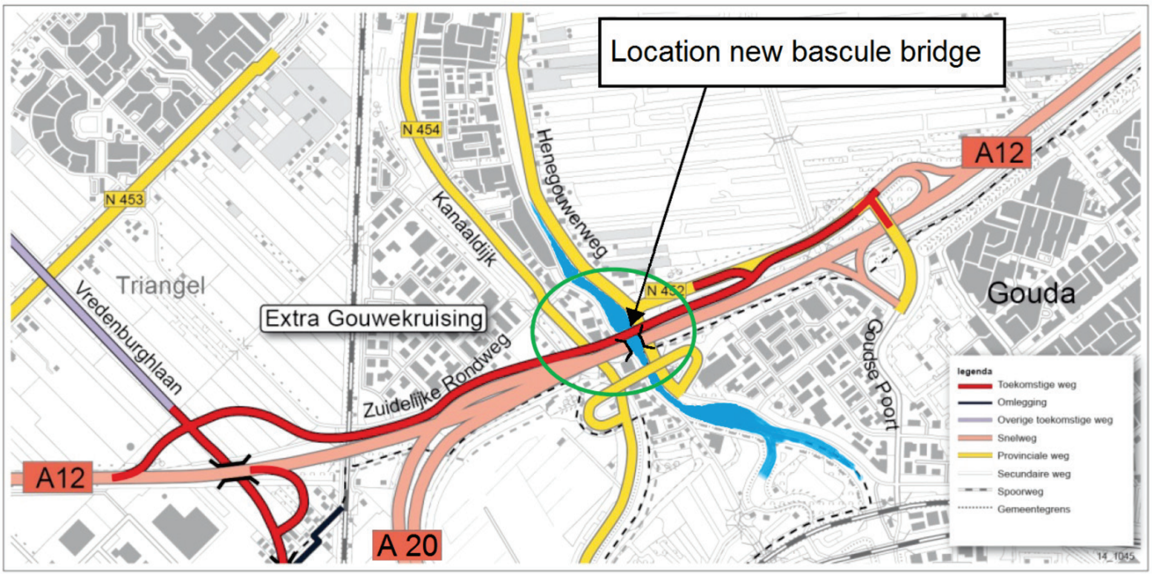


Figure 1.1 - Map of project location with the new bascule bridge over the Gouwe next to the aquaduct

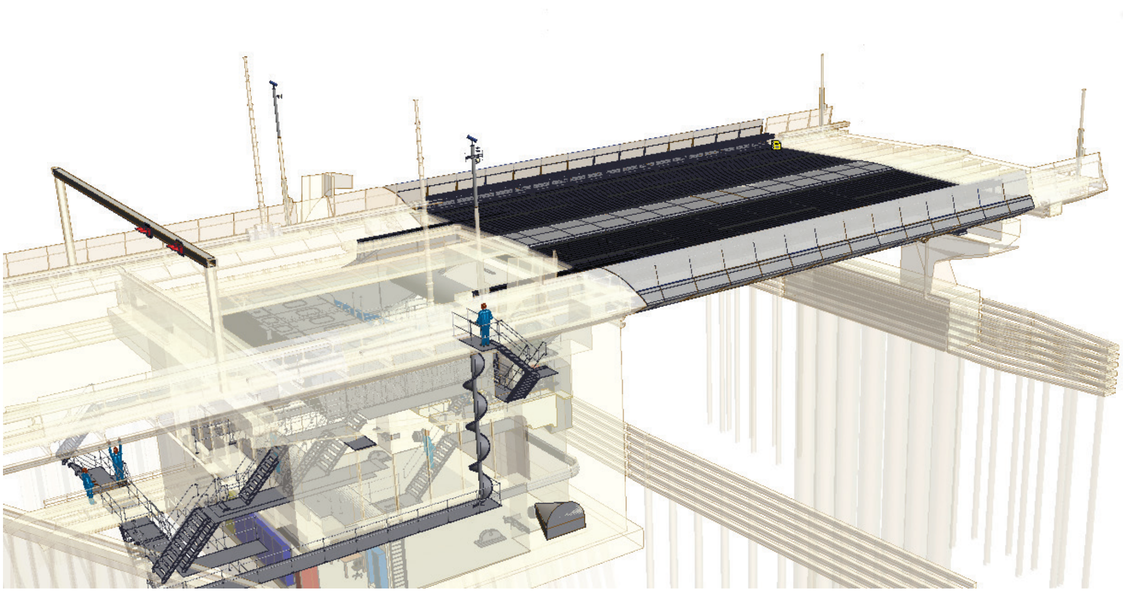


Figure 1.2 - Overview of the bridge and construction around

1.2.2 RESEARCH OBJECTIVE

As stated, knowledge about the behaviour and interaction of the dynamic and static structure is important for optimisation, but also regarding forces occurring on the operating mechanism. The objective of this thesis is to investigate the actual forces on operating mechanisms which occur due to offsets. These loads are influenced by several factors. This leads to another objective of the thesis, determining which factors influence the force on the operating mechanism and how to adapt these factors in such a way that the static and/or dynamic structure is not significantly compromised.

1.3 RESEARCH QUESTIONS

Main question
As in the objective of this thesis is described, the main question to answer in order to reach the objective can be formulated as:

> *"Which factors influence the force distribution between the operating mechanisms in a bascule bridge and how can these factors be taken into account to optimise the design to reduce the occurring force distribution?"*

Sub questions
In order to find an answer to the main question, a set of sub-questions have been formulated. These sub-questions should provide an answer to the main question once answered.

1 What is the background of the force distribution used in the VOBB?

2 What are the actual forces on the operating mechanisms due to offsets and secondary effects?

3 What are the main factors and components that influence the occurring forces on the operating mechanism?

4 What are effects of adaptations to these components on the force distribution and the structure?

1.4 BOUNDARIES

In order to determine the depth and the focus of the research, the boundaries of the thesis will be discussed. The research of the thesis is on the boundary of mechanical and civil engineering, so a well defined boundary is required, as structural mechanics of civil engineering is the master of this graduation.
Figure 1.3 shows an overview of the main components of the bridge, which are depicted in figure 1.4. The main focus of analysis will be on the connection, a buffer spring-element, between the leaf

and the operating mechanism. Almost the entire operating system self will be out of scope, as this is governed by mechanical engineering. The operating system comprises the panamawheel, shafts, bearings, gearbox and engine. Only the panamawheel will be used in the analysis since it is part of the four rod mechanism.
The leaf mainly consists out of the counterweight and the deck. The deck will be taken into account for determination of the axial forces. The design of the reference project is used, so the structural design will not be looked at.

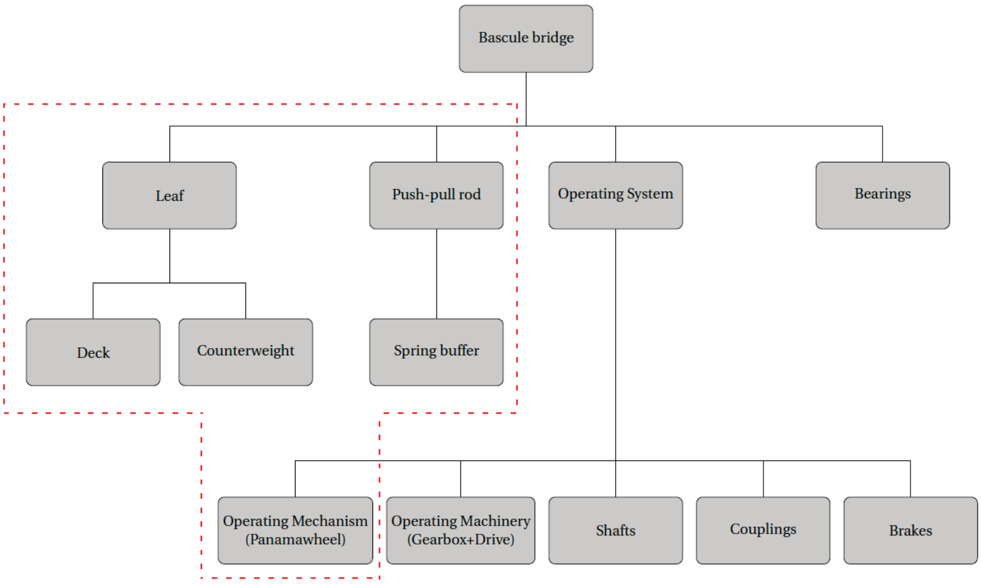


Figure 1.3 - Overview main components in the bascule bridge and boundary box of focus scope

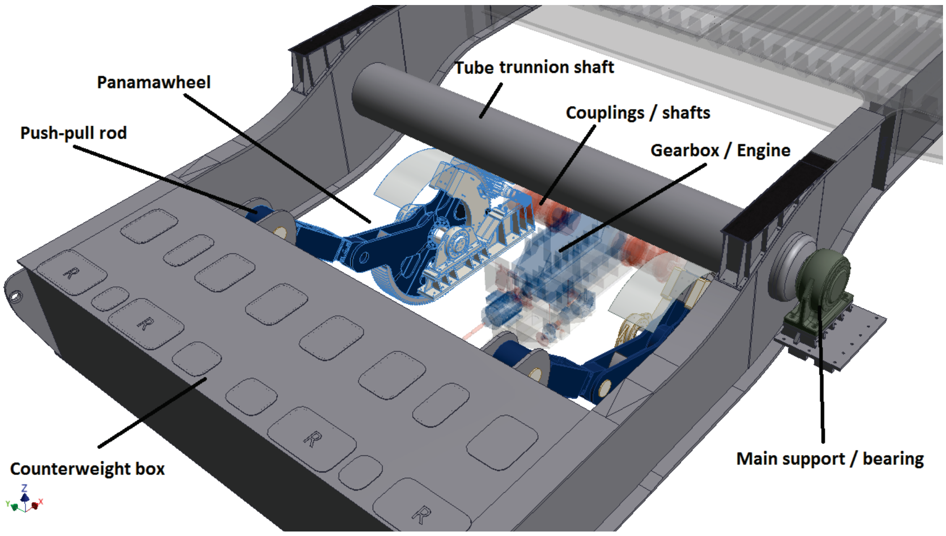


Figure 1.4 - Main components which are located in the basement of the bascule bridge

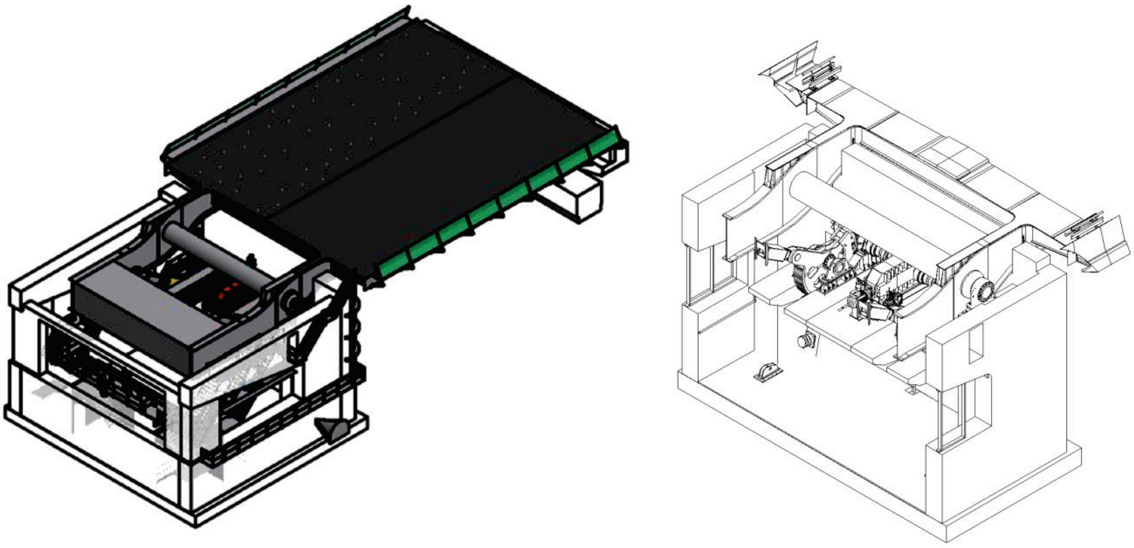


Figure 1.5 – Overview bridge and bascule basement without the counterweight

The scope will focus on the normal operation. Construction and maintenance phases will be left out. These phases only cover a rather small time span during the lifetime of the bridge. Further special facilities can be provided for these phases to prevent (unwanted) forces on the operating system.

2

MOVABLE BRIDGES

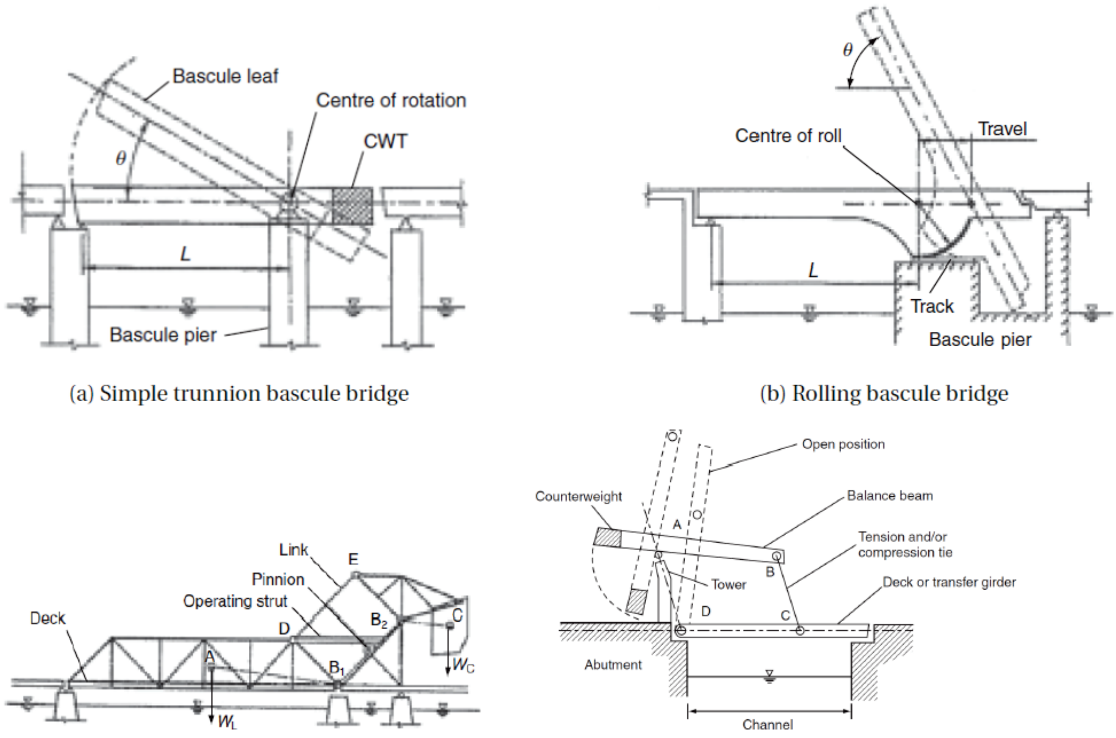
Bridges have been around already for thousands of years. The earliest were short spanned fixed bridges over small waters. Over time bridges have had a major development and have become an important key in infrastructure. Nowadays spans up to almost 2.000 metres are not unthinkable. At the same time fixed bridges were not always the option as they obstruct the waterway and larger ships will not be able to pass. To overcome this problem, bridges with a movable span have been created. The earliest movable bridges can be sought in the medieval times at castles, the drawbridge. The motive, however, for the drawbridge was different as it was a military defense mechanism.
The industrial revolution had a major impact on the development of movable bridges. Ships were used for shipping goods and became larger over time as well, demanding a larger clearance to not obstruct ships and deny their access to important regions, e.g. cities and harbours. To overcome the clearance problem, movable bridges were a good solution. Different types of movable bridges were developed and by 1800 the main principles were known. Nowadays there are three major movable bridge types which are most often applied, known as:

- Bascule bridge; Rotates around the horizontal axis
- Swing bridge; Rotates around the vertical axis
- Vertical lift bridge; Translation along vertical axis

The type of movable bridge applied depends on several factors. The structural aspect, e.g. span and clearance, but also architectural aspects, i.e. aesthetics regarding the environment, have an influence. Each type of bridge has its advantages. As the bridge in the reference project is a bascule bridge and the problem mainly focuses on this type of bridge, only the bascule bridge will be discussed further in this thesis.

2.1 BASCULE BRIDGE

In case an unlimited clearance is required, a bascule bridge is one of the options. They can be seen as modernized drawbridges of medieval times and are the most common applied movable bridge nowadays, i.e. about 60 percent of all movable bridge (Koglin, 2003).
A bascule bridge is pivoted on the horizontal axis and normally makes use of a counterweight. The position of this counterweight depends on the type of bascule bridge. The four main types of bascule bridge are depicted in figure 2.1.



(a) Simple trunnion bascule bridge

(b) Rolling bascule bridge

(c) Heel bascule bridge

(d) Balance beam bascule bridge

Figure 2.1 – Types of bascule bridges (Parke & Hewson, 2008)

The Netherlands is one of the lead engineering countries on movable bridges. With the large area of waterways in The Netherlands movable bridges are indispensable. There is, however, quite a difference between type of movable bridges used in The Netherlands and other countries which also hold a large number of movable bridge. The first is that the simple trunnion and balance beam bascule bridge are most applied. Of the approximately 1500 movable bridges in the Netherlands, about 1100 are of these two types (Nederlandse bruggenstichting, 2009). For example in the United States the heel bascule and rolling bascule are more common. Secondly nearly all the bridges are single-leaf bridges, while the double-leaf is more common in other countries. Only about 50 double-leaf bridges exist in The Netherlands, which are nearly all smaller bridges in the cities like Amsterdam.

It should be noted that there is some controversy on what is classified as bascule bridge. While in the international community the bascule bridge comprises several types including those depicted in figure 2.1, in The Netherlands each type of these bascule bridges is seen as a separate type. For further reading the *bascule bridge* should be read as *simple trunnion bascule bridge*, unless otherwise mentioned.

During the design the type of movable bridge is chosen. Each type has its own advantages. The bascule bridge easily blends in with the rest of the structure and the environment. The machinery is normally fitted into a basement out of sight for people. The construction of a basement might be a downside, but some components require certain conditions, e.g. temperature and humidity, which are easier controlled in a basement.

2.1.1 COUNTERWEIGHT

Normally bascule bridges are equipped with a counterweight. Depending on the rest of the structure this counterweight is placed either in the pier or at the abutment in a basement. The function of the counterweight is to balance the deck in order to reduce the power required to operate the bridge. The gravitational point of the leaf is shifted closer towards the pivot. Therefore the moment created by the leaf and which should be overcome by the operating system is lowered.

The steel case for the balance is filled with material. The material used for filling depends on the required weight and the volume possible. Concrete is a cheap filling, but comes with a low density. To increase the density of the counterweight, a mixture between concrete and steel waste is used. Other materials are possible, however, the costs might increase as well significantly and therefore only applied if no other option.

At the toe of the leaf a small support force is required in closed position in order to prevent uplift due to wind or other effects created by live load. This support force is normally created by a small overweight of the deck compared to the counterweight. The counterweight exists for a small part of adjustable weight. These are steel plates of 23 kg, maximum allowable weight to be carried according to Dutch HSaWA (Health and Safety at Work Act), which can be added or removed. The reason for an adjustable weight in the counterweight is due to changing weight of the bridge during maintenance, e.g. in case the asphalt or wearing layer is renewed. After maintenance the bridge has to be balanced again, which can be achieved by the adjustable counterweight.

Although the required torque by the machinery is lowered by changing the gravitational point of the leaf, the counterweight also comes with a downside. Due to the added mass the mass moment of inertia is increased. According to the equation of motion, equation (1), this means that an increased mass also requires an increase of force in order to change the velocity of the mass. This has effect on the operation of the bridge. A larger torque will be required to start opening the bridge but also in order to stop the rotation of the bridge.

$$m\ddot{u}_z(t) = \sum F_z(t) \quad (1)$$

A second disadvantage is vibrations, which is also related to equation (1). The counterweight is part of the leaf which is subjected to traffic load. The deck deflects due to traffic, which also influences the counterweight. At the transition of the normal road to the bridge-deck at the counterweight side these vibrations can be magnified due to the sudden additional or removed force in case traffic enters or leaves at this transition. Although these vibrations have small amplitudes, each vibration introduces changes in stress, affecting the fatigue life

2.1.2 SUPPORTS

Bascule bridges require the ability to rotate at the main support in order to open. To achieve this ability bearings are used. There are several configurations on how the girders, bearings and supports are connected with each other, figure 2.2. The configuration of the straddle bearings and tube trunnion shaft are most applied, depending on the size of the bridge, space available in basement and the costs.

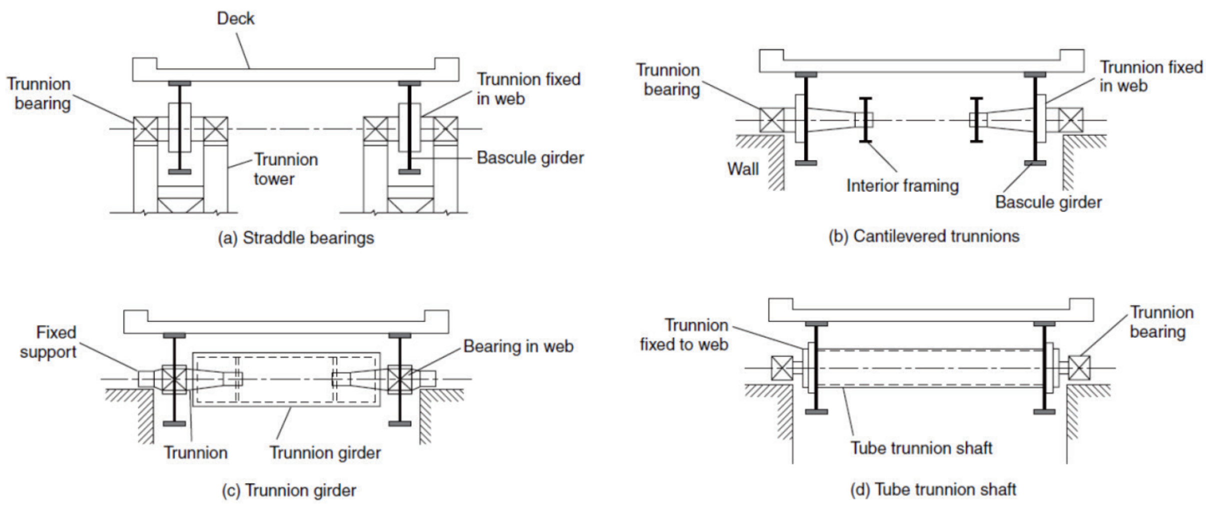


Figure 2.2 - Overview different configurations of simple trunnion bascule bridges (Parke & Hewson, 2008)

During operation nearly the entire dead load of the bridge is on the main bearings. Therefore these bearings must be resistant against high loads. Simultaneously the bearings should also provide a low friction factor to mitigate the contribution to the operating load. Spherical roller bearings are a logical choice for the main bearings as these can withstand high loads, as they have a large contact surface, and have a low friction factor, due to the rollers. Spherical plain bearings are used as well. Their capacity is higher, but they also come with a higher friction.

2.1.3 OPERATING SYSTEM

A movable bridge has been chosen on purpose at a certain location and should operate when requested. Therefore the operating system should be reliable in order to avoid hinder for waterway traffic.
In figure 1.3 the main components of the operating system have been identified. The shafts and coupling transfer the rotation from one component to the other and are designed to withstand the loads. For the operating machinery, the operating mechanism and the brakes there are additional requirements which should be taken into account.

Normally the entire system is either mechanical or hydraulic. A combination is possible as well, though not recommended. A large disadvantage of a combination is that for maintenance both expertise on mechanical components as well as hydraulic components is required. The mechanical system will only be discussed further as this is applied in the reference project.

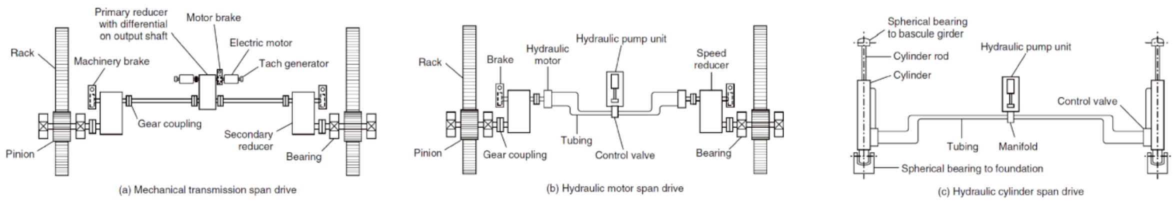


Figure 2.3 - Overview of operating machinery (Parke & Hewson, 2008)

2.1.3.1 OPERATING MACHINERY

The operating machinery drives the operating mechanisms. The main components in the machinery are the electro-engine and the gearbox. The outgoing shaft of the engine will rotate with about 1500 to 1800 rounds per minute but with low torque. To open the bridge, however, a low rotational speed and a high torque is required. To achieve this, a gearbox reduces the rotational speed which automatically means an increase in torque, as denoted by the following equations:

$$P = \tau * \frac{\partial \theta}{\partial t} = \tau \omega \qquad (2)$$

$$\tau_{in}\omega_{in} = \tau_{out}\omega_{out} \tag{3}$$

Nowadays the engines can be regulated. The speed of the engine is increased in phases, figure 2.4. The phases can be identified as:

1. Creep opening (20-30 sec.)
2. Full speed opening (30-70 sec.)
3. Creep stop opening (70-80 sec.)
4. Full speed closing (100-140 sec.)
5. Creep closing (140-160 sec.)

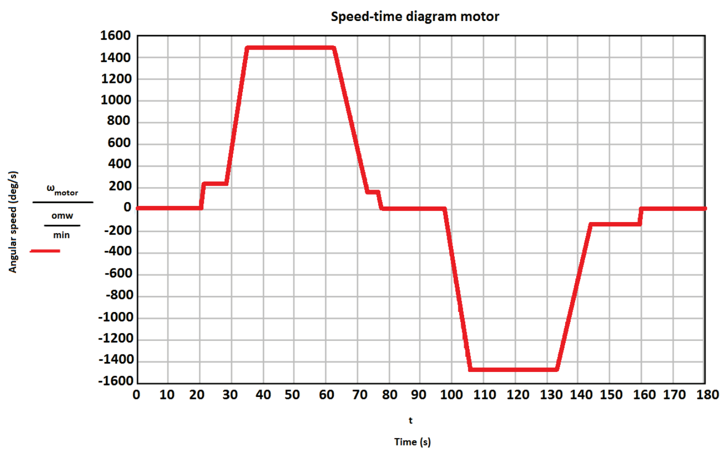


Figure 2.4 - Angular speed over time diagram during normal operation

At start of opening the bridge, all the mechanisms need to settle first, e.g. the teeth of gears have a small space for motion. In order to prevent damage, a slow rotational speed is used at start to make sure all the space for motions are cleared and full contact is made. Once everything has settled the engine can increase to full speed.
As mentioned the counterweight increased the mass moment of inertia. A full stop will create a large force on the mechanism as the counterweight wants to keep its rotational speed and additionally large vibrations occur. Therefore the speed is reduced the last few seconds of opening, to mitigate the force but also the vibrations.

In open position the leaf will normally have its gravitational point still on the span-side of the pivot. Therefore the gears have full contact in this position, and a creep speed is not always necessary, but sometimes still applied.
The last seconds of closing are also in slow speed. The leaf should not bump at high speed on the supports at the resting pier. This can cause great damage to the operating mechanism, as there is an abrupt stop, and to the toe of the leaf itself.

2.1.3.2 OPERATING MECHANISM

The operating system is often referred to as the operating mechanism since this is the main part on which the entire design is determined. The engine, gearbox and couplings will only change in specifications or size, depending on the type of mechanism and available space. For the design of the mechanism different types can be chosen, e.g. gear rack, panamawheel etc.
The reference project consists of a panamawheel (described as panamawheel from this point onwards), figure 2.5, which is a four rod mechanism. The idea behind the four rod mechanism is two fixed pivots and two pivots which change position during operation with respect to the fixed pivots, figure 2.6. In the case of the panama crank mechanism, the fixed pivots are those of the main bearing support of the leaf (A) and the panamawheel (B). The panamawheel has an integrated crank which is connected to the leaf by a push-pull rod. The two ends of the push-pull rod, (C) and (D), are the two pivots which change position during operation. (C) will rotate about (B), and (D) about (A). Since the two points do not rotate about the same axis, this also creates a difference in angular speed between the panamawheel and the leaf, figure 2.7.

Figure 2.5 - Operating mechanism in Ketelbrug, The Netherlands
A: panamawheel, B: pinion, C: push-pull rod

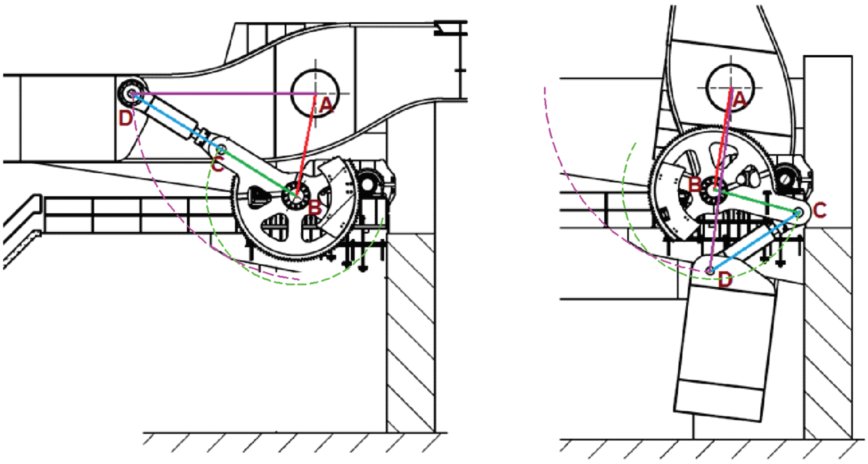
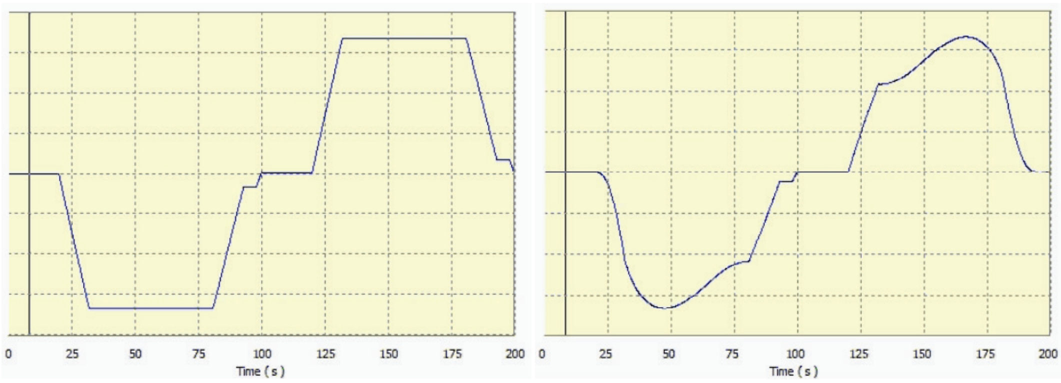


Figure 2.6 - Four rod mechanism with use of panama crank mechanism



Motor Leaf

Figure 2.7 - Angular speed versus time

2.1.4 PUSH-PULL ROD

The push-pull rod is a mechanism on its own, containing a spring to allow the push-pull rod to elongate or shorten due to the active forces. The rod is situated between the leaf and panamawheel, and during operation of the bridge causes the leaf to follow the panamawheel. As both ends are hinged, only an axial force is present.

The rod has a double acting spring, meaning the spring will be active under both a compressive as a tensile force, depicted in figure 2.8. The design of the rod causes the spring to always compress, irrespective of a compressive or tensile force. The rod self, however, will shorten or elongate depending on the force. For reading, *compression of the spring* will be used throughout the thesis for shortening or elongation of the rod.

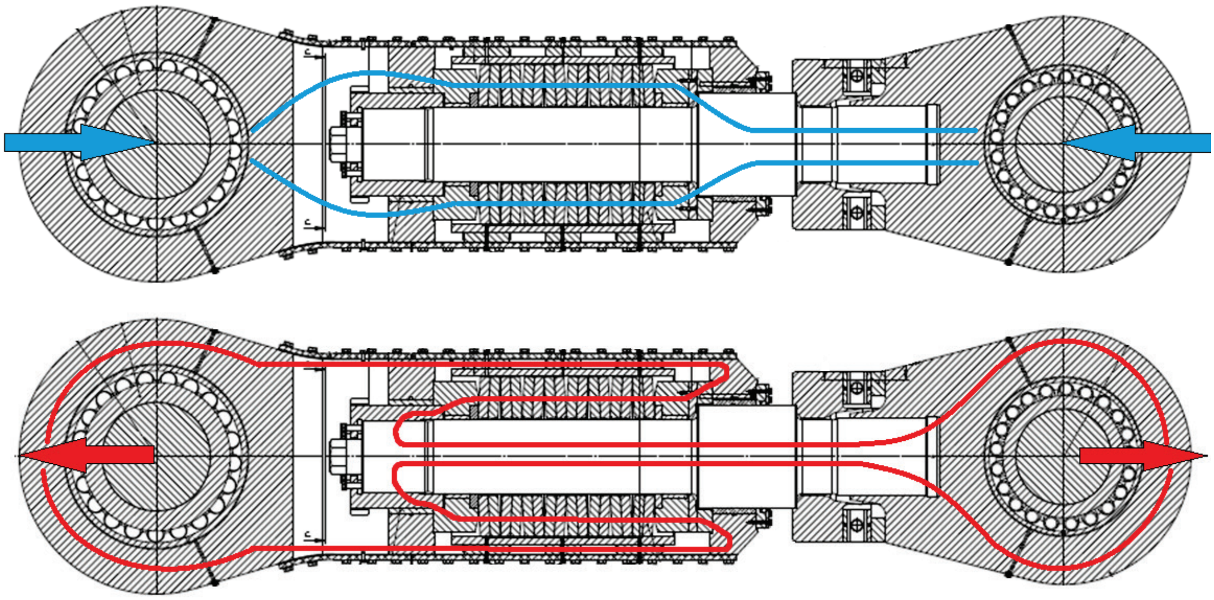


Figure 2.8 – Force flow in the push-pull rod under a compressive force (top) and a tensile force (bottom).

The spring is installed for sudden large forces. Especially the emergency stop causes these large forces. The emergency stop can be defined as two situations:

- An emergency occurs causing the bridge to be stopped *manually*; The bridge decelerates and is stopped within a few seconds.
- Failure of electricity; the engine stops instantly cause large forces throughout the entire operating system.

As discussed before, mass moment of inertia plays an important role with acceleration and deceleration. The largest effect is of the leaf acting on the push-pull rod, i.e. the leaf has a significantly higher mass moment of inertia compared to the shafts, couplings and gearbox. In order to stop the leaf, the kinematic energy has to be absorbed. The leaf rotates around the main supports, so the push-pull rods are the only "fixed" points to prevent the leaf from rotating further. An almost instant stop means a large kinematic energy which is transferred. In case no spring is used, the entire force will flow directly into the panamawheel and further into the operating system, which might cause severe damage. In order to reduce the energy that is transferred further towards the panamawheel, the spring stores a portion of that energy.

2.1.4.1 PRESTRESS

During operation of the bridge, a rigid element is preferred over a flexible one. Therefore the spring in the push-pull rod will be prestressed. By prestressing the spring, the push-pull rod will have a tri-linear behaviour, depicted in figure 2.9. Due to the prestress the push-pull rod will act rigidly up to the point where the prestress force is surpassed (F_p). Once the prestress is overcome, the spring will become active and the stiffness of the rod changes. The spring has a maximum compression,, after which the push-pull rod will act rigidly again.

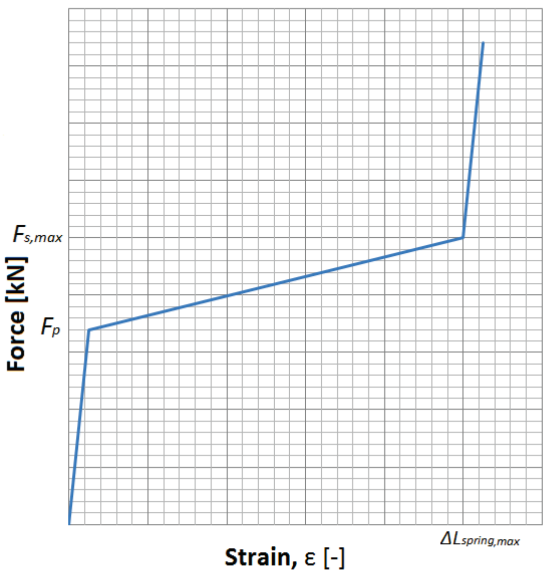


Figure 2.9 - Strain of the push-pull rod due to axial force

The prestress is an internal force of the rod. The internal design of the rod is made in such a way that the spring is restraint by the rod and body to decompress. The external force acting on the push-pull rod will have to surpass the prestress force in order to compress the spring further. Therefore the rod is rigid up to that point.

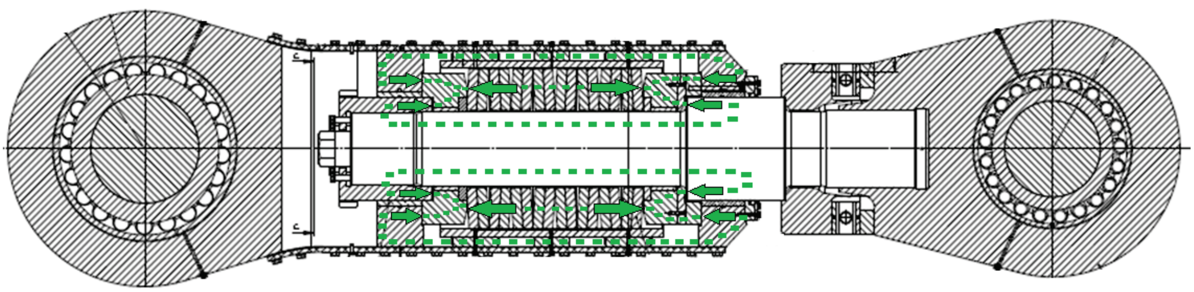


Figure 2.10 - The internal force flow in the push-pull rod of the prestress

As discussed at the start and end of opening/closing the bridge, the speed is lowered to avoid damage. The prestress makes the push pull rod act as a rigid rod up to the point where prestress force in the spring is surpassed. Even though a slow speed is used, a shock will go through the mechanisms when the bridge is closed and hits the support. A spring would be a solution to absorb the energy partly, but a large disadvantage of an immediate acting spring is vibrations. In closed position, the operating mechanism exerts a force on the leaf to create the required support force at the front supports. A flexible connection between the leaf and panamawheel would mean that the counterweight is able to vibrate.

2.2 MANUFACTURING AND ERECTION

An important phase during the entire project of a new bridge is the manufacturing and erection of the bridge. The manufacturing must match the design and needs to be ready on time. Significant errors which have to be corrected can cause a problem for the planning. The waterway is inaccessible during the time period that the bridge is installed. This time period is often planned far ahead and cannot be postponed without consequences. Therefore the components need to be ready at the scheduled day.

For a movable bridge quite some components are ordered at a specific manufacturer, as these are specialist at these components, e.g. gearbox, engine, couplings and bearings. During the design there is already close contact with the manufacturer which specifications are required and the best solution for that specific project. The manufacturing of these parts are rather specific and detailed. Besides, these are often machinery work instead of manually constructed. The structural components, e.g. the leaf, requires more manual work, increasing the probability of errors. This will be further discussed in 3.2.

The installation of a movable bridge requires a good planning. Preparations are required for the installation of the bridge. These preparations reduce the necessary time of installation, hence reducing the hinder. Further the preparations will increase the accuracy of placement. The main preparations to be done are in the basement, as the entire operation system is placed there. In 3.3 this is further discussed. After the installation of the operating system and leaf has taken place, the leaf is often set in fully open position. A locking device will be used for this, so the operating mechanism is not under influence of the wind and work can still be done until the bridge will be taken into operation.

2.3 LOADS

A movable bridge is subjective to additional loads compared to a fixed bridge. In closed position, a movable bridge can be seen as a fixed bridge and is designed that way. However, for the operating mechanism also the open position is of importance. For the design of the operating mechanisms these additional loads should be taken into account. The (additional) loads that should be taken into account for the design of the operating mechanism will be discussed in this section. The focus is on the relevance regarding the study of the force distribution between the operating mechanisms.

2.3.1 WIND

Compared with most loads that have to be taken into account for the operating mechanism, wind load is one of the most complex loads since the load is dynamic. Besides, for a movable bridge wind is one of the governing loads, certainly if the dimensions of the deck increase. In 1993 the code has changed significantly on the wind load (Stroosma & Tol, 1993) and several aspects will determine the wind load. The aspects that determine the wind load are:

- Availability of the movable bridge
- Type of waterway
- Maximum clearance in closed position
- Region; At coastal region there are higher average wind speeds than inland
- Distance between water level and highest point of the leaf
- Surface roughness

Some of these aspects are dependent on other aspects. With all these aspects the exerted force on the leaf can be determined by equation (4).

$$p_w = \frac{1}{2}\rho \cdot \left\{ U_R \cdot \frac{\ln\left(\frac{h}{z_0}\right)}{\ln\left(\frac{z_{ur}}{z_0}\right)} \right\}^2 \cdot \left\{ 1 + \frac{7}{\ln\left(\frac{h}{z_0}\right)} \right\} \qquad (4)$$

Another aspect that should be kept in mind is that during operation the wind gets more grip on the leaf. The wind shape factor, C_t, is determined by the opening angle of the leaf, the direction of the wind as well as the ratio of the deck size. Figure 2.11 shows the wind shape factor, which is the result of wind-tunnel testing (Allaart, 1949) and (Bouma & Rem, 1950).

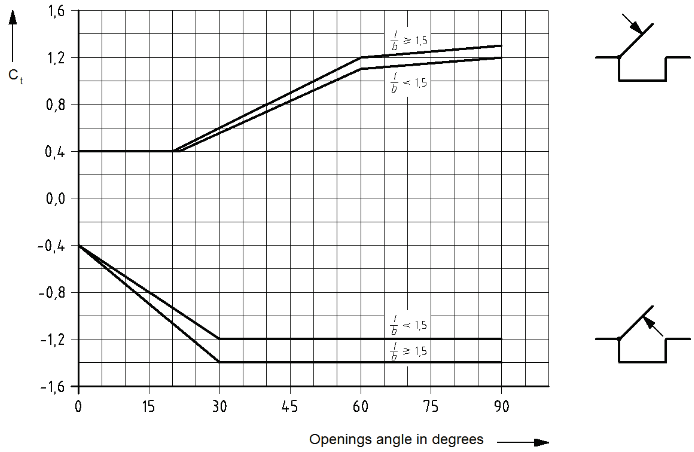


Figure 2.11 - Wind shape factor per angular displacement of the leaf for determination of the moment caused by wind

For the moment caused by wind, the following formula counts:

$$M_{w,brug,rep} = C_{dim} \cdot C_t \cdot \varphi_w \cdot p_w \cdot S \quad (5)$$

With:

- C_{dim} *Factor for the dimensions of the bridge;* $C_{dim}=0.95$
- C_t *Wind shape factor*
- φ_w *Dynamic enlargement factor;* $\varphi_w=1.15$
- p_w *Wind pressure on the leaf*
- S *First moment of area of the deck*

The wind load that is taken into account is taken as a uniform distributed pressure on the leaf. For the force distribution between the two mechanism this has no effect. However, wind gusts could cause a one side of the deck have an additional load from wind. Wind gusts are of short time span however, and in addition need to be quite strong in order to really affect the force distribution between the two operating mechanisms. The total contribution of the wind gusts during the lifetime of the bridge is therefore so small regarding the effect on the fatigue, that this load will be neglected further in this study.

2.3.2 SNOW

Snow load can be neglected for bascule bridge during operation.

2.3.3 TRAFFIC LOAD

The deck structure is designed according to the Eurocode for the closed position. Traffic load is one of the governing loads for the design of the superstructure. For the design of the operating mechanism this load can be neglected as there is no traffic present on the bridge during operation.

2.3.4 TEMPERATURE

Temperature can have a large influence on the behaviour of structures. In a static undetermined structures a change in temperature internal forces and moments can occur. If these additional forces and moments are not taken into account, a structure can actually fail due to this extra loading.
The conditions that should be taken into account for movable bridges can be found in the VOBB, paragraph 8.2.4. For a movable bridge there is beside the deck also the basement where the temperature plays a role.

2.3.4.1 STANDARD

The VOBB states the following in the remarks on paragraph 8.2.4:

> *"In general it is recommended to prevent that deformations of the bridge, caused under influence of temperature, have an influence on the components of the mechanical equipment."*

In the code the temperature is taken into account in a load combination together with other loads in order to check the required moment that has to be overcome. The influence of the temperature load on where the load causes a difference between the two operating mechanisms is not mentioned and not taken into account. The check on temperature can be divided in three situations.

- Bridge is in closed position
- Bridge is in open position, but out of use
- Bridge is in operation

For this study the closed position is not of interest. In case the bridge is in open position but out of use, the code states that a uniform distributed temperature has to be taken into account between -25°C and +45°C. As a uniform distributed temperature has no effect on the force distribution of the push-pull rods this situation can be neglected, as the load self is already in the combination.

In the last situation, during operation, there are several conditions that should be checked, under which non-uniform distributed temperature load of the deck. The loads are already taken into account in the load combinations for determination of required , however, the influence of this load on the two mechanisms is not. Therefore consequences for the push-pull rods needs to be analysed under the influence of a non-uniform distributed temperature. Further the basement should be checked with a uniform distributed temperature load.

2.3.4.2 DECK

The VOBB states a few conditions that should be taken into account regarding temperature. For this study certainly the effect of the temperature on the mounting points is of importance. In this case mainly a contrary reaction force on the mounting points is interesting, as these will increase the force distribution between the two mechanisms.

As mentioned for the deck the non-uniform distributed temperature loads during operation are of interest. The VOBB states different temperature loads depending on the in table 2.1 are applicable.

Component	Temperature difference
Main girders	30K between top and bottom of the girder, with the highest temperature on top 15K between the two outer girders
Transverse girders	30K between top and bottom of the girder, with the highest temperature on top

Table 2.1 - Applicable temperature loads on the deck structure

In order to get a contrary reaction force on the mounting points, the deck has to twist. To achieve a twist in the deck, only the temperature difference between the main girders would cause this effect. As the temperature loads are normally checked apart of each other, a different approach is used.

For this approach the deck is assumed to be heated up with a slight gradient. In transverse direction between the two sides of the bridge of 5K will be applied. Further a gradient in vertical direction of 30K on the main and transverse girders will be applied as mentioned by the code with 30K. Figure 2.12 shows the temperature gradients. For the input in the FEM model, the temperature underneath the deck plate is decreased more. For the troughs a temperature of -15K is taken. This temperature is the reference for the girders as well, i.e. the top of the girder is ± -15K and the bottom approximately -30K. The difference of 15K is neglected for the reference and the transverse gradient is used instead. The reason for this is that the main girders will not be susceptible to the sun as they are quite far to the inside.

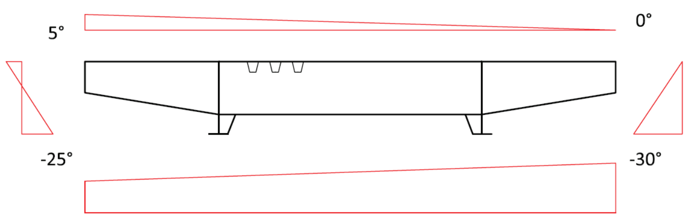


Figure 2.12 - Temperature gradients on deck structure

A Scia Engineer model is used to analyse the effect of the temperature gradients on the mounting points. Appendix A.2 shows the applied temperature loading in the model. The conclusion of the analysis shows that temperature can be neglected for effects on the force distribution. No additional force will be introduced on the mounting points due to the deformation of the deck under influence of the temperature.

2.3.4.3 BASEMENT

The temperature throughout the basement can be assumed to be uniform. The sun has no direct influence on components, and the temperature in the basement is mostly dependent on the long-term outdoor temperature. According to the VOBB the temperature in the basement should be taken between -5°C and +25°C. The influence of the temperature can be neglected for almost all components in this case as the components are of small size and most components are also constraint.

The two mounting points on the counterweight can shift however in the transverse direction. The change in length (ΔL), and thereby the shift of the mounting points, are determined by the temperature change (ΔT), the transverse length to the main support (L), and the material expansion coefficient (α).

$$\Delta L = \alpha \cdot \Delta T \cdot L \tag{6}$$

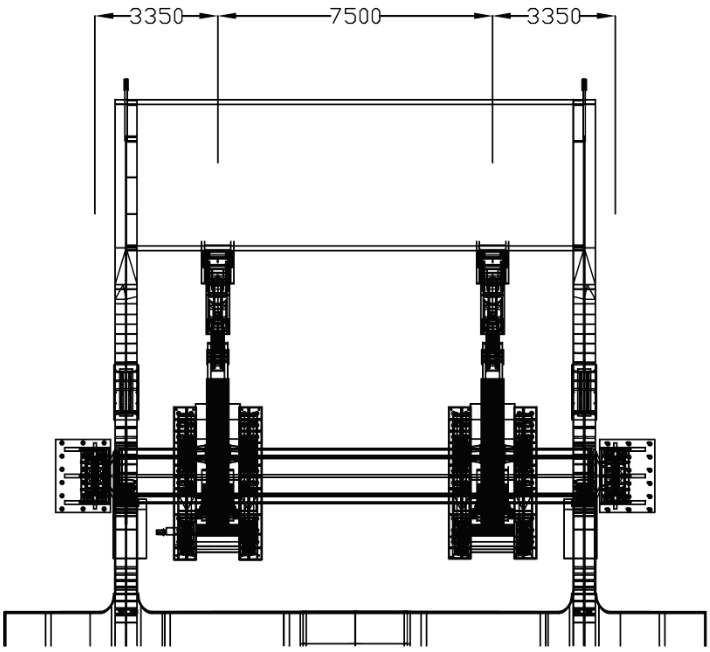


Figure 2.13 - Distance between main supports and mounting points. The left bearing is fixed and right is a gliding bearing in transverse direction.

One of the main supports is fixed in all direction. The transverse length between this support and the two mounting points are respectively 3.4m and 10.9m. Compared with the installation temperature, a difference of approximately 20K can occur. This would cause a shift of respectively 0.8mm and 2.6mm. For the push-pull rods this small shift has no influence. A spherical bearing has one main free rotation axis, however, can also allow small angular displacements about the other axis. Therefore the shift due to the temperature can be neglected. As the spherical bearing allows small displacements sideways, the entire y-axis is left out as the influence of this axis on the axial force in the push-pull rod can be neglected.

2.3.5 SELF WEIGHT

Self weight has an influence on the operating mechanism. The self weight is one of the loads that determines the required torque of the engine. Although the bridge is balanced, due to the rotation of the leaf, the gravitational point of the leaf can shift and therefore cause a load on the operating mechanism. The bridge is symmetric, so the self weight will be symmetric as well and therefore has no effect on the force distribution between the two mechanisms. This load is taken into account for the standard operation load of the operating mechanisms but not further discussed throughout the thesis.

2.3.6 EXCESS LOAD

The excess load is the unbalanced load of the bridge. The front supports need to meet a requirement for its support force. This support force ensues from the unbalanced load, which can be seen as a symmetric load as well. Therefore this load has no effect on the force distribution between the two mechanisms and can be neglected further.

2.3.7 VARIABLE DECK WEIGHT

Due to wear and replacement of the asphalt and/or wear layer during its lifetime, the deck weight can differ over its lifetime. This should be taken into account by assuming a difference of ±50N/m^2 can occur for electro-mechanical movable bridges with steel deck. This load has no effect on force distribution between the two operating mechanisms and therefore neglected.

2.3.8 FRICTION

During operating the bridge has to rotate on several points, i.e. main supports, mounting points of push-pull rods and supports of the panamawheels and pinions. Friction should be reduced as much as possible, which is done by the use of bearings. Each type of bearing still has a friction factor, causing a friction load that should also be overcome for operation. The assumption of no effect on the force distribution between the operating mechanisms can safely be made and therefore friction is neglected.

2.3.9 DYNAMIC LOAD

Acceleration and deceleration have a significant impact on the force of the operating mechanism. There are requirements for the acceleration and deceleration times of the bridge in normal situation and in emergency case. The load introduced by this has no influence however on the force distribution between the two mechanisms.

2.4 SCHEMATISATION

For the normal calculations and verifications the bridge is schematised as in figure 2.14. In this schematisation the entire bascule bridge is simplified to one mechanism. This also results in an overall load and there is assumed to be no difference between the two mechanisms. So effects that cause a contrary force between the mechanisms are therefore not taken into account.

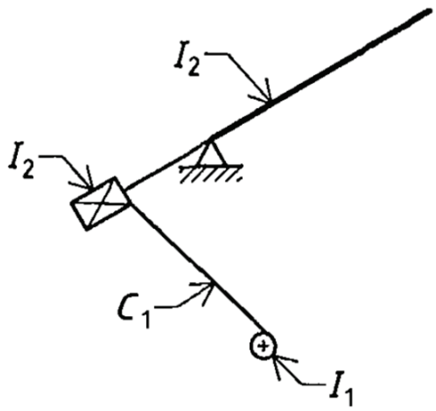


Figure 2.14 - Schematisation used for a bascule bridge

For this study the results from a single schematisation are used as a basis and assumed that each mechanism will take half of the acting force. This would also be the case if the bridge is installed perfect and no non-symmetric loads would occur. The schematisation used for this thesis will be further discussed in 4.1.

3

TOLERANCES

A lot of fields of work make use of tolerances, also referred to as margins of error. For example, financial, sociology and statistics sector all make use of these margins of error, but also in the engineering sector tolerances need to be taken into account. In some fields these tolerances are more important than the other, and are therefore rather strict. That is also seen between the civil engineering and mechanical engineering sector.

Where civil structures are static, mechanical structures, like a movable bridge, are dynamic. Mechanical structures are more subjective to the effect of tolerances than civil structures, which is why the tolerances in the mechanical engineering are often far more strict than in the civil engineering. In a static structure a tolerance has mostly no significant effect for the structure regarding stability, strength and force distribution. In dynamic structures this however differs as small tolerances can have a larger effect during operation. The tolerances can influence for example the rotation, creating differences between mechanisms which are not taken into account during the design. A forced displacement might be the result of these differences, which will lead to additional forces in components of the dynamic structure, as the forced displacement is constraint by the structure itself. This chapter will discuss this further regarding the bascule bridge and four rod mechanism.

Type of structure	Tolerance of manufacturing
Concrete	± 10 mm
Steel civil structure	± 1 mm
Mechanical	± <0.1 mm

Table 3.1 - Tolerances of different types of constructions

For reading, both *tolerances* and *offsets* are used. *Tolerances* will be used for the possible difference of a coordinate that occurs during the manufacturing and installation in comparison with the design. *Offset* is used for the actual difference in coordinates that is present after the bridge has been installed.

3.1 IMPACT OF TOLERANCES

The focus of the tolerances is on the four rod mechanism system of the bridge. A bridge can contain either one or multiple operating systems. With only one operating system the tolerances are less of a problem, as the leaf will always follow the mechanism. The reference project contains two four rod mechanisms, in which tolerances might cause a problem. Although the mechanisms will rotate almost similar, due to the tolerances the radius and/or rotating axis might slightly differ between the two mechanisms. This results that the two mechanism will have a different rotation, causing forced displacements. As the operating system is assumed infinitely rigid, these forced displacements have to occur at the leaf. These forced displacements will create twist in the deck, and bending of the counterweight box and girders. This results in the leaf resisting the forced displacements, and therefore introduce a force at the mounting point at the leaf and simultaneously in the push-pull rods. This will be discussed later in section 4.9.

The tolerances can be placed in two categories.

- Manufacture tolerances
- Installation tolerances

Further the loads should be kept in mind. Temperature and wind load are the only loads which can occur non-symmetric. The loads will not be taken into account however, as the influence is neglectable, as discussed in 2.3.

3.2 MANUFACTURING

Manufacturing can have an influence on the coordinates of the main points in the four rod mechanism. The main components which influence the main points in the four rod mechanism are the leaf, panamawheel and the push-pull rod. The components of the bridge should be produced within certain tolerances. The components that are manufactured using manual labour are more subjective to possible offsets. The main components will be further discussed here.

3.2.1 LEAF

The leaf is the largest component and consists mainly of plates being welded together. As the deck becomes larger, self weight increases and can cause deflections. Beside these deflections the welds also cool down and shrinkage takes place. Shrinkage is one of the major issues to deal with during manufacturing. Shrinkage gives a distortion to the plates. For the deck itself this is lesser of an issue, but during the assembly of the deck with the counterweight box, this can cause a distortion in the counterweight box not being entirely perpendicular to the girders.

Conservation of the leaf should also be taken into account during the manufacturing process. The dimensions of the parts will have to fit in that factory hall. The leaf is subdivided into four parts known as; deck, girders, coupling shaft and counterweight box. The deck is for the reference project too large, and therefore split into two. The girders are already connected with the deck before conservation. The coupling shaft and counterweight box are manufactured separately of the leaf as well, as seen in figure 3.1.

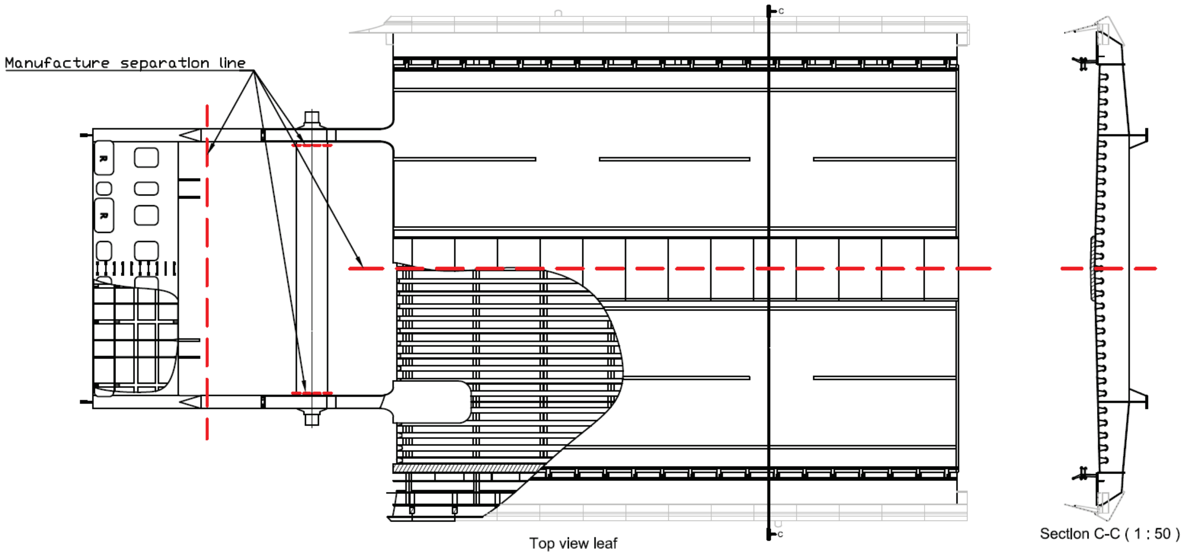


Figure 3.1 - Overview of separation lines of the leaf for manufacturing

After conservation, the entire leaf is assembled. Due to shrinkage of the weld, the order of assembly must be taken into account. Weld distortion cause unwanted displacements. Especially for the main rotating points of the four rod mechanism these displacements should be mitigated. Combining the deck has little influence on the misalignment, however, the assembly of the deck with the counterweight-casing will have influence on the main points of the four rod mechanism. Shrinkage of the counterweight box with the girders causes length change between the mounting point and main rotation point. As both sides will be different, this might cause a misalignment.

The counterweight box will not yet be filled. This is done after the installation of the leaf. Filling the counterweight beforehand will cause to increase the entire weight of the leaf significantly which creates an issue for transport, e.g. the reference project's weight of the leaf without counterweight is already 350 tonnes, and including the counterweight the weight is over 800 tonnes.

3.2.1.1 ROTATIONAL POINTS

The misalignment of the main points, the mounting point at the leaf and the main rotational point of the leaf, in the four rod mechanism must be mitigated. Although a lot of research is done on shrinkage, there will always be a factor of uncertainty. By boring out the main points in the leaf after welding, these points will be located more accurate. The only difference is the measurement error and error of boring out.

3.2.2 PANAMAWHEEL

In comparison with the leaf, the panamawheel has a different manufacturing process. Mainly the manufacturing takes place by a machine, and therefore the errors in dimensions and offsets are small. Welding is part of the panamawheel, but has little influence on the two main points in the wheel and can be neglected.

3.2.3 PUSH PULL ROD

The push-pull rod has three main aspects which should be taken care of. The first is the prestressing of the disc springs within the rod. Secondly the length is important. In idle condition, the push-pull rod needs to be a certain length. In closed position of the bridge, the spring of the push-pull rod will be compressed. Although this length is known theoretically, the compression length might differ per mechanism due to difference in position of the main points of the mechanisms. Depending on the design of the push-pull rod, the length might be slightly adjustable during the installation. These have to fulfil the requirements of the fitting for the bearing.

3.3 INSTALLATION

A perfect installation would mean there are no offsets to be found in the structure, and the bridge will work as theoretically determined. In reality, this is a utopia and will never be the case. It is defined that if a structure is manufactured and installed within its tolerances, the structure will satisfy its requirements and therefore work correctly. It is however important to know if the tolerances which are set, are also reliable and what the possible consequences are in case tolerances are in place. In this analysis this is done by looking at the four rod mechanism and the offsets applied to the main points of the four rod mechanism. The influence of loadings have been discussed in 2.3 and are assumed to be neglected.

The installation of a movable bridge requires a good planning. Before the leaf is installed, preparations need to be made, so the installation time is reduced as much as possible. Mainly this means that the entire basement should be ready when the leaf will be lifted in place.

3.3.1 BASEMENT

Within the basement the entire operating system is placed. It is, however, mainly a wide open space as the counterweight needs be able to rotate. For the installation of the bridge, the concrete basement is poured. The operating system is placed on a platform, while the main supports are resting on the sidewall of the basement.

The operating system rests on several foundation frames which are installed on the platforms. Preferred is to install all components on one foundation frame, though this is not always possible. In case of a panama crank mechanism, the issue is that the panamawheel needs to rotate and the push pull rod needs to have a free profile for rotation. Therefore, the panamawheel is often already resting on two separate foundation frames. The pinion can rest on the same foundation frame as the panamawheel, which increases also the precision of installation between these the pinion and panamawheel.

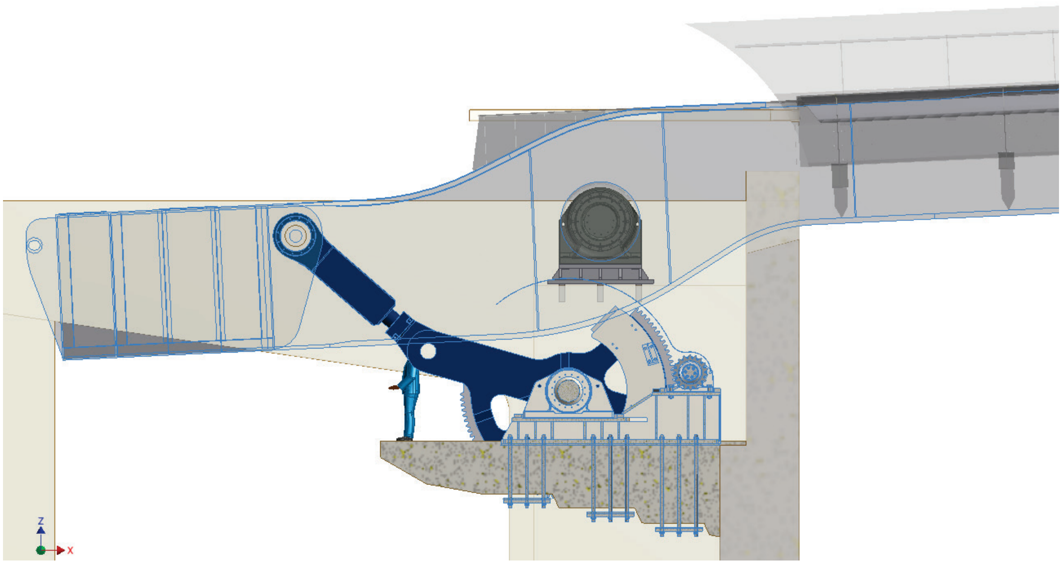


Figure 3.2 – Side view of the basement with panama crank mechanism anchored to the platforms.

3.3.2 PREPARATIONS

As the concrete basement is poured, there will be some preparations required before the rest of the installation can take place. These preparations are important for the accuracy of the placement, as well as to reduce the installation time.

Within the platforms the anchors are placed, on which the foundation frames can later be installed. After the anchors are placed, measurements are taken of the position of the anchors and the difference in height of the platforms. With these measurements, the holes can be drilled at the right spots and the height of the frames can be levelled off so that the cradles of the bearings are on the same height.

The foundation frames will be installed beforehand on the platforms. The cradles, which will be placed on top of the foundation frames, are assembled with the component, i.e. leaf and panamawheel. The assembly of the cradles with the component is done prior of installation since this way is easier to assemble.

3.3.3 ERECTION

Once all preparations are made, the leaf and operating system can be installed. Transportation of the leaf is often via the waterway since the dimensions are too large for road transportation. The panamawheels and pinions will be placed at first, as more room is available while the leaf is not yet installed. With the placement of the panamawheels, the leaf can be installed on its place. Since the foundation frames are already present, the cradles can be placed just on top so the bolts fit in. As the holes for the bolts in the foundations frames are slightly larger, minor adjustments might be required for higher accuracy of placement.

3.3.3.1 PUSH-PULL ROD

Once the leaf and panamawheels are installed, the push-pull rods can be installed in between the two. The installation is made easier as the ballast is not yet added. The mounting points at the leaf will be higher at this moment as due to the added weight, the counterweight will deflect. Therefore the arm between the mounting point at the leaf and the crank is larger. Once the ballast is added, the push-pull rod will be compressed due to the deflection of the counterweight.

3.3.3.2 COUNTERWEIGHT

Once the entire operating system has been installed correctly, the ballast is added. The front supports of the bridge require a specific support force. The ballast is added in two phases. Firstly the bulk weight is added, which consists of a certain type of material. In case loose material is used, grout or concrete is poured in to fixate the material so it is restraint from movement during operation of the bascule bridge. The second phase is the adding adjustable ballast. The support force at the front support is already present, but the leaf should be balanced as much as possible to reduce the required power during operation.

Once ballast is added, and the entire operating system is installed the bridge is set in open position so the waterway is not obstructed.

3.4 MAGNITUDE OF TOLERANCES

To obtain the magnitude of the tolerances, several experts of reputed companies in the field of movable bridges have been contacted. In the conversations the tolerances and accuracy has been discussed, from which the following sections are the result.

3.4.1 MANUFACTURE TOLERANCES

As discussed in section 3.2 the sequence of manufacturing is important. Each component has its manufacture tolerance which should be met. The panamawheel, push-pull rod and leaf are the main components in this.

3.4.1.1 LEAF

The leaf contains two main points of each four rod mechanism. The main rotational points and mounting point for the push-pull rod. The points are created after the assembly welding has taken place. Therefore the errors of manufacturing are reduced as shrinkage does not affect the points anymore. Measurements of the position can be quite exact with a tolerance of ±0.5mm. The placement of the bore machinery, also has an accuracy. An accuracy of ±0.2mm can be achieved, leading to a total tolerance of ±0.7mm.

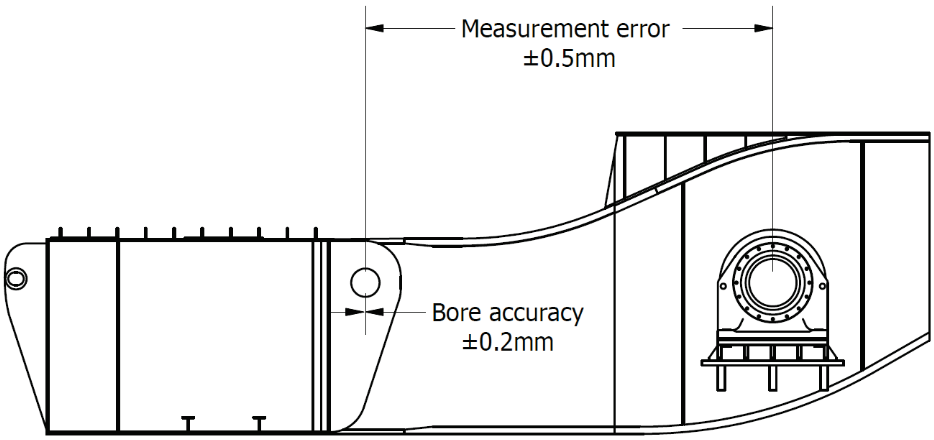


Figure 3.3 - Accuracy of manufacturing the mounting point with respect to the main rotational point

3.4.1.2 PANAMAWHEEL

The panamawheel is produced on a machine, which increases the accuracy of manufacturing enormously. The dimensions, however, are rather large. For the manufacturing mainly the length between the rotational point and the mounting point is important. The accuracy of manufacturing for this length is ±0.1mm.

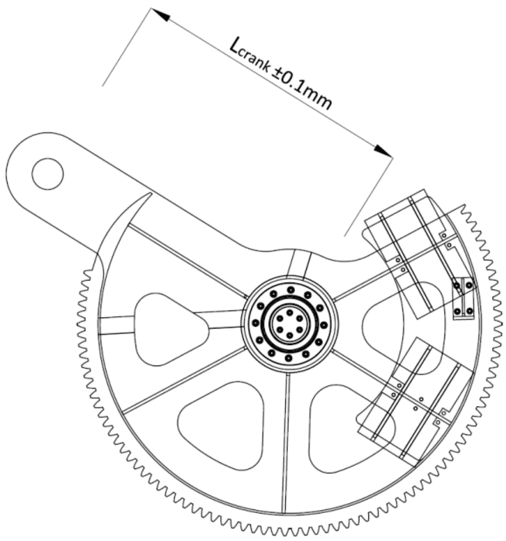


Figure 3.4 - Manufacture tolerance of the crank, ±0.1mm

3.4.1.3 PUSH-PULL ROD

For the push-pull rod the length between the centres of the mounting points is important. The push-pull rods will be slightly adaptable during installation, therefore the manufacture tolerance can be neglected.

3.4.2 INSTALLATION TOLERANCES

Beside the manufacture tolerances, the positioning during installation should also be taken into account. The manufacture tolerances can be quite exact. Positioning accurate becomes harder as you have to deal with heavy components. During the preparations the foundation frames are already installed. These can be lined out with each other with an accuracy of ±0.5mm. The cradles which will be installed on top of the foundation frames, will already be attached to the components for easier and more accurate installation. The holes for bolts determine the accuracy that can be reached. The bolts used are of size M56. The NEN-EN 1090-1 (A1 Table 11) states that for bolts larger than M27 holes should have a nominal clearance of 3mm. For the placement of the cradle on the foundation frame this means that positioning can be accurate within ±1.5mm. Both the leaf and the panamawheel are subjective to this tolerance.

For the panamawheel an additional point of interest is the angle of placement. As the foundations frames of both cradles per panamawheel should be levelled, about the x-axis there is not angle possible. Neither would this angle have much influence. The angle about the z-axis has mainly influence on the y-coordinate, which will not be taken into account, see section 0, so can be neglected as well. However, the angle about the y-axis influences both the x- and z-coordinate of the mounting point. During installation the crank should be in line with the push-pull rod.

3.4.3 SUMMARY OF OFFSETS

The offsets per point/component which will be used during the analysis are in table 3.2. A shift of the leaf applies to both the main rotational point and mounting point leaf. The shift panamawheel applies to the rotational point of the panamawheel and the mounting point crank.

Offset	X-direction	Z-direction	Type of tolerance
Mounting point leaf	±0.7mm	±0.7mm	Manufacture
Shift leaf	±1.5mm	±0.5mm	Installation
Shift panamawheel	±1.5mm	±0.5mm	Installation
Crank length	±0.1mm in length		Manufacture

Table 3.2 - Tolerances due to manufacturing and installation of mechanism and bridge

4

ANALYSIS INPUT

For the analysis a few design assumptions and specifications need to be defined. The choice for these assumptions might influence the behaviour of the four rod mechanism and the final results for the reference project. This should be taken into account when defining the assumptions.

4.1 SCHEMATISATION OF MECHANISMS

The analysis can be done with a simplified schematisation. The operating mechanism will have the same schematisation. In the calculations the interaction between the two by the leaf is taken into account. The schematisation shown in figure 4.2 is for better understanding also visible in a transparent model of the bridge, figure 4.1. Although the bridge is a three-dimensional structure, the focus is mainly on two dimensions, the x-axis and z-axis. Each mechanism will be looked at on the XZ-plane. The effect of the y-direction is neglectable, section 2.3.4, and therefore not taken into account.

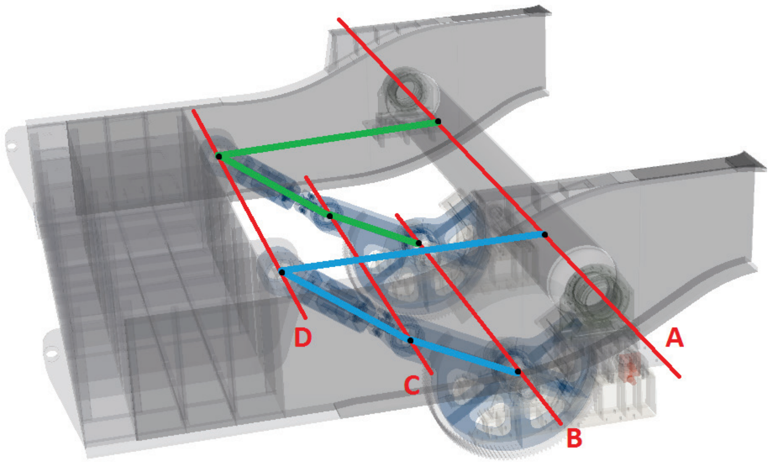


Figure 4.1 - The two mechanisms in the bascule bridge and the axes

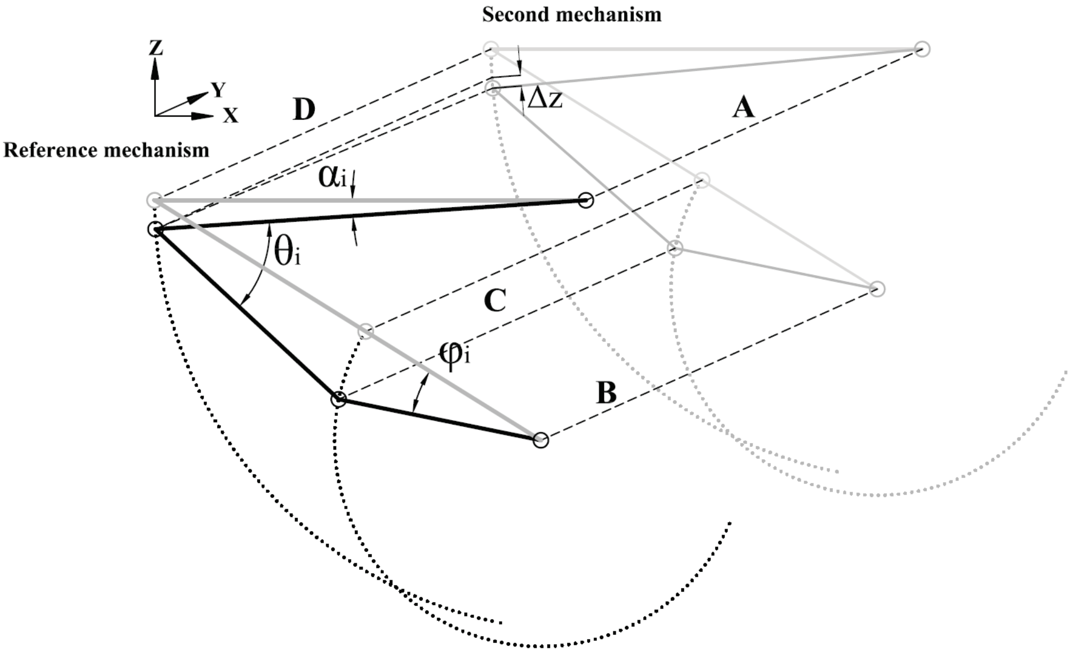


Figure 4.2 - Schematisation of both mechanisms including the axes (figure 4.1) and important angles for the analysis.

4.2 GLOBAL COORDINATE SYSTEM

The origin for the global coordinate system (GCS) is taken in the main rotational point of the leaf, as this is one of the fixed points and therefore does not change during operation. The mounting point can quite easily be determined from this point as well, as the mounting point rotates about the main rotational point.

The tolerances might also influence the main rotational point. Since the origin of the GCS is always set in the main rotational point, a shift is required of the entire system.

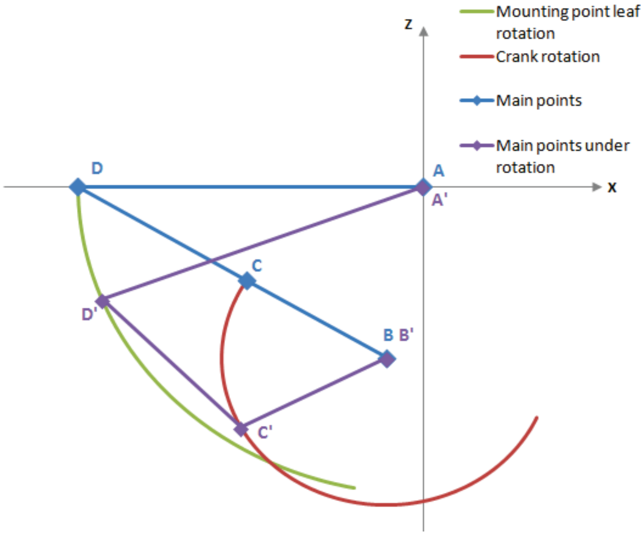


Figure 4.3 - Four rod mechanism in closed position and under a certain angle.

4.3 LOCAL COORDINATE SYSTEM

During operation the bridge undergoes a rotation. This results in changing position of the main points of the four rod mechanism. For a better understanding of what happens during the process and to simplify the calculations, a local coordinate system (LCS) will be used. The local coordinate system will rotate along with the leaf and is also defined with the origin in the main rotational point.

The coordinates of the GCS will need to be expressed in terms of the LCS. A transformation of the global coordinates will be required to get the local coordinates, which can be achieved by using equation (7).

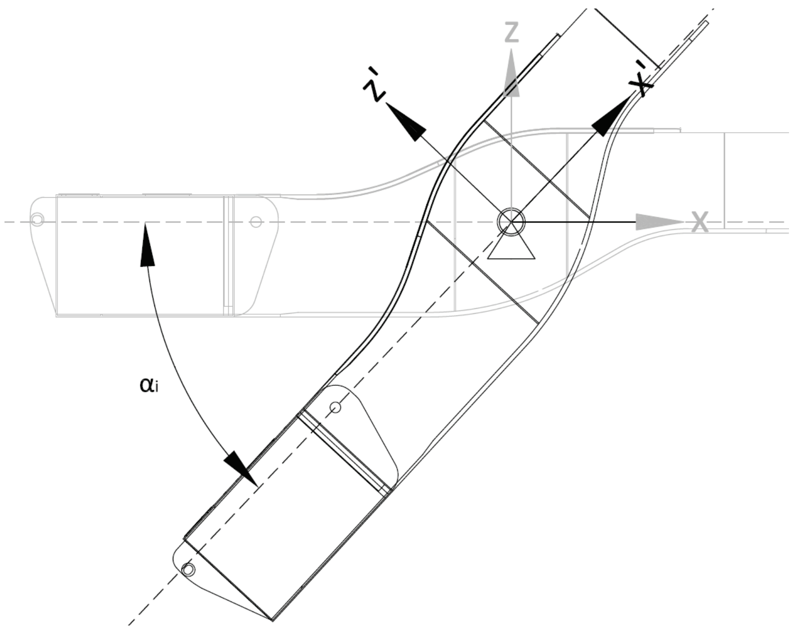


Figure 4.4 - Local and global coordinate system of the leaf under angle α

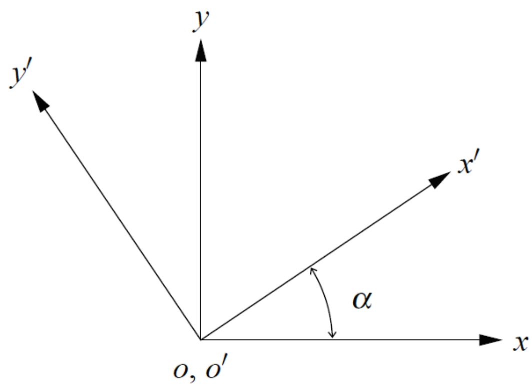


Figure 4.5 - Transformation of global to local coordinate system. α is the angle of the leaf

$$\begin{pmatrix} x' \\ z' \end{pmatrix} = \begin{bmatrix} \cos(\alpha) & \sin(\alpha) \\ -\sin(\alpha) & \cos(\alpha) \end{bmatrix} \begin{pmatrix} x \\ z \end{pmatrix} \quad (7)$$

4.4 MAIN COORDINATES

The bridge and mechanism are designed with the coordinates of the main points in closed position according to table 4.1. The coordinates of the mounting point crank are actually determined by the length of the crank and the angle the crank has with regards to the panamawheel horizontal. The offsets due manufacturing and installation are added to these coordinates. The main rotational points are the reference points per mechanism. Therefore these points are set at (0;0). Any offset of the main rotational points can be applied to the other points by a shift in opposite direction, i.e. if the main rotational point has a tolerance of 1mm in x-direction, the other three main points get a -1mm displacement in x-direction and the main rotational point stays at (0;0).

Point		x-coordinate	z-coordinate
A	Main rotational point	0	0
B	Rotation point panamawheel	-600	-3200
C	Mounting point crank	-2936	-1749
D	Mounting point leaf	-5750	0

Table 4.1 - Coordinates of the main points of four rod mechanism without tolerances taken into account

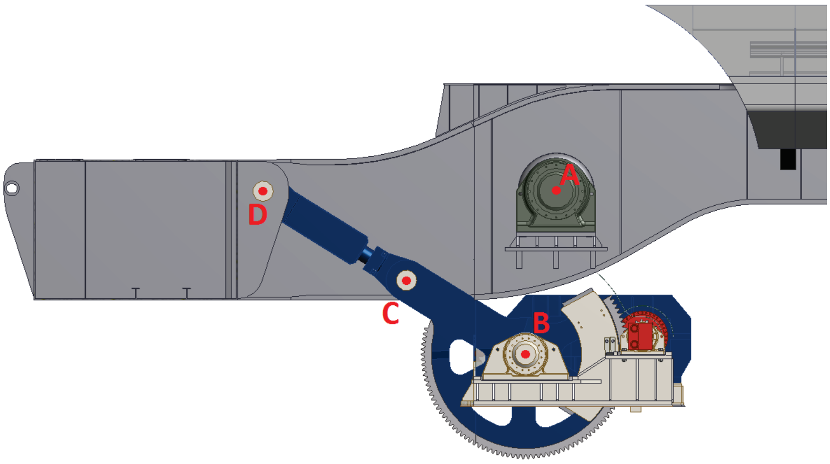


Figure 4.6 – Main points in the four rod mechanisms

4.5 Push-pull rod

For the analysis the specifications of the rod are of importance. The main specifications are seen in table 4.2. During manufacturing, the rods will have their design length. However, this length is still slightly adaptable during installation of the rods. This will be further discussed during the results. As a start the following specifications are assumed for both rods.

Data	Value
Design length	3333.6 mm
Prestress force	640 kN
Spring stiffness	39.5 kN/mm

Table 4.2 - Specifications of the push-pull rod

The stiffness of the spring is assumed constant. The stiffness changes slightly during the compression, though the change is neglectable. The average stiffness of the spring is used for the analysis.

The push-pull rod has a tri-linear behaviour, figure 2.9, which should be taken into account for the calculations. The maximum additional compression of the spring is 58mm, at which a force of 2940kN is present. The spring is designed so that this maximum compression is never reached during the lifetime, i.e. even in worst case scenarios like emergency stop, the maximum additional compression should not be overcome. Therefore, the rod will be assumed with a bi-linear stiffness.

For further simplification, the push-pull rod is assumed to be fully rigid up to the point where the prestress is reached. The actual strain of the push-pull rod can be neglected. This strain would however result in a slightly lower forced displacement of the mounting point at the leaf, which is positive. Therefore a fully rigid rod would mean an upper boundary.

4.6 PANAMAWHEEL

The panamawheels will be the key component in the calculations. The panamawheel is driven by the engine and the leaf follows the panamawheel accordingly via the push-pull rod. Since one engine drives both panamawheels, the assumption can be made that the panamawheels will start rotating at the same time and will rotate at the same speed. Time, and therefore speed, are not taken into account for the rotation in the calculation however, since these have no effect on the additional load. By assumption of equal angular speed for both mechanisms, the angle of the panamawheel will be the same for both mechanisms at all times.

With the panamawheel as the key component for the calculation, all the plots will be set out against the angular displacement of the panamawheel. The angular displacement of the panamawheel will always be the same for each situation. Although the angular displacement of the leaf would seem to be logical, the tolerances have an effect on this, and therefore are not the same for each situation. Therefore this is not a good reference point for comparison and the angular displacement of the panamawheel is used instead. The panamawheel will undergo a total of 188 degrees before the final position is reached where the bridge is fully open.

4.7 OPERATING SYSTEM

In the operating system all components are assumed to be infinitely stiff except for the push-pull rod as discussed in previous paragraph. The shafts, couplings, pinion and gearbox all have in reality a finite stiffness. As a result by assuming these components as infinitely stiff, the differences between the four rod mechanisms that occur during rotation will be forced to take place at the mounting point at the leaf. This point will undergo a forced displacement, which will cause a reaction force from the leaf.

When the actual stiffness of the operating system is used, the additional axial force will be lower. The operating system can be seen as an additional spring in this case. Therefore both the operating system and the leaf will deform due to the differences between the mechanisms. By using a infinitely stiff operating mechanism instead, the results are an upper boundary of the force distribution.

4.8 STIFFNESS LEAF

The forced displacement which is introduced at the mounting point at the leaf, will be restrained by the entire leaf. To determine the additional axial force in the rods, the stiffness of the leaf is of importance. This stiffness is depending on the girders, deck and counterweight box. To determine the stiffness, a uni-displacement in the vertical direction is applied on one of the mounting points. The required force to cause the uni-displacement, is the stiffness of the leaf with respect to the mounting points.

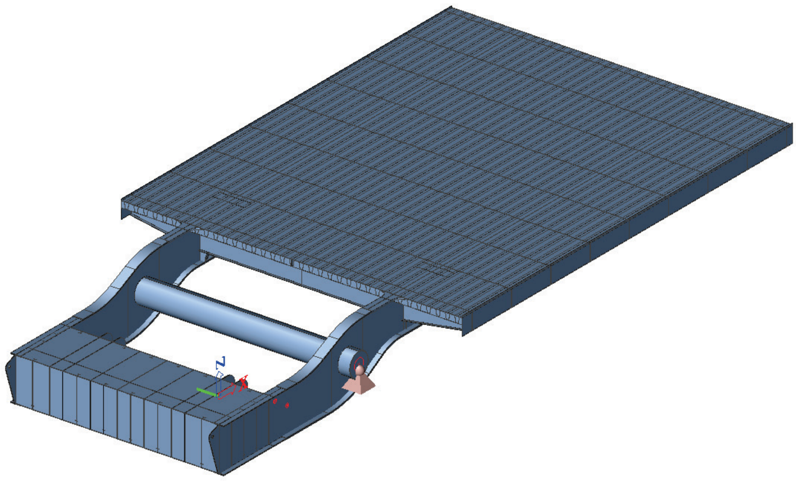


Figure 4.7 - Scia model of the bridge

The bridge of the reference project is modelled in Scia Engineer, which will be used to ascertain the stiffness. The Scia Engineer model is discussed in Appendix A. The supports are set at the main supports and the mounting points, depicted in figure 4.8. Table 4.3 shows the restraints per support. Since the stiffness during rotation is required, the front supports are not taken into account. The mounting point, S4, will undergo the 1mm forced displacement.

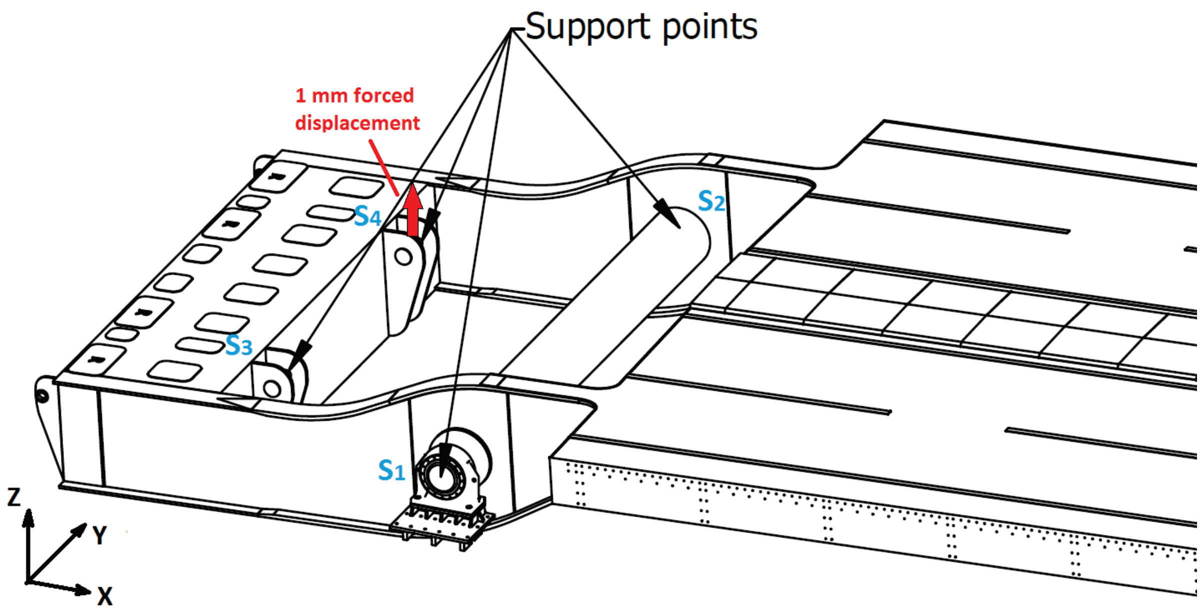


Figure 4.8 - Support points in model and the forced uni-displacement to determine the stiffness of the leaf

Supports	X	Y	Z	Rx	Ry	Rz
S1 - Main support	Yes	Yes	Yes	-	-	-
S2 - Main support	Yes	-	Yes	-	-	-
S3 - Mounting point	-	-	Yes	-	-	-
S4 - Mounting point	-	-	Yes	-	-	-

Table 4.3 - Restraints of the supports used in the Scia Engineer model

Looking at the XZ-plane of figure 4.8, a uni-displacement of S4 in the z-direction can only be restraint by the other mounting point, S3, to create equilibrium and avoid a mechanism. From this the conclusion can be drawn that the reaction force in S3 and S4 will be the same in opposite direction. Consequently S1 and S2 will also be of the same magnitude in opposite direction. Looking at the YZ-plane, the supports have similarity as a four point bending test. Since S1 and S2 are hinged, the ratio between S1 and S4 can be determined by $\frac{distance\ rods}{distance\ main\ supports} = \frac{7.5}{14.2} \approx 0.53$, (figure 2.13).

Applying a uni-displacement on support S4 in Scia Engineer, results in the reaction forces shown in table 4.4. From this the stiffness of the leaf with respect to the mounting points can be concluded as $k_{z,leaf} = 197kN/mm$.

Supports	Rx [kN]	Ry [kN]	Rz [kN]	Mx [kNm]	My [kNm]	Mz [kNm]
S1 - Main support	0,00	0,00	105,41	0,00	0,00	0,00
S2 - Main support	0,00	0,00	-105,42	0,00	0,00	0,00
S3 - Mounting point	0,00	0,00	-196,77	0,00	0,00	0,00
S4 - Mounting point	0,00	0,00	196,78	0,00	0,00	0,00

Table 4.4 - Reaction forces due to uni-displacement in z-direction of a mounting point

4.9 INTERACTION LEAF AND PUSH-PULL ROD

The forced displacement of the mounting point will , which is causes a reaction force. This exerted force by the leaf will give an additional force in the push-pull rod. Only an axial force is able to transfer through the push-pull rod, so the angle between the exerted force and the push-pull rod needs to be taken into account. Beside this, the angle between the leaf and push-pull rod changes during operation, which also influences the resulting additional force in the push-pull rod.

As soon as the axial force in the push-pull rods becomes larger than the prestress force, the spring can be compressed. This compression leads to either an elongation or shortening of the push-pull rod. An external force for opening and closing the bridge is also present, which is same for both rods. Since the additional force is opposite of each other, the sum of the additional force and external force is different. Therefore the stiffness of the push-pull rods do not have to change at the same time. With this in mind the entire interaction between the leaf and push-pull rods can be seen as three different trajectories.

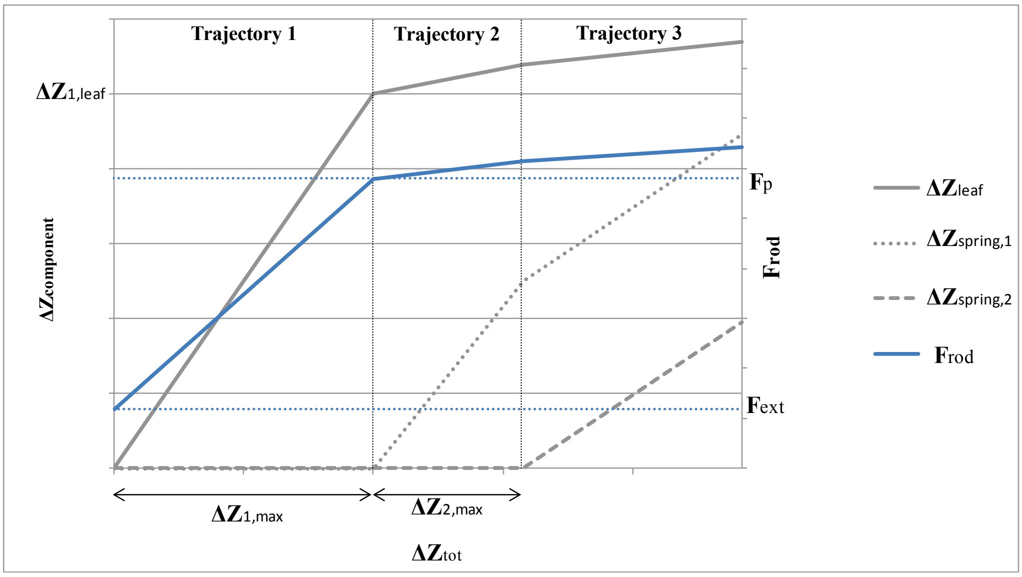


Figure 4.9 - Trajectories with corresponding displacement of each component and the corresponding force in the rod as Δz_{tot} increases.

Trajectory 1. Only leaf is deforming and springs are not active yet. Forces in push-pull rods are below the prestress force.

Trajectory 2. The leaf and only one spring is active. Only one push-pull rod reached prestress force.

Trajectory 3. The leaf and both springs are active. Both push-pull rods have reached the prestress force.

Examining how the axial force in the push-pull rods evolves, trajectory 2 is only the case when an external force is present. If no external force is present, the axial force in the push-pull rods is exerted by leaf deformation only. Therefore the push-pull rods will reach the prestress force at the same time and go instantly into trajectory 3 after the first trajectory, so $\Delta z_{2,\max} = 0$.
At a certain point the spring in a push-pull rod can be completely compressed. This would mean the push-pull rod will act rigid again. For the analysis this state will not be taken into account. During an emergency stop the highest load would occur, and the spring is normally designed that it will not get fully compressed during an emergency stop. Therefore during normal operation this will never be the case either.

4.9.1 REQUIRED VERTICAL DISPLACEMENT

As discussed, a difference between the two mechanism will occur during operation due to the offsets. A small angular displacement of the leaf nearly only affects the local z-coordinate, i.e. the change in the x-coordinate can be neglected. This is also the reason only the stiffness in z-direction is determined. The required vertical displacement is obtained in several ways, depending on the approach that will be used, 5.1.

In case the length of the rod is used for coordinate determination, the coordinates have to be transformed to the local coordinate system from which the difference in z-direction can easily be ascertained. The already present offset should be kept in mind however, the offset self of the mounting point does not introduce an additional force, and therefore should subtracted from the determined difference between the mounting points.

The other approach is to use the same angular displacement of the leaf for both mechanisms. Now no additional difference between the two mounting points other than the offset is present. However, the rod length of the second mechanism has a length difference, Δl. The rod will be rigid until the prestress force is overcome, so a Δz is applied to the mounting point, giving the push-pull rod its free length. In figure 4.10 this displacement and rod length difference is depicted for which Δz can be defined by equation (8).

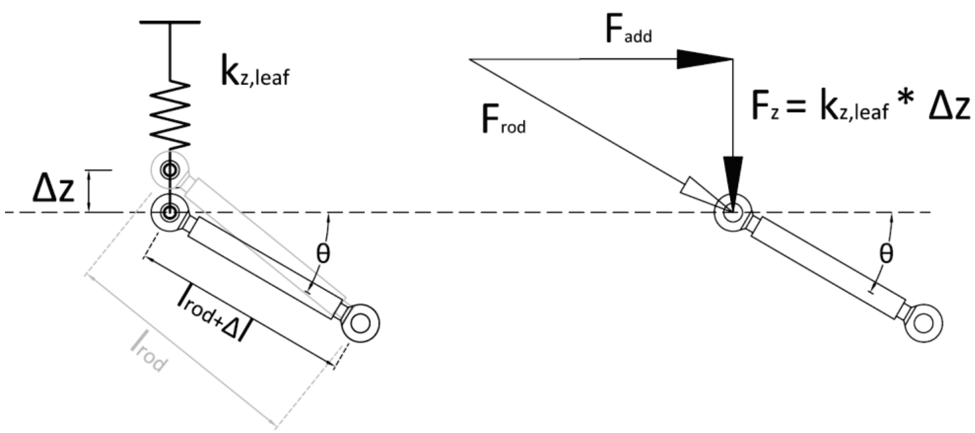


Figure 4.10 - Additional force on the push-pull rod due to extra displacement Δz.

$$\Delta z = \frac{-\Delta l}{\sin \theta_{\varphi_i}} \tag{8}$$

4.9.2 TRAJECTORIES

4.9.2.1 TRAJECTORY 1

The first trajectory is quite simple. Assuming $\Delta z \leq \Delta z_{1,max}$, then the entire displacement is taken by the leaf. Therefore the exerted force by the leaf is determined as follows by equation (10). $\Delta z_{1,max}$ is the maximum displacement before one of the push-pull rods reaches the prestress force and will be discussed in 4.9.3.

$$F_{z,1,\varphi_i} = k_{z,leaf} \cdot \Delta z_{1,\varphi_i} \tag{9}$$

The push-pull rod is unable to transfer shear force and moments, and therefore the exerted force has to be transformed to an axial force for the push-pull rod. An additional force, F_{add}, comes into play, that works perpendicular to F_z. The resulting force in the rods, F_{rod}, caused by the exerted force F_z follows from:

$$F_{rod,1,\varphi_i} = \frac{F_{z,\varphi_i}}{\sin \theta_{\varphi_i}} = \frac{k_{z,leaf} \cdot \Delta z_{1,\varphi_i}}{\sin \theta_{\varphi_i}} \tag{10}$$

With:

θ_{φ_i} *Angle between leaf and push-pull rod at the corresponding angular displacement of the panamawheel at step "i", φ_i.*

$\Delta z_{1,\varphi_i}$ *Forced displacement of the leaf at corresponding angular displacement in the first trajectory*
$k_{z,leaf}$ *Stiffness of leaf*

4.9.2.2 TRAJECTORY 2

When the prestress force is overcome in *one* of the push-pull rods, that spring will get a finite stiffness. Therefore the interaction changes between the leaf and the push-pull rods. Figure 4.11 depicts the situation of this trajectory. One push-pull is still rigid and is connected by the leaf to the other push-pull rod which is now a spring. For simplicity the angle of the rods is not shown, though should be kept in mind with $\Delta l = -\Delta z \cdot \sin\theta_{\varphi_i}$
The displacement that the leaf undergoes in the first trajectory, Δz_1, is already determined and present. The remaining part, Δz_2, is distributed over the spring and the leaf, where $\Delta z_2 \leq \Delta z_{2,\max}$. This is the maximum displacement before the other push-pull rod will also reach its prestress force and have a change in stiffness, discussed in 4.9.3. This is the point that trajectory 3 starts.

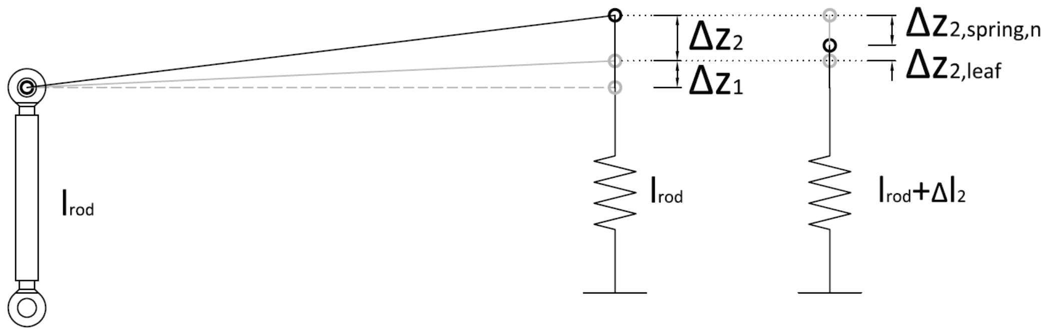


Figure 4.11 - The interaction between the leaf and the push-pull rods in the 2nd trajectory.

The displacement is distributed over the leaf and the active spring. The following is thus known:

$$\Delta z_{2,\varphi_i} = \Delta z_{2,leaf} + \Delta z_{2,spring,n} \tag{11}$$

Another condition which is known, is that there has to be equilibrium. The force from the leaf in the second trajectory should be equal to that of the spring. To check the equilibrium, the force of the spring, eq. (12), needs to be transformed to the local z-direction, eq. (13). This leads to the following set of formulas.

$$F_{spring,n} = k_{spring} \cdot \Delta l_{\mathrm{n}} = k_{spring} \cdot (\Delta z_{\mathrm{spring,n}} \cdot \sin\theta_{\varphi_i}) \tag{12}$$

$$F_{z,spring,n} = F_{spring,n} \cdot \sin\theta_{\varphi_i} = k_{spring} \cdot \Delta z_{\mathrm{spring,n}} \cdot \sin^2\theta_{\varphi_i} \tag{13}$$

$$F_{z,leaf} = k_{z,leaf} \cdot \Delta z_{leaf} \tag{14}$$

Combining the equations (11) to (14) gives:

$$k_{z,leaf} \cdot \Delta z_{2,\varphi_i} - k_{z,leaf} \cdot \Delta z_{2,spring,n} = k_{spring} \cdot \sin^2 \theta_{\varphi_i} \cdot \Delta z_{2,\mathrm{spring,n}} \tag{15}$$

Rewriting this equation gives the z-displacement taken by spring. The deformation of the leaf follows automatically using equation (11).

$$\Delta z_{2,\mathrm{spring,n}} = \frac{k_{z,leaf} \cdot \Delta z_{2,\varphi_i}}{k_{spring} \cdot \sin^2 \theta_{\varphi_i} + k_{z,leaf}} = \frac{\Delta z_{2,\varphi_i}}{\beta \cdot \sin^2 \theta_{\varphi_i} + 1} = \Delta z_{2,\varphi_i} \cdot \gamma_{2,\varphi_i} \tag{16}$$

With: $\beta = \frac{k_{spring}}{k_{z,leaf}}$

$$\gamma_{2,\varphi_i} = \frac{1}{\beta \cdot \sin^2 \theta_{\varphi_i} + 1}$$

Now the effect of the ratio between the stiffness of the leaf and the spring can also be seen. Increasing the stiffness of the spring will lead to a smaller portion of displacement which is taken by the spring, therefore a larger deformation of the leaf.

The extreme cases would be no spring stiffness, i.e. $k_{spring} = 0\ \mathrm{N/mm^2}$, and the rigid spring, i.e $k_{spring} = \infty\ \mathrm{N/mm^2}$. The latter is the case of the 1st trajectory, causing the full displacement goes to deformation of the leaf. In case the spring has no stiffness, the full displacement would be taken by the spring.

In the equations *n* represents the mechanism of the spring. Which mechanism has an active spring depends if the axial force in that mechanism reached the prestress force and can be determined by:

$$n = \begin{cases} 1 \quad \text{if} \begin{cases} F_{ext} - \dfrac{k_{z,leaf}}{\sin\theta_{\varphi_i}} \cdot \Delta z_{1,max} = F_p & \text{if } \Delta z<0 \\ F_{ext} + \dfrac{k_{z,leaf}}{\sin\theta_{\varphi_i}} \cdot \Delta z_{1,max} = F_p & \text{if } \Delta z>0 \end{cases} \\ 2 \quad else \end{cases} \tag{17}$$

4.9.2.3 TRAJECTORY 3

When the second spring becomes also active once its prestress force is surpassed, the third trajectory starts. A small modification to the spring-model has to be made as an additional spring comes into play. The displacement which the leaf undergoes in trajectory 1 and 2 is known at this point. Figure 4.12 shows the remaining displacement, Δz_3, that still has to be distributed over the two springs and the leaf. In figure 4.12a the displacement of the first two trajectories are also shown.

In this trajectory the leaf still exerts a force on both push-pull rods, with the difference that now two springs compress. The compression of the springs in both push-pull rods will be the same, i.e. the spring stiffness is the same. Therefore the formula of trajectory 2 can be adapted to the following:

$$\Delta z_{3,\varphi_i} = \Delta z_{3,leaf} + 2 \cdot \Delta z_{3,spring,n} \tag{18}$$

Since both springs will be compressed equally in this trajectory, the exerted force by Δz_3 reduces twice as fast, while the equation of the force of the spring stays the same, eq. (13). For simplicity, the two rods are assumed to have the same angle with the leaf. The influence of the angle difference can be neglected with respect to the magnitude of the outcome.

Using equations (12) to (14) and eq. (18), the displacement taken by each spring can be determined, which is given by the following formula:

$$\Delta z_{3,\mathrm{spring,n}} = \frac{k_{z,leaf} \cdot \Delta z_{3,\varphi_i}}{k_{spring} \cdot \sin^2 \theta_{\varphi_i} + 2 \cdot k_{z,leaf}} = \frac{\Delta z_{3,\varphi_i}}{\beta \cdot \sin^2 \theta_{\varphi_i} + 2} = \Delta z_{3,\varphi_i} \cdot \gamma_{3,\varphi_i} \tag{19}$$

With: $\gamma_{3,\varphi_i} = \frac{1}{\beta \cdot \sin^2 \theta_{\varphi_i} + 2}$

Although this equation is almost similar to equation (16), the sum of both springs from equation (19) is not equal to that of equation (16). The force in the springs is lower than the leaf in that case, therefore the springs need to compress slightly more to reduce the force from the leaf and create equilibrium.

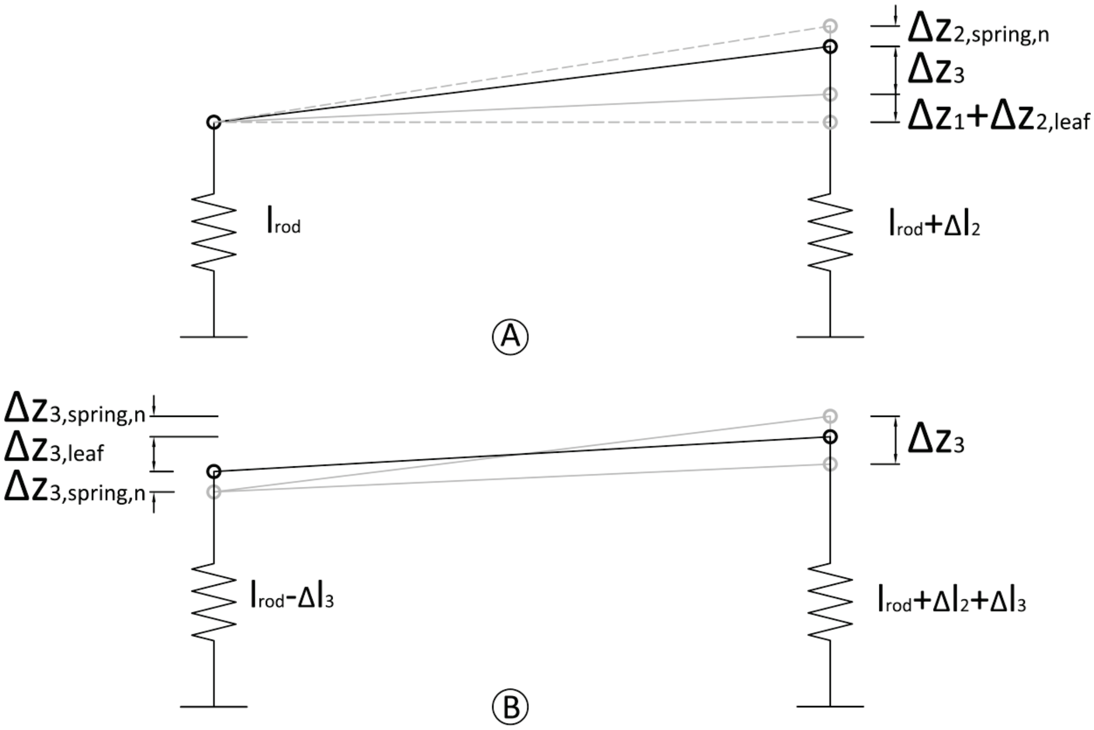


Figure 4.12 - Interaction in trajectory 3. One push pull rod elongates while the other shortens.

4.9.2.4 EXTERNAL FORCE

There is another situation that should be taken into account. The external force which will be present during operating for opening and closing the bridge can be larger than the prestress force. In this case, both springs will already be compressed, so $\Delta z_{1,\max} = \Delta z_{2,\max} = 0$ (figure 4.9), but the push-pull rods will both be either shortened or elongated, while the additional displacement due to tolerances causes one push-pull rod to elongate and the other to shorten.

The compression of the spring due to the external force is known. Using eq. (19) the maximum Δz can be determined before one of the rods will reach its free length again. In case equation (20) holds, the interaction of the leaf and springs will be entirely as in trajectory 3. Otherwise a part will the forced displacement will be in trajectory, as depicted in figure 4.14.

$$\frac{\Delta z_{\text{ext}}}{\gamma_3} = \frac{\Delta l_{\text{ext}}}{\sin\theta_{\varphi_i} \cdot \gamma_3} = \frac{|\mathrm{F}_{\text{ext}}| - \mathrm{F}_{\mathrm{p}}}{\mathrm{k}_{\text{spring}} \cdot \sin\theta_{\varphi_i} \cdot \gamma_3} \leq \Delta z \tag{20}$$

Since equilibrium must hold, the leaf will also undergo a small displacement before going into trajectory 3. Therefore the remaining part that will go into trajectory 2 is as follows:

$$\Delta z_{rest} = \Delta z - \frac{\Delta z_{\text{ext}}}{\gamma_3} = \Delta z - (2 \cdot \Delta z_{\text{ext}} + \Delta z_{\text{ext,leaf}}) \tag{21}$$

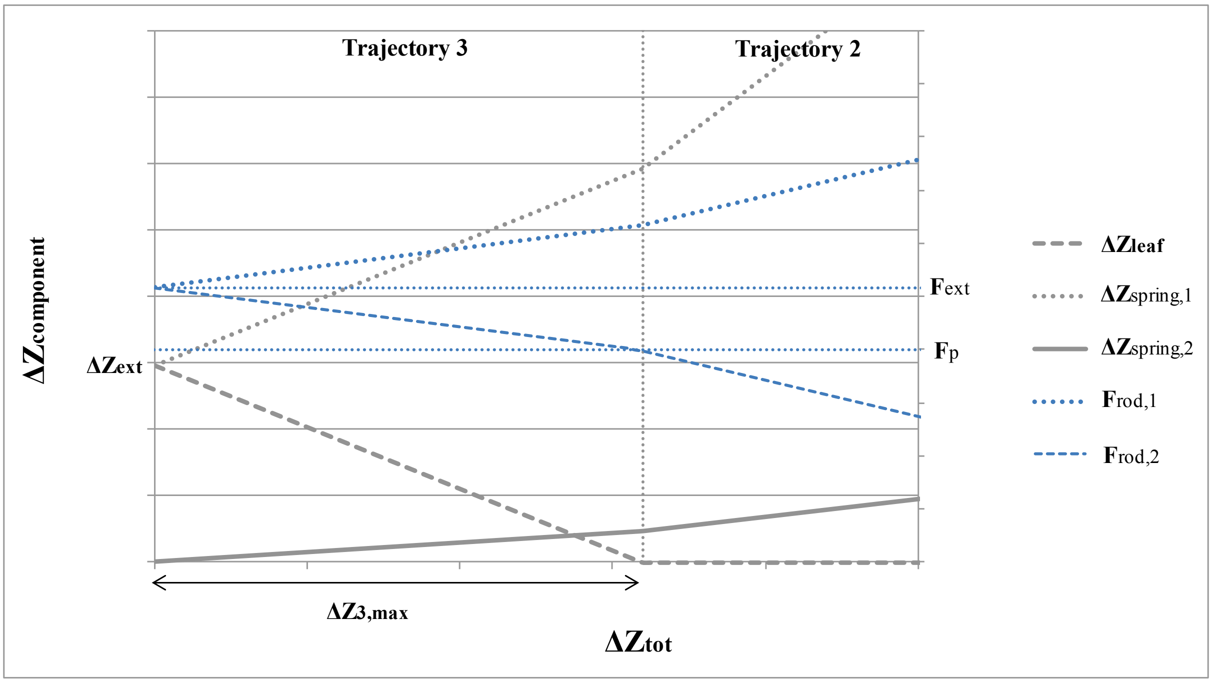


Figure 4.13 – Displacement per component in case $F_{ext} \geq F_p$.

It can easily be concluded that at the moment trajectory 2 comes into play, the spring that will stay active now has twice the compression as due to the external force, while the other is back in rigid form, figure 4.13. The active spring will get an additional displacement, which can be determined the same as discussed in 4.9.2.2, with $\Delta z_2 = \Delta z_{\text{rest}}$.

When $|F_{ext}| > F_p$ then it must be checked for which spring the compression will increase and for which the compression will decrease due to the offsets. This depends on the required vertical displacement and the external force.

Required vertical displacement		External force	Spring of rod 1	Spring of rod 2
$\Delta Z > 0$	and	$F_{ext} > 0$	Increase	Decrease
$\Delta Z > 0$	and	$F_{ext} < 0$	Decrease	Increase
$\Delta Z < 0$	and	$F_{ext} > 0$	Decrease	Increase
$\Delta Z < 0$	and	$F_{ext} < 0$	Increase	Decrease

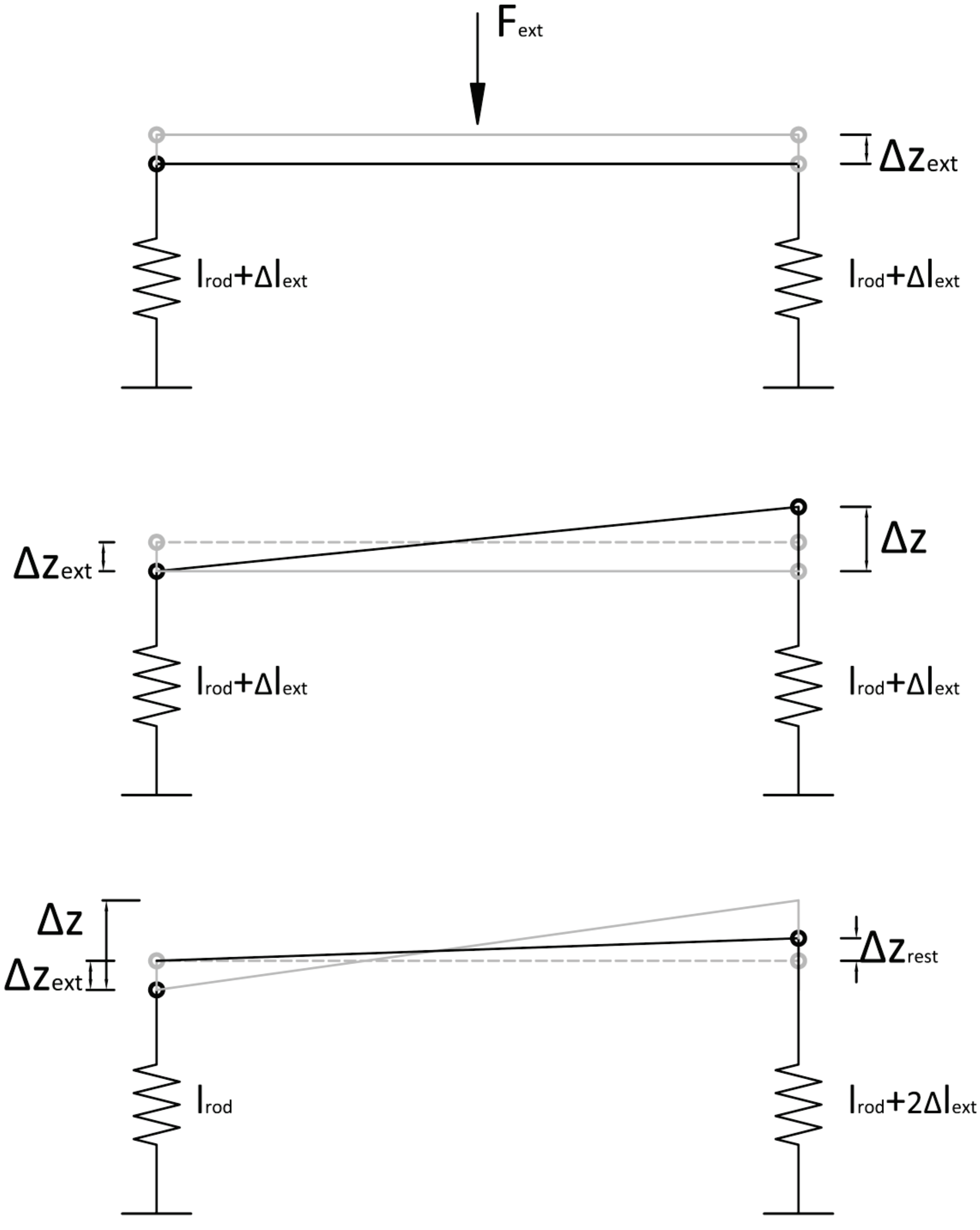


Figure 4.14 - Interaction between the springs and leaf under an external larger than the prestress force.

4.9.3 MAXIMUM DISPLACEMENTS

In order to determine the displacement taken per component, the start and end of the trajectories are required, i.e. $\Delta z_{1,max}$, $\Delta z_{2,max}$ and $\Delta z_{3,max}$. The main factors that determine the maximum displacement allowed in the trajectories are:

- External axial force
- Angle of push-pull rod
- Stiffness of the spring
- Stiffness of the leaf
- Prestress force

4.9.3.1 MAXIMUM DISPLACEMENT TRAJECTORY 1

In the first trajectory the springs are still rigid and is only present in case $|F_{ext}| < F_p$. They are rigid up to the point where one of the push-pull rods reaches the prestress force. Since the push-pull rod contains a double-acting spring, the prestress force works for both a tensile as a compressive force. Therefore the maximal displacement of the leaf follows by the following formula:

$$\Delta z_{1,\max} = \frac{F_p - |F_{ext}|}{k_{leaf,z} \cdot \sin \theta_{\varphi_i}} \geq 0 \tag{22}$$

The value will be equal to or greater than zero. In case the external force, the force which is already present in order to open the leaf, is greater than the prestress force, the springs will be active and no additional displacement of the leaf is allowed, so $\Delta z_{1,\max} = 0$.

If the following formula holds the leaf will deform under the entire displacement and neither of the springs will become active.

$$\left|\Delta z_{\varphi_i}\right| \leq \Delta z_{1,\max} \tag{23}$$

Otherwise the spring(s) will be active and trajectory 2 and/or 3 need to be taken into account.

4.9.3.2 MAXIMUM DISPLACEMENT TRAJECTORY 2

The second trajectory only one push-pull rod has the spring stiffness while the other is still rigid. The maximum displacement is determined by looking at when the other push-pull rod will also reach the prestress force and therefore become active.

Since the two push-pull rods work against each other due to displacements, the force in the second rod will *decrease* when the first rod increases.

Example: Assume the external force is 350 kN and a forced displacement large enough to reach trajectory 2. Therefore the prestress force at the point trajectory 2 starts is in the first rod equal to the prestress force of 640 kN in tension. This means 290kN additional axial force so far. Since the push-pull rods work against each other, the second push-pull rod has at this point a tensile force of 60 kN left. This force will only decrease due to forced displacement and therefore need an additional 700 kN decrease to reach the prestress force under compression, i.e. -640 kN. At this point the first rod would have an axial force of 1340 kN.

$$\Delta z_{2,\max} = \min \begin{cases} \dfrac{F_p + |F_{ext}| - \dfrac{(k_{leaf,z} \cdot \Delta z_{1,\max})}{\sin\theta_{\varphi_i}}}{k_{spring} \cdot \sin\theta_{\varphi_i} \cdot \gamma_{2,\varphi_i}} \\ \dfrac{2 \cdot F_p}{k_{spring} \cdot \sin\theta_{\varphi_i} \cdot \gamma_{2,\varphi_i}} \end{cases} \tag{24}$$

Equation (24) shows the maximum displacement in the second trajectory. Prior to trajectory 2 there can be either trajectory 1 or 3. The first formula holds in case the first trajectory is prior to the second trajectory. If trajectory 3 is prior the second formula holds. In equation (24) this is automatically taken into account. Since $\Delta z_{1,max} = 0$ and $|F_{ext}| \geq F_p$ if trajectory 3 will be prior, the other formula automatically will be smaller.

Since the force is in axial direction of the rod, this needs to be transformed to the local z-direction. This is where the sinus is introduced. Lastly the γ_{2,φ_i} represents the interaction of the leaf and the spring in the second trajectory, and takes the leaf also into account for the maximum displacement of the second trajectory since the leaf will also undergo a small deformation.

4.9.3.3 MAXIMUM DISPLACEMENT TRAJECTORY 3

The maximum displacement in this trajectory is only required to calculate in case $|F_{ext}| \geq F_p$. Otherwise the maximum displacement is assumed infinitely, discussed in 4.9. Due to the external force spring would already be compressed. The maximum displacement is the moment that the present spring compression is overcome. Therefore maximum displacement in trajectory 3 is as follows:

$$\Delta z_{3,\max} = \frac{|F_{ext}| - F_p}{k_{spring} \cdot \sin\theta_{\varphi_i} \cdot \gamma_{3,\varphi_i}} \geq 0 \tag{25}$$

4.9.4 TOTAL DISPLACEMENT PER COMPONENT

With the distribution of the required vertical displacement per trajectory known, the total displacement per component can be calculated. If multiple trajectories are addressed then a summation of each trajectory per component must be done, which is done by equations (26) to (28). The displacement taken by each spring can be used to verify the length of the rods. This verification follows after the axial force is calculated per rod.

$$\Delta z_{\mathrm{tot},spring,1} = \Delta z_{2,spring,1} + \Delta z_{3,spring,1} + \Delta z_{\mathrm{ext},spring,1} \quad (26)$$

$$\Delta z_{\mathrm{tot},spring,2} = \Delta z_{2,spring,2} + \Delta z_{3,spring,2} + \Delta z_{\mathrm{ext},spring,2} \quad (27)$$

$$\Delta z_{\mathrm{tot},leaf} = \Delta z_{1,leaf} + \Delta z_{2,leaf} + \Delta z_{3,leaf} \quad (28)$$

5
COORDINATE ANALYSIS

During operation of the bridge, the coordinates of the two mechanism will change. Especially the coordinates of the two mounting points are essential to know with respect to each other. The occurring difference between the two mounting points will introduce the additional axial force in the push-pull rods.

As discussed in 4.6 the panamawheel will be the key component for the determination of the coordinates. During the entire rotation the coordinates of each point are of interest. Therefore a number of steps are required. Since speed will not be of importance, the panamawheel will each time undergo a small angular displacement per step. In the first trajectory that the push-pull rod is still in compressed state, the panamawheel will undergo steps of 0.1 degree. By doing so, the position at which the leaf starts to rotate along can be determined more accurately. After the leaf starts to rotate along, the angle increment of the panamawheel is increased to 1 degree per step.

5.1 METHODS

In order to determine Δz_{φ_i}, the coordinates of the mounting points at the leaf need to be known. These can be determined by either the length of the rod or the angle of leaf. Since the angle of leaf is depending on the coordinates of the mounting point, the first (reference) mechanism must be done by the length of the rod. The start of the operation of the bridge is the same for both approaches though. While the panamawheel rotates, the leaf will stay in its place up to the point where the free length of the push-pull rod has been reached. The leaf will be in closed position on its front supports and no additional difference between the two mounting points will occur. Therefore no additional load is so far present in the push-pull rod.

5.1.1 APPROACH VIA LENGTH OF ROD

The trajectory on which the coordinates of the mounting point must be situated is known. Further the length of the rod and the angular displacement of the panamawheel per step are known. Therefore the corresponding coordinates per angular displacement of the panamawheel can be found using a script, Appendix A. Figure 5.2 and figure 5.3 show a flowchart of the steps undertaken in the script. In the first part the leaf stays in its normal position as the springs are still compressed and will elongate until the free length is reached. As soon as the free length of the push-pull rod is reached, the leaf will start to rotate along and the second stage of the script will start. The steps that are undertaken in the script and calculation will be discussed in the following sections.

5.1.2 APPROACH VIA ANGLE OF THE LEAF

The coordinates of the mounting point of the second mechanics can be determined by a different approach. For the determination of the coordinates in this approach, the leaf is assumed to be infinitely stiff. Once the corresponding coordinates per angular displacement of the panamawheel are known, the calculation can be done by using the actual stiffness of the leaf.

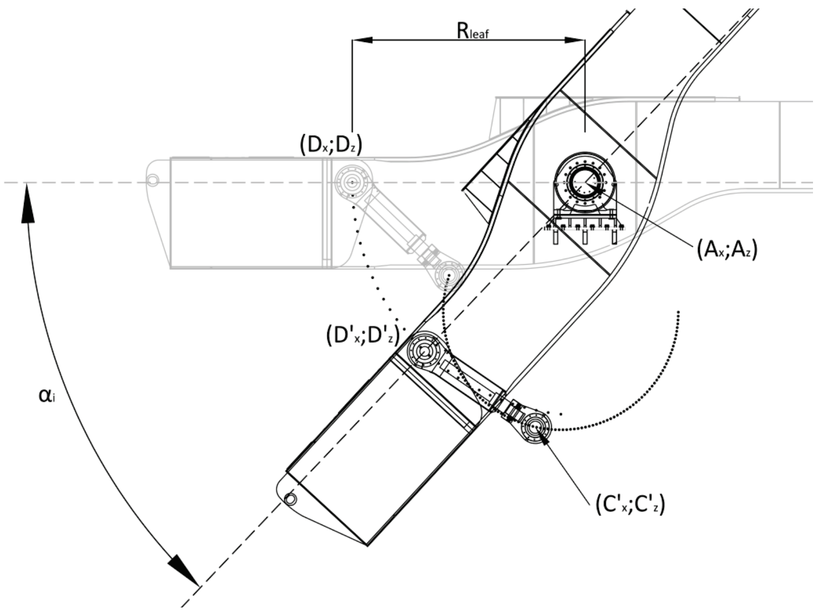


Figure 5.1 - Angular displacement of the leaf, α_i, of the reference mechanism at a arbitrary angular displacement of the panamawheel. The α_i will be used for the second mechanism as well.

By assuming the leaf to be infinitely stiff, the coordinates of the mounting point of the second mechanism can be approximated quite exact. An infinitely stiff leaf would mean that for both mechanisms the leaf undergoes the same angular displacement. The angular displacement of the leaf is already known from the reference mechanism and therefore can be used to approximate the coordinates.

By using the same angular displacement of the leaf, the length of the rod does not correspond to its free length. Until the axial force in the rod is larger than the prestress, the rod is fully rigid. The difference in length can therefore be seen as a required vertical displacement to make the rod have its free length again, previously discussed in 4.9.1. From this required vertical displacement the calculations can take place, from which the axial forces in the rods, the compression of the springs and deformation of the leaf will follow.

5.1.3 METHOD USAGE

As mentioned the reference mechanism will use the approach of using the length of the rod in order to determine the coordinates during operation. The reference mechanism is only required to determine once, since this mechanism will be assumed to be as designed. The offsets are applied to the second mechanism.

For the second mechanism the approach with angular displacement of the leaf is used. The reason for using this method is that the script is not required. All the variables to determine the coordinates are now known. Therefore an adjustment to the offset will mean the coordinates are instantly recalculated, from which the entire calculation is also adapted. This saves time for the analysis, and a quicker understanding of the influence of a typical offset can be observed.

5.2 REFERENCE MECHANISM

Although both of the panamawheels will rotate simultaneously, the leaf will follow one of the mechanisms, i.e. assuming an offset is present to one of the mechanisms. Therefore one of the mechanisms will act as a reference mechanism. This mechanism will rotate as designed, and the offsets are applied to the other mechanism. The coordinates of the mounting point at the crank can be directly determined by the angular displacement that the panamawheel has undergone. The coordinates of the mounting point at the leaf are dependent on the angle of the leaf and the length of the rod. The approach of using the length of the rod is used for the reference mechanism, thus the script.

There is a possibility that the second mechanism is actually the leading mechanism instead of the reference mechanism. This will not affect the occurring difference between the two mechanisms. In this case the Δz_{φ_i}, section 4.9, is in opposite direction, e.g. $\Delta z_{\varphi_i} = -1\text{mm}$ instead of $\Delta z_{\varphi_i} = 1\text{mm}$. The exerted forces by leaf are still working in the same direction however on both rods. This is important to consider since this will determine when and which spring will become active.

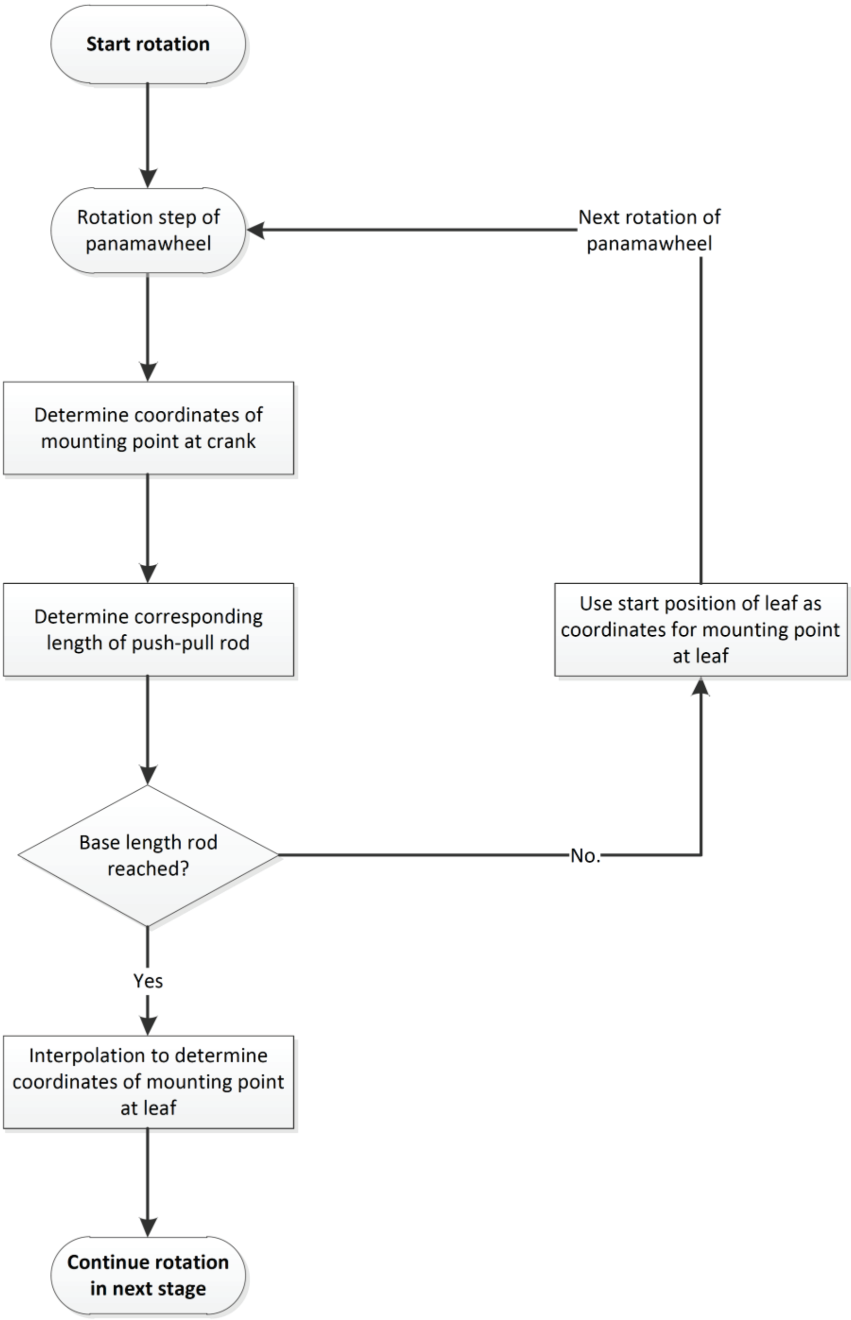


Figure 5.2 – Flow diagram of the first stage of the script where the leaf stays in closed position

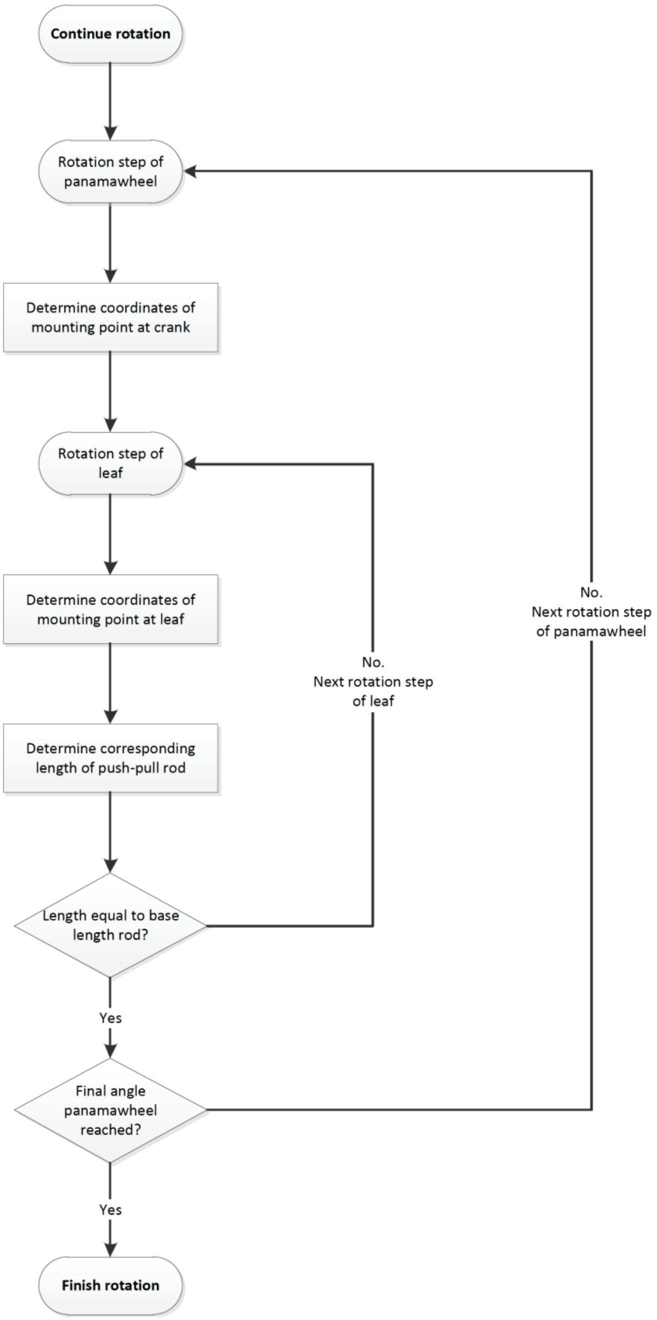


Figure 5.3 – Flow diagram of the second stage of the script where the leaf is rotation along

5.2.1 ROTATION STEP OF PANAMAWHEEL

The panamawheel will undergo each time small angular displacements per step. In the first stage of the script the steps are of size 0.1 degree. The reason for using small steps is to determine the moment that the leaf starts to rotate along more accurate. Once the leaf starts to rotate along, the second stage starts. In this stage the steps of angular displacements of the panamawheel will be increased to 1 degree per step.

5.2.2 ROTATION STEP OF LEAF

As soon as the free length of the push-pull rod is reached, the leaf will start to rotate along. The leaf has to undergo smaller steps than the panamawheel. The leaf has a larger radius, and therefore the same angular displacement steps as the panamawheel would lead to a larger displacement of the mounting point at the leaf. This means the length of the rod will never equal the base length of the rod and no convergence will be found in the script.

The leaf will therefore undergo smaller steps. Depending on the accuracy required the steps of the angle leaf will be determined. In case of 2 decimals accuracy the steps will be of size 10^{-5} degree.

5.2.3 DETERMINATION COORDINATES CRANK

The coordinates of the mounting point at the crank can easily be determined by the angle of the panamawheel. The coordinates follow from the following equations:

$$C_{x,\varphi_i} = B_x - R_{pan} \cdot \cos(\varphi_i + \varphi_0) \tag{29}$$

$$C_{z,\varphi_i} = B_z - R_{pan} \cdot \sin(\varphi_i + \varphi_0) \tag{30}$$

With:

B_x	*x-coordinate panamawheel*
B_z	*z-coordinate panamawheel*
R_{pan}	*Radius of the panamawheel; distance between rotation point to mounting point*
φ_i	*Angular displacement of step i*
φ_0	*Start angle of rotation point to mounting point with regard to horizontal*

In closed position of the bridge, the mounting point at the crank is not horizontal with its rotation points. This angle, φ_0, needs to be taken into account. Figure 5.4 shows the panamawheel in closed position and under a rotation angle.

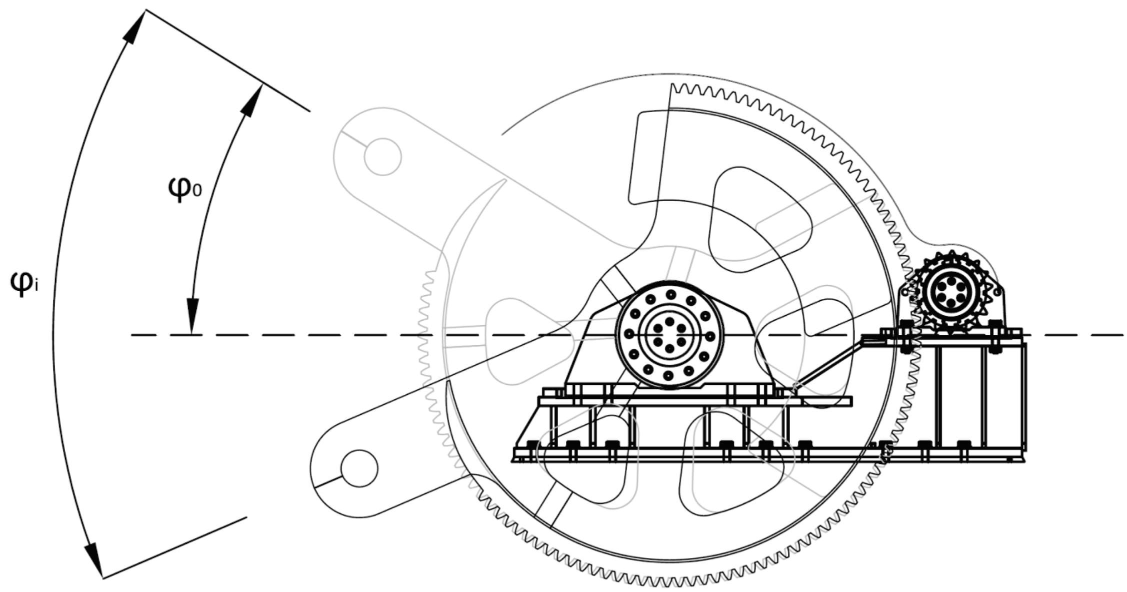


Figure 5.4 - Angle rotation of the panamawheel

5.2.4 DETERMINE COORDINATES MOUNTING POINT LEAF

The coordinates of the mounting point at the leaf depends on the angle that the leaf undergoes. To find the exact coordinates, temporary coordinates are determined per rotation step of the leaf, 5.2.2. These follow from equations (31) and (32), and are used in 5.2.5 to check the length of the rod.

$$D_{x,j} = A_x - R_{leaf} \cdot \cos(\alpha_j + \alpha_0) \tag{31}$$

$$D_{z,j} = A_z - R_{leaf} \cdot \sin(\alpha_j + \alpha_0) \tag{32}$$

With:

A_x	*x-coordinate main rotation point (normally 0)*
A_z	*z-coordinate main rotation point (normally 0)*
R_{leaf}	*Radius of leaf; distance between rotation point to mounting point*
α_j	*Angular displacement of leaf at step j*
α_0	*Start angle of leaf; rotation point to mounting point with regard to horizontal (with perfect installation α_0=0)*

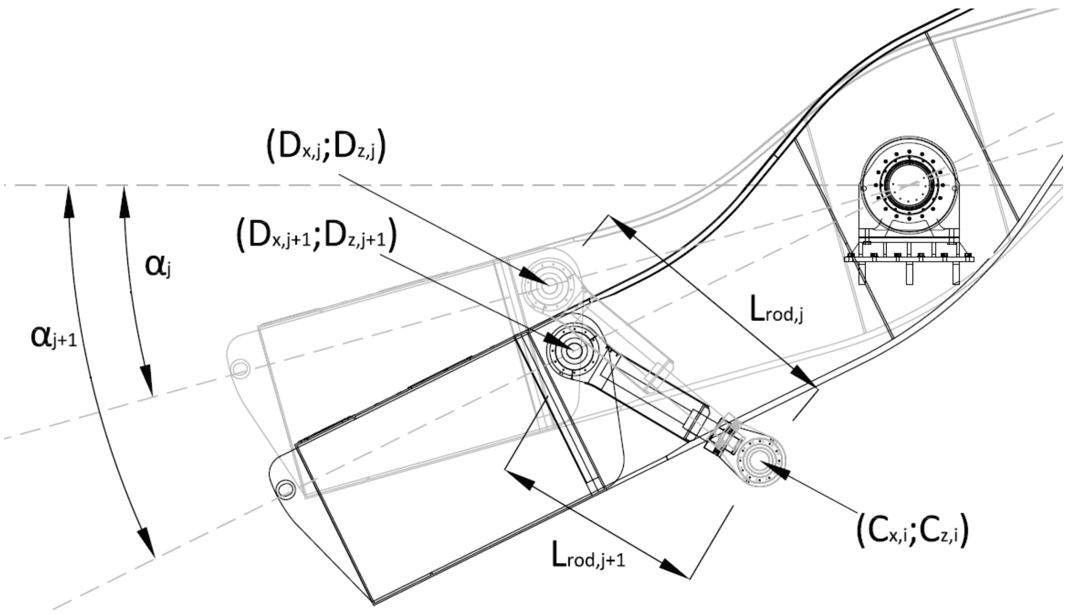


Figure 5.5 - Coordinates of the leaf and length of the rod for a step forward in the script angular displacement of the leaf

5.2.5 CHECK LENGTH PUSH-PULL ROD

In the first stage the leaf will stay in its closed position and the coordinates of the mounting point at the leaf (D_x ; D_z) are the starting coordinates. Otherwise the coordinates are determined in 5.2.4.

By these coordinates the length between the mounting points of both ends of the push-pull rod can be determined using equation (33).

$$l_{rod,j} = \sqrt{\left(D_{x,j} - C_{x,i}\right)^2 + \left(D_{z,j} - C_{z,i}\right)^2} \tag{33}$$

In the first stage of the script the length needs to reach the free length. In case the length is smaller than the free length, the coordinates of the leaf will still be those of the closed position. The first time that the length of the rod is larger, an interpolation is done. With the interpolation the coordinates of the leaf can be determined.

In the second stage the length has to be equal to the free length. If this is the case, the temporary coordinates are used as actual coordinates and the next step for angle of the panamawheel can be taken. Otherwise the next step for angle of the leaf is taken and new temporary coordinates can be determined.

5.3 SECOND MECHANISM

Once the entire reference mechanism is known, also the second mechanism can be decided. The method used is assuming the leaf of this mechanism will undergo the same angular displacement per angular displacement of the panamawheel as the reference mechanism. Equations (31) and (32) can be used for determining the coordinates, in which α_j is the corresponding angle of the reference mechanism of step i. With all the coordinates of the second mechanism also known, the required vertical displacement can be determined by using the length of the rod.

5.4 FOUR ROD MECHANISM

With the coordinates of the four rod mechanism known over the rotation, the bridge rotation can be analysed. Due to the four rod mechanism the angular displacements are not linear and simultaneously also the angle between components changes. There are two aspects that should be kept in mind to analyse the results per tolerance. The first aspect is the rotation of the leaf with respect to the panamawheel. The second is angle of the push-pull rod with respect to the leaf.

5.4.1 LEAF VERSUS PANAMAWHEEL

The leaf does not rotate along the first few degrees of the panamawheel. The angular displacement of the leaf is not linear with the angular displacement of the panamawheel. This is important to bear in mind during the design of the operating system. The effect is caused by the four rod mechanism and the rotating trajectories. In case the panamawheel would be situated at the different location, this also effects the rotation of the leaf. The angle of the leaf also affects the angle of the push-pull rod.

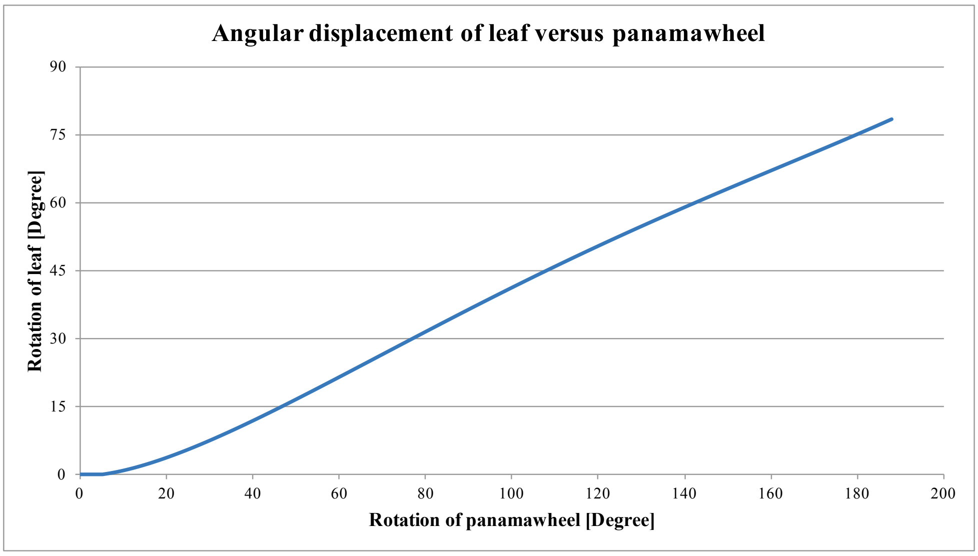


Figure 5.6 - The angular displacement of the leaf versus that of the panamawheel

5.4.2 ANGLE PUSH-PULL ROD

The angle of the push-pull rod with respect to the leaf is often emerging in the calculations, as seen in 4.9. Since the rotating trajectories of the panamawheel and leaf are different, the angle of the push-pull rod will change during the rotation. In figure 5.7 the angle is plotted over the rotation of the panamawheel. The coordinates of the four rod mechanism have an influence on this angle develops. So for a different bridge this angle may vary. The offsets are too small to have a significant influence on the angle. For the calculations the angle can each time easily determined since the coordinates are known, and therefore are taken into account for the entire calculation.

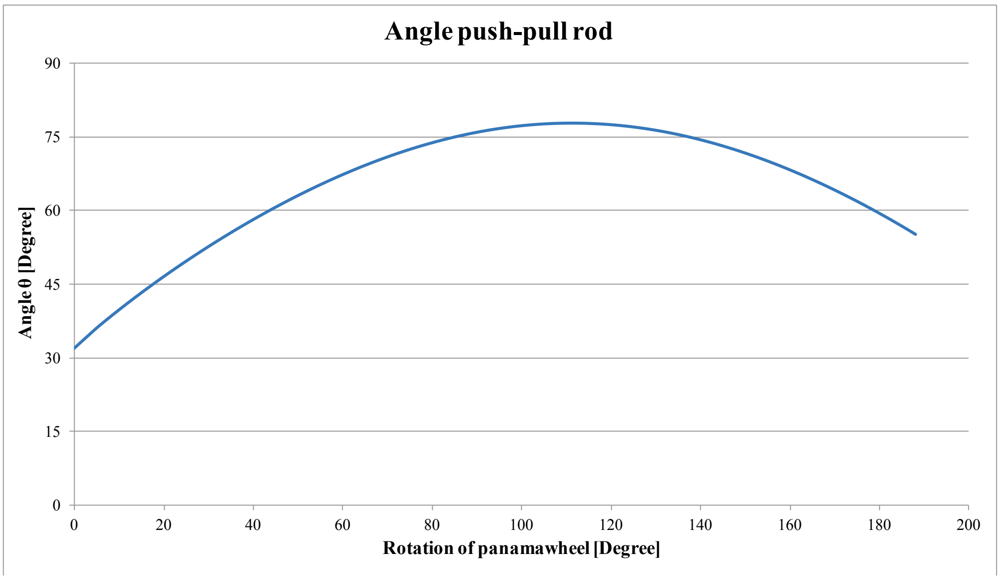


Figure 5.7 - Angle of the push-pull rod with respect to the leaf during operating

5.5 INFLUENCE PER TOLERANCE

In chapter 3 the tolerances are discussed. The impact per tolerance is important to know so the worst case scenario can be determined. In the worst case scenario the tolerances are chosen in a way that all work together and the largest Δz will occur. A larger Δz will result in a larger additional force for the push-pull rods, and therefore the difference of contribution per rod increases.
Another reason to analyse the influence per tolerance is to know which has which kind of impact. During manufacturing and installation special attention can be given to these tolerances to mitigate the offset and thereby mitigate the additional axial force.

In the analysis three different situations will be looked at. The way of installing the push-pull rod influences its length. Since this is part of the four rod mechanism, this will also affect the rotation and thereby influence the difference of the two mountings points. The three situations which will be analysed are:

1. The push-pull rods will be installed with both the design length.

2. The panamawheels will be set under a small angular displacement. i.e. to the point where the leaf would start to rotate along according to the design and the reference mechanism equals the design length. The rod of the reference mechanism is installed with its design length and the other rod will be adapted in length to fit.

3. The leaf is in full open position. The push-pull rods will be installed in this situation where the rod of the reference mechanism will be its designed length and the other adapted in length to fit.

Situation 1 would mean that one of the rods is forced into its mechanism. In this case the angle of the bridge can be set in the same position as in situation 2 or 3, with the difference that instead of adapting one rod in length, the rod is forced into place with its design length. Situations 2 and 3 are depicted in figure 5.8. φ_i is the angular displacement of the panamawheel, φ_0 is the starting angle of the crank with respect to the horizontal and φ_{max} is the maximum rotation that the panamawheel undergoes for fully open position, 188 degrees for the reference project. The reason to look at these three situations is to get insight on the impact of the installation.

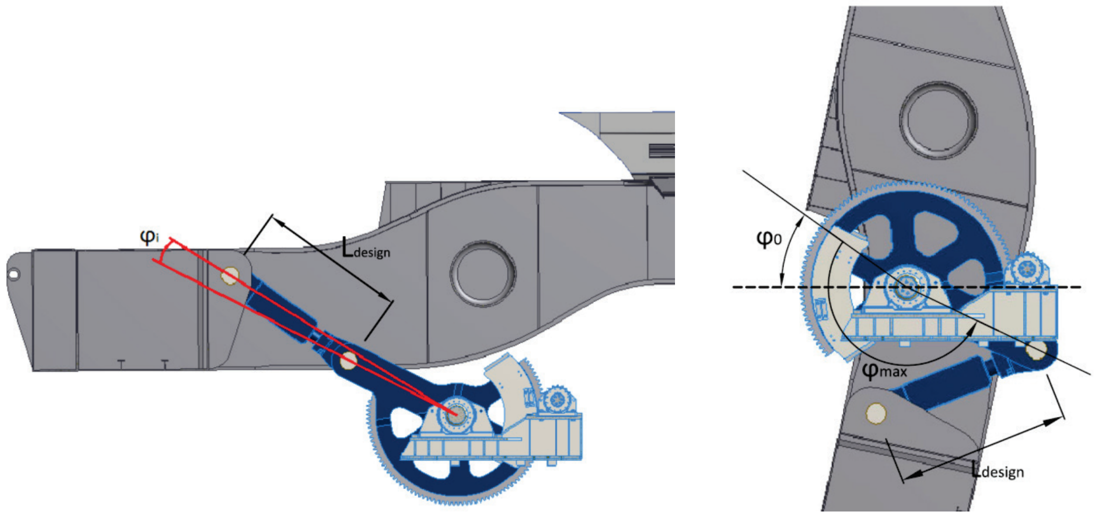


Figure 5.8 – Position of the bridge and mechanism during installation of the push-pull rod. Left the situation of the moment the leaf starts to rotate along, right the situation of the bridge in fully open position.

The manufacture tolerances are only for the mounting point at the leaf and the length of the crank, and only affect that specific point. The installation tolerances influence the entire component, i.e. an offset of a main rotational point during installation will affect the entire leaf of the corresponding mechanism and therefore also give an offset to the corresponding mounting point at the leaf. Therefore, for single offsets only the mounting point at the leaf and the length of the crank are discussed. For the rotational points of the leaf and the panamawheel, a shift of the entire component will be discussed.

During opening of the bridge, until the moment where the leaf starts to rotate along, no difference between the two mounting points will occur. From this point onwards a difference can occur as one of the rods will be rigid. Note that the leaf would still be on the supports at the transition point, and therefore the leaf cannot be pushed upwards, so the spring will compress instead. This is not taken into account in the calculation however, and therefore a jump might occur at the moment that the leaf starts to rotate along. This should be kept in mind during the analysis. The difference will occur quickly though as a small rotation of the leaf already has quite a large effect on the z-coordinate of the mounting point at the leaf.

In closed position the push-pull rods exert a force upon the leaf to create the support force on the front supports, as discussed in section 2.1. During closure of the bridge, after the leaf reached its closed position, the panamawheel will undergo another angular displacement of about 5 degrees. This is for the required support force at the toe supports. Since the leaf will not rotate along, the axial force in the rods are increasing and with that the springs will compress. This force that is exerted by the push-pull rods in this situation causes a deformation of the leaf. This deformation is not taken into account in the calculation and analysis since this has no effect on the force distribution of the mechanisms.

5.5.1 RESULTS

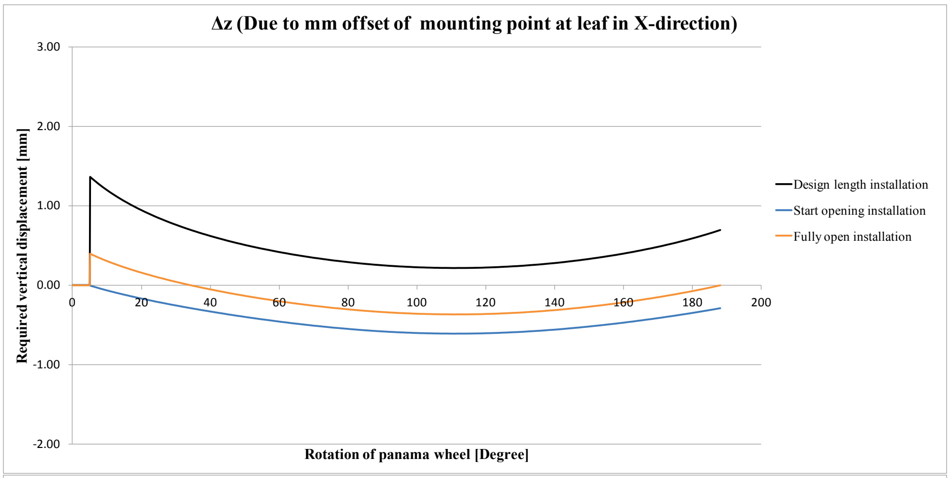
As mentioned the following five tolerances are examined:

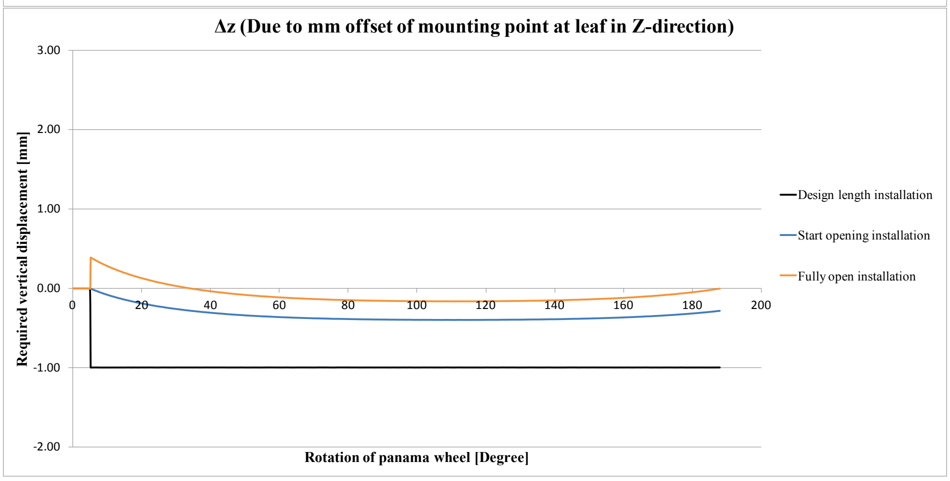
- Offset in x-direction of the mounting point leaf
- Offset in z-direction of the mounting point leaf
- Length difference of the crank
- Shift in x-direction of the leaf
- Shift in z-direction of the leaf

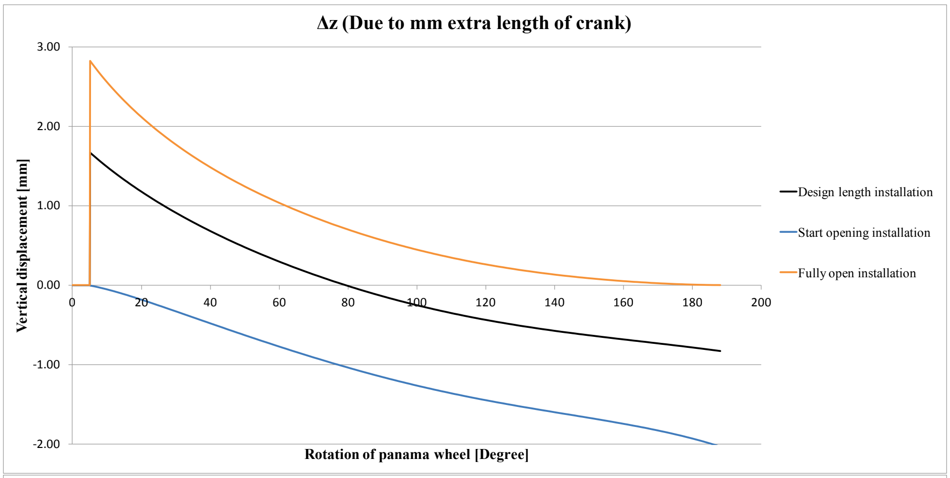
A shift of the panamawheel is the same as a shift of the leaf in the opposite direction. Therefore a shift of the leaf can be multiplied by -1 in order to obtain the influence of a shift of a panamawheel.

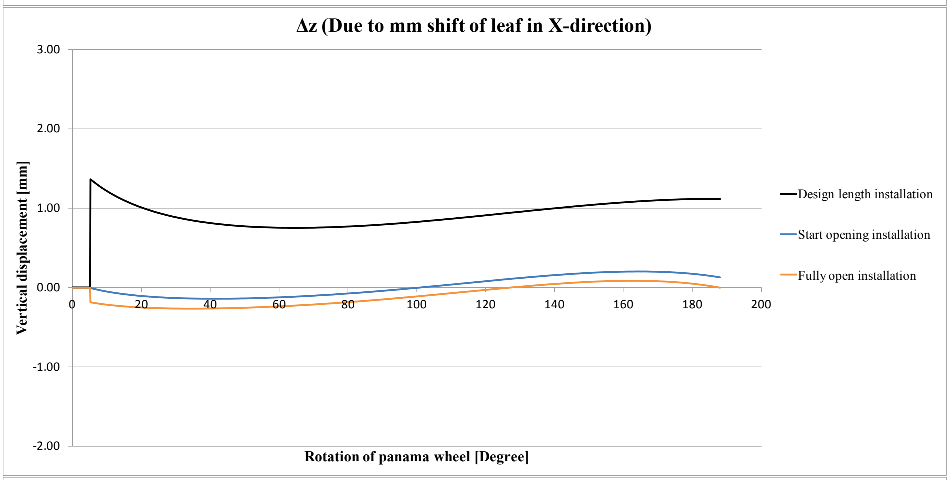
The following graphs show the required vertical displacement per tolerance if a millimetre offset is applied of that typical tolerance. The same scale is applied for each tolerance to see the magnitude in comparison to the others. The first few degrees no required vertical displacement is present as the leaf is still in closed position, as mentioned. As soon as the leaf starts to rotate along, a difference can start to occur. For the installation situations 1 and 3 a jump might occur at this start. Since situation 2 is installed at this point, no required vertical displacement is required but will gradually develop. At the end of the rotation the same goes for situation 3. Since that situation is installed in that situation, the required vertical displacement will gradually go to zero.

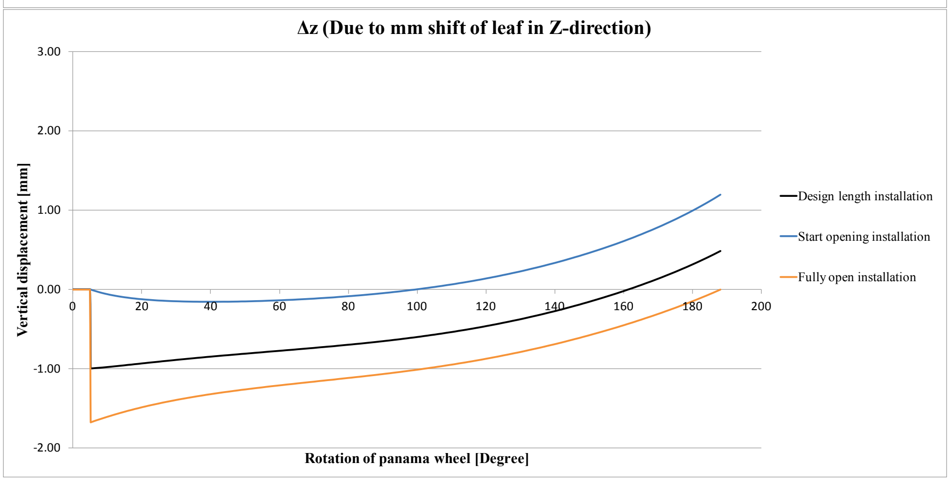
The manner of installation of the push-pull rods has a distinct influence on the required vertical displacement per type of tolerance. In case the design length is used for both rods, the impact is significantly larger for most tolerances. Further has a length difference of the crank a significant effect on the required vertical displacement. It should be noted however that this tolerance also has a high accuracy, i.e. tolerance of ±0.1mm.











Another situation that stands out is the offset of the mounting point in z-direction. The situation where the design length of the rods is used, the required vertical displacement is constant, while any other situation and tolerance has a gradient. The constant required vertical displacement can easily

be explained. The angle of the leaf is assumed to be the same for both mechanisms, thus the millimetre offset is in the LCS always 1mm in z-direction. The required vertical displacement is also determined in the z-direction in the LCS and therefore will automatically be always the same as the present offset.
The other two situations are installed by adapting the length of the rod, and therefore has at the installation point no required vertical displacement. One could think that for these two situations the required vertical displacement would also be constant during the operation of the bridge. But the rods have a different length, and the angle of the push-pull rod with respect to the leaf changes during the rotation. Therefore the required vertical displacement does change.

There is one aspect that should be kept in mind about these required vertical displacements per tolerance per situation. They are specific for the reference project. The magnitude of the required vertical displacement is depending on the size of the bridge. A different size of the bridge means the size of the operating system, and the dimensions and coordinates of the four rod mechanism will change as well. Although the idea is the same, the magnitude of the required vertical displacement will change. Certainly if the required vertical displacement is compared relatively to the dimensions of the four rod mechanism of the specific bridge.

5.5.2 TOLERANCE ATTENTION

As mentioned the installation scenario has a significant effect on the required vertical displacement. Adapting the push-pull rod slightly during the installation is recommended. Even when the rod is adapted, it is good to know which tolerances requires special attention.

For installation situation 1, most tolerances all have a significant contribution to the required vertical displacement. The offset of the mounting point in z-direction and the offset of the leaf and panamawheel in x-direction are rather uniform over the rotation of the bridge. Therefore these require more attention. In situation 2 is especially subjective for the required vertical displacement by the offsets of the mounting point and the offset of the leaf and panamawheel in z-direction. Situation 3 requires special attention to the offset of the leaf and panamawheel in z-direction. The required vertical displacement is for a shift of the leaf the opposite of that of a shift of the panamawheel. Therefore a shift to the same side would be preferable. This could be taken into account during the installation.

5.6 OTHER METHODS

Determination of the coordinates are now done by the using an infinitely stiff leaf. So the mounting points will undergo the same rotation, from which a length change of the rod will occur. This length change is used to determine the required vertical displacement. Another method would be by using a finite stiff leaf but a fully rigid rod. For determination of the coordinates, no interaction is assumed yet and each mechanism will rotate depending on its own coordinates. Due to the offsets the dimensions of the four rod mechanism are different, and therefore undergo a different angular displacement. Unlike previous method where a difference in rod length would occur, now a difference between the coordinates of the mounting points will occur. The difference can then be transformed to displacements per component and the axial force.

One of the biggest differences between the two methods is that the second mechanism needs to undergo the script as well. Since that takes time, this method is more time consuming, although the calculation time short. Since the same calculation is applied, the only difference will be in the required vertical displacement Δz.

Both methods approach the occurring displacements and forces from the other side. The actual values would be in between the two methods. Since the method using the rigid rod is more time consuming, looking at the final occurring results could provide an answer on which to use. By a test with the second method, the difference between the two methods is neglectable. On a axial force of magnitude 10^2 kN, the difference is of magnitude 10^{-1}kN.

5.6.1 ALTERNATIVE OF RIGID ROD

The method with the rigid rod could be adapted, by doing the calculation during the script. Per step the coordinates of both mechanisms are determined. Since the calculation can automatically follow, also the length of the rod can be determined. This length could be used for the next rotation step, or an iteration could be undertaken for the same step. This adaptation would only be an advantage if the difference between the earlier discussed methods would be significantly. Since this is not the case, the adaptation is not recommended. The two alternatives have been shortly researched, but cancelled due to occurring divergence.

Iteration could cause a problem with convergence causing the displacements and axial force to diverge. Using the length for the next step could cause a problem with finding the correct coordinates. This could be solved by starting the leaf every step in its starting position, though the result of that is that the script time increasing drastically.

6

ANALYSIS OF INFLUENCES

The additional axial force in the push pull rods is caused by the displacement difference of the mounting points. The displacement difference depends on the occurring offsets, which are not designed and therefore should be taken as random data. Using the worst case scenario where the largest required vertical displacement occurs, there are a few factors that can be adapted to influence the axial force, interaction of between springs and leaf, and force distribution.

6.1 INFLUENCE OF EXTERNAL FORCE

An external force close to the prestress is preferable, since this will reduce the ratio of the force distribution between the two mechanisms. As the prestress is hit, the stiffness changes. This causes the axial force to increase less quick, and with that the difference of the axial force in the rods will not increase that much either.

The external force to operate the bridge can differ per operation. Most loads that contribute to the external force are constant and the changes that do occur can be neglected, e.g. wear of the surface layer. Wind is the most important factor that changes the external force. The balance could be reduced and with that increasing the external force. However this has a negative side effect on the power usage, and therefore is not really an option. Although the external force has an influence on the reaction of the mechanisms, there is little room to improve the force distribution.= between the mechanisms

6.2 INFLUENCE OF PRESTRESS

The springs in the push-pull rods are prestressed. The main reason for the prestress is to increase the fatigue life of the springs. From analysis the prestress force has quite an impact on the axial force of the push-pull rods.

The main influence that the prestress has, is the moment that the springs become active. A lower prestress force will mean the springs are earlier addressed. This automatically has also effect on the axial force in the rods. Due to the changing stiffness of the bridge at the moment that the prestress is surpassed, the increment of the axial force per millimetre required vertical displacement is significantly lower (note that this does depend on the stiffness of the springs as well, 6.2).

The influence of the prestress is examined with several values. The axial force is depicted in figure 6.1 and the compression of the spring of one the rods in figure 6.2. A lower prestress reduces the additional axial force significantly. This is a positive effect for the distribution between the two mechanisms. An active spring can be a disadvantage however for the dynamics. This also depends on the stiffness of the spring.

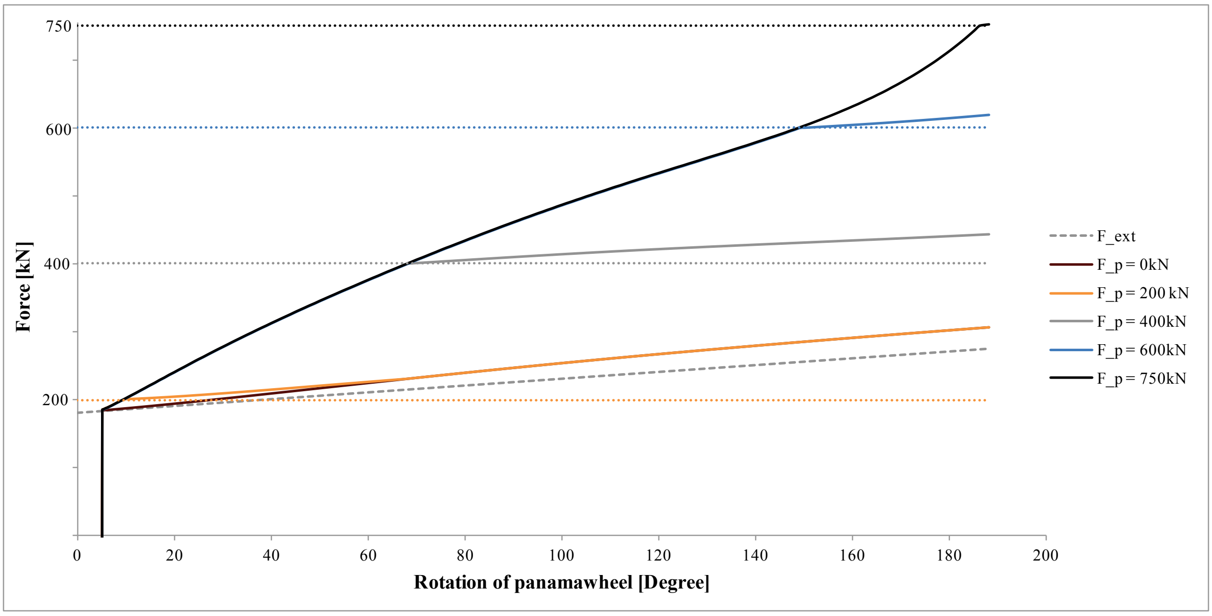


Figure 6.1 - The influence of the prestress on the development of the axial force

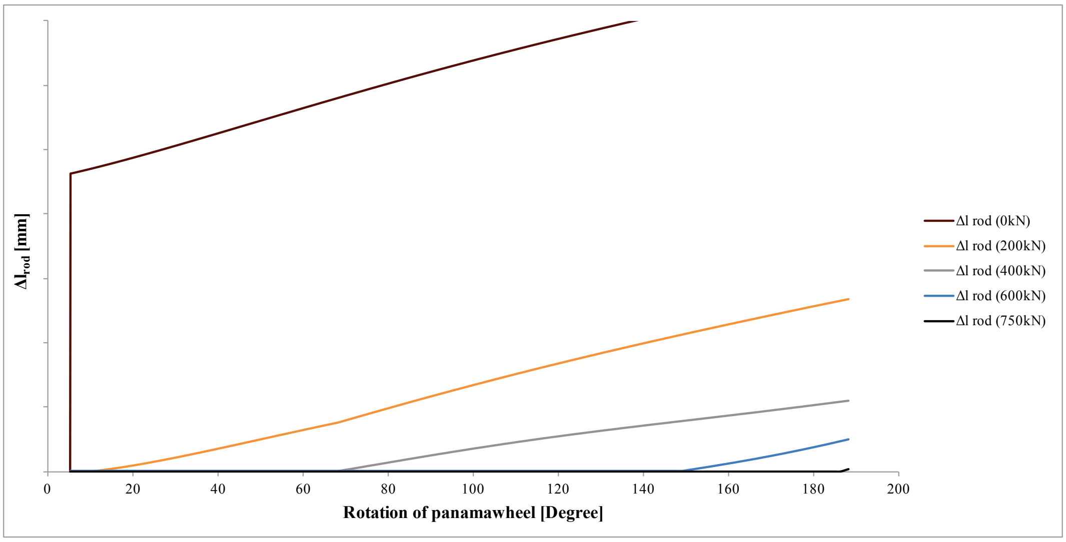


Figure 6.2 - Length change that occurs under different prestress forces

6.3 INFLUENCE OF STIFFNESS SPRING AND LEAF

The additional axial force and the displacement taken per component depends on the stiffness of the springs and the leaf. The additional axial force is introduced due to the deformation of the leaf. After the spring(s) become active, the change in stiffness also changes the increase of the axial force. The spring stiffness of the spring has an influence on this part as well. Further the ratio between the stiffness of the leaf and spring has an effect on the displacement each component takes.

6.3.1 STIFFNESS LEAF

A high stiffness of the leaf leads to faster increment of the axial force in the rods. Therefore the prestress force is also faster surpassed and the springs can become active. Figure 6.3 shows the influence of the stiffness of the leaf on the axial force. A small constant external force is applied. $F_{add,max,p}$ is the maximum additional force before the prestress force is reached, and the stiffness changes because a spring is active.

When $k = 100kN/mm$ the prestress is not reached. At the end of the rotation the axial force increases faster. Both the required vertical displacement and the angle of the push-pull rod has an influence on this. The angle of the push-pull becomes smaller with the result that an exerted force in z-direction by the leaf is magnified. This is less visible for the other stiffness's since the stiffness of the spring has the overhand.

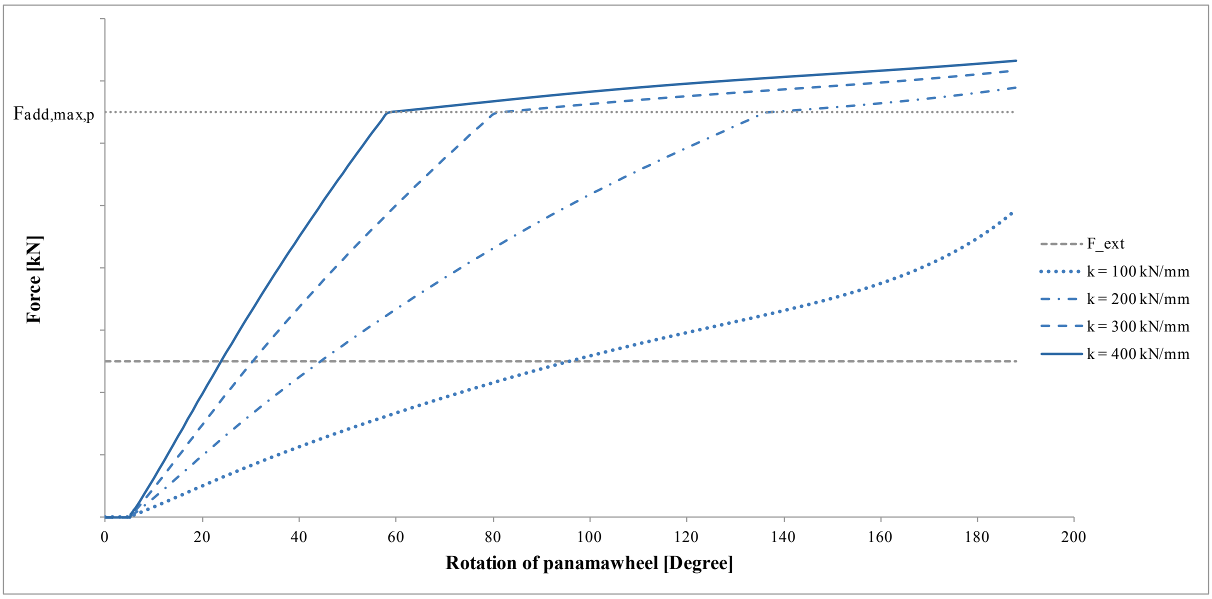


Figure 6.3 - Influence of adapting the stiffness of the leaf

The stiffness of the leaf depends on several structural components of the bridge. The deck, tube trunnion shaft and the counterweight box all have an influence on the stiffness. These components each have their own structural contribution for the bridge.

6.3.1.1 DECK

When the bridge is closed, the traffic will go over the deck. Heavy live load, e.g. trucks, can cause large deflections. Since a certain clearance should be satisfied in order to allow smaller ships to pass without opening the bridge, the deck needs its stiffness to mitigate the deflection due to loads.
The main girders contribute mainly to the longitudinal stiffness and the transverse girders to the transverse stiffness regarding the deflection.

When looking to the stiffness of the leaf with respect to the mounting points, the transverse girders have a large influence. A displacement of one mounting point will cause a twist in the deck, as there is an angular displacement between the two main girders. This twist is resisted by the transverse girders. Looking more local at the transverse girders in case of a twist the deck, the effect for the girders are seen as a displacement. Changing the stiffness of the transverse girders could contribute to the stiffness at the mounting point, however, also affect the main structural aspect of the girders which cannot be compromised. So the stiffness at the mounting point could be increased only by the transverse girders.

For the main girders he same goes as the transverse girders. The main girders are under bending due to forced displacement of the mounting point. Since the girders carry the deck as well as the counterweight, adaptations are more difficult to realise. Regarding the structural design, the main girders under the deck have little room for stiffness change. The main girders determine the clearance and therefore cannot be increase in height, nor can they decrease in height as this would influence the structural strength. The tail side of the main girder have to carry the counterweight. The deflection due to the counterweight can be taken into account during the manufacturing. Decreasing the stiffness of the main girders at the tail side will cause an increase of that deflection. Since that can be countered, a change of the tail side of the main girders would be an option. The capacity of the main girders should be checked though as the shear force and moments need to be transferred.

6.3.1.2 TUBE TRUNNION SHAFT

At the main rotational axis of the bridge a tube trunnion shaft connects the two main girders. When the two main girders are under a different angle, this causes a twist in the tube trunnion shaft. The angle difference can occur due to the vertical displacement of one of the mounting points. The torsional stiffness of the tube trunnion shaft will contribute to the stiffness of the leaf regarding the vertical displacement. The contribution to the stiffness should be kept in mind during the design of the tube trunnion shaft.

During the design of the bridge the choice of the bearing configuration is made. Several factors play a role in the choice for the configuration. Costs, available space in the basement and the size of the bridge for example all need to be taken into account. The chosen configuration also has an effect on the stiffness. The tube trunnion shaft and straddle bearings are the most common applied configuration.

Straddle bearings are an option which makes no use of a tube trunnion shaft. There is no interaction between the two main girders with straddle bearings, and therefore the stiffness of the leaf is also lower, about 13% (Appendix A.3). The friction of the additional bearings has nearly no effect on the stiffness of the leaf and can be neglected. A disadvantage of straddle bearings are costs. Bearings are a costly component, definitely in comparison with a steel tube element. Besides, additional foundations are required which also come with a price.

If straddle bearings are definitely not an option due to available space, the tube trunnion shaft is a good solution. Since the inner bearings are now gone, the main girders act as an eccentric load on the outer bearings, causing a moment and deformation of the bearing shaft. Besides, the main girders undergo a deflection and lateral torsion. Connection the main girders via a *transverse girder*, e.g. a tube trunnion shaft, these effects can be reduced. Therefore the transverse girder requires a bending stiffness, but torsional stiffness is not required. However, during operation the transverse girder will rotate along, but the bending stiffness is still required on the same axis of the global coordinates system. This is why a tube trunnion shaft is a perfect solution since the bending stiffness will always be the same. The tube trunnion shaft has therefore less options to be adapted. Increasing stiffness is not a problem if that is required for the stiffness of the leaf. But for the force distribution between the mechanism a lower stiffness is more likely to be required. Since the tube trunnion shaft is also a structural component regarding the bearings, decreasing the stiffness is more difficult.

Options for lower torsional stiffness are available, but come with a price, losing the advantage over the straddle bearings. Besides, the tube trunnion shaft could be seen as a structural component for the deck as well. In this case adaption of the tube trunnion shaft also has consequences for the structural behaviour of the deck, i.e. twist and deflection.

6.3.1.3 COUNTERWEIGHT BOX

The stiffness of the counterweight box is mainly to carry the counterweight inside. The counterweight balances the deck and therefore requires a huge weight, e.g. 600 tonnes for the reference project. Besides, during operation the box rotates along with the leaf, and therefore the stiffness in z-direction changes. The entire box requires therefore large stiffness.

The mounting points at the leaf are situated on the counterweight box. This allows to adapt the stiffness of the leaf locally. An adaption of the connection of the mounting points to the counterweight box would be the best option to reduce the stiffness of the leaf. The reason is that the structural integrity of the bridge is not compromised, which is important for normal use. Further, the adaptation can be more easily optimised, i.e. choice of stiffness and the maximum displacement.

6.3.2 STIFFNESS SPRING

Where the stiffness of the leaf has influence on the increment of the additional load up to the prestress force is reached, the spring stiffness influences the increment of the additional load afterwards, depicted in figure 6.4.

A low stiffness would seem preferable. A downside of a low stiffness is the dynamic effect after the prestress is reached. In open position, wind has a large effect on this. The deck of the bridge has a length of 26m where the rotating point is approximately 6m behind the main rotational point. This means the toe of the leaf will undergo a magnified displacement of the compression of the spring. Up to a certain point this is no problem. However, the eigenfrequency of the structure should not be close to frequency of wind gusts. Therefore attention needs to be paid to stiffness of the spring.

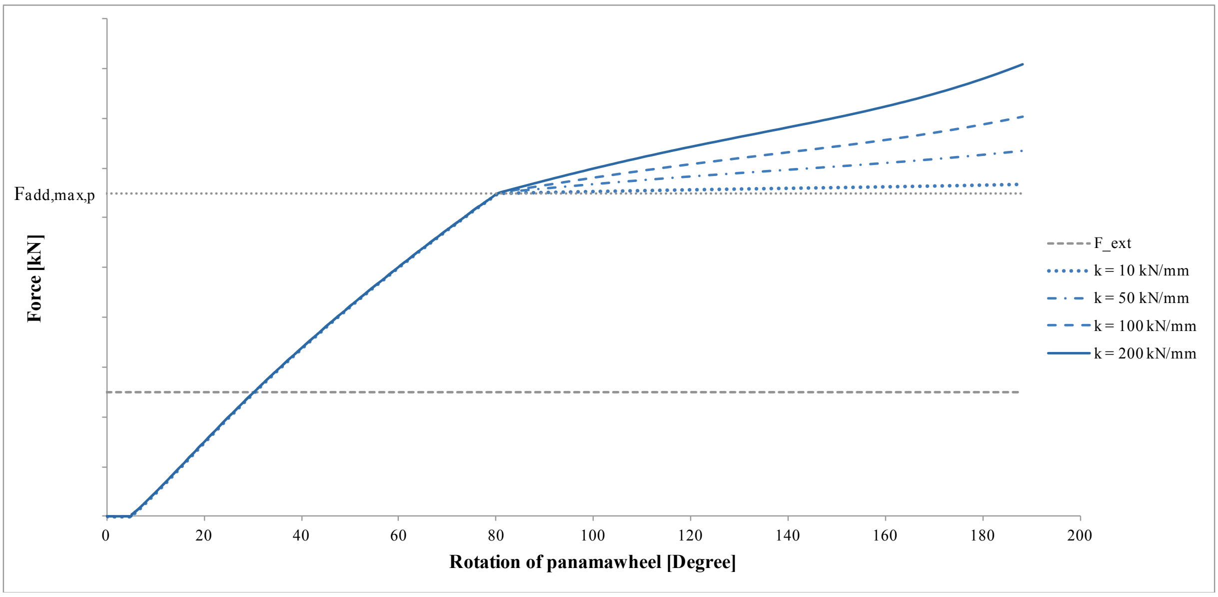


Figure 6.4 - Influence of the spring stiffness on the axial force

6.3.3 STIFFNESS RATIO

As seen each stiffness alone has effect on the axial force in the push-pull rod. Though a stiffness change also causes the stiffness ratio between the spring and leaf to change. This stiffness ratio, $\beta = \frac{k_{spring}}{k_{z,leaf}}$, has an effect on the displacement each components takes after the prestress is reached.

To examine the influence of the ratio, both trajectory 2 and 3 examined. These are the trajectories where the ratio has an influence. Both trajectories will be examined separately for which 1mm required displacement has to be overcome. In figure 6.5 and figure 6.6 several ratios are plotted for trajectory 2. A lower ratio means the spring will take more displacement.

The displacement taken by the components varies. This is due to the angle change of the push-pull rod during rotation of the bridge. Therefore the stiffness of the spring changes with respect to the leaf. This should be kept in mind when determining the stiffness during design, since the displacement taken by the leaf can increase up to 20%. This has immediate effect on the axial force.

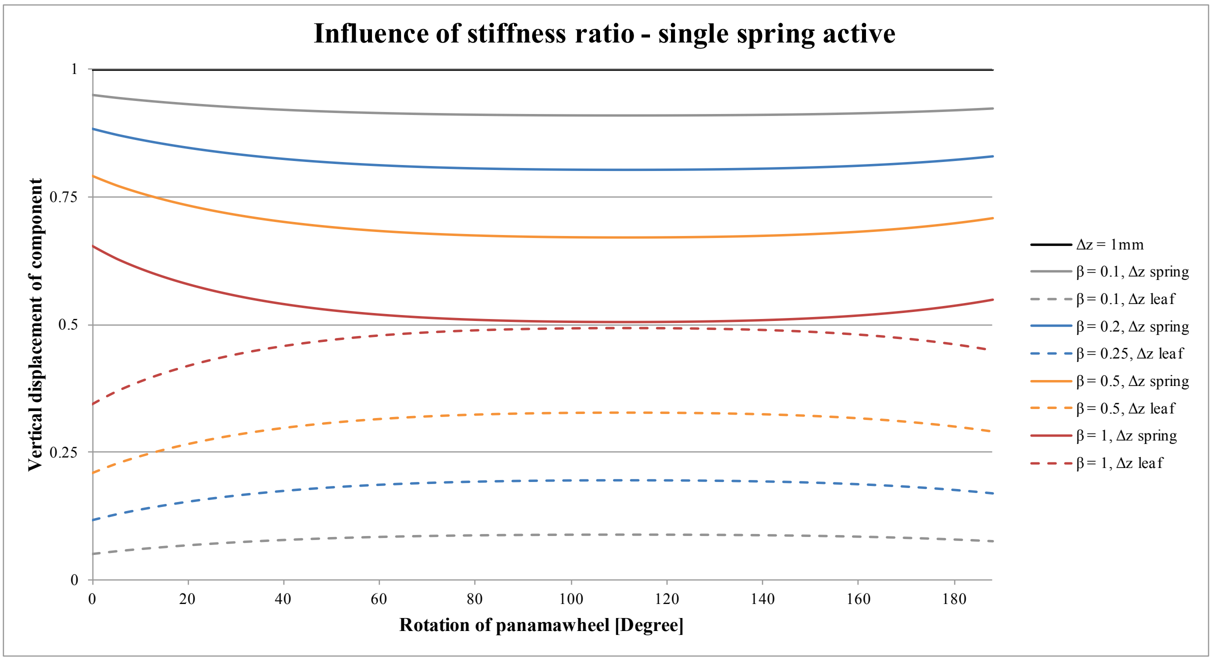


Figure 6.5 - The influence of the stiffness ratio on the displacement taken by the spring and leaf in case one spring is active

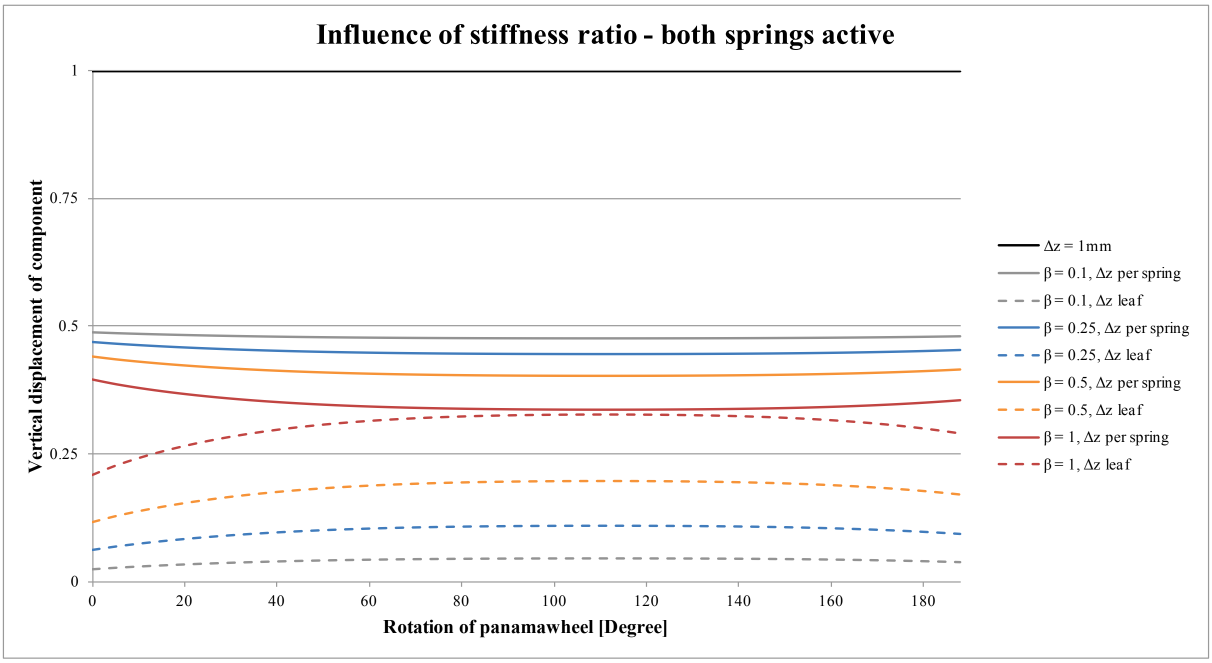


Figure 6.6 - The influence of the stiffness ratio on the displacement taken by the spring and leaf in case both springs are active

7

REFERENCE PROJECT

7.1 WORST CASE SITUATIONS

With the possible offsets, discussed in 3.4.3, and the results of the required displacements per offset obtained in the previous chapter, a combination can be selected for each of the installation types. The required displacement for a typical tolerance can change during the rotation from a positive to a negative required displacement. Therefore per installation there are two situations which are looked at, so both the worst case near the start and near the end of the rotation can be examined. Table 7.1 shows the tolerances used per situation.

Using these tolerances as input, the largest displacement difference between the two mounting points at the leafs will occur, and therefore also the largest additional axial force in the rods.

7.1.1 REQUIRED VERTICAL DISPLACEMENT

Using the offsets of table 7.1 the required vertical displacement follows from figure 7.1. Situation 1a and 1b have a significant higher required vertical displacement than the other situations. From this the conclusion can be drawn that adapting one of the rods during the installation is preferred.

Offset	Installation					
	1. Design length		2. Start opening		3. Fully open	
	a) Max near start	b) Max near end	a) Max near start	b) Max near end	a) Max near start	b) Max near end
Mounting point leaf X	+0.7	+0.7	-0.7	-0.7	+0.7	-0.7
Mounting point leaf Z	-0.7	-0.7	-0.7	-0.7	+0.7	-0.7
Crank length	+0.1	-0.1	-0.1	-0.1	+0.1	+0.1
Shift leaf X	+1.5	+1.5	-1.5	+1.5	-1.5	+1.5
Shift leaf Z	-0.5	+0.5	-0.5	+0.5	-0.5	-0.5
Shift panamawheel X	-1.5	-1.5	+1.5	-1.5	+1.5	-1.5
Shift panamawheel Z	+0.5	-0.5	+0.5	-0.5	+0.5	+0.5

Table 7.1 - Several situations with the offset in millimeters of a point/component per installation

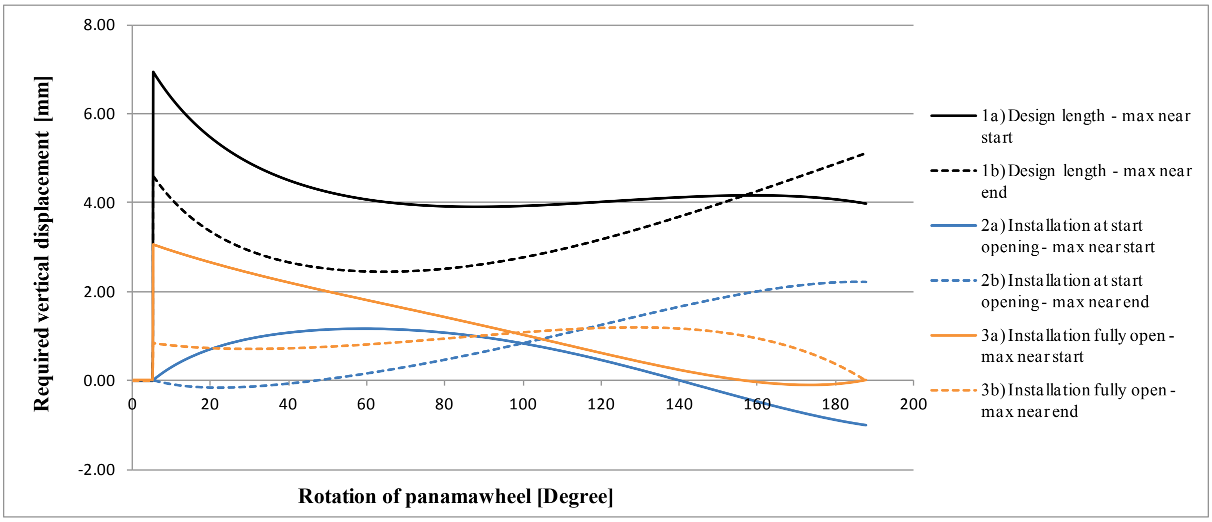


Figure 7.1 – Vertical required displacement using the worst case combinations per installation

7.1.2 DISPLACEMENT DISTRIBUTION OVER SPRINGS AND LEAF

Now that the worst case scenarios with respect to the required vertical displacement are known, the displacement per component can be determined. Before discussing the results for the reference project in section 7.2, the interaction between the springs and the leaf from section 4.9 examined. Two situations will be extracted and given a closer look to discuss the displacement per component. These situations will be 1b and 2b.

7.1.2.1 SITUATION 1B

In this situation no external load will be applied. Therefore trajectory 1 and 3 are applicable, and both springs will undergo equal compression and with that take the same portion of the required vertical displacement.

In figure 7.2 the total required vertical displacement and the displacement per component is depicted. Further the maximum allowed displacement of the leaf before the prestress is reached, $\Delta z_{1,\max}$ (eq. (22) in 4.9.3.1), is given. Up to a rotation of the panamawheel of about 40 degrees, the required vertical displacement is larger than $\Delta z_{1,\max}$. Therefore the springs are active, since the axial force in the push-pull rod is larger than the prestress force. Since trajectory 3 is the case, both springs are active. One of the rods will elongate and the other shorten in this specific case, figure 7.3. The displacement taken by the springs is nearly half of the remaining part Δz_{rest}. A slight portion of the remaining part is taken by deformation of the leaf, which can also been seen in the figure as the total displacement taken by the leaf is a bit more than $\Delta z_{1,\max}$.

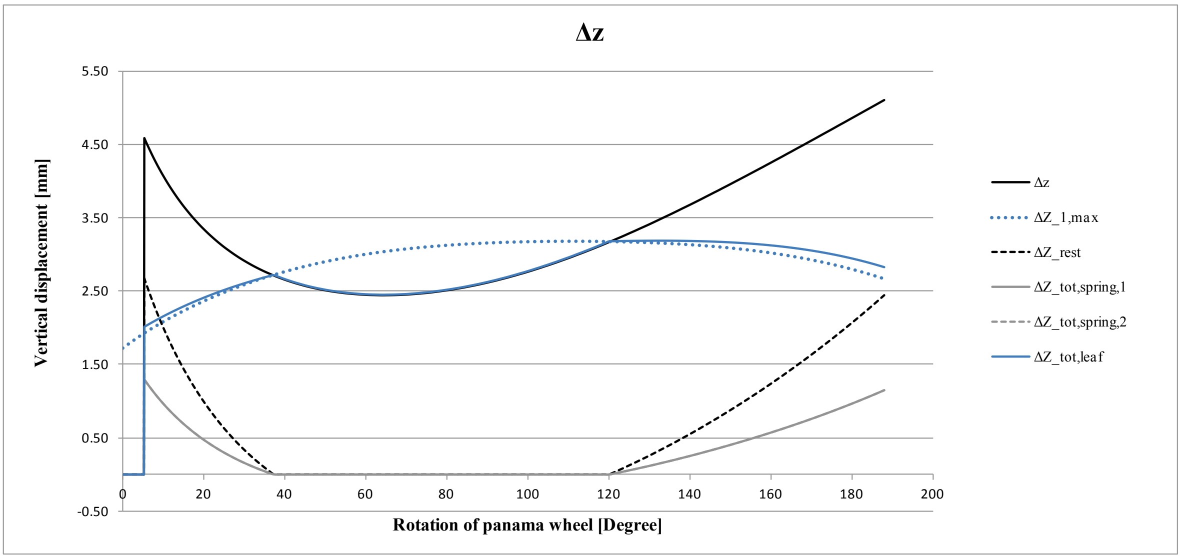


Figure 7.2 - Required vertical displacement and displacement per component in worst case situation of 1b with no external load

Between an angle rotation of the panamawheel of 40 to 120 degrees, the required vertical displacement is lower than the maximum allowed $\Delta z_{1,\max}$. So the axial force in the rods is lower than the prestress force, and therefore the leaf will deform the entire displacement. After 120 degrees the required displacement is larger again, and the springs become once more active.

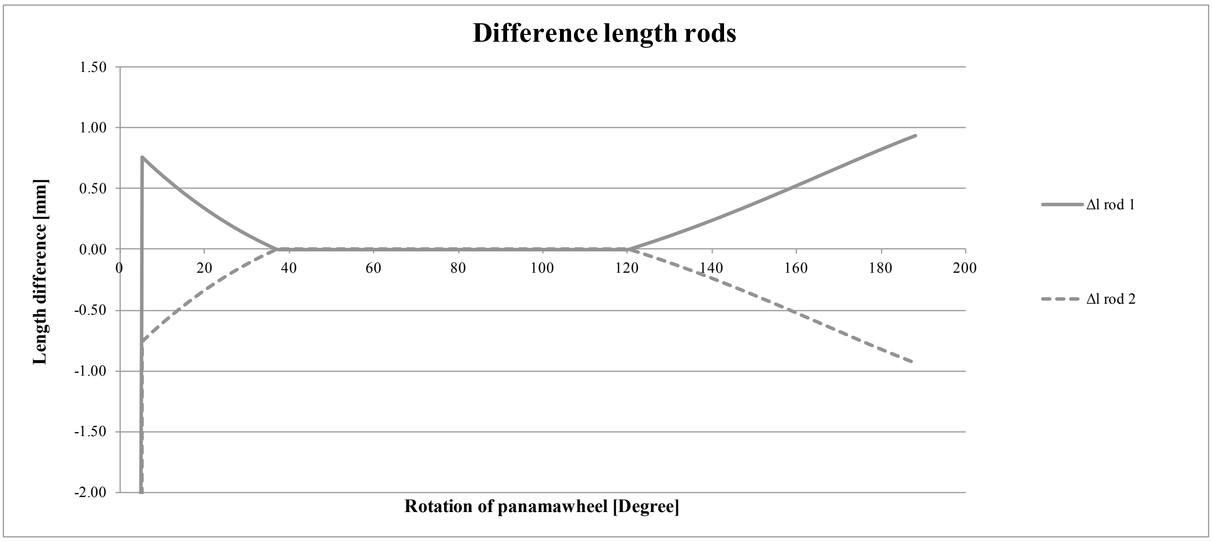


Figure 7.3 - Δl of the rods due to compression of the spring in situation 1b.

7.1.2.2 SITUATION 2B

For explanation of situation 2b a fictional external load will be applied with a linear increase of 362kN to 550kN.. Figure 7.4 shows the required vertical displacement in situation 2b. The external force does not have an influence on this required displacement, but the maximum allowed displacement is lower, which can be seen when comparing figure 7.4 and figure 7.2 . The external force causes the prestress force to be reached, and therefore a spring can become active. In contradiction with situation 1b where both springs are active, now only one spring is active.

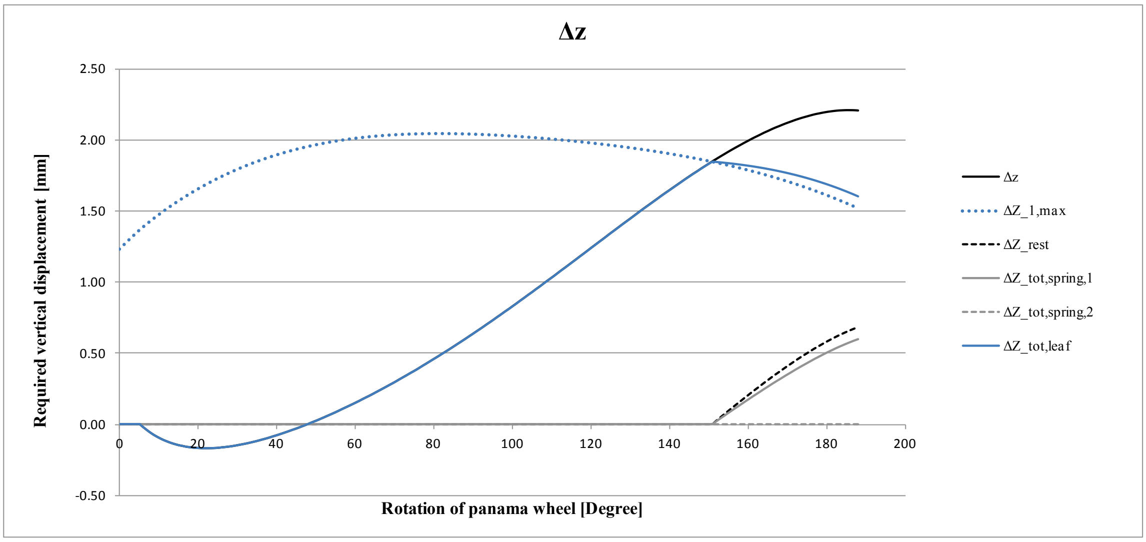


Figure 7.4 - Required vertical displacement and the displacement per component in worst case situation of 2b with external load

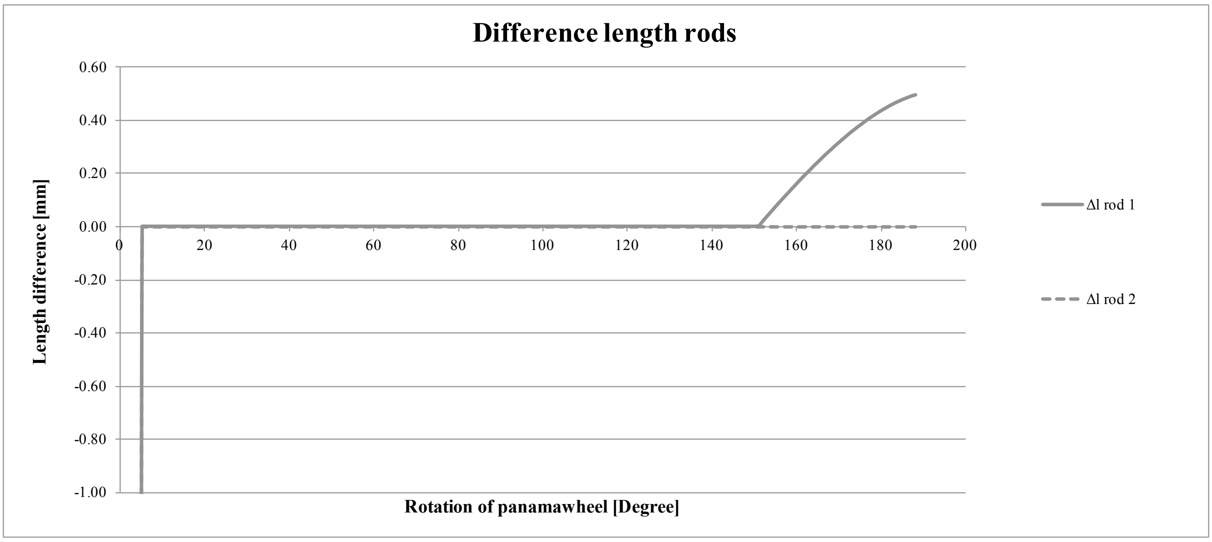


Figure 7.5 - Δl of the rods due to compression of the spring in situation 2b with an external force

7.2 RESULTS REFERENCE PROJECT

The required forced displacement per situation will be discussed with the reference project data. In order to do so, the external force will be applied and the force distribution between the two mechanisms will be examined.

7.2.1 EXTERNAL FORCE

Each operation the wind speed and direction are different. For the wind there are three different scenarios taken into account; positive wind, no wind and negative. Further there are the operation can be for opening or closing. This gives 6 scenarios total.

The axial force shown in figure 7.6 are calculated for the fatigue, each of the mechanisms will take half the force. These external force will be used for combining with the additional force from offsets. A higher wind load is possible during operation, though the chance of occurring is small that the effect on the fatigue life can be neglected. Besides, a maximum wind speed can be specified at which the bridge will still open.

At the start and end of the cycle of figure 7.6, the axial force is a large compressive force, which is due to setting up the bridge. Further some jumps can be seen. These jumps occur due to acceleration or deceleration. The mass moment of inertia of the leaf will introduce extra force for velocity change. Since time is not essential to determine the total axial force of the rods, the axial force is also set out against the rotation of the panamawheel, figure 7.7

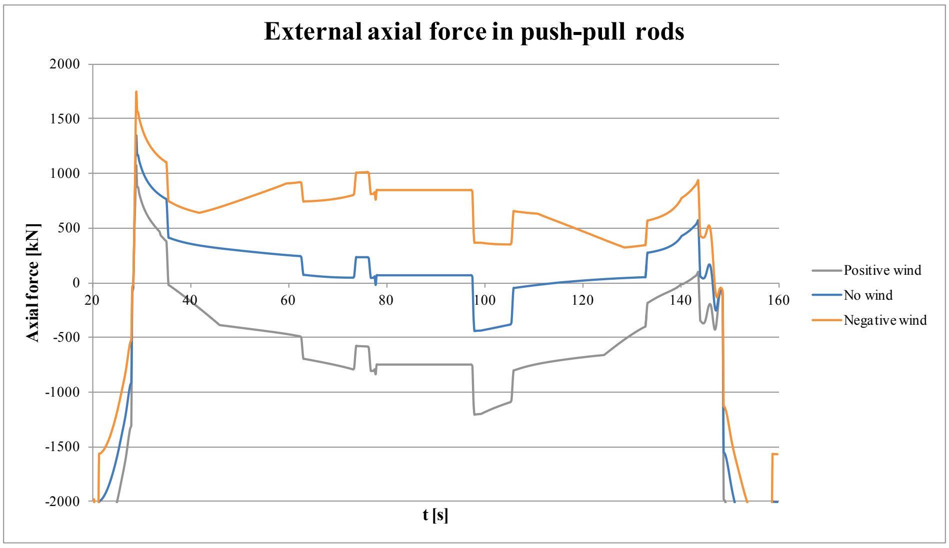


Figure 7.6 - Required force to open and close the bridge over time

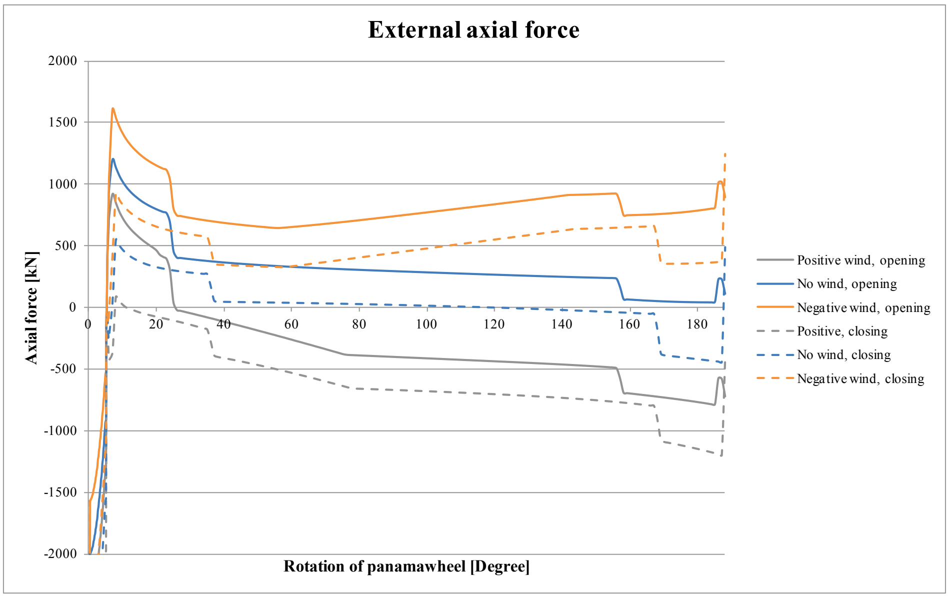


Figure 7.7 - Required force to open and close the bridge per rotation of panamawheel

7.2.2 AXIAL FORCE PUSH-PULL RODS

The axial force in the push-pull rods can be calculated by the deformation of the leaf only using equations (34) and (35). Because $\Delta z_{tot,leaf,\varphi}$ can change sign, depending on the occurring Δz, the type (compression/tension) of additional axial force is automatically decided.

$$F_{rod,1,\varphi_i} = F_{ext} + \frac{k_{leaf,z} \cdot \Delta z_{leaf,tot,\varphi_i}}{\sin \theta_{\varphi_i}} \tag{34}$$

$$F_{rod,2,\varphi} = F_{ext} - \frac{k_{leaf,z} \cdot \Delta z_{leaf,tot,\varphi_i}}{\sin \theta_{\varphi_i}} \tag{35}$$

From the axial force follows the length of the rod for that particular step. The prestress force must be kept in mind though. The length of the rod will be linear with the axial force.

$$l_{rod,1,\varphi_i} = \begin{cases} l_{base,rod1} - \dfrac{F_{rod,1,\varphi} - F_p}{k_{spring}} & \text{if } F_{rod,1,\varphi} < -F_p \\ l_{base,rod1} & \text{if } \left|F_{rod,1,\varphi}\right| < F_p \\ l_{base,rod1} + \dfrac{F_{rod,1,\varphi} - F_p}{k_{spring}} & \text{if } F_{rod,1,\varphi} > F_p \end{cases} \tag{36}$$

$$l_{rod,2,\varphi_i} = \begin{cases} l_{base,rod2} - \dfrac{F_{rod,2,\varphi} - F_p}{k_{spring}} & \text{if } F_{rod,2,\varphi} < -F_p \\ l_{base,rod2} & \text{if } \left|F_{rod,2,\varphi}\right| < F_p \\ l_{base,rod2} + \dfrac{F_{rod,2,\varphi} - F_p}{k_{spring}} & \text{if } F_{rod,2,\varphi} > F_p \end{cases} \tag{37}$$

A verification that can be done is to check if the length of the rod corresponds with the part of Δz that the rod takes. If there is a difference, there is something wrong with the equilibrium. For the check the conversion should be kept in mind that $\Delta z = \frac{\Delta l}{\sin \theta_{\varphi_i}}$.

Appendix C shows all the graphs of the axial force of all installation situations and wind scenarios. For a few situations a closer look will be taken and discussed. In Figure 7.8 situation 1a is looked at with two different external loads, negative wind and no wind. Although the external force changes between the two cases, the axial force in the first rod has little change. The axial force in the second rod has a significant change however. In case a negative wind is present, the second rod barely contributes to opening the bridge. While if no wind would be present, the second rod would counterwork the first rod. This can be seen with the other load scenarios as well. Besides, in all the load scenarios of situations 1 one of the springs is active.

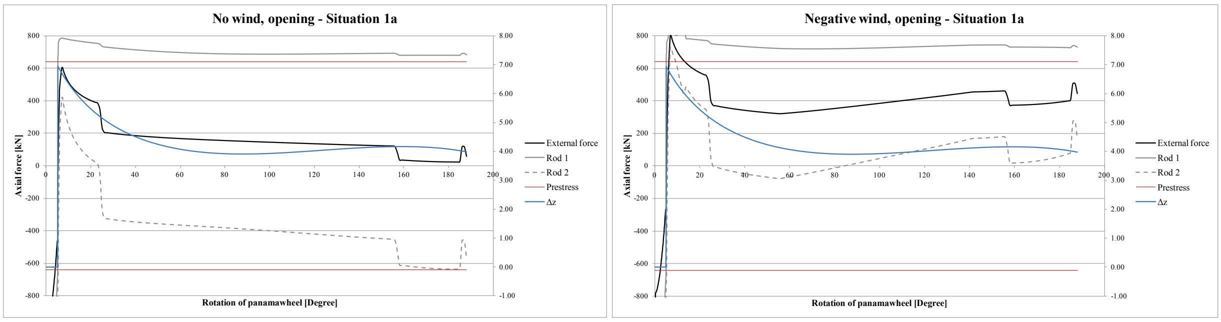


Figure 7.8 - The axial force in the rods of situation 1a under two different loads

Looking at situation 1a and 1b with no wind during opening of the bridge, the two rods are counterworking each other. While one rod is pulling on the leaf, the other is pressing against the leaf. This is exactly the case which should be avoided as the operating systems are not designed on this.

The results are set out against opening of the bridge. The time is not taken into account, however, this should be kept in mind during the analysis. During operation each angle will only appear shortly, but only in normal operation. However, to let the ships pass, the final angle will be longer the case. This means that the mechanisms are subjective to the loads for a longer period of time. As wind gusts could change the external force, also the axial force is altered. At this point, due to dynamics, it is unwanted have a compressed spring.

7.2.3 DISTRIBUTION RATIO

The main question of the thesis is if the distribution of 1/3 – 2/3 on the mechanism is correct. In order to answer this question, a closer look at the results of the axial force will be given. The mechanisms are designed for the highest occurring load scenario, which is the negative wind scenario. The distribution between the two mechanisms might be worse in other scenarios, though the magnitude of the forces are lower.

The examination of the force distribution is done while the leaf is rotating along as well. Prior to this point the mechanisms are in their springs due to exert a support force. The distribution of 1/3 – 2/3 is about fatigue during normal operation, and therefore the first few degrees are not of interest. In table X the contribution per mechanism for the maximum distribution difference is shown per situation. The angular displacement at which the maximum distribution difference occurs can differ per situation, e.g. situation 1a has the maximum at 55 degrees while situation 2b at 155 degrees rotation of the panamawheel.

Situation	Contribution at maximum distribution difference	
	Mechanism 1	Mechanism 2
1a – Design length	1.12	-0.12
1b – Design length	1.04	-0.04
2a – Start opening installation	0.88	0.12
2b – Start opening installation	0.89	0.11
3a – Fully open installation	1.02	-0.02
3b – Fully open installation	0.79	0.21

Table 7.2 - The contribution per mechanism at the point where maximum distribution difference occurs.

In the situation where the design length of the rod is used during installation, one of the mechanisms is doing all the work. The other mechanism is partially counterworking, increasing the work for the other mechanism. Taking the axial force also into account, the conclusion can be drawn that adapting the push-pull rod in length during the installation is recommended.

The other two scenarios are more positive, however, still do not fulfill the requirement of 1/3 – 2/3. For the second situation the two different offset scenarios show both quite similar results. The third situation has the most favourable distribution, however, in case the offsets are in other directions than one rod might do all the work. Therefore the second installation method would be recommended regarding the force distribution of the rod.

7.2.4 CONCLUSION

A quick conclusion can be drawn that the offsets of the main points can have a significant effect on the axial force in the rods. The ratio of 1/3 – 2/3 does not hold ground in the calculations and from examining several situations, the conclusion can be drawn that one rod takes the full load while the other is not contributing at all. When there is no wind during the operation, barely any operation load is required. The rods are counterworking each other, with a force about the same as when there is wind present.

The results are set out against opening of the bridge. The time is not taken into account, however, this should be kept in mind during the analysis. During operation each angle will only appear shortly, but only in normal operation. However, to let the ships pass, the final angle will be longer the case. This means that the mechanisms are subjective to the loads for a longer period of time. As wind gusts could change the external force, changing also the axial force. At this point, due to dynamics, it is unwanted have a compressed spring. Installation in fully open position would be preferred in this case, since the mechanisms have no additional forces due to offsets.

7.3 ALTERNATIVE DESIGN

In addition to the analysis, a look at a possible alternative design for the mechanism is made. The analysed results can be used to optimise the design of the four rod mechanism. Several aspects need to be taken into account during the design.

- Support force at front supports in closed position
- Maximum displacement of alternative design
- External force
- Installation method of push-pull rods

In closed position the bridge requires a support force at the front supports which is currently exerted by the operating mechanisms. A possibility is to use a locking device which ensures that uplift is not possible. Otherwise in the alternative design the exerted force by operating mechanisms should be taken into account to satisfy the requirements of the support force.

The alternative design should lower the leaf stiffness. The support force requires a high stiffness however. Besides, during operation a rigid mechanism is preferred to mitigate unwanted vibrations to go through the operating system. To achieve this, a component with a maximum deformation can be applied. After the deformation is reached, the stiffness of the leaf will take over. The maximum deformation can be chosen in such a way that the maximum difference between the mounting points can be absorbed, yet the support force is not compromised too much.

The external force in order to operate the bridge will already apply a deformation on the alternative design. Since the external force is an arbitrary force during each operation, this is hard to take into account. The maximum axial force in the rods is however quite the same for all wind scenarios, Appendix C. Negative wind causes the largest operating force. The force required by negative wind should not overcome the maximum deformation too far. As soon as the deformation is overcome, the stiffness of the leaf is once again the case. The leaf will already deform slightly, which has to be reduced first again. This is the same effect that occurs as trajectory 3 when the external force is larger than the prestress, discussed in 4.9.2.4.

Each installation method causes a different required vertical displacement. With the alternative design the installation method could be taken into account, with a note that the push-pull rod should be installed in a certain way. By doing so, the required vertical displacement can be used for the alternative design so that the force distribution is mitigated.

7.3.1 DRAFT

Taking these aspects into account, a draft of an alternative can be designed. The installation method is taken as situation 2, i.e. a push-pull rod is adapted during installation where the panamawheel is set in the position where the leaf would start to rotate along. The reason for this is that at the start of the rotation the forces are higher due to the acceleration. Therefore it is convenient to make sure the distribution difference between the two mechanisms is small. Besides, the direction of the offsets cannot be determined, so required vertical displacement is actually unknown.

The external force should not overcome the maximum deformation of the alternative design. This could be done by making sure the force required to overcome the maximum deformation is higher than the maximum external force of the SLS. Further the angle of the push-pull changes during the rotation, which changes the external force in local z-direction as well. This also affects the stiffness of the leaf. Figure 7.9 shows how the stiffness of the leaf develops due to the changing angle of the push-pull rod with respect to the leaf. At the start of the rotation the stiffness decreases significantly after which the stiffness becomes rather constant. This is useful in order to have a low stiffness during operation but a high stiffness to exert enough force on the leaf to create the required support force.

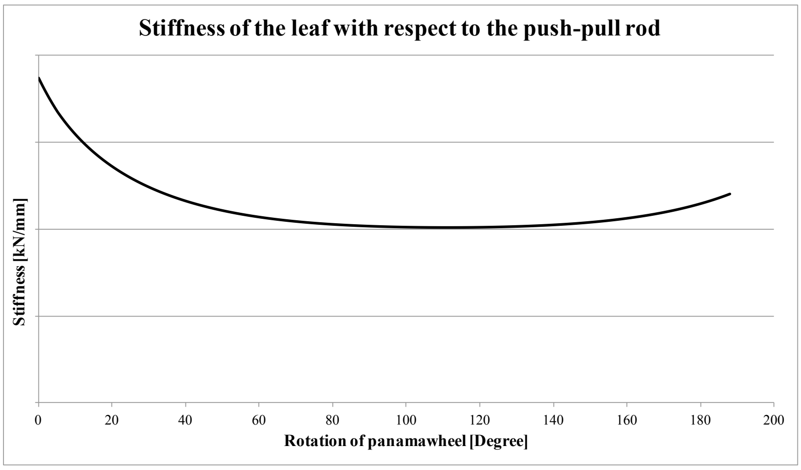


Figure 7.9 – Changing leaf stiffness due to the angle change of the push-pull rod

Since the external force should not overcome the maximum deformation, a safe maximum deformation would be 10mm in both directions of the z-axis. Depending on the stiffness this allows some additional deformation which occur due to the offsets. The stiffness can be chosen in a way that in case the full deformation is occurring and the leaf will gain full stiffness again, that the springs of the push-pull rod will go into its springs. This point is about 100 to 120 degrees of the panamawheel, figure 7.9. The angle of the push-pull rod is at this point about 78degree. By not adapting the prestress of the rod, the stiffness for the alternative design can be determined as follows:

$$k_{z,leaf,alt} = \frac{F_p \cdot \sin\theta_{\varphi=100}}{\Delta z} = \frac{640kN \cdot \sin 78°}{10mm} = 63\ kN/mm \tag{38}$$

For fixating the bridge the support force must be satisfied. Although the prestress is reached, the displacement of the mounting point is already larger, so the spring will compress less for the setup. The support force might therefore not be satisfied. This has to be checked and might be solved by increasing the stiffness of the spring in the rods.

Of course there are multiple ways of applying a spring. One of the most used in civil structures is by use of a rubber block. Applying a rubber block, figure 7.10, would mean an adaptation of the counterweight box.

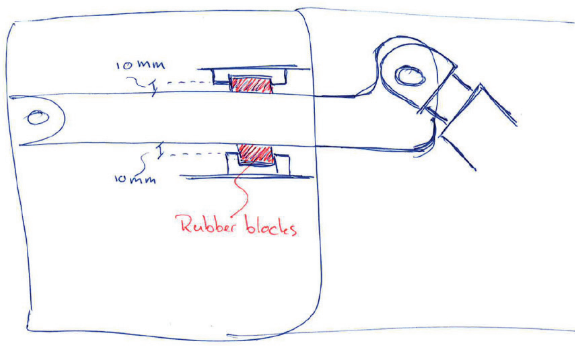


Figure 7.10 - Alternative by applying lever arm which has restraint by rubber block blocks inside the counterweight box

Another solution would be by applying a rubber disc in the mounting point. The shaft which connects the push-pull rod with the counterweight box would have a disc at the counterweight box plates. An advantage of this solution is that all direction are taken into account. The operating force would therefore be better distributed.

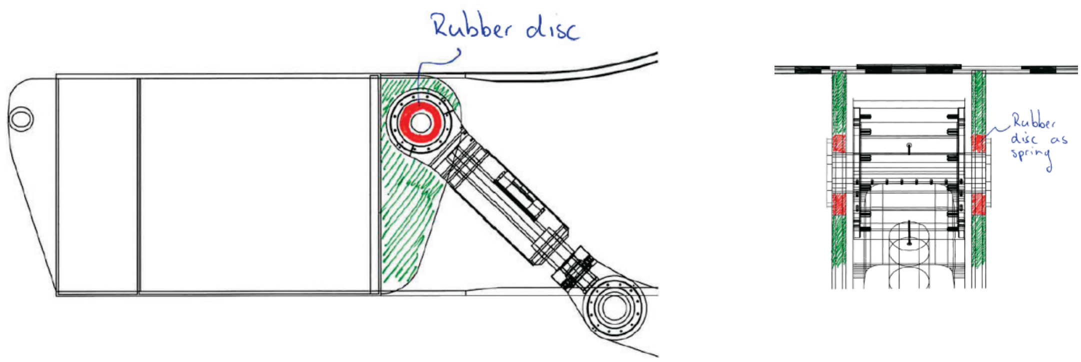


Figure 7.11 - Alternative by applying a rubber bearing block in the mounting point

8

CONCLUSIONS AND RECOMMENDATIONS

The conclusions that have been drawn due in the analysis will be discussed in this chapter. With the knowledge obtained from the analysis also recommendations for further research are made.

8.1 CONCLUSIONS

8.1.1 FORCE DISTRIBUTION.

One of the questions was on the origination of the force distribution of 1/3 – 2/3 between the mechanisms. Background research shows there is little information to find about. The earliest document which is found where the 1/3 – 2/3 is mentioned, is the NBD08001 from 1987. There are no references made in this document nor any support on the choice for the distribution of 1/3 – 2/3. Therefore is seems to be picked rather randomly.

The analysis of the influence on the force distribution due to tolerances shows that the distribution of 1/3 – 2/3 does not hold ground in case offsets are in place. When offsets are in place, the rods could counterwork each other, meaning one of the rods is tension while the other is in compression.

Since wind is one of the governing loads for the operating force, this load has a large influence on the distribution. Due to the balance of the bridge the operating force is close to zero when there is no wind load during the operation. The operating mechanisms counterwork each other in this case. Although the two mechanisms are counterworking each other, the axial force in both rods is lower than the scenario with heavy wind. For that situation one of the mechanisms takes the full load while the other mechanism does not contribute at all.

Regarding the force distribution between the mechanisms, the installation method is important to take into account. The distribution can differ from 1/10 – 9/10 up to a distribution of -1/10 – 11/10 per mechanism depending on the method used.

	Contribution at maximum distribution difference	
Situation	**Mechanism 1**	**Mechanism 2**
1a – Design length	1.12	-0.12
1b – Design length	1.04	-0.04
2a – Start opening installation	0.88	0.12
2b – Start opening installation	0.89	0.11
3a – Fully open installation	1.02	-0.02
3b – Fully open installation	0.79	0.21

a) **Worst case scenario of offsets with maximum near start of rotation**
b) Worst case scenario of offsets with maximum near end of rotation

8.1.2 PRESTRESS

Prestress contributes to the support force at of the front supports. A high prestress is favourable for reaching the required support force. Besides, the fatigue life of the springs would increase by a higher prestress force, since variation of stress is lower. A low prestress, however, is preferable regarding the force distribution between the mechanism. The prestress has a significant influence on the force distribution. No prestress force would mean the springs are directly active, and the increment of the axial force difference between the mechanisms is significantly smaller. A low prestress will mean the springs are addressed earlier, and therefore has a positive effect on the axial force distribution between the mechanisms.

8.1.3 INSTALLATION

During the erection of the bridge, the push-pull rods can be installed in various ways. One option is to use the design length of the push-pull rods, meaning one rod may be forced into place. The two other situations which are examined, one of the rods is adapted in length during installation. This means that there is always one point during the rotation where no required vertical displacement is present due to the tolerances. The analysis shows that the installation has quite a large impact on

the force distribution between the rods. Adapting the push-pull rods during the installation is highly recommended to reduce the occurring force distribution.
The type of tolerances that requires special attentions depends on the installation method. Overall it can be concluded that the offset in z-direction of the leaf and panamawheel have a significant effect on the required vertical displacement, and therefore the force distribution between the two mechanisms. Besides, the tolerances of the crank has a large impact. This last tolerance has the advantage of being manufactured by machinery, which increases the accuracy and therefore mitigating the effect on the required vertical displacement.

8.2 RECOMMENDATIONS

The following recommendations are done to improve research more on this topic.

8.2.1 ANALYSIS INCLUDING MECHANICAL SYSTEM

The current analysis assumes the mechanical system to be infinitely stiff. Therefore no deformations will take place in the operating system. The axial force in the push-pull rods from the analysis can therefore be seen as an upper boundary. In reality the mechanical system is not infinitely stiff, and therefore an analysis based on the mechanical side would be useful. The axial force distribution will not change significantly by finite stiffness of the operating system, however, analysis would be useful to see how the mechanical system could be adapted in favour of the push-pull rods. By more research on the interaction between the mechanical system and static structure the operating mechanism can be further optimised. Besides, a lower upper boundary can be found.

In this thesis the distribution is examined regarding the push-pull rod. The interaction of the push-pull rod with the operating system is interesting how the axial force flows further into the mechanism. The distribution in the push-pull rods changes over the opening angle of the bridge. This is an interesting point to analyse further regarding the interaction of the push-pull rod with the rest of the operating system.

8.2.2 VERIFICATION TESTS IN PRACTICE

Currently few data is available on the offsets of operating mechanisms. Therefore the used values in this thesis are based on interviews with experts on the possible tolerances within components can be placed. The magnitude of these tolerances are small, and the offsets can relatively quickly increase. Measurement on existing bridges can provide a more clear view on the actual offsets. Also for new bridges it is recommended to collect the data, since new techniques might provide a better accuracy. The data for both existing and new bridges can provide a better insight on the offsets. Not just on the overall, but also regarding the size of the bridge. If these offsets are larger than used in this thesis, it might be wise to revise the standard on the tolerances allowed during installation, but also certainly on the distribution of 1/3 – 2/3.

Beside the measurement on the offsets also the measurements on the axial force in operating mechanism could provide a verification of the analysis.

8.2.3 REVIEW STANDARD

A review of the standard could be required regarding the load distribution between the operating mechanisms. The current 1/3 – 2/3 distribution does not hold ground in case offsets are present. Large bridges with high stiffness of both the leaf and the operating system require a more severe distribution up to a distribution of 1 – 0 .

Analysis shows that the installation method of the push-pull rod has a huge impact on the distribution. If the rod length is not adapted during installation and offsets are in place, then the required deformation is significantly larger than if the rod length is adapted. Choosing a installation method before the design is made mean that the operating mechanism can be designed such that it satisfies the distribution in worst case scenario of the offsets.

8.2.4 DYNAMICS

In the analysis the dynamic effect of the stiffness has not been taken into account. The structural dynamics are an important aspect in bridges, and certainly movable bridges. Since the stiffness of components play a significant role in the dynamic behaviour of a structure, this also applies to analysed operating system. The dynamics due to change of stiffness and prestress should be more carefully analysed and requires more research. The alternative design can be better optimised for bascule bridges if the dynamic effect of stiffness changes is known.

BIBLIOGRAPHY

Allaart, P. (1949). *Een onderzoek naar de winddruk op beweegbare bruggen met horizontale draaiingsas.* De Ingenieur.

Bouma, A., & Rem, H. (1950). *Winddruk op klapbruggen.* De Ingenieur.

Koglin, T. (2003). *Movable bridge engineering.* Wiley.

Nederlandse bruggenstichting. (2009). *Bruggen in Nederland, 1950-2000.* Walburg Pers.

NEN 6786. (2001). *Voorschriften voor het ontwerpen van beweegbare bruggen.* Nederlands Normalisatie-Instituut.

Parke, G., & Hewson, N. (2008). *ICE Manual of bridge engineering, second edition.* Thomas Telford Ltd.

Stroosma, D., & Tol, R. (1993). *Nieuwe VOBB beschrijft beter invloed van wind en dynamica op mechanische uitrusting.* Bouwen met Staal.

Wells, G. (2003). *The finite element method: An introduction.* University of Cambridge & Delft University of Technology.

LIST OF FIGURES

A
Scia Engineer model

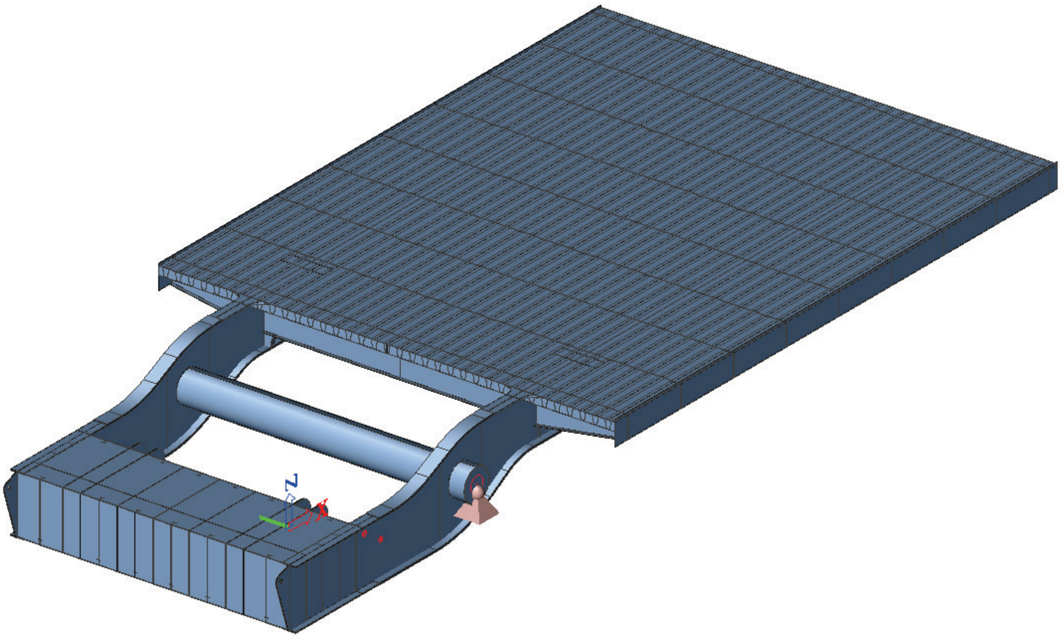
The bridge is modelled in Scia Engineer. In the thesis this model is used for the following:

- The influence of temperature gradients on the mounting points
- Determining the stiffness of the leaf due to a uni-displacement of a mounting point
- The influence of the tube trunnion shaft on the stiffness of the leaf

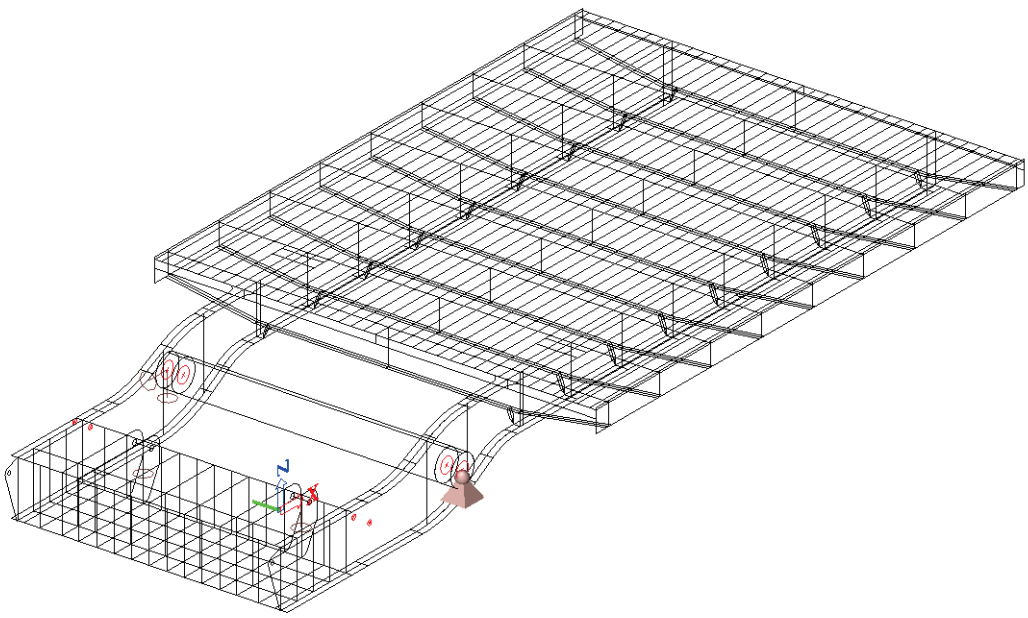
The model will be briefly discussed. Further the loads and results of the previous points will be discussed.

A.1 STANDARD MODEL

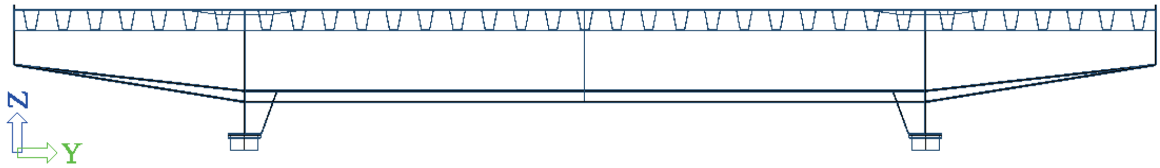
In Scia Engineer the bridge is modelled with mainly 2D-elements, i.e deck, girders and counterweight box. The troughs are modelled as 1D-elements. The supports are modelled at the position of the main rotational points and the mounting points. In closed position the bridge has front supports at the toe, but these are not modelled since the model is used assuming the bridge is in open position.



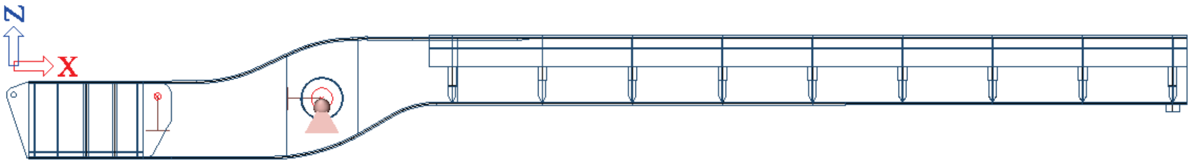
Bridge model in Scia Engineer with all construction elements visible



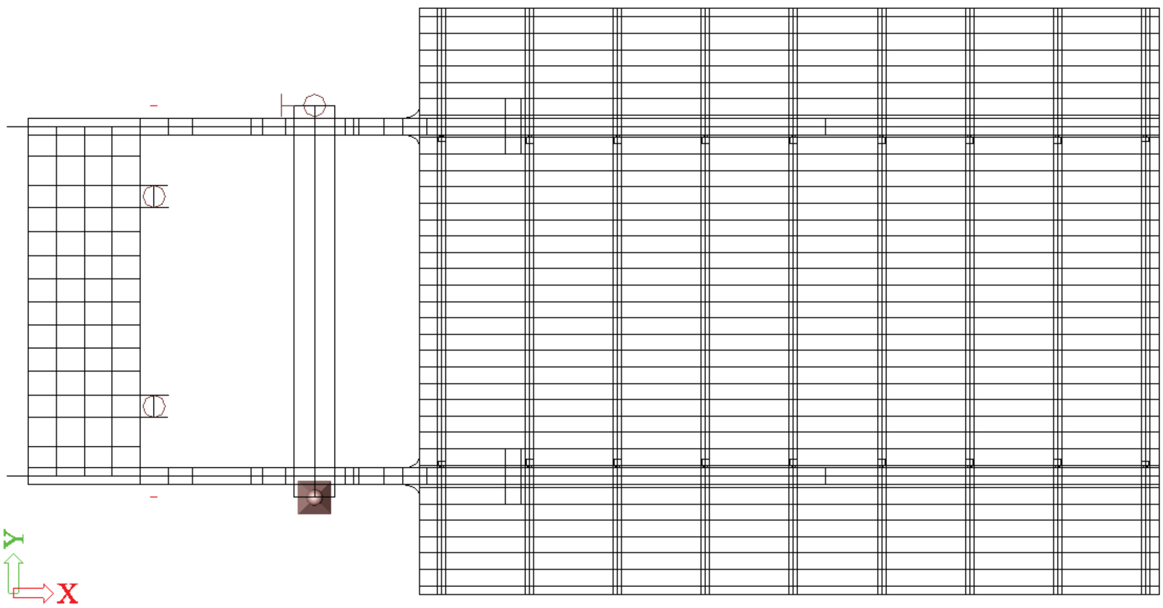
Framework of the 2D-elements.



Front view of the deck



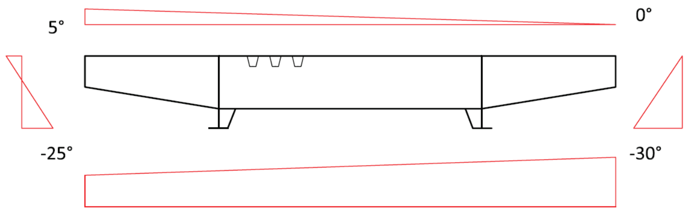
Side view of the model



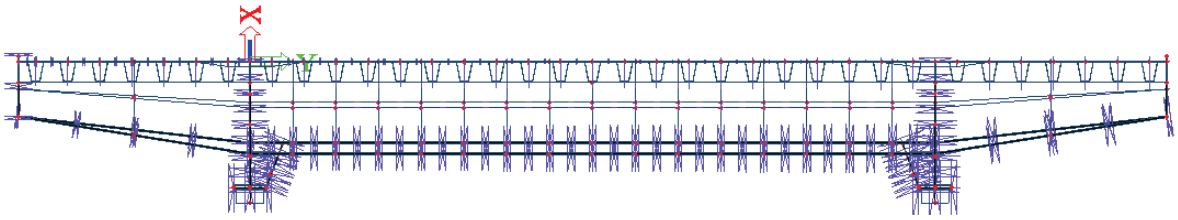
Top view of the model

A.2 TEMPERATURE

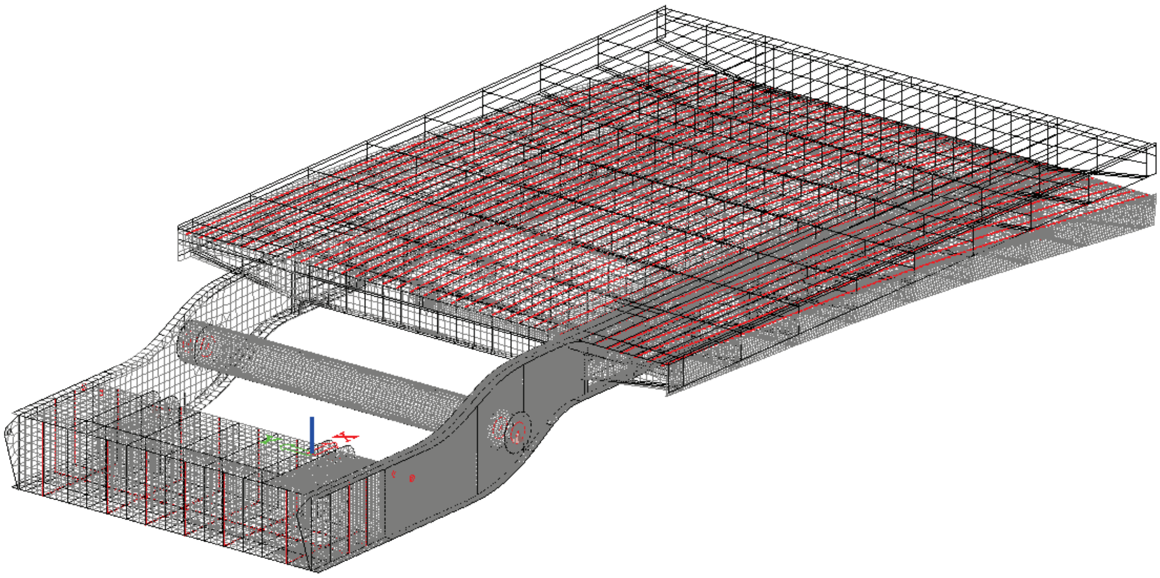
A twist in the deck has effect on the mounting points. Due to temperature gradients a twist might occur. The temperature gradients that are taken into account are as follows:



Since temperature is captured underneath the deck the troughs are already modelled as with a lower temperature. The temperature is modelled in Scia Engineer as follows:



The deck will undergo a deformation due to the temperature. The reaction forces however are small and therefore temperature regarding the deck can be neglected.

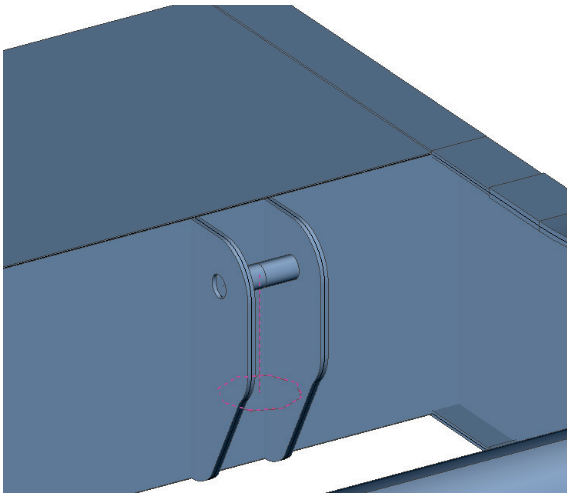


Reaction forces due to temperature:

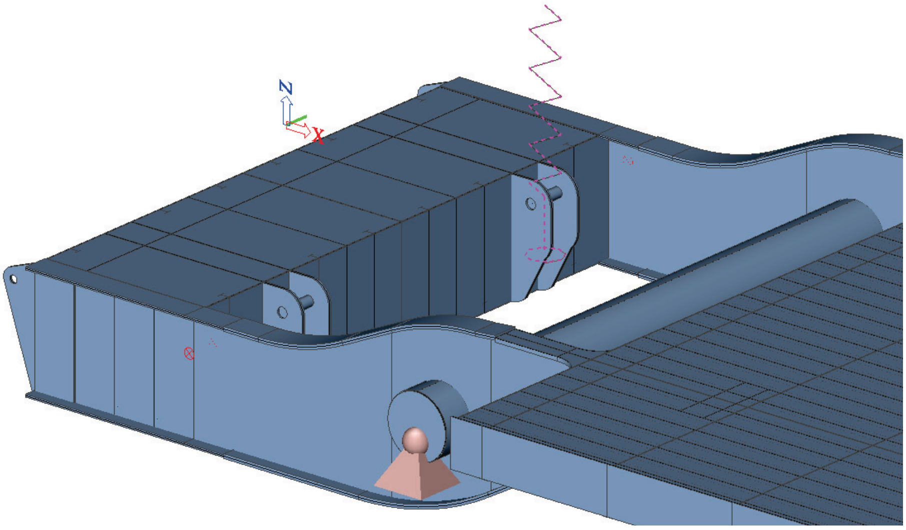
Supports	Rx [kN]	Ry [kN]	Rz [kN]	Mx [kNm]	My [kNm]	Mz [kNm]
S1 - Main support	0,00	-2,84	0,08	0,00	0,00	0,00
S2 - Main support	0,00	-2,88	-0,01	0,00	0,00	0,00
S3 - Mounting point	0,00	2,81	-0,11	0,00	0,00	0,00
S4 - Mounting point	0,00	2,90	0,03	0,00	0,00	0,00

A.3 STIFFNESS LEAF

For determining the stiffness of the leaf, a uni-displacement is applied to one of the mounting points. The support of the mounting point is modelled as a point on a bar. In reality the push-pull rod is connected with a shaft and therefore is not a point load, but has uses the full length of the bar. Therefore no deformation of the shaft will occur, which should be taken into account for the model. The bar will be modelled as a rigid bar, so no deformations will take place and both sides of the mounting point will undergo the same displacement.

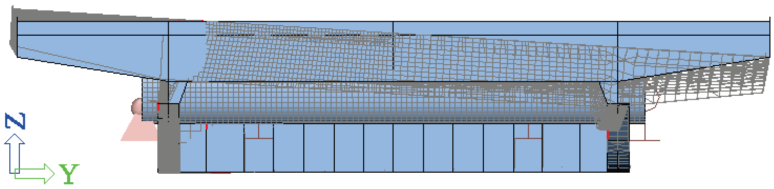


One of the mounting points where the support is modelled in the middle of the bar.

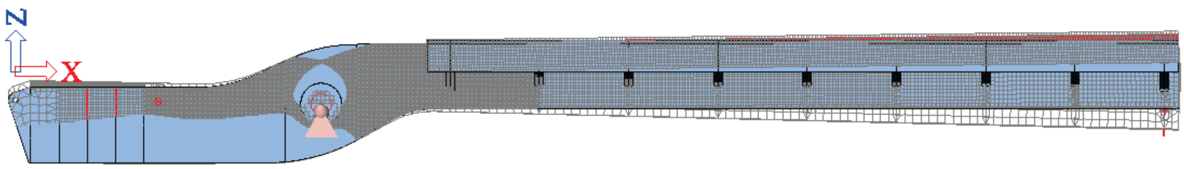


Applied uni-displacement in z-direction on the mounting point

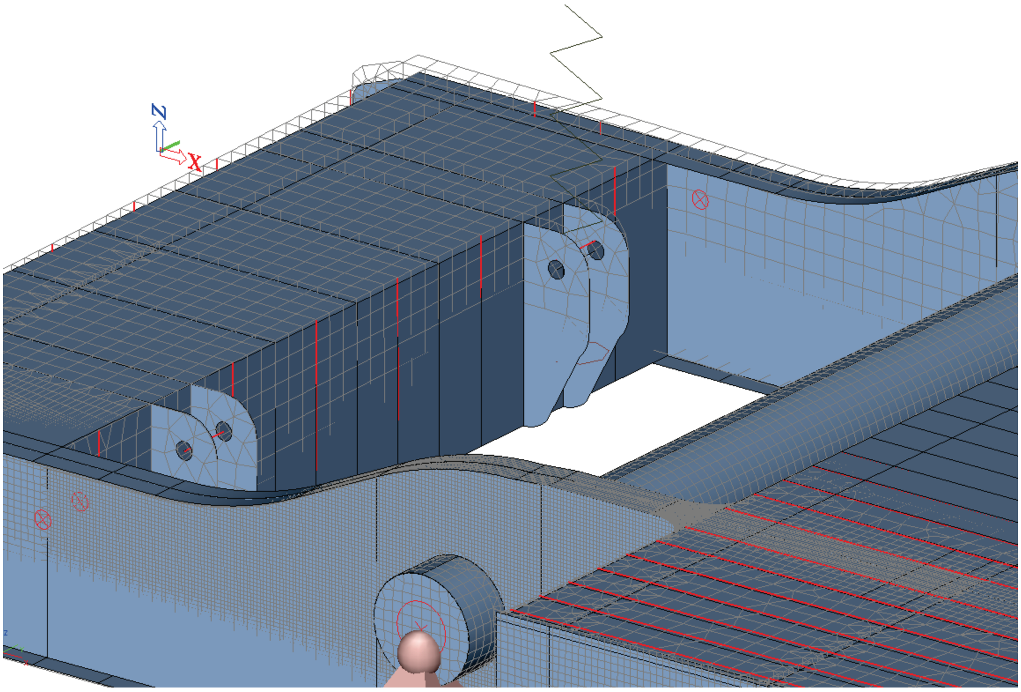
The applied uni-displacement will cause deformations. The deck will undergo a twist, which can be seen in the front and side view.



Deformation of the deck from the front view



Deformations in deck from the side view



Deformation of the counterweight box

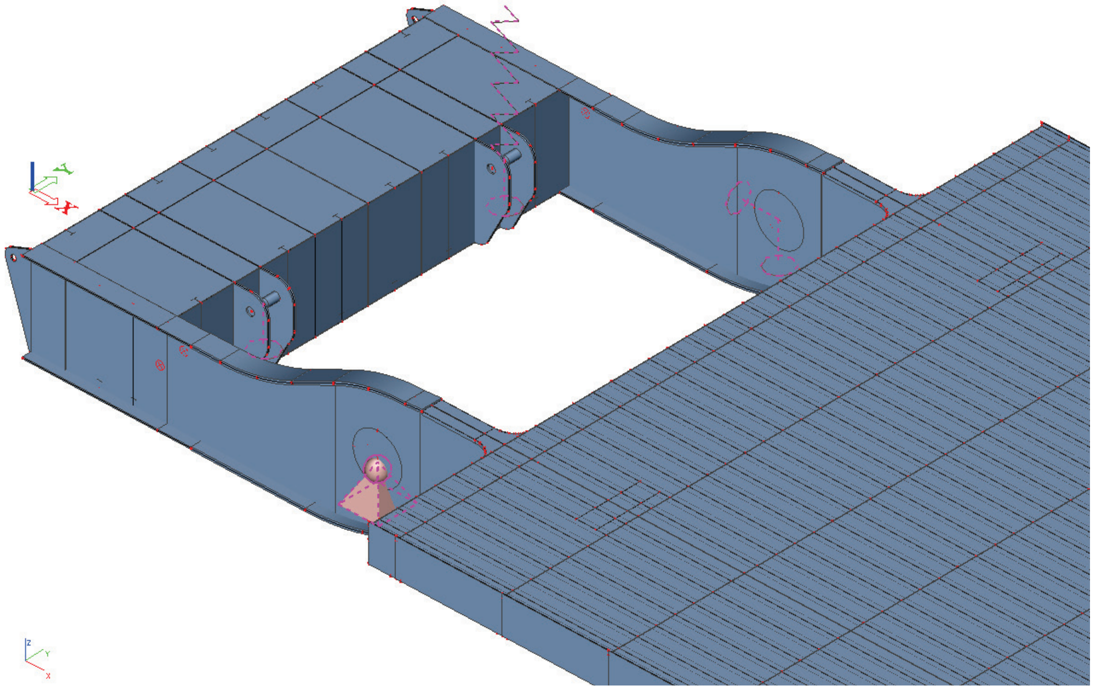
The reaction forces in the supports due to a uni-displacement are as follows:

Supports	Rx [kN]	Ry [kN]	Rz [kN]	Mx [kNm]	My [kNm]	Mz [kNm]
S1 - Main support	**0,00**	**0,00**	**105,41**	**0,00**	**0,00**	**0,00**
S2 - Main support	**0,00**	**0,00**	**-105,42**	**0,00**	**0,00**	**0,00**
S3 - Mounting point	**0,00**	**0,00**	**-196,77**	**0,00**	**0,00**	**0,00**
S4 - Mounting point	**0,00**	**0,00**	**196,78**	**0,00**	**0,00**	**0,00**

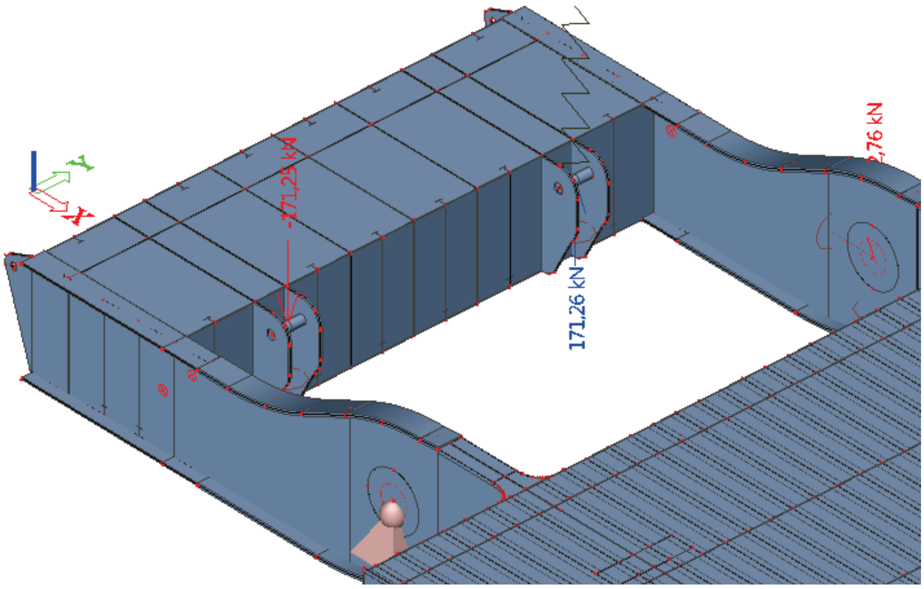
A.4 TUBE TRUNNION SHAFT

The tube trunnion shaft increases the stiffness of the leaf. The bridge can be designed without one as well, therefore having insight in the contribution of the tube trunnion shaft to the stiffness of the leaf is desired.

To determine the contribution the same model as is used with a small modification. The tube trunnion shaft will be removed. The required force for a uni-displacement will be lower. The new force can be compared with the required force from 0 and the contribution can be determined. This contribution does depend on the design of the bridge as well and can therefore differ. However, during the design this will be a good approximation if this ratio is used.



Modified Scia Engineer model with the tube trunnion shaft is removed. The supports will be stay the same as in A.3, as well as the applied uni-displacement.



Supports	Rx [kN]	Ry [kN]	Rz [kN]	Mx [kNm]	My [kNm]	Mz [kNm]
S1 - Main support	0,00	0,00	102,75	0,00	0,00	0,00
S2 - Main support	0,00	0,00	-102,76	0,00	0,00	0,00
S3 - Mounting point	0,00	0,00	-171,25	0,00	0,00	0,00
S4 - Mounting point	0,00	0,00	171,26	0,00	0,00	0,00

The stiffness of the leaf is without the tube trunnion shaft $171 kN/mm$.

$$\frac{171}{196} \approx 0.87$$

The contribution of the tube trunnion shaft is 13%. Although each bridge design is different, an estimation of the contribution of the tube trunnion shaft of about 10-15% would be a good approximation for use.

B
Visual basic code

The following code has been used in the data sheet to determine the coordinates

```
Sub Run_rotation()
    Dim angle_pan_start As Double
    Dim start_angle_leaf As Double
    Dim starttime, finishtime As Date
    Dim Accuracy As Double

    starttime = Now()
    'Clearing old tables
    Call clear_tables

    Sheets("Design input").Activate

    'Determine coordinates mechanisms
    A_x1 = Range("A_x").Value + Range("C9").Value + Range("E9").Value
    A_z1 = Range("A_z").Value + Range("D9").Value + Range("F9").Value
    B_x1 = Range("B_x").Value + Range("C10").Value + Range("E10").Value
    B_z1 = Range("B_z").Value + Range("D10").Value + Range("F10").Value
```

```
    C_x1 = Range("C_x").Value + Range("C11").Value + Range("E11").Value
    C_z1 = Range("C_z").Value + Range("D11").Value + Range("F11").Value
    D_x1 = Range("D_x").Value + Range("C12").Value + Range("E12").Value
    D_z1 = Range("D_z").Value + Range("D12").Value + Range("F12").Value '+
Range("disp_leaf_set").Value

    A_x2 = Range("A_x").Value + Range("C13").Value + Range("E13").Value
    A_z2 = Range("A_z").Value + Range("D13").Value + Range("F13").Value
    B_x2 = Range("B_x").Value + Range("C14").Value + Range("E14").Value
    B_z2 = Range("B_z").Value + Range("D14").Value + Range("F14").Value
    C_x2 = Range("C_x").Value + Range("C15").Value + Range("E15").Value
    C_z2 = Range("C_z").Value + Range("D15").Value + Range("F15").Value
    D_x2 = Range("D_x").Value + Range("C16").Value + Range("E16").Value
    D_z2 = Range("D_z").Value + Range("D16").Value + Range("F16").Value '+
Range("disp_leaf_set").Value

    'Total rotation that panama crank mechanism undergoes
    Max_rotation = Range("Max_rot_pan").Value
    angle_round = Max_rotation
    Accuracy = Range("accuracy").Value
    size_steps = 0.1 ^ (2 + Accuracy)
    base_length_rod = Range("base_length_rod").Value

    'Fill out the coordinates in the cells for each mechanism
    Sheets("Mechanism 1").Activate
    Cells(2, 3).Value = A_x1
    Cells(2, 4).Value = A_z1
    Cells(3, 3).Value = B_x1
    Cells(3, 4).Value = B_z1
    Cells(4, 3).Value = C_x1
    Cells(4, 4).Value = C_z1
    Cells(5, 3).Value = D_x1
    Cells(5, 4).Value = D_z1
    Length_AD_1 = Cells(2, 7).Value
    Length_AB_1 = Cells(3, 7).Value
    Length_BC_1 = Cells(4, 7).Value
    Length_CD_1 = Cells(5, 7).Value

    'Main information to determine coordinates throughout process
    X_main = Cells(2, 3).Value 'Start value main rotational point
    Z_main = Cells(2, 4).Value 'Stat value main rotational point
    R_leaf = Cells(2, 7).Value 'Radius of leaf (length between two rotation points of leaf)
    R_pan = Cells(4, 7).Value 'Radius of Panama crank
```

```
   X_pan = Cells(3, 3).Value 'Start value of X-coordinate crank
   Z_pan = Cells(3, 4).Value 'Start value of Z-coodinate crank
   angle_pan_closed = Cells(4, 9).Value 'Start angle closed position crank -> The angle between horizontal of heart panamawheel to rotational point in crank
   angle_leaf_closed = Cells(2, 9).Value 'Start angle closed position leaf -> Angle between main rotational point leaf and rotational point of push pull rod at leaf
   start_angle_leaf = 0 'DO NOT CHANGE! Is the start value that leaf undergoes during operation


   length_rod_set = Round(Cells(5, 7).Value, Accuracy) 'Rounds off the length of the push pull rod by X decimals. Change the last number to change number of decimals
   'Cells(1, 20).Value = length_rod
   'length_rod = length_rod_set + stroke_bridge_set

   row_output = 9 'Start output row
   'Loop where panama crank mechanism is rotated per small angle to determine corresponding coordinates
   For angle_pan = 0 To Max_rotation Step 0.1
      If angle_pan < angle_round Then
         angle_pan_rad = Application.WorksheetFunction.Radians(angle_pan) 'Change degree to radians

         tempXpan = X_pan - R_pan * Cos(angle_pan_rad + angle_pan_closed) 'X-Coordinate crank at corresponding angle
         tempZpan = Z_pan - R_pan * Sin(angle_pan_rad + angle_pan_closed) 'Y-Coordinate crank at corresponding angle

         'Fill out table for crank with rotation and position of current angle
         Cells(row_output, 1).Value = angle_pan
         Cells(row_output, 2).Value = angle_pan_rad
         Cells(row_output, 3).Value = tempXpan
         Cells(row_output, 4).Value = tempZpan

         temp_length_rod = Round(Sqr((Range("C5").Value - tempXpan) ^ 2 + (Range("D5").Value - tempZpan) ^ 2), Accuracy)
         If temp_length_rod < base_length_rod Then
            Cells(row_output, 6).Value = 0
            Cells(row_output, 7).Value = 0
            Cells(row_output, 8).Value = Range("C5").Value
            Cells(row_output, 9).Value = Range("D5").Value
            n_1 = temp_length_rod

         ElseIf angle_pan < angle_round Then
```

```
        If k = False Then
            angle_round = Application.WorksheetFunction.RoundUp(angle_pan, 0)
            angle_pan_no_comp = (angle_pan - 0.1) + (angle_pan - (angle_pan - 0.1)) / (temp_length_rod - n_1) * (base_length_rod - n_1) 'Determines angle point where the push pull rod is at the point of the prestress.
            Cells(1, 18).Value = Application.WorksheetFunction.Radians(angle_pan_no_comp)
            k = True
        End If

        'invoeren interpolatie coordinaten
        'angle_pan_no_comp = (angle_pan - Range("steps").Value) + (angle_pan - (angle_pan - Range("steps").Value)) / (temp_length_rod - n_1) * (base_length_rod - n_1) 'Determines angle point where the push pull rod is at the point of the prestress.
        'Cells(1, 16).Value = angle_pan_no_comp
        'tempXnocomp =

        'Loop to determine position of rotational point push pull rod at leaf corresponding to rotation of panamawheel - 0 degrees point bridge starts rotating due to settle force became 0.
        For angle_leaf = start_angle_leaf To 90 Step size_steps 'Small steps to get good accuracy; For smaller/higher accuracy, also change number of decimals which length_rod and temp_length_rod are round of in.

            angle_leaf_rad = Application.WorksheetFunction.Radians(angle_leaf)

            tempXleaf = -R_leaf * Cos(angle_leaf_rad + angle_leaf_closed) + X_main 'X-coordinate rotational point leaf at corresponding angle of leaf
            tempZleaf = -R_leaf * Sin(angle_leaf_rad + angle_leaf_closed) + Z_main 'Y-coordinate rotational point leaf at corresponding angle of leaf

            'Check length of push pull rod
            temp_length_rod = Round(Sqr((tempXleaf - tempXpan) ^ 2 + (tempZleaf - tempZpan) ^ 2), Accuracy)

            'Check if length push pull rod correspond with standard length; If yes, correct angle/coordinates are found, filled in and next degree of panamawheel will be taken; If not next step for leaf angle is taken
            If temp_length_rod = base_length_rod Then
                Cells(row_output, 6).Value = angle_leaf
                Cells(row_output, 7).Value = angle_leaf_rad
                Cells(row_output, 8).Value = tempXleaf
                Cells(row_output, 9).Value = tempZleaf
                start_angle_leaf = angle_leaf
                Exit For
```

```
            End If
        Next angle_leaf
      End If
    Else
      angle_pan_start = angle_pan - 0.1
      Exit For
    End If
    row_output = row_output + 1 'Next degree, so set new output row
  Next angle_pan

  'angle_pan_start = Round(angle_pan_start, 1)
  'Continue loop where panama crank mechanism is rotated per degree to determine corresponding coordinates
  For angle_pan = angle_pan_start + 1 To Max_rotation Step 1
    angle_pan_rad = Application.WorksheetFunction.Radians(angle_pan) 'Change degree to radians

    tempXpan = X_pan - R_pan * Cos(angle_pan_rad + angle_pan_closed) 'X-Coordinate crank at corresponding angle
    tempZpan = Z_pan - R_pan * Sin(angle_pan_rad + angle_pan_closed) 'Y-Coordinate crank at corresponding angle

    'Fill out table for crank with rotation and position of current angle
    Cells(row_output, 1).Value = angle_pan
    Cells(row_output, 2).Value = angle_pan_rad
    Cells(row_output, 3).Value = tempXpan
    Cells(row_output, 4).Value = tempZpan

    'temp_length_rod = Round(Sqr((Range("C5").Value - tempXpan) ^ 2 + (Range("D5").Value - tempZpan) ^ 2), 3)
    ''invoeren interpolatie coordinaten
    'angle_pan_no_comp = (angle_pan - Range("steps").Value) + (angle_pan - (angle_pan - Range("steps").Value)) / (temp_length_rod - n_1) * (length_rod - n_1) 'Determines angle point where the push pull rod is at the point of the prestress.
    'tempXnocomp =

    'Loop to determine position of rotational point push pull rod at leaf corresponding to rotation of panamawheel - 0 degrees point bridge starts rotating due to settle force became 0.
    For angle_leaf = start_angle_leaf To 90 Step size_steps 'Small steps to get good accuracy; For smaller/higher accuracy, also change number of decimals which length_rod and temp_length_rod are round of in.

      angle_leaf_rad = Application.WorksheetFunction.Radians(angle_leaf)
```

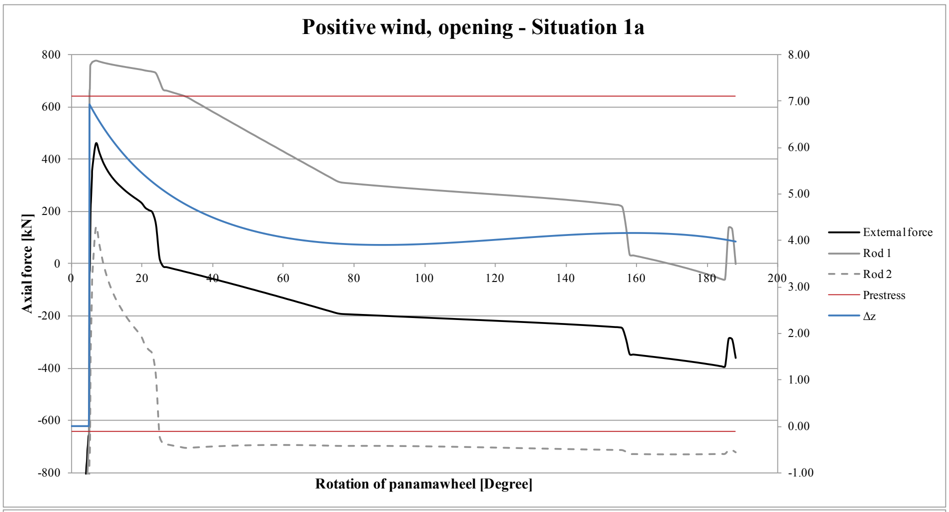
```
        tempXleaf = -R_leaf * Cos(angle_leaf_rad + angle_leaf_closed) + X_main 'X-coordinate rotational point leaf at corresponding angle of leaf
        tempZleaf = -R_leaf * Sin(angle_leaf_rad + angle_leaf_closed) + Z_main 'Y-coordinate rotational point leaf at corresponding angle of leaf

        'Check length of push pull rod
        temp_length_rod = Round(Sqr((tempXleaf - tempXpan) ^ 2 + (tempZleaf - tempZpan) ^ 2), Accuracy)

        'Check if length push pull rod correspond with standard length; If yes, correct angle/coordinates are found, filled in and next degree of panamawheel will be taken; If not next step for leaf angle is taken
        If temp_length_rod = base_length_rod Then
          Cells(row_output, 6).Value = angle_leaf
          Cells(row_output, 7).Value = angle_leaf_rad
          Cells(row_output, 8).Value = tempXleaf
          Cells(row_output, 9).Value = tempZleaf
          start_angle_leaf = angle_leaf
          Exit For
        End If
      Next angle_leaf
      row_output = row_output + 1 'Next degree, so set new output row
    Next angle_pan

    'Fill out the corresponding tolerances used for the output; to prevent input is changed and tolerances in this sheet do not correspond to data
    Sheets("Output difference").Activate
    'Worksheets("Output difference").Cells(2, 3).Value = A_x2 - A_x1
    'Worksheets("Output difference").Cells(2, 4).Value = A_z2 - A_z1
    'Worksheets("Output difference").Cells(3, 3).Value = B_x2 - B_x1
    'Worksheets("Output difference").Cells(3, 4).Value = B_z2 - B_z1
    'Worksheets("Output difference").Cells(4, 3).Value = C_x2 - C_x1
    'Worksheets("Output difference").Cells(4, 4).Value = C_z2 - C_z1
    'Worksheets("Output difference").Cells(5, 3).Value = D_x2 - D_x1
    'Worksheets("Output difference").Cells(5, 4).Value = D_z2 - D_z1

    'Worksheets("Output difference").Cells(2, 8).Value = Worksheets("Mechanism 2").Range("Length_AD_2").Value - Worksheets("Mechanism 1").Range("Length_AD_1").Value
    'Worksheets("Output difference").Cells(3, 8).Value = Worksheets("Mechanism 2").Range("Length_AB_2").Value - Worksheets("Mechanism 1").Range("Length_AB_1").Value
    'Worksheets("Output difference").Cells(4, 8).Value = Worksheets("Mechanism 2").Range("Length_BC_2").Value - Worksheets("Mechanism 1").Range("Length_BC_1").Value
```

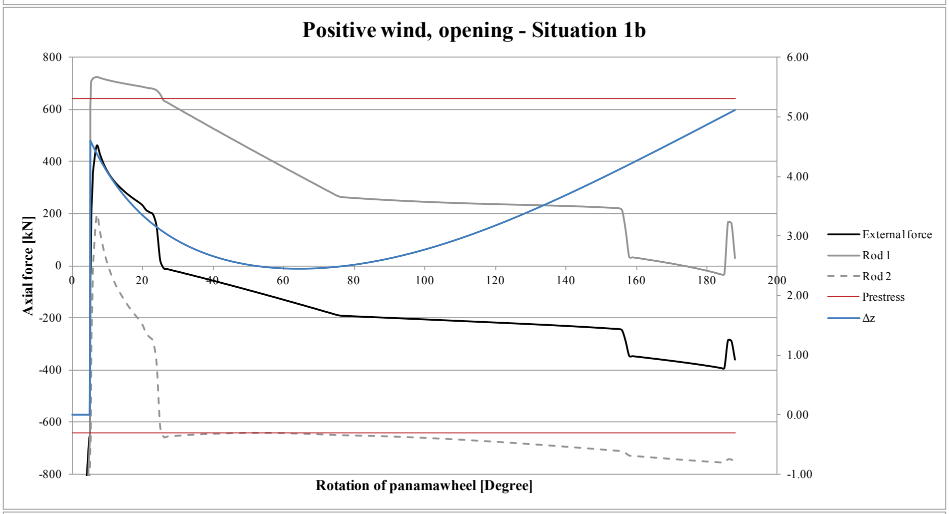
```
   'Worksheets("Output difference").Cells(5, 8).Value = Worksheets("Mechanism 2").Range("Length_CD_2").Value - Worksheets("Mechanism 1").Range("Length_CD_1").Value

   Call Autofill

   finishtime = Now()
   Range("M1").Value = starttime
   Range("M2").Value = finishtime
   Range("M3").Value = finishtime - starttime

End Sub

‘To clear all old data in the table
Sub clear_tables()
   Dim tbl As ListObject
   Dim WS As Worksheet
   Dim i, j As Single

   For Each WS In Worksheets
      If WS.Name = "Design input" Then

      ElseIf WS.Name = "External Load" Then

      Else
         For Each tbl In WS.ListObjects
             On Error Resume Next 'Some tables only contain formulas, no xlCellTypeConstants will be found and error occurs. Loop will continue at next table.
                tbl.Range.AutoFilter
                tbl.DataBodyRange.Offset(1).Resize(tbl.DataBodyRange.Rows.Count - 1, tbl.DataBodyRange.Columns.Count).Rows.Delete
                'tbl.DataBodyRange.SpecialCells(xlCellTypeConstants).ClearContents
             On Error GoTo 0
         Next tbl
      End If
   Next WS
End Sub

Sub Autofill()

   i = 1
   For Each rw In Range("Mech1Crank").Rows
      i = i + 1
   Next rw
```

```
    'Set Rng1 = Range("Mech1Angle[#All]").Resize(i, 2)
    'Set Rng2 = Range("OutputCrankGCS[#All]").Resize(i, 5)
    Set Rng3 = Range("OutputDiffGCS[#All]").Resize(i, 4)
    Sheets("Mechanism 1").Activate
    ActiveSheet.ListObjects("Crank1LCS").Resize Range("Crank1LCS[#All]").Resize(i, 2)
    ActiveSheet.ListObjects("Leaf1LCS").Resize Range("Leaf1LCS[#All]").Resize(i, 2)
    ActiveSheet.ListObjects("Mech1Angle").Resize Range("Mech1Angle[#All]").Resize(i, 3)
    ActiveSheet.ListObjects("LengthRod1").Resize Range("LengthRod1[#All]").Resize(i, 3)
    ActiveSheet.ListObjects("AddLoad1").Resize Range("AddLoad1[#All]").Resize(i, 5)

    Sheets("Mechanism 2").Activate
    ActiveSheet.ListObjects("Mech2Crank").Resize Range("Mech2Crank[#All]").Resize(i, 4)
    ActiveSheet.ListObjects("Mech2Leaf").Resize Range("Mech2Leaf[#All]").Resize(i, 4)
    ActiveSheet.ListObjects("Crank2LCS").Resize Range("Crank2LCS[#All]").Resize(i, 2)
    ActiveSheet.ListObjects("Leaf2LCS").Resize Range("Leaf2LCS[#All]").Resize(i, 2)
    ActiveSheet.ListObjects("Mech2Angle").Resize Range("Mech2Angle[#All]").Resize(i, 3)
    ActiveSheet.ListObjects("LengthRod2").Resize Range("LengthRod2[#All]").Resize(i, 3)
    ActiveSheet.ListObjects("Adapt_leaf_2").Resize Range("Adapt_leaf_2[#All]").Resize(i, 6)
    ActiveSheet.ListObjects("Calc_values").Resize Range("Calc_values[#All]").Resize(i, 8)
    ActiveSheet.ListObjects("delta_z").Resize Range("delta_z[#All]").Resize(i, 13)
    ActiveSheet.ListObjects("Add_Load").Resize Range("Add_Load[#All]").Resize(i, 5)
    ActiveSheet.ListObjects("Length_rods").Resize Range("Length_rods[#All]").Resize(i, 5)


    'Resizing Difference between mechanism self in GCS and LCS
    Sheets("Output difference").Activate
    ActiveSheet.ListObjects("OutputCrankGCS").Resize Range("OutputCrankGCS[#All]").Resize(i, 5)
    ActiveSheet.ListObjects("OutputCrankLCS").Resize Range("OutputCrankLCS[#All]").Resize(i, 5)
    ActiveSheet.ListObjects("OutputLeafGCS").Resize Range("OutputLeafGCS[#All]").Resize(i, 5)
    ActiveSheet.ListObjects("OutputLeafLCS").Resize Range("OutputLeafLCS[#All]").Resize(i, 5)

    'Resizing Total difference leaf-crank
    ActiveSheet.ListObjects("OutputDiffGCS").Resize Range("OutputDiffGCS[#All]").Resize(i, 3)
    ActiveSheet.ListObjects("OutputDiffLCS").Resize Range("OutputDiffLCS[#All]").Resize(i, 3)

    ActiveSheet.ListObjects("Angle_push_pull_rod").Resize
Range("Angle_push_pull_rod[#All]").Resize(i, 2)

    ActiveSheet.ListObjects("Angle_Leaf").Resize Range("Angle_Leaf[#All]").Resize(i, 1)

End Sub
```

C
Graphs of results

On the next page the axial force in the push-pull rods per load per situation will be shown. These are determined by the worst case scenarios of 7.1.


Positive wind, opening - Situation 1a
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz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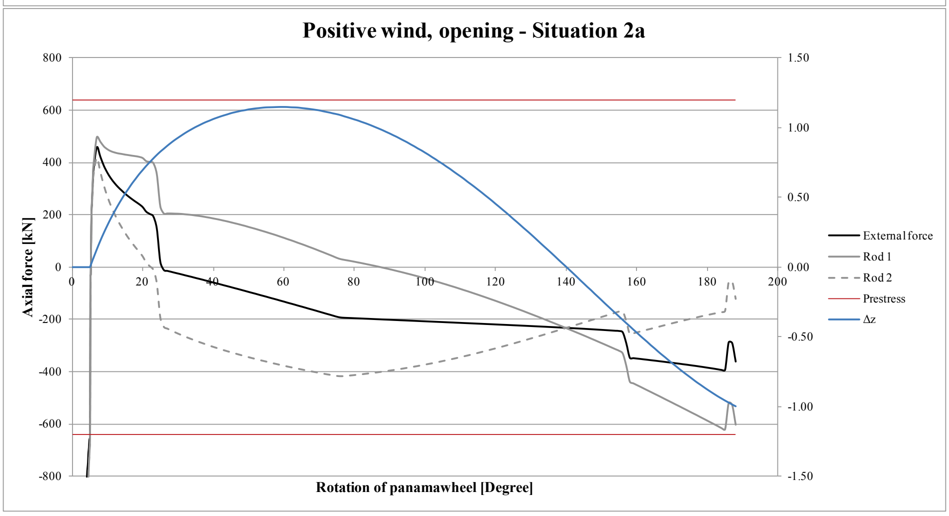
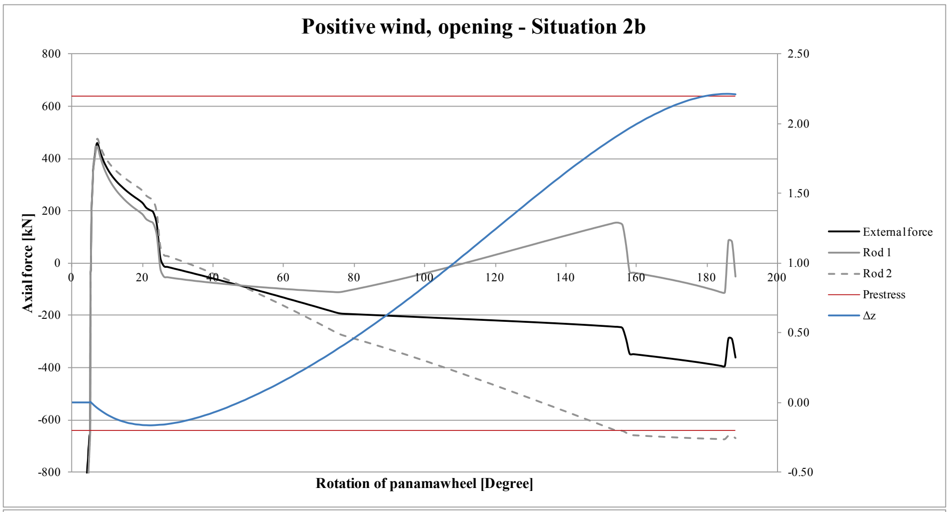
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz


Positive wind, opening - Situation 2a
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz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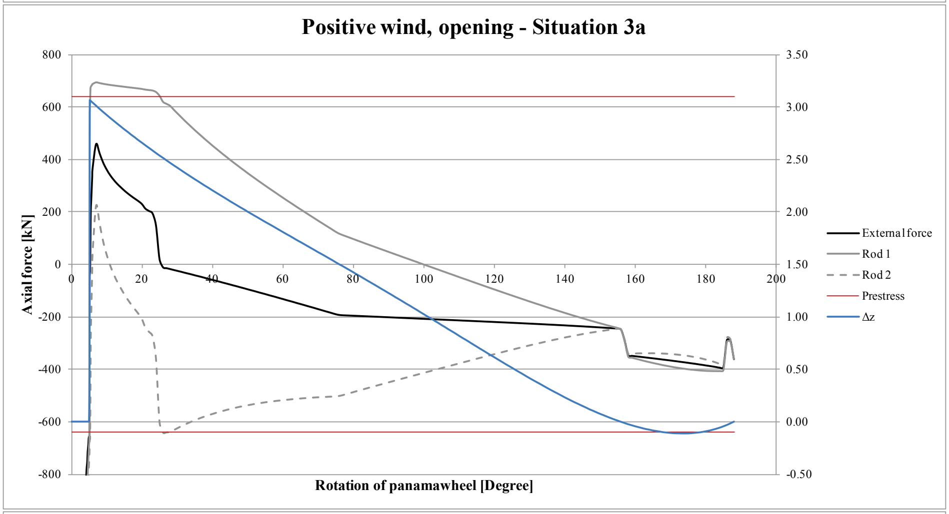
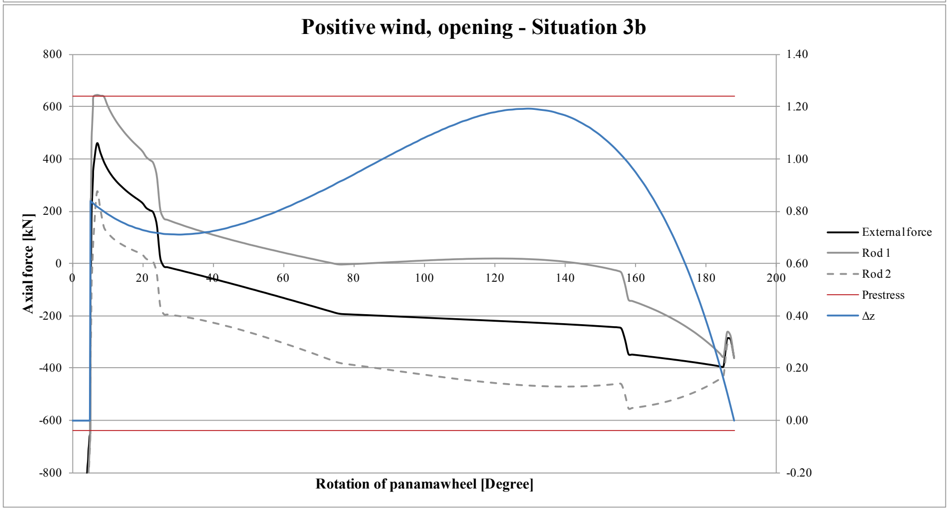
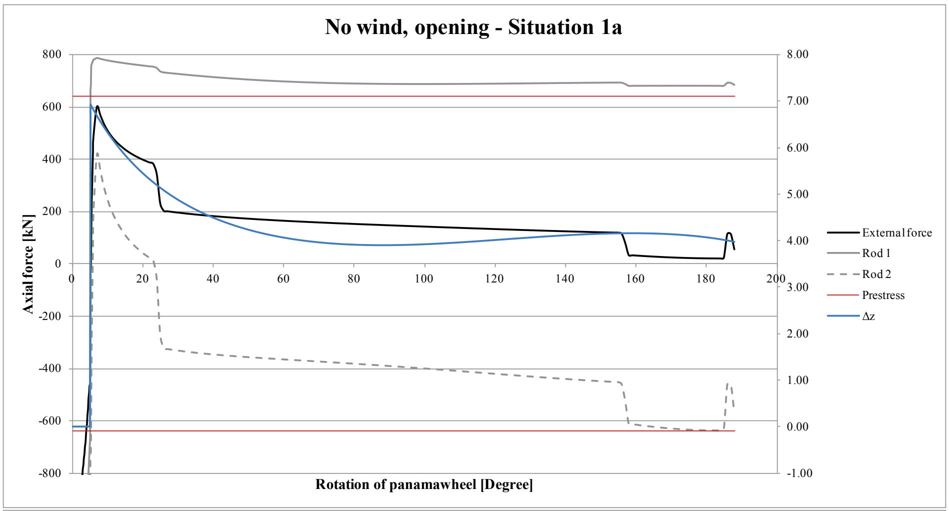
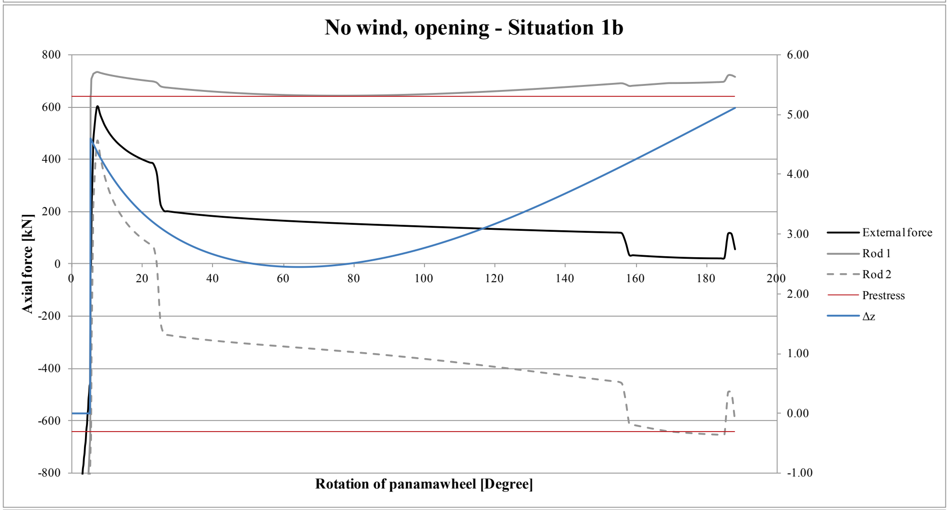
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz


Positive wind, opening - Situation 3a
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz

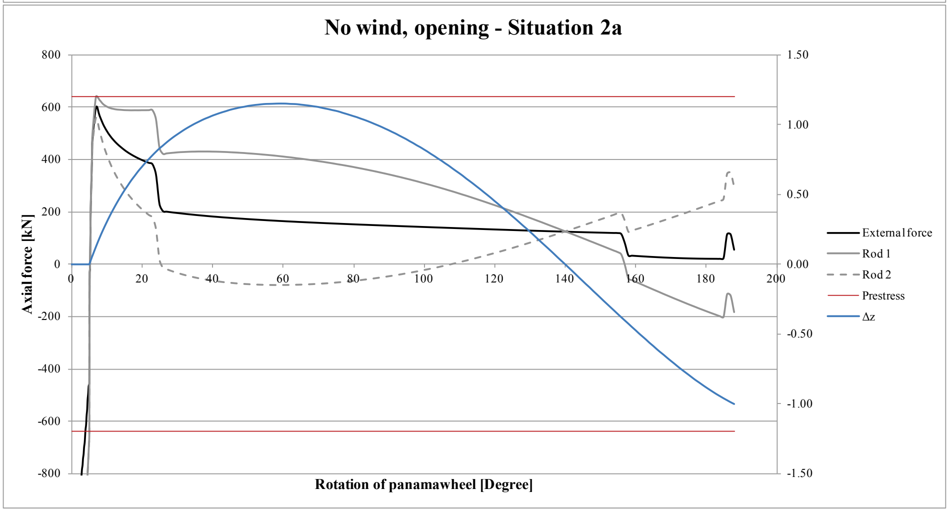

Positive wind, opening - Situation 3b
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz



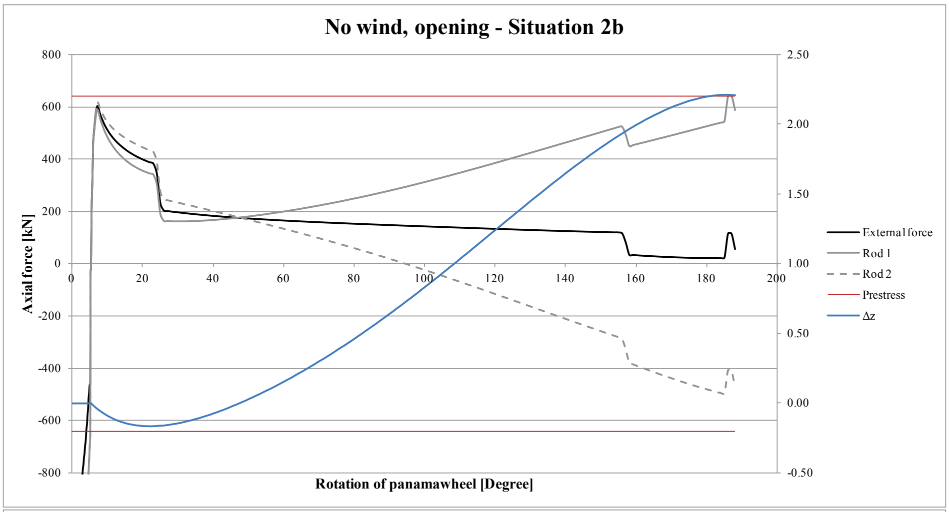
No wind, opening - Situation 1a
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz



No wind, opening - Situation 1b
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz



No wind, opening - Situation 2a
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz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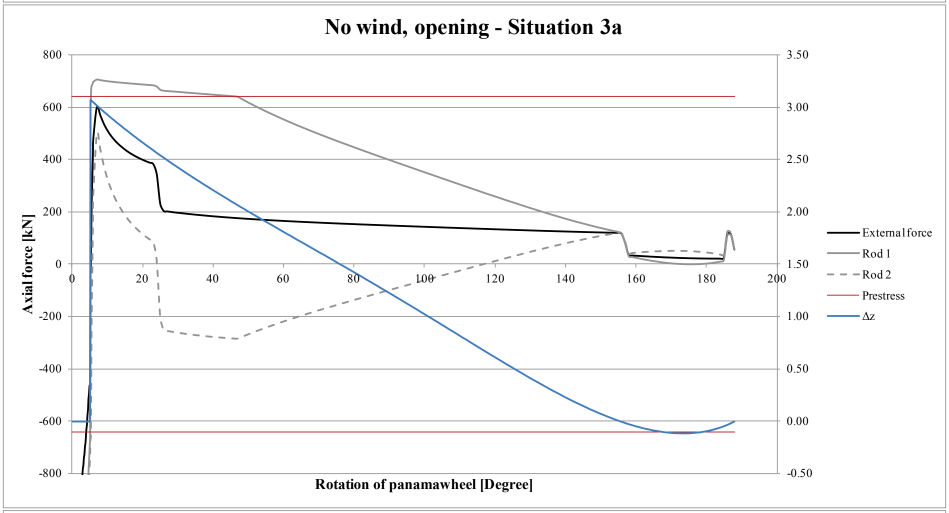
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz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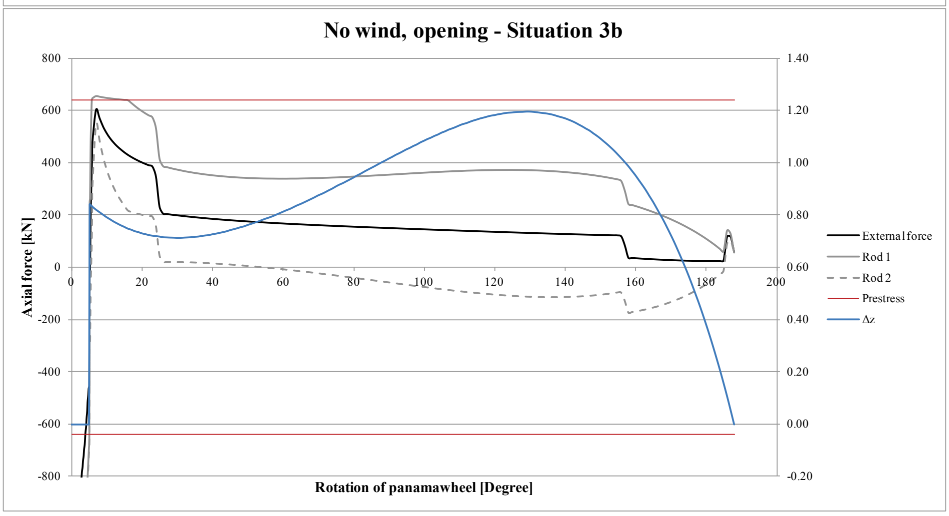
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz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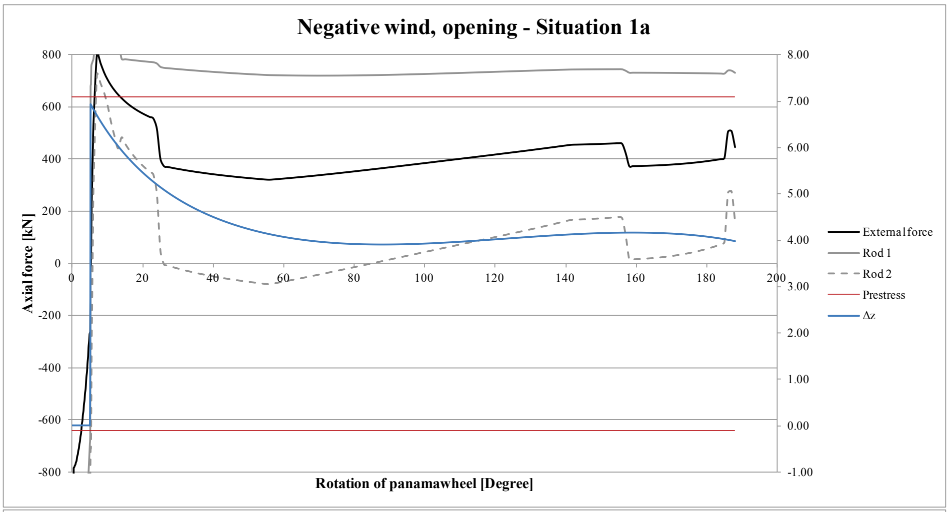
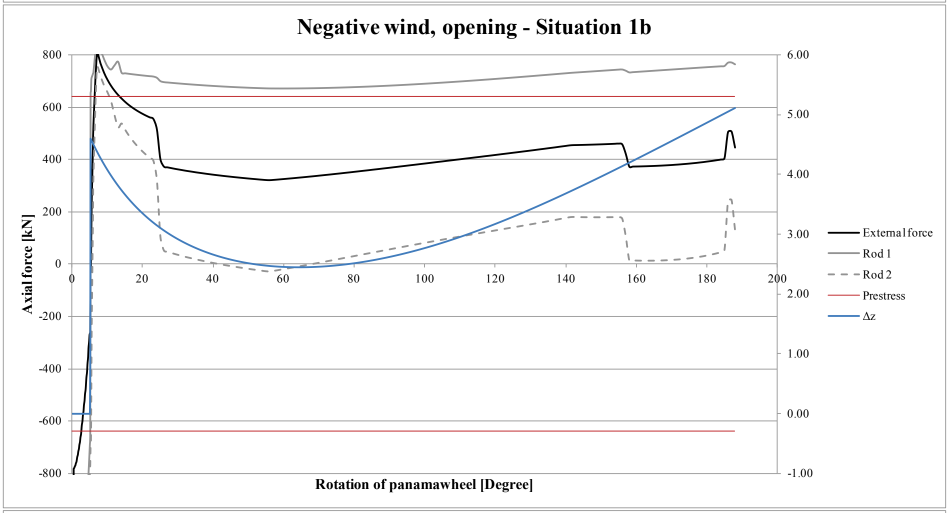
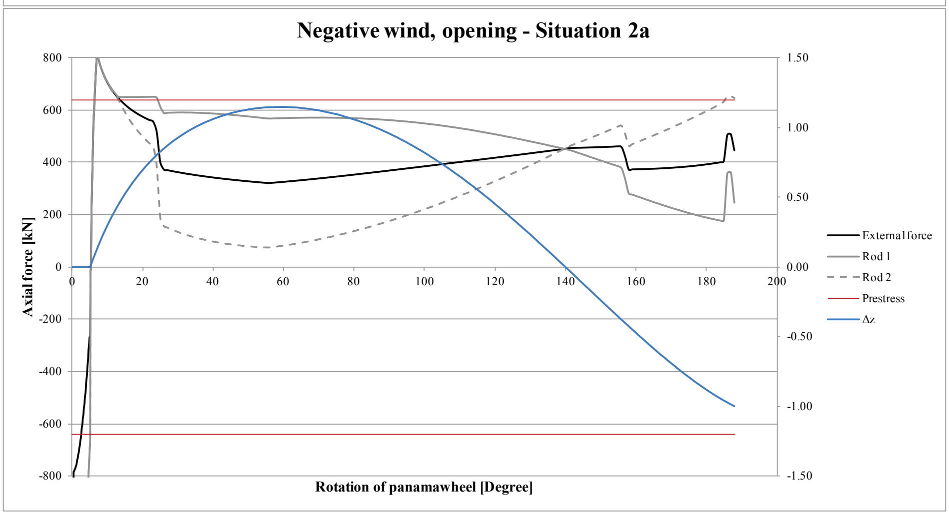
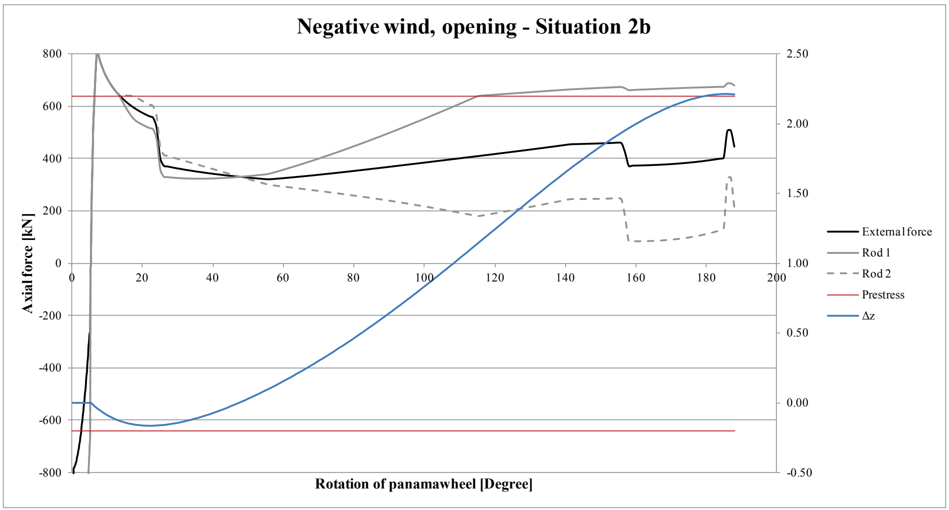
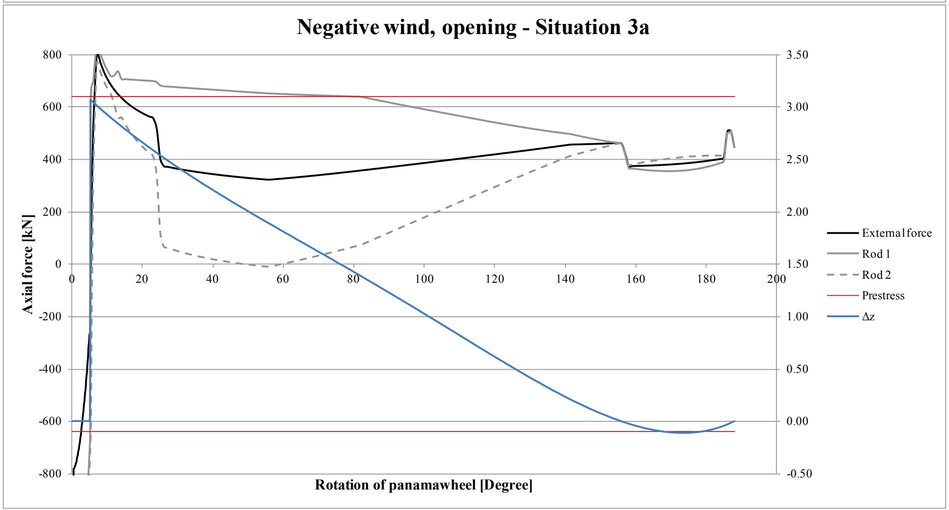
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz

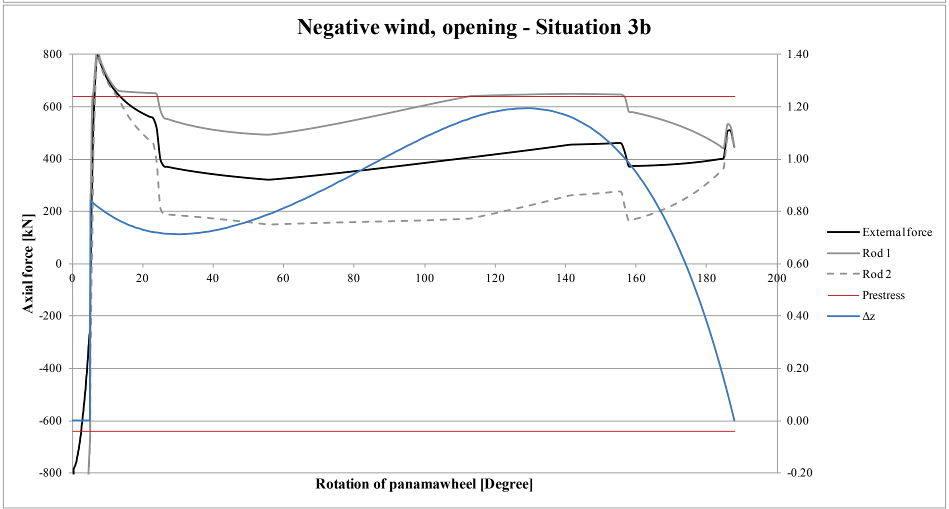

Negative wind, opening - Situation 1a
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz

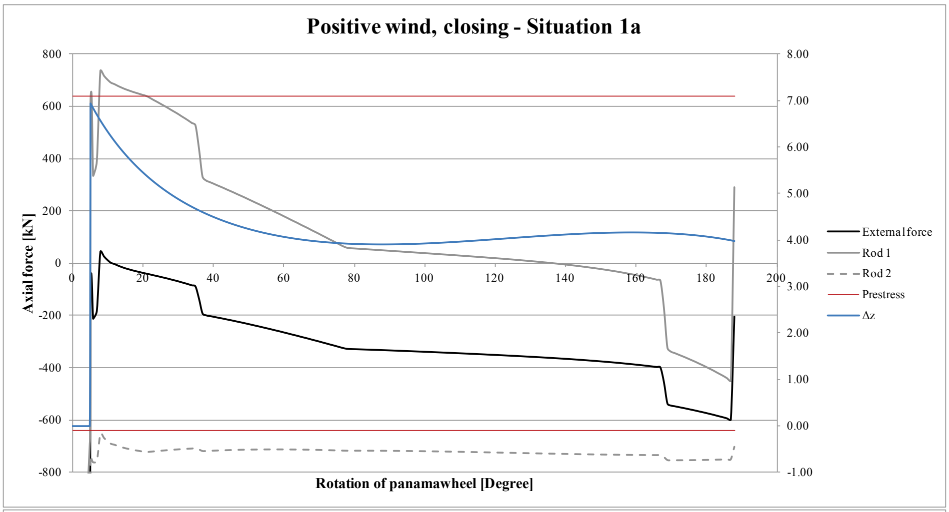

Negative wind, opening - Situation 1b
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz

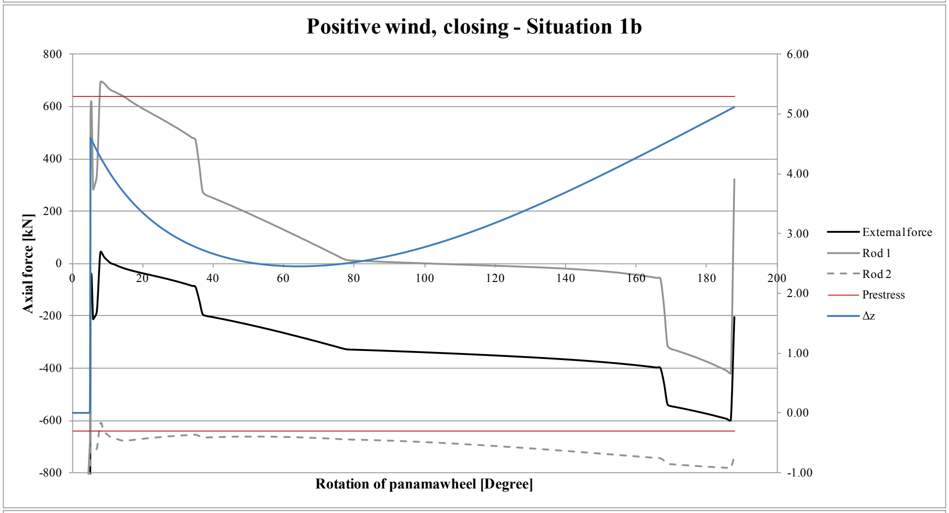

Negative wind, opening - Situation 2a
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz


Negative wind, opening - Situation 2b
Axial force [kN]
800
600
400
200
0
-200
-400
-600
-800
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
0
20
40
60
80
100
120
140
160
180
200
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz


Negative wind, opening - Situation 3a
Axial force [kN]
800
600
400
200
0
-200
-400
-600
-800
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
0
20
40
60
80
100
120
140
160
180
200
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz


Negative wind, opening - Situation 3b
Axial force [kN]
800
600
400
200
0
-200
-400
-600
-800
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
0
20
40
60
80
100
120
140
160
180
200
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz


Positive wind, closing - Situation 1a
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz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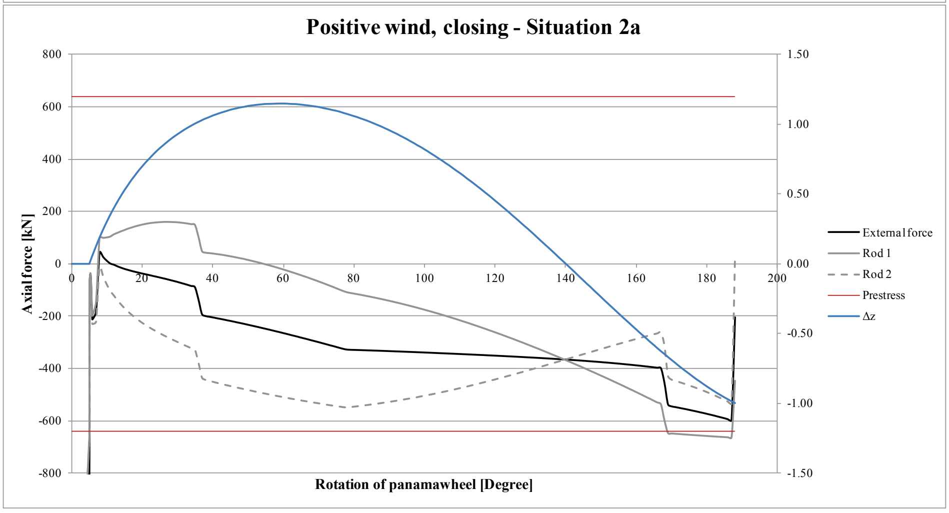
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz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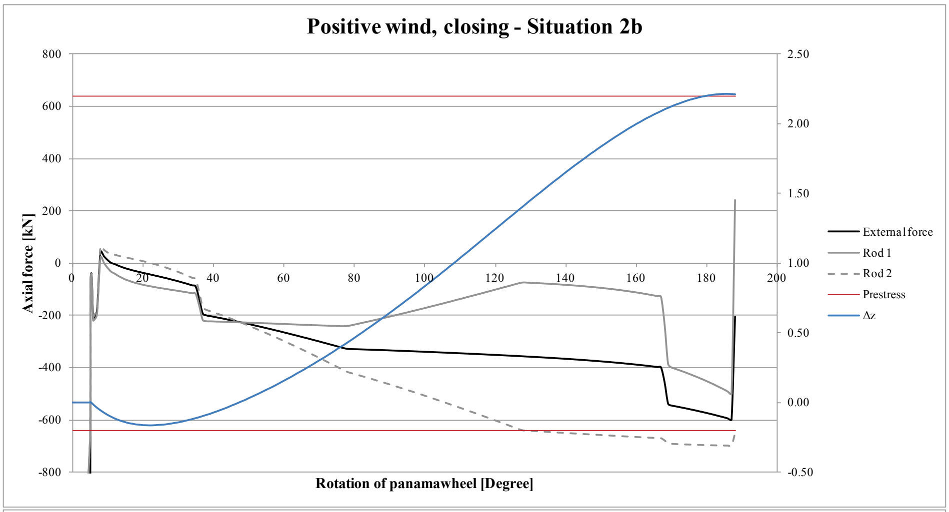
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz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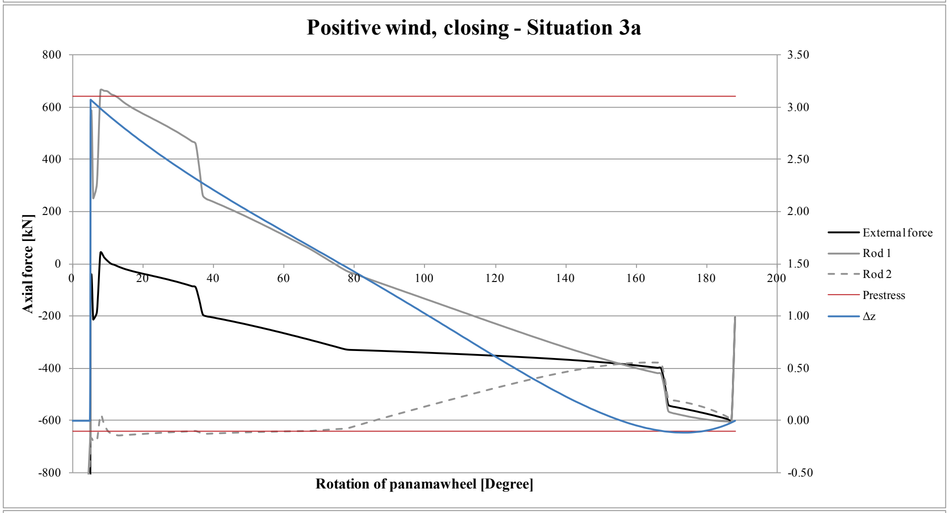
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz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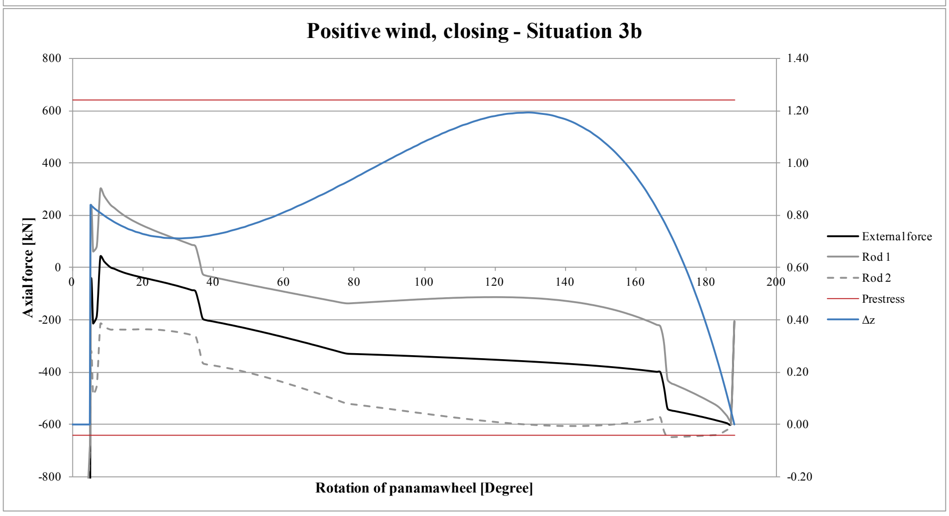
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz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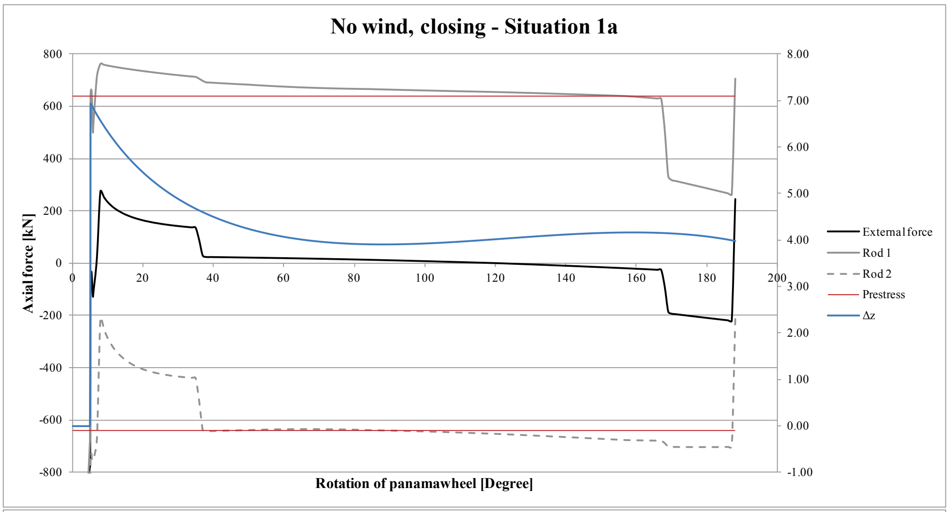
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz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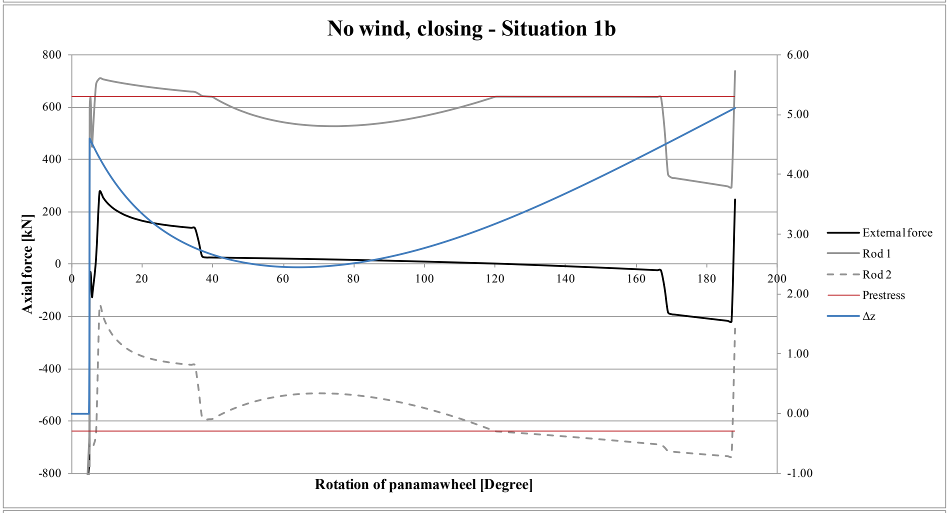
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz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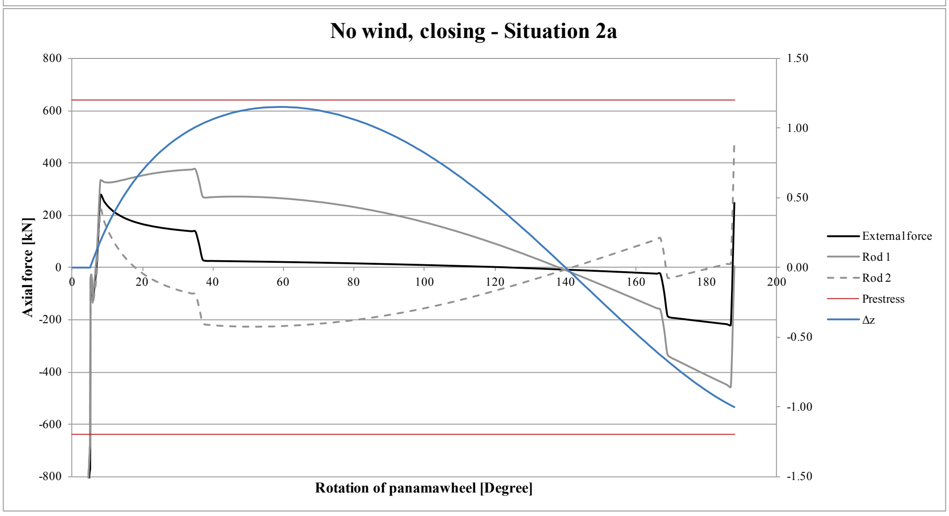
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz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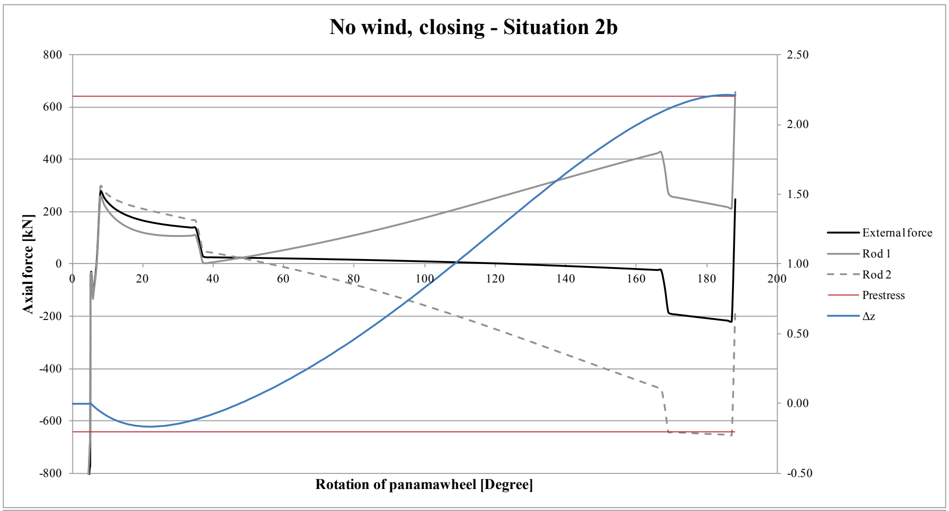
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz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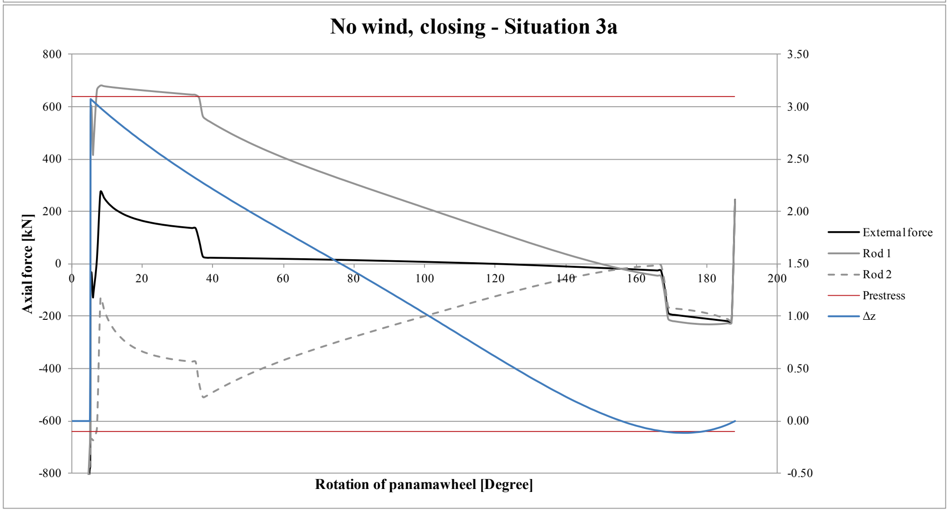
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz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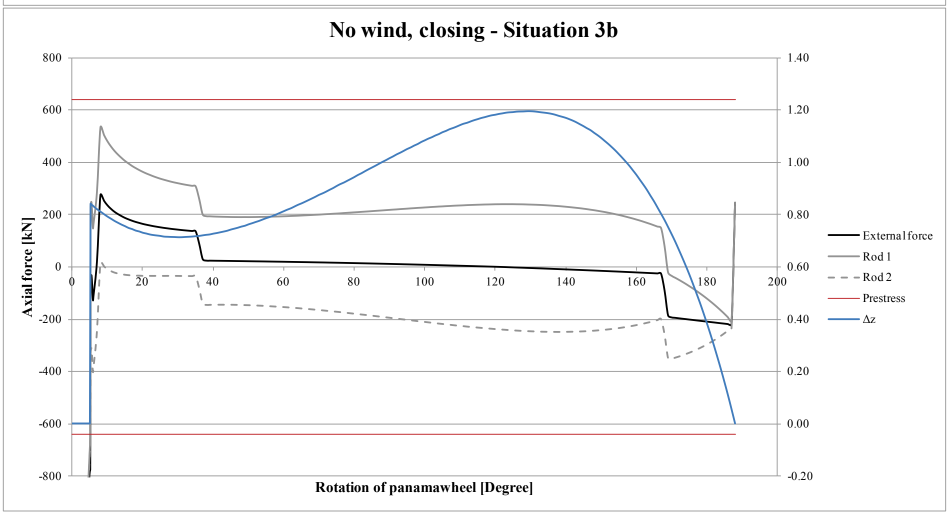
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz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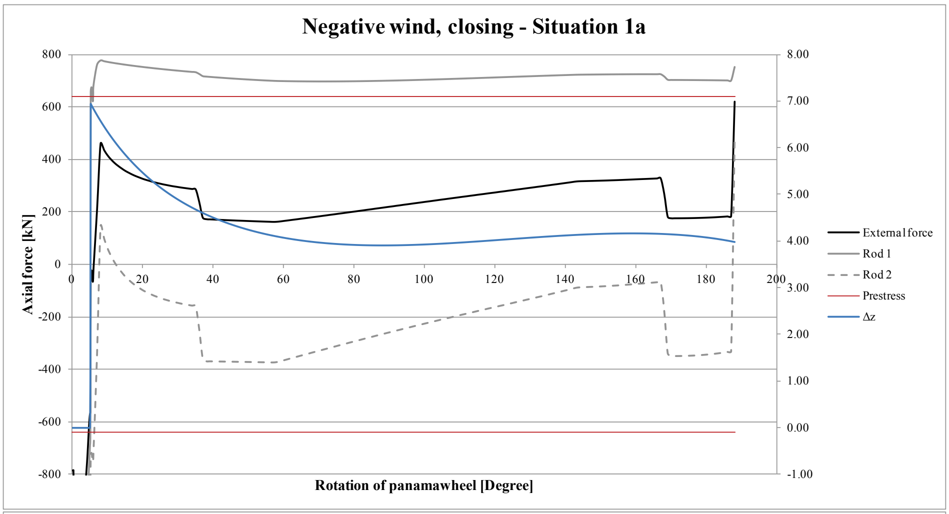
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz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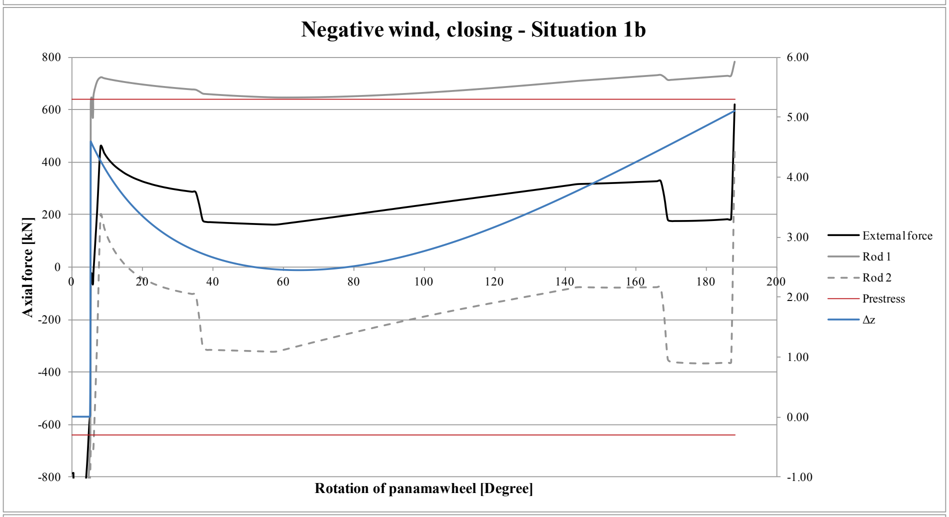
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz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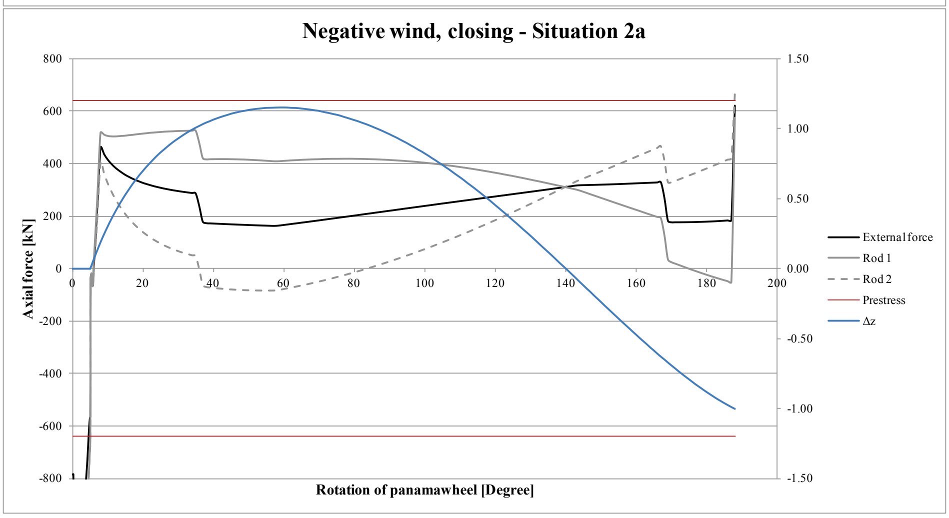
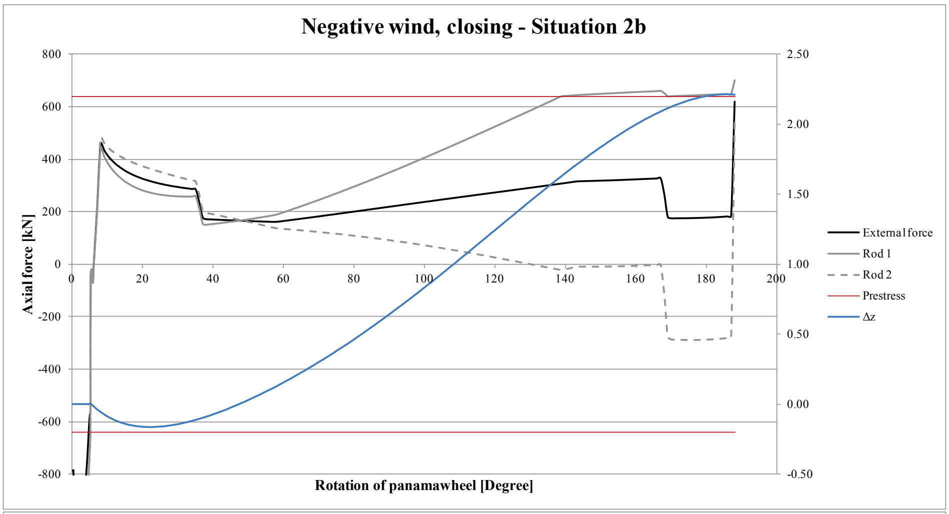
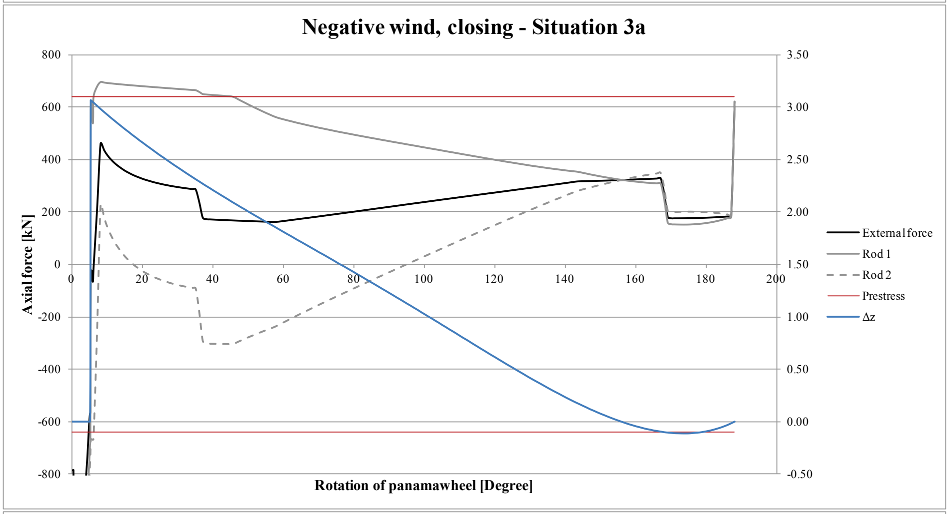
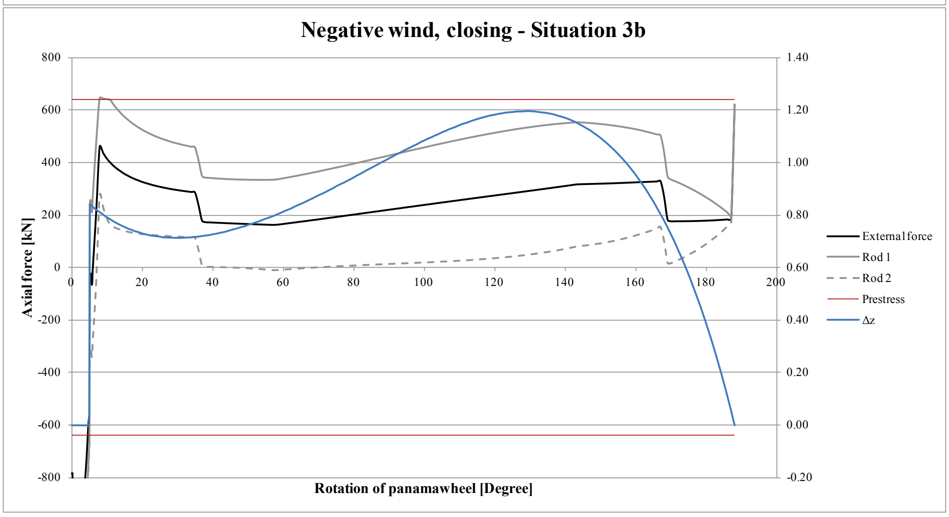
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz

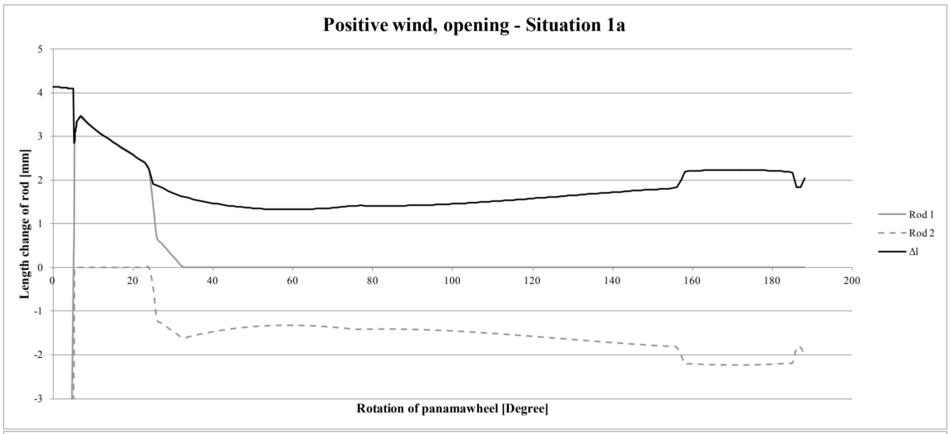

Negative wind, closing - Situation 2a
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz

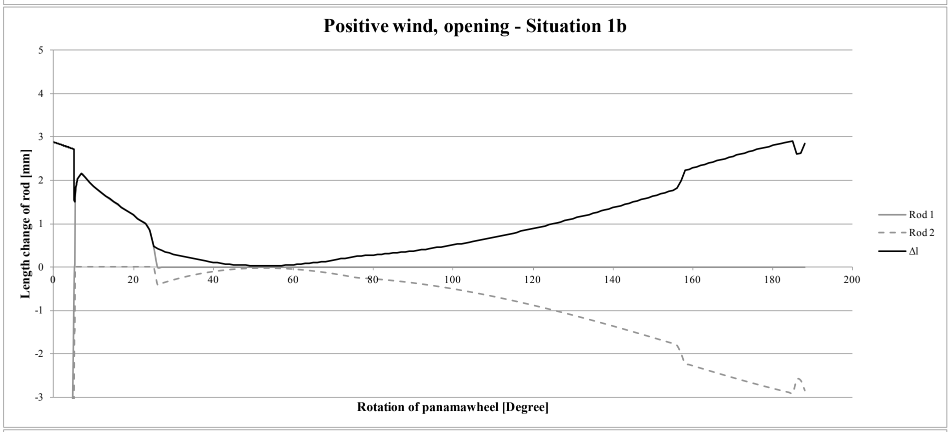

Negative wind, closing - Situation 2b
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz

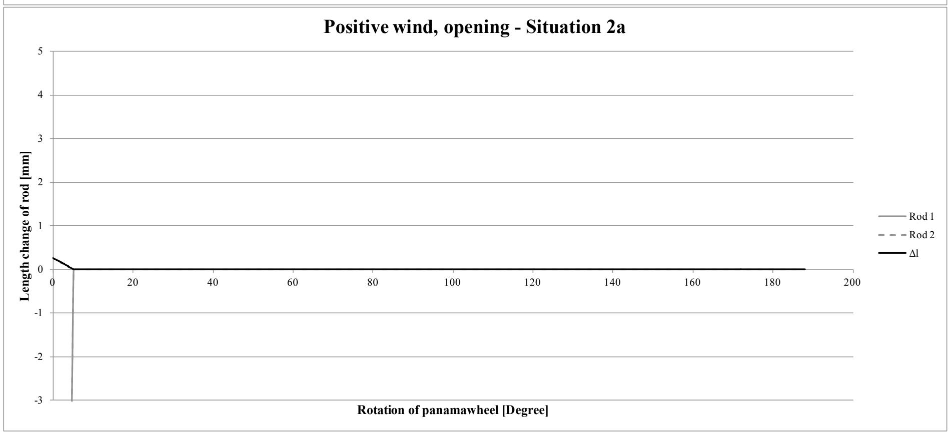

Negative wind, closing - Situation 3a
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz

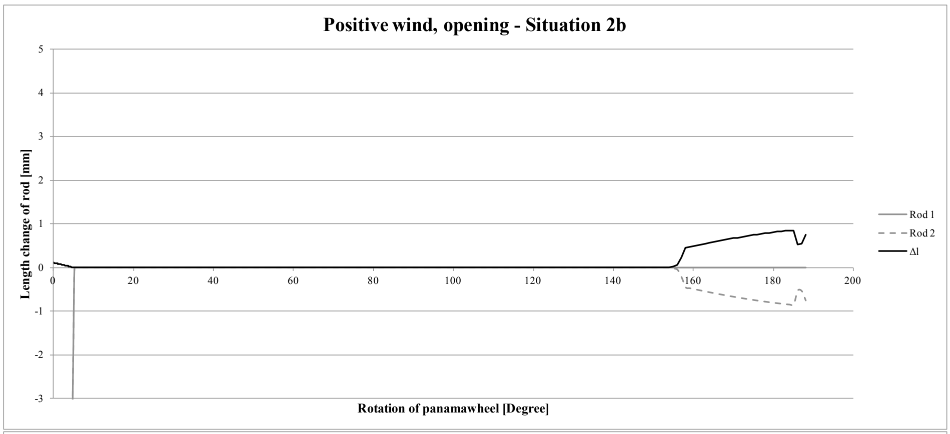

Negative wind, closing - Situation 3b
Axial force [kN]
Rotation of panamawheel [Degree]
External force
Rod 1
Rod 2
Prestress
Δz

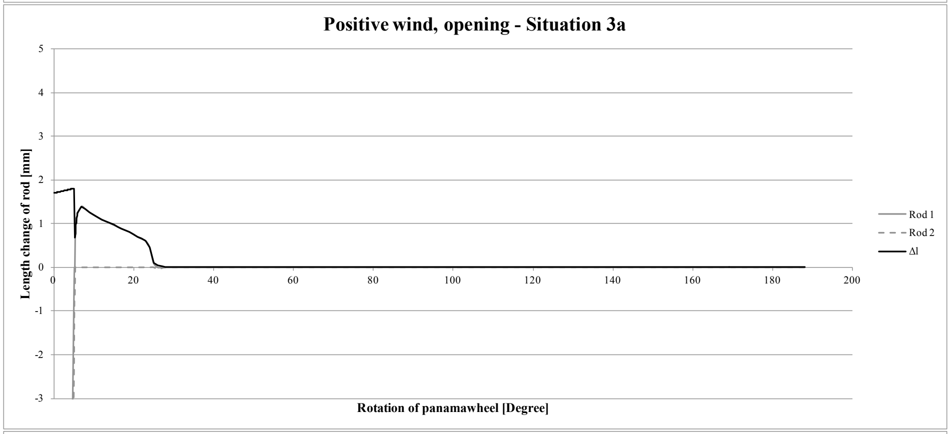
Length change of rods

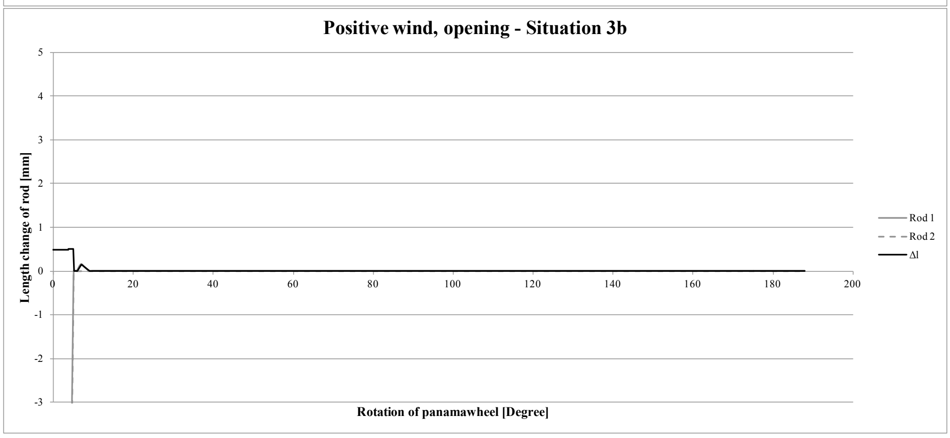


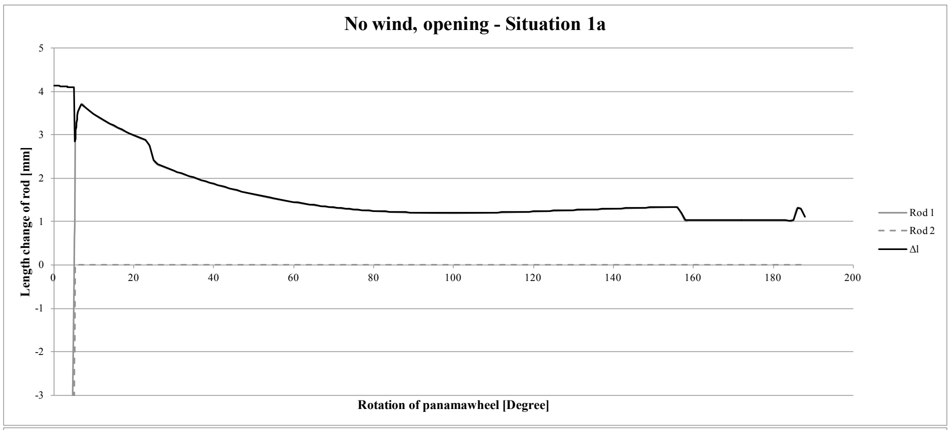


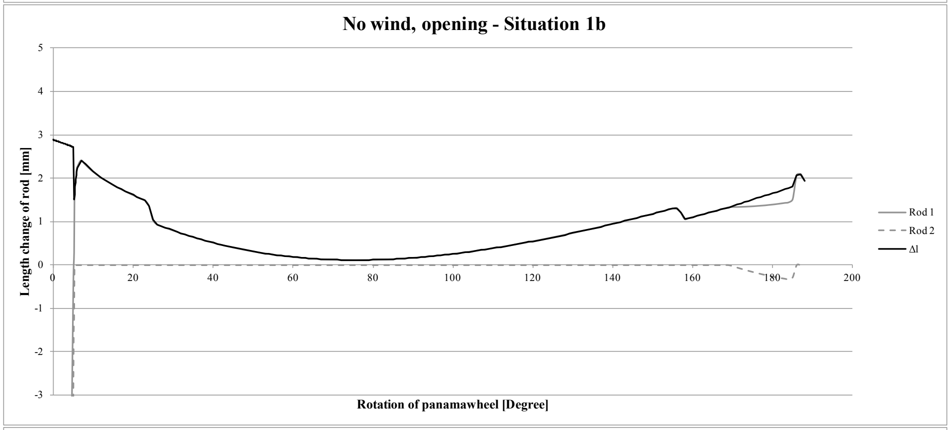


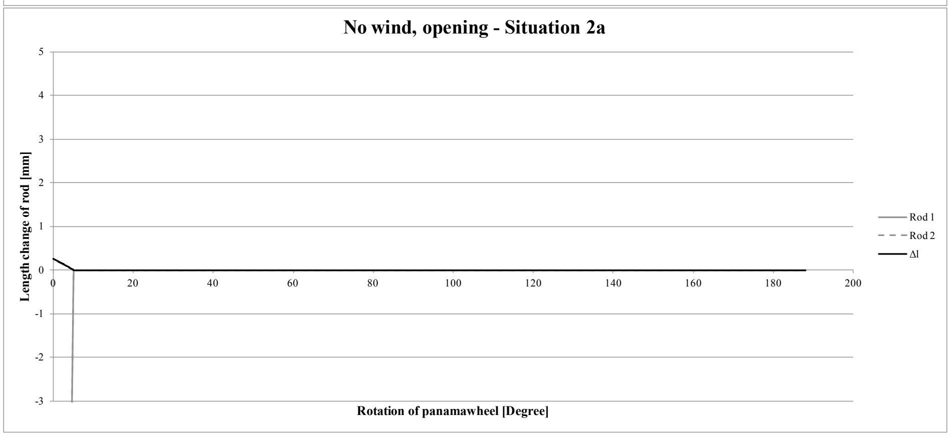

Positive wind, opening - Situation 2b
Length change of rod [mm]
Rotation of panamawheel [Degree]
Rod 1
Rod 2
Δl

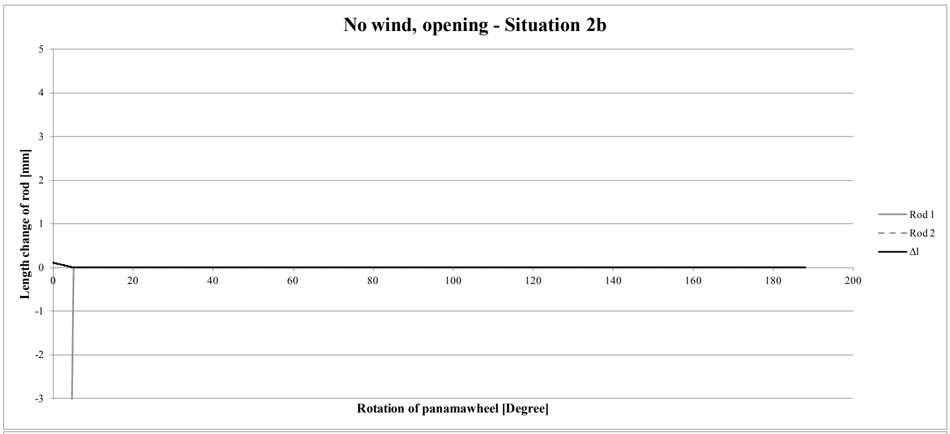

Positive wind, opening - Situation 3a
Length change of rod [mm]
Rotation of panamawheel [Degree]
Rod 1
Rod 2
Δl


Positive wind, opening - Situation 3b
Length change of rod [mm]
Rotation of panamawheel [Degree]
Rod 1
Rod 2
Δl


No wind, opening - Situation 1a
Length change of rod [mm]
Rotation of panamawheel [Degree]
Rod 1
Rod 2
Δl


No wind, opening - Situation 1b
Length change of rod [mm]
Rotation of panamawheel [Degree]
Rod 1
Rod 2
Δl


No wind, opening - Situation 2a
Length change of rod [mm]
Rotation of panamawheel [Degree]
Rod 1
Rod 2
Δl


No wind, opening - Situation 2b
Length change of rod [mm]
Rotation of panamawheel [Degree]
Rod 1
Rod 2
Δl
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0
-1
-2
-3
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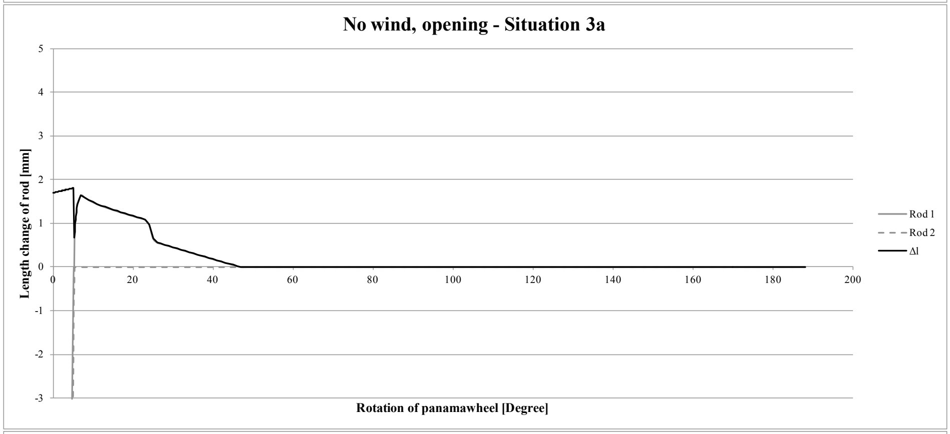
No wind, opening - Situation 3a
Length change of rod [mm]
Rotation of panamawheel [Degree]
Rod 1
Rod 2
Δl
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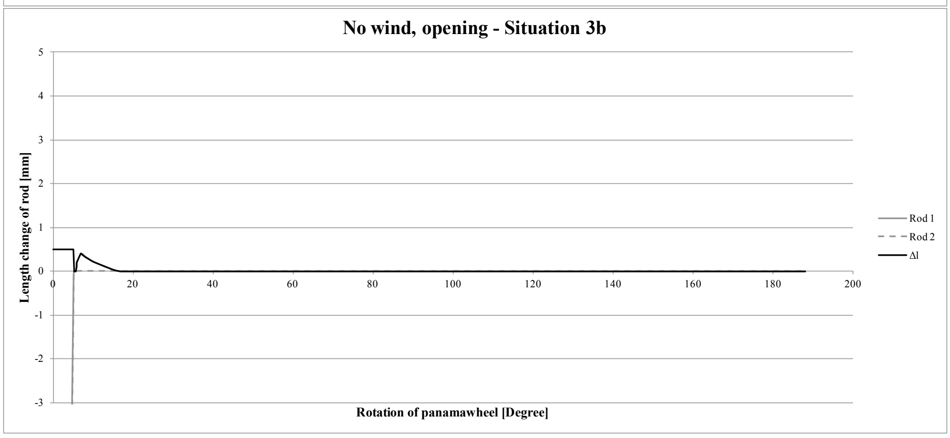
No wind, opening - Situation 3b
Length change of rod [mm]
Rotation of panamawheel [Degree]
Rod 1
Rod 2
Δl
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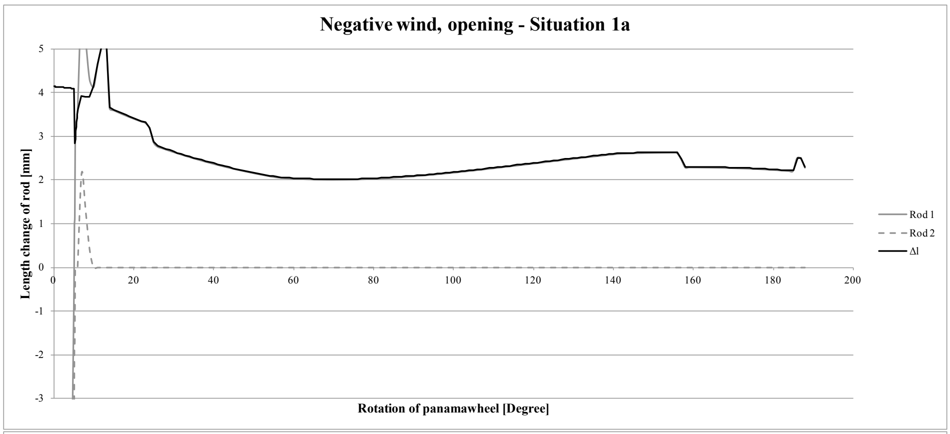
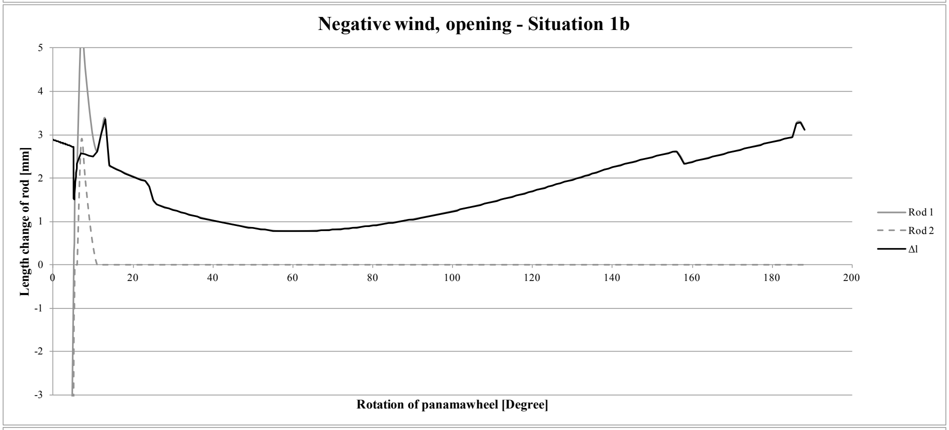
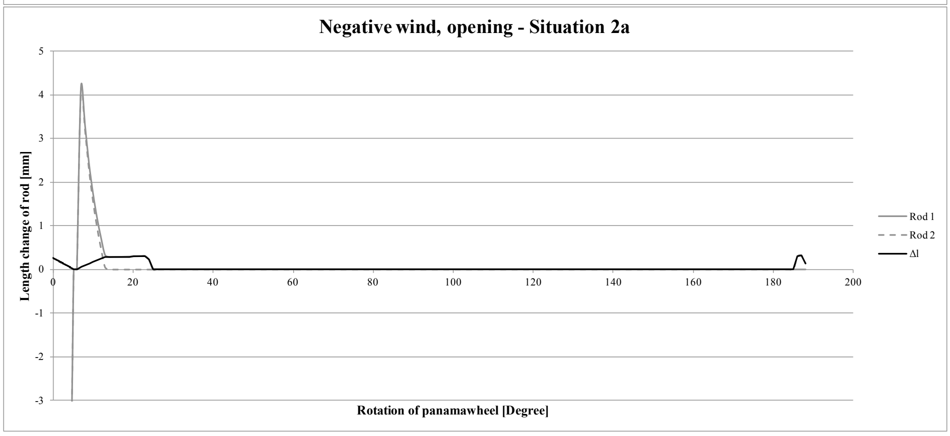

Negative wind, opening - Situation 1a
Length change of rod [mm]
Rotation of panamawheel [Degree]
Rod 1
Rod 2
Δl


Negative wind, opening - Situation 1b
Length change of rod [mm]
Rotation of panamawheel [Degree]
Rod 1
Rod 2
Δl


Negative wind, opening - Situation 2a
Length change of rod [mm]
Rotation of panamawheel [Degree]
Rod 1
Rod 2
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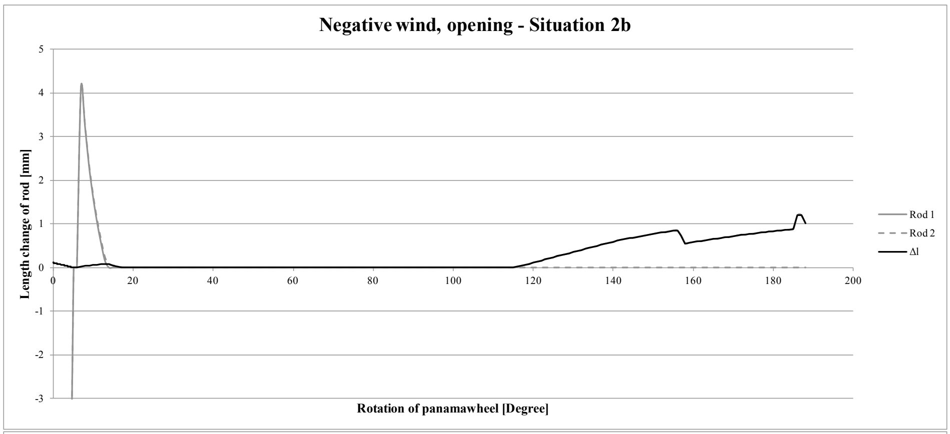
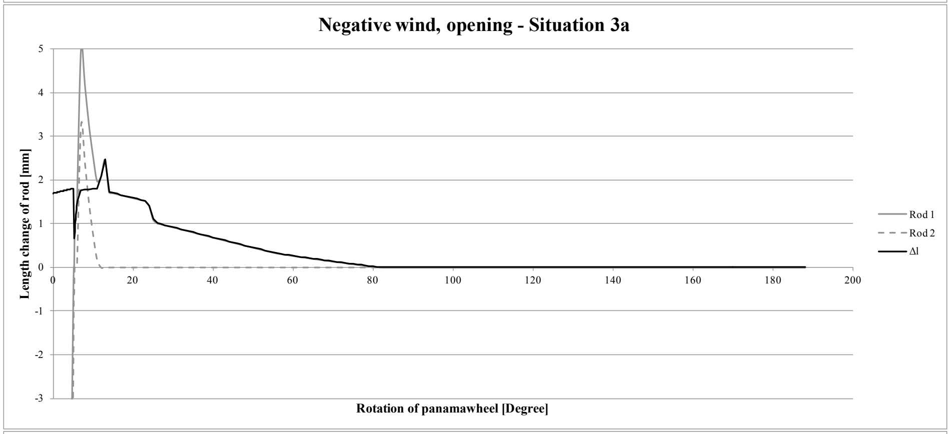


Negative wind, opening - Situation 2b
Length change of rod [mm]
Rotation of panamawheel [Degree]
Rod 1
Rod 2
Δl



Negative wind, opening - Situation 3a
Length change of rod [mm]
Rotation of panamawheel [Degree]
Rod 1
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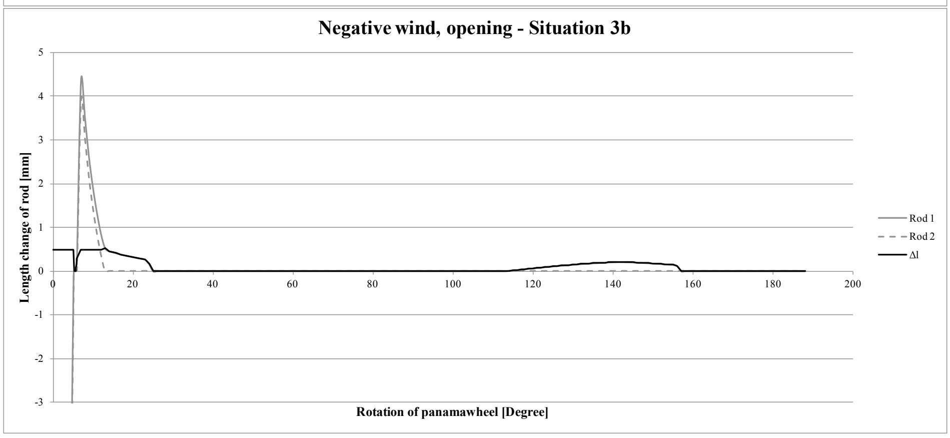

Negative wind, opening - Situation 3b
Length change of rod [mm]
Rotation of panamawheel [Degree]
Rod 1
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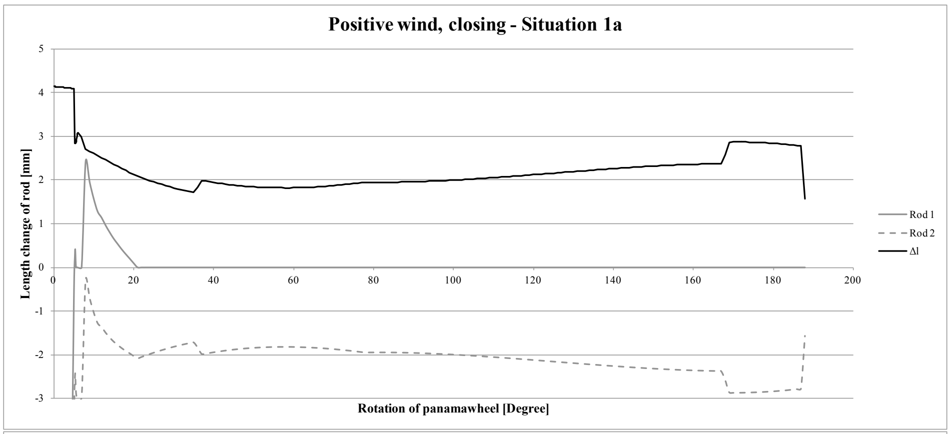
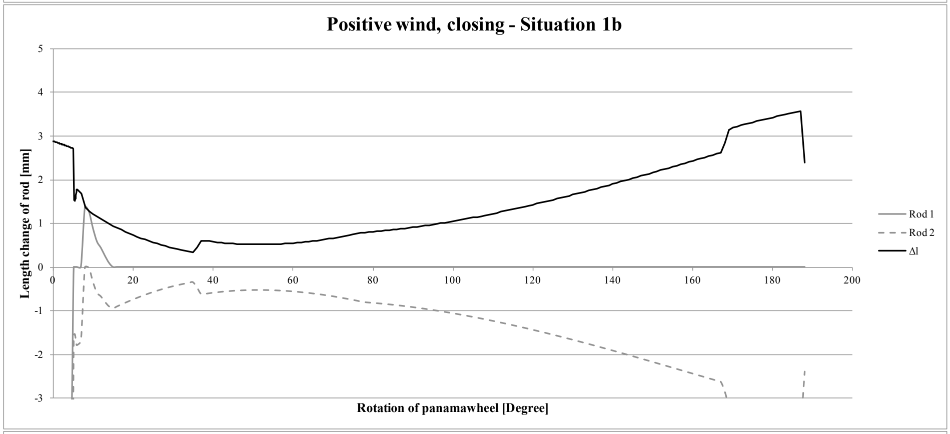

Positive wind, closing - Situation 1a
Length change of rod [mm]
Rotation of panamawheel [Degree]
Rod 1
Rod 2
Δl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Length change of rod [mm]
Rotation of panamawheel [Degree]
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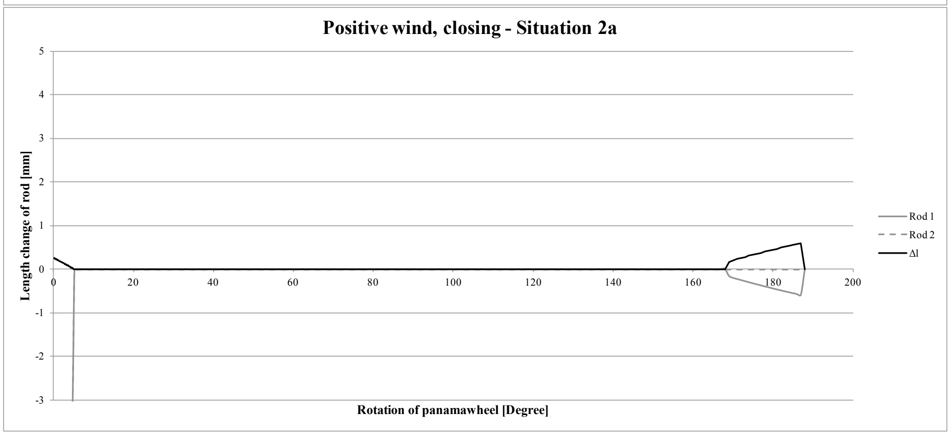
Δl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Length change of rod [mm]
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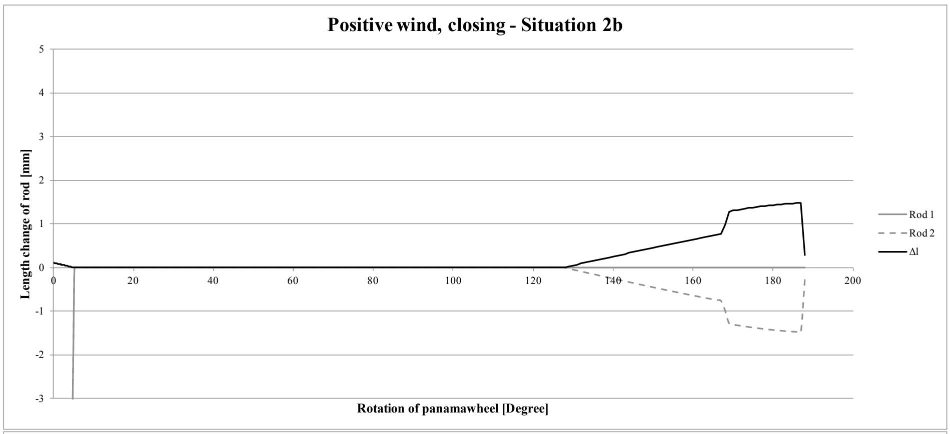
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Length change of rod [mm]
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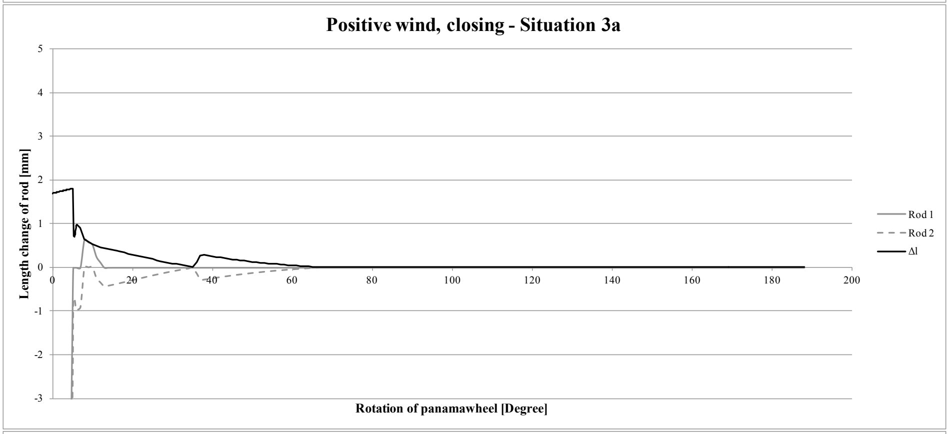
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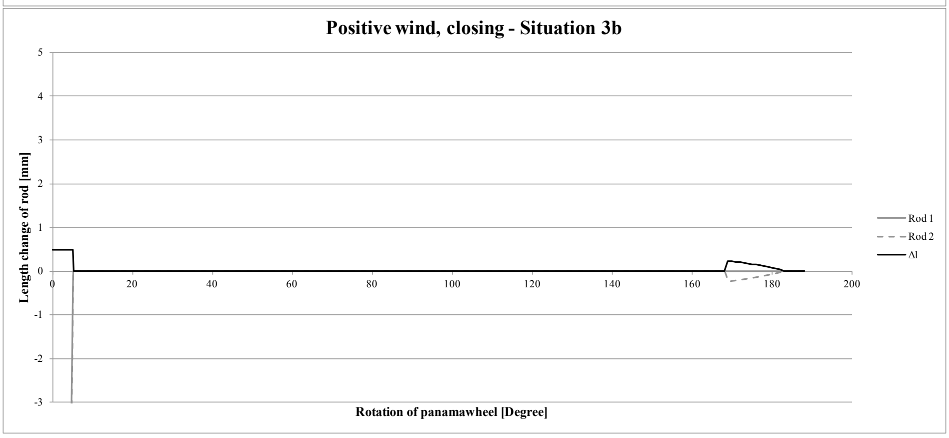
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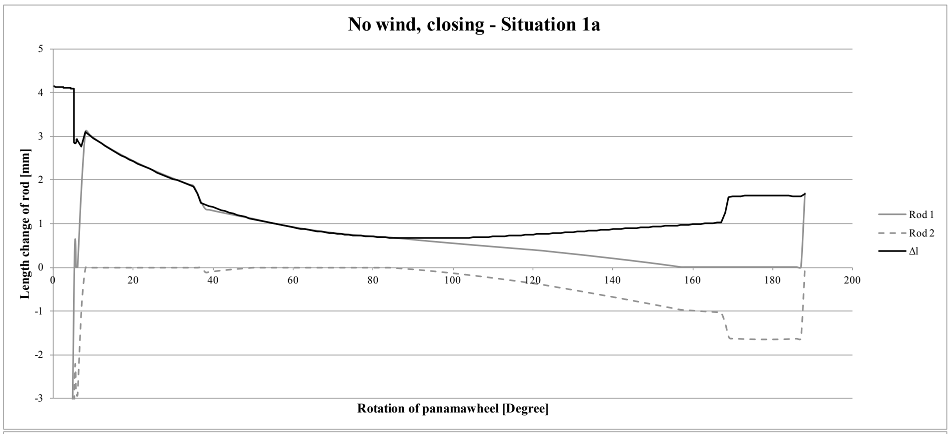
No wind, closing - Situation 1a
Length change of rod [mm]
Rotation of panamawheel [Degree]
Rod 1
Rod 2
Δl
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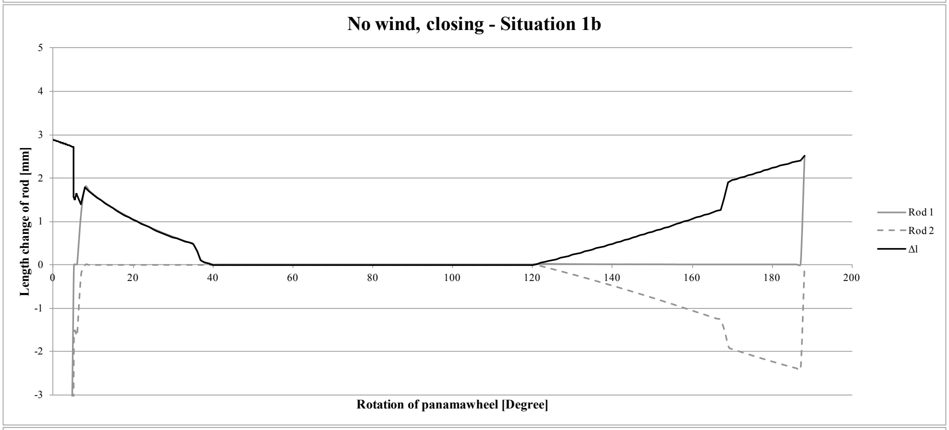
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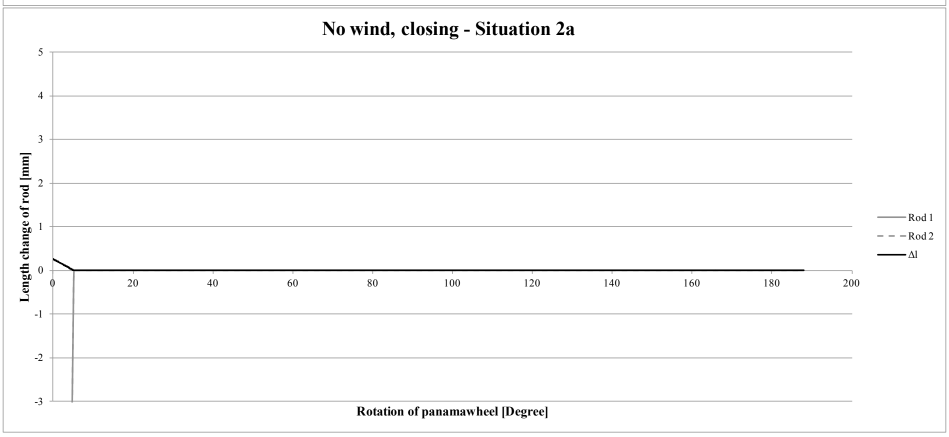
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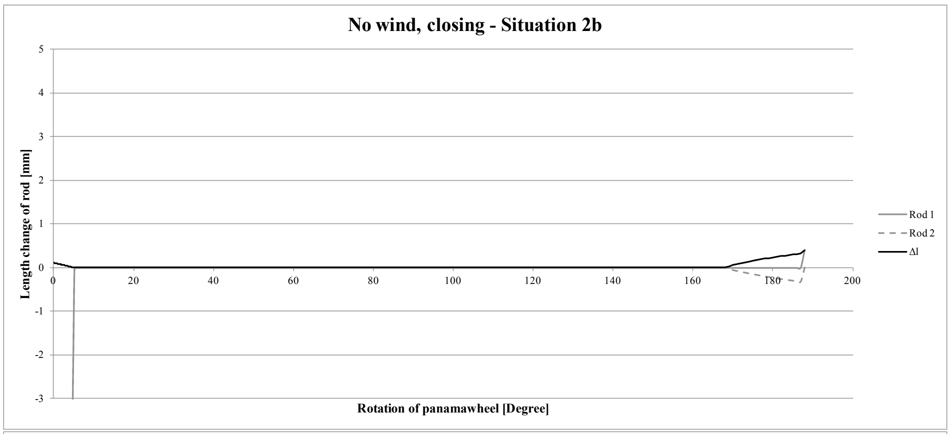
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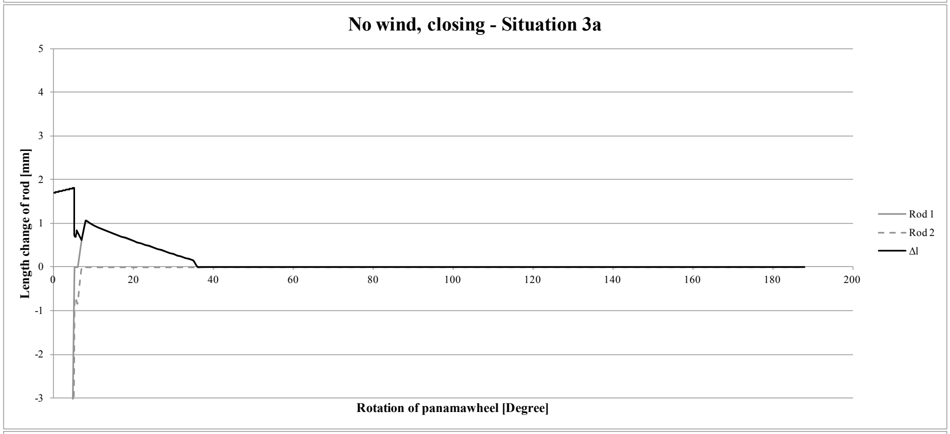
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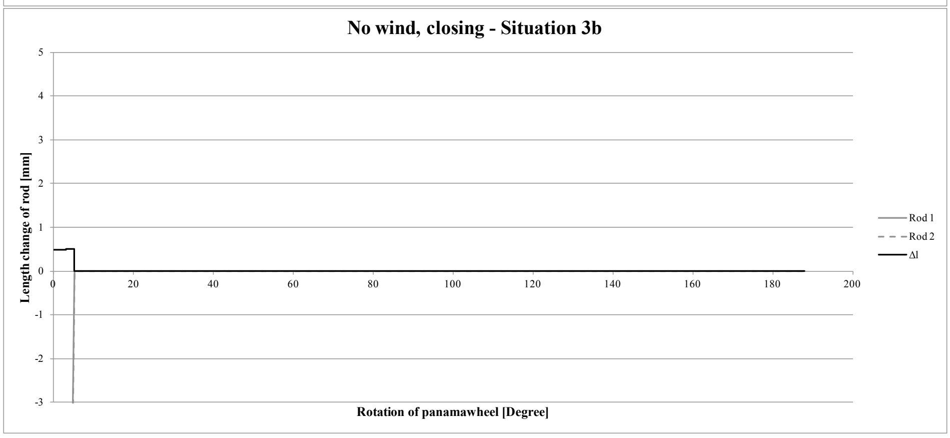
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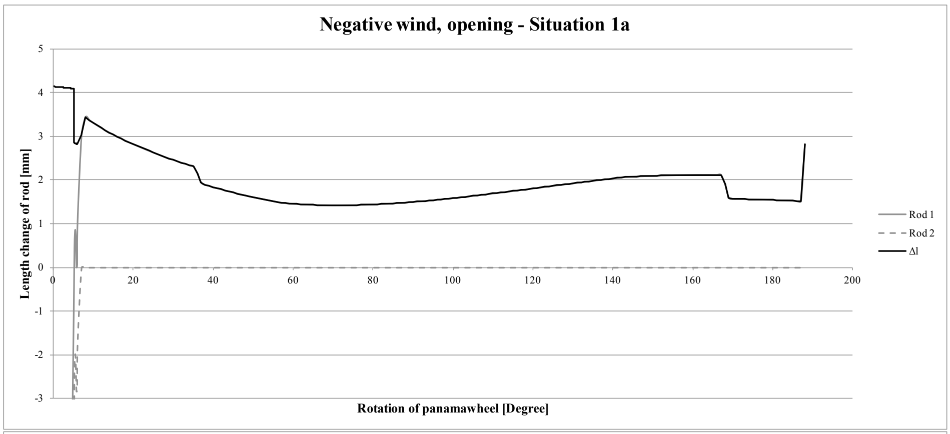
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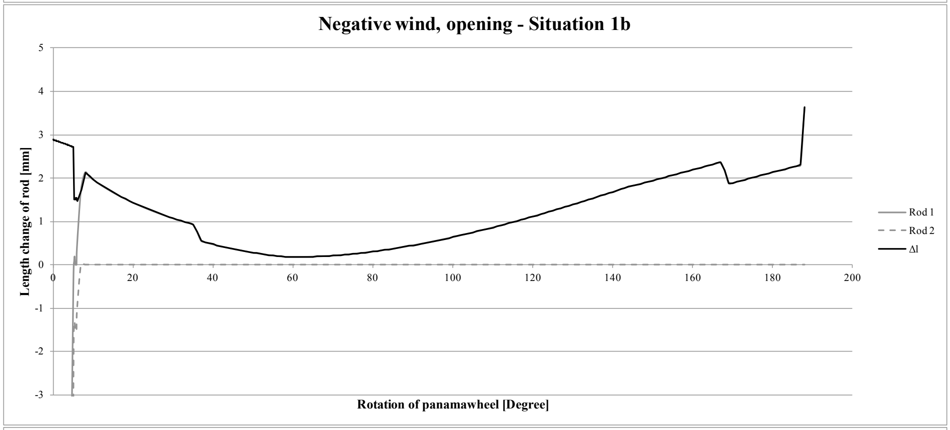
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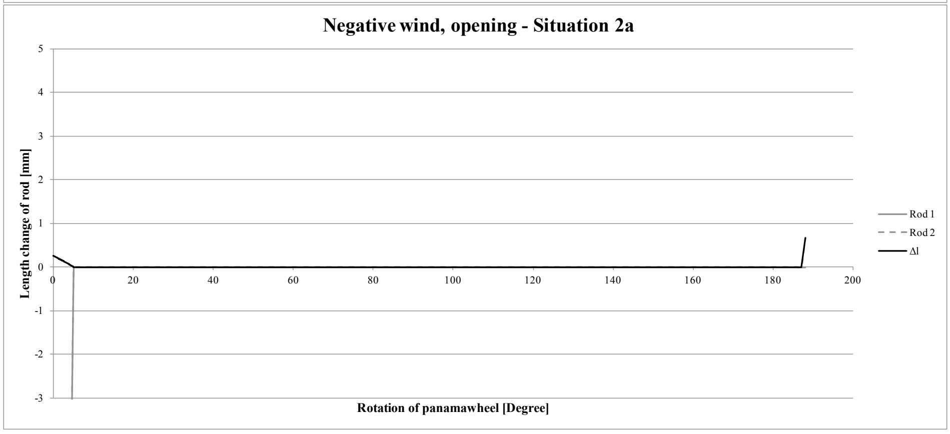
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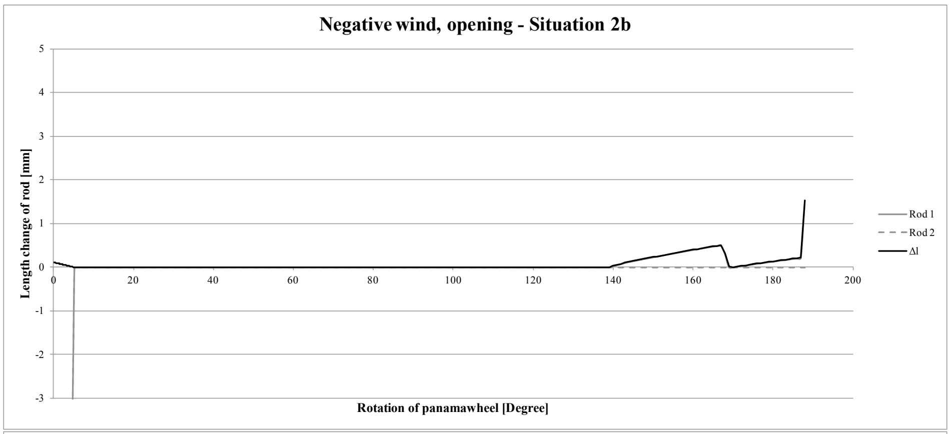
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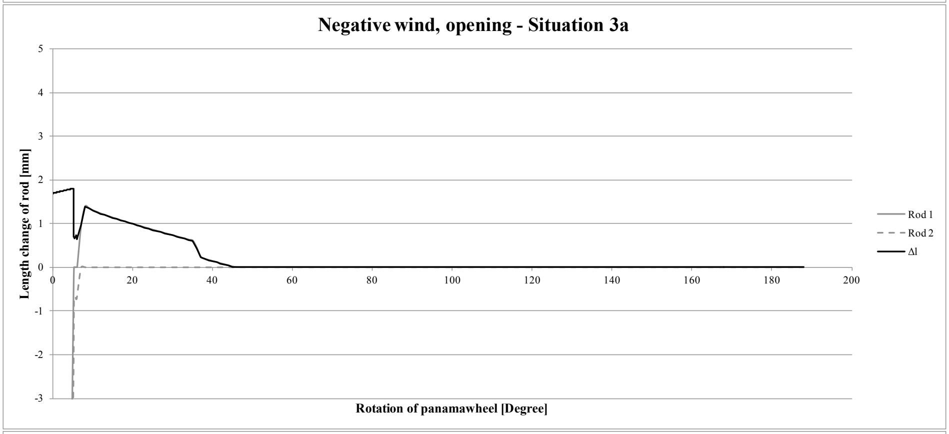
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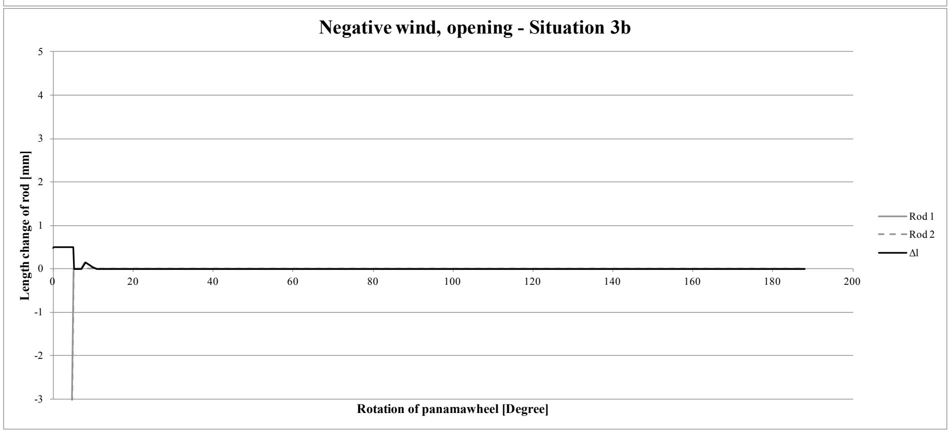
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