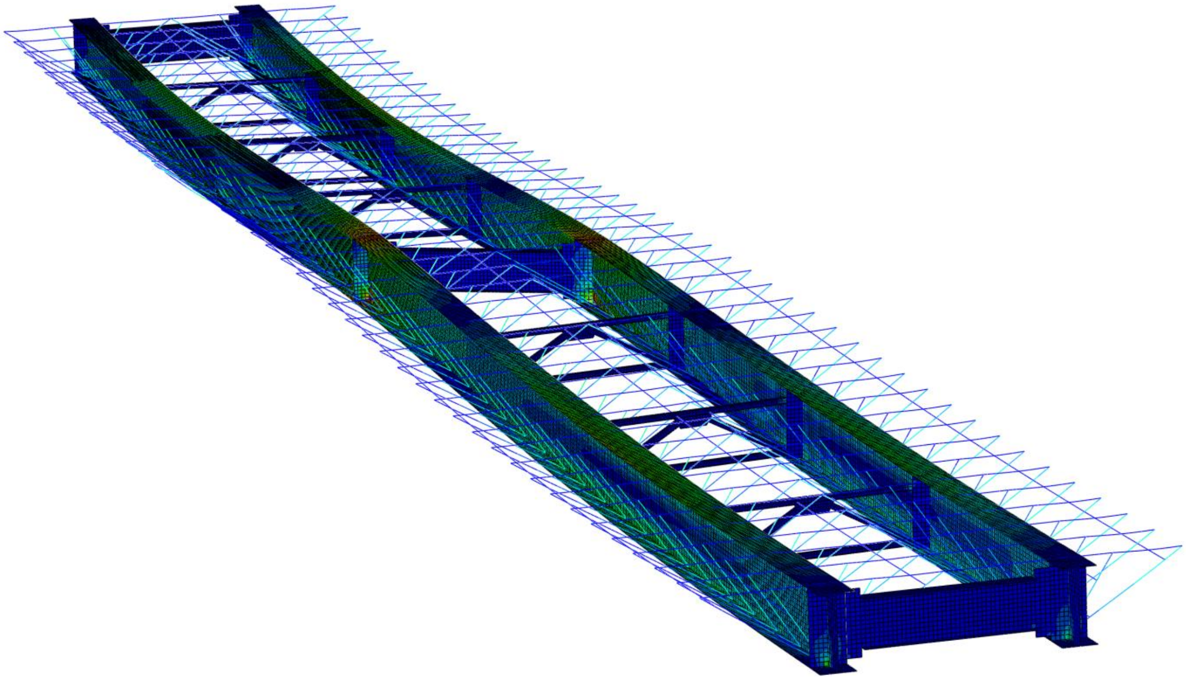
Division of Structural Engineering
Lund Institute of Technology, Lund University

Temporary formworks as torsional bracing system for steel-concrete composite bridges during concreting of the deck



ANDREAS WINGE

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Temporary formworks as torsional bracing system for steel-concrete composite bridges during concreting of the deck

Master's thesis by:
Andreas Winge

Supervisor:
Hassan Mehri, PhD Student
Div. of Structural Engineering

Examiner:
Roberto Crocetti, Prof.
Div. of Structural Engineering

Lunds University
Division of Structural Engineering
P.O. Box 118
SE-221 00 Lund, Sweden
www.kstr.lth.se

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The idea for the work performed herein comes from my supervisor Hassan Mehri's ongoing PhD project, where temporary formworks are experimentally examined as a potential bracing source against lateral torsional buckling. Therefore I was allowed to use the same dimensions as his test setup.

I wish to thank all people I have been in contact with during my investigation and research. Many of whom I've never met but who has each contributed to make this work possible.

I especially want to thank Hassan Mehri, who has been there helping me, answering my questions and giving me guidance. Without him the work achieved herein would have been much harder and I wish Hassan the best of luck in his future research.

With this thesis completed the last task has been done and my time at LTH is over. It has been a long journey but still rewarding in so many ways. Thanks to all friends I have and also to all people I have met for making these years memorable!

Andreas Winge

Lund 2014

ABSTRACT

A critical stage for the construction of steel-concrete composite bridges occurs during casting of the bridge deck, when the wet concrete has still not hardened. The entire construction load is then taken by the non-composite steel sections. Bracing may be needed to make the slender girders rigid enough to resist lateral torsional buckling during this phase. If temporary formwork could be attached and be shown to work as torsional bracing; material could be saved and the construction phase could be safer.

Within this thesis some of the commonly used temporary formworks are described and analyzed to see if some of them could work as discrete torsional bracing. Findings from this investigation were that the often used formwork system CUPLOK was easy and suitable to be modified and attached to the girders as discrete torsional bracing.

With the modified CUPLOK system attached, three different systems were numerically analyzed using the finite element program Abaqus. One with formwork attached to a laboratory test beam set-up with dimensions according to Mehri and two on real bridges with trapezoidal respective I-girder cross section.

Findings from analyzes were that with the modified CUPLOK system attached, the stiffness were increased dramatically on the slender I-girder system and also, but relatively less, on the less slender real bridge I-girder system. No stiffening effect was shown on the specific trapezoidal cross section analyzed herein.

Finally the findings are discussed and further research proposed.

KEYWORDS:
BRACING, BRIDGE GIRDERS, CONCRETING, STABILIZING, TEMPORARY FORMWORKS

LIST OF ABBREVIATIONS

Abbreviations

FE	Finite element
FEA	Finite element analysis
FEM	Finite element method
LTB	Lateral torsional buckling
UDL	Uniformly distributed load

Latin letters

C_w	Warping constant
E	Modulus of elasticity
G	Shear modulus
I_z	Moment of inertia around the weak axis
J	Torsional constant
L_b	Buckling length
M_{cr}	Critical moment
M_p	Plastic moment capacity

CONTENTS

1 INTRODUCTION

1.1 BACKGROUND

For steel-concrete composite bridges a critical design stage occurs during casting of the concrete deck, when the non-composite steel girders must carry the entire construction load, including the self-weight of wet concrete (Mehri & Crocetti, 2012). In this type of bridges, either a temporary or permanent formwork system is normally needed to transfer the construction loads to the steel girders.

These temporary formworks are not attached and have therefore no bracing effect. Permanent bracing are needed to make the slender girders capable enough to resist lateral torsional buckling during concreting. If temporary formwork could be attached and be shown to work as torsional bracing; material could be saved and the construction phase could be safer.

1.2 PURPOSE

The purpose is defined by the following:

- Describe and compare some of the worlds most used temporary formworks.
- Analyze the most suitable one and check if it can be modified and adapted to serve as discrete torsional bracing.
- See if the chosen system has any stabilizing effect if applied as discrete bracing to steel-concrete composite bridges.

1.3 OBJECTIVE

The main objective of this thesis is to investigate the use of temporary formworks as discrete torsional bracings.

1.4 SCOPE

This thesis concerns numerical analyses to investigate the effect of commonly used formworks on improving the lateral torsional resistance against buckling for steel-concrete composite bridges. However, even if modifications to the formworks are mentioned and necessary to be able to attach the formworks to the girders, those alterations are not part of this thesis.

To delimit the thesis only one type of formwork will be subjected to a more detailed numerical analysis, after that different solutions has been evaluated. That system will be analyzed on a laboratory test beam set-up, with dimensions according to Mehri's ongoing experimental work within his PhD project. The formwork system will then also be applied and analyzed on two real bridges.

1.5 OUTLINE OF THE REPORT

This report evaluates how one type of commonly used temporary formwork can be modified and adapted to serve as lateral torsional bracing during casting of the concrete in steel-concrete composite bridges. This system will be numerically tested and evaluated along with two other real-life steel-concrete composite bridges.

This report has been divided into the following chapters:

- **Introduction** – Opening chapter where a brief background is given as well as the purpose, objective, scope and outline of the report.
- **Used concepts** – Includes a short presentation of within the thesis used concepts.
- **Formwork systems** – Within this chapter different formwork systems are described and evaluated as torsional bracing.
- **Finite element modelling** – Here within the method of the analyses are described together with how the finite element modelling is performed.
- **Numerical analyses chapters** – Three chapters containing description, testing method and result for three different systems.
- **Conclusion** – Final conclusions are made and the purpose is answered.

2 LITERATURE REVIEW AND USED CONCEPTS

Within this chapter a literature review and a short presentation of, within this thesis, used concepts is done.

2.1 LITERATURE REVIEW

Lateral torsional buckling is a failure mode that involves lateral movement and twist of the girder cross section, as shown in Figure 2.1.

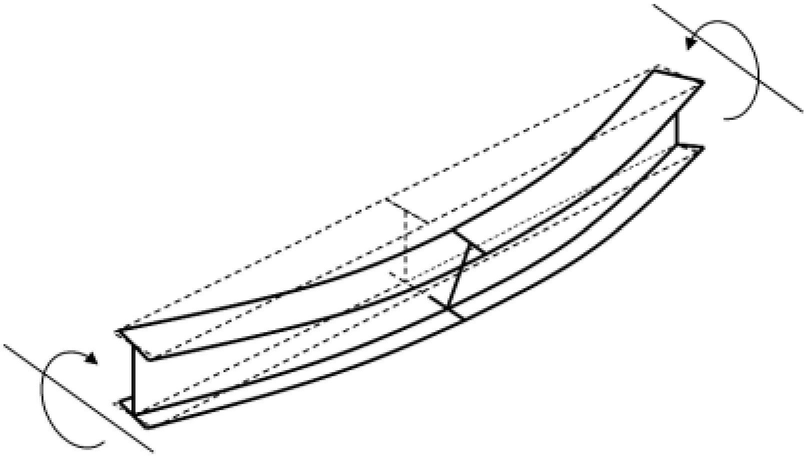

Figure 2.1 - Lateral displacement and torsion of the girder

Elastic lateral torsional buckling capacity for a single, simply supported and doubly symmetric beam subjected to uniform bending moment, M_0, about the strong axis is given by Eq. (2.1) (Timoshenko & Gere, 1961).

$$M_0 = \frac{\pi}{L_b}\sqrt{EI_zGJ + \frac{\pi^2 E^2 I_z C_w}{L_b^2}} \tag{2.1}$$

Design equations for LTB of doubly symmetric beams in bridge and building design specifications are based on Eq. (2.1). As can be seen in Eq. (2.1), the moment capacity is increased if the buckling length, L_b, is decreased. Thus bracing are used to decrease the buckling length so that yielding and not buckling is controlling the strength of the girder (Yura, et al., 2008).

Modifications have previously been done to Eq. (2.1) by Yura, et al. (2008) to account for single symmetric sections, different loading conditions and systems with two or more girders. Finite element analyses have been done for I-girder systems with discrete torsional bracing by Park, et al. (2010) and Choi & Park (2010).

Within this work the author wishes to use temporary formworks as torsional bracing system for steel girder systems and with finite element analyses see if they attached could work in a stabilizing way. The idea to this investigation comes from Mehri's ongoing PhD project where he does experimental studies on formworks as a potential bracing source against lateral torsional bracing.

2.2 BRACING OF STEEL-CONCRETE COMPOSITE BRIDGES

Having a good bracing system is very important for a steel-concrete composite bridge. A small amount of extra steel as bracing can make a huge increase in the bending resistance of the main girders. The bracing serves as buckling control elements during the bridge construction phase, but they also serve as load distributers as well as making sure that the distance between the girders are constant.

The bracing system will often come to most use during the construction phase, when pouring the wet concrete on top of the girders. The load from the wet concrete imposes significant bending in the bare steel girders and the compression flange tends to buckle laterally, i.e. in the direction of the minor axis, what's known as lateral torsional buckling. Before the concrete has hardened the girders must be braced either by direct lateral restraints to the compression flanges or by torsional restraints to the whole girder. A few weeks later when the concrete has hardened the bracing are of less or none use to the girders and could possibly be removed. The stiff concrete now provide lateral restraint to the top flanges and only the bottom flanges can buckle laterally over the intermediate supports.

The bracing system also serves as load distributers between the girders. Vertical loading such as traffic and lateral loading such as wind load but also collision load can be transferred and shared between the girders through the bracing. The bracing makes all girders work more like one and the resistance of all girders make up for a much stronger system all together. But sometimes load transfer isn't desirable and at time the bracing itself can attract significant forces, making it prone to overloading and fatigue effects.

Bracing can also serve as dimensional control. As a result of deviation from exact geometry as well as unequal loading, the distance between adjacent girders may vary. Introducing just a few bracing elements can tie the girders together and reduce the deviation.

2.3 BEAM BRACING

Beam bracing is more complicated than column bracing due to the fact that rather than just bending, as with columns, beam buckling involves both flexure and torsion (Yura, 2001). Beam bracing may be divided into two main categories, i.e. lateral and torsional bracing. Concrete slabs are an example of a system that works both as lateral and torsional bracing. These kinds of bracings are more effective, but since bracing requirements are minimal it is more practical to develop separate design recommendations for these two types of systems (Yura, 2001).

2.3.1 LATERAL BRACING

Direct lateral restraints to the compression flanges are known as lateral bracing or plan bracing. Lateral bracing is maybe the most direct approach to restrain the compression flange from moving sideways, when it is connected directly to the flange.

Connecting the flanges of the main girders with diagonal members formed as a truss makes a structure that is very stiff in response to lateral movement. Instead of the flanges buckling between the supports they now buckle between the bracing points instead, see Figure 2.2.

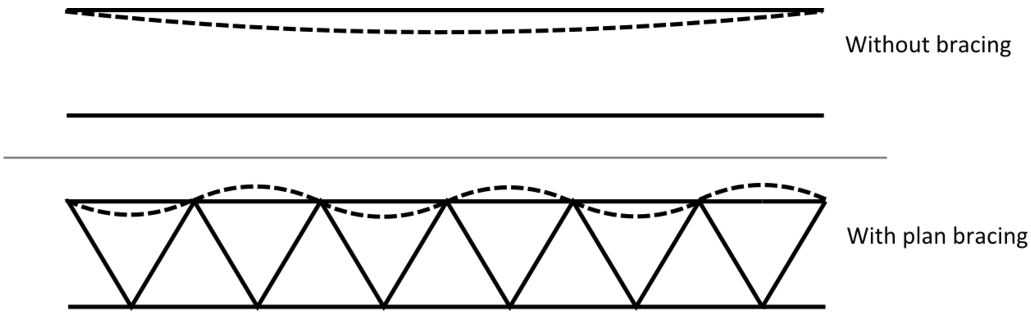

Figure 2.2 - Truss used between top flanges reduces the buckling length. Reproduced from (Yura, et al., 2008)

Although lateral bracing is the most direct way of preventing lateral torsional buckling it is not relevant in this thesis and will not be discussed further.

2.3.2 TORSIONAL BRACING

The differentiation of a torsional brace from a lateral brace is that twist of the cross section is restrained directly (Yura, 2001).

Torsional bracing does not provide any lateral restraint to the compression flange. In the case of lateral movement of the compression flange the bracing will only push the compression flange of the other girder sideways as well (Yura, 2001).

Torsional bracing instead prevents twisting of the individual single girder, because the braced girders will have to move simultaneously to each other, resulting in that if one girder is pushed down the other will have to move up. What provides resistance against buckling is just the sum of the total resistance to this movement from each individual girder, i.e. the moment of inertia, see Figure 2.3 (Yura, et al., 2008).

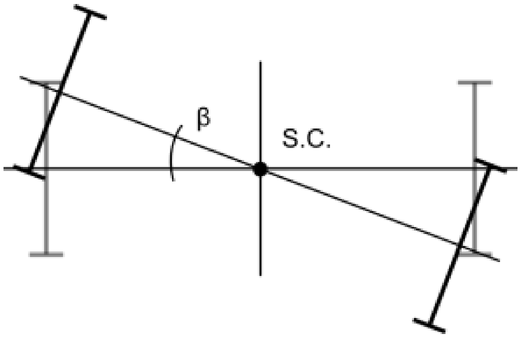

Figure 2.3 – Twist of a twin I-girder system if connected with torsional bracing. Reproduced from (Yura, et al., 2008)

Torsional bracings can be either discrete or continuous (Yura, 2001). They can take many different forms, see Figure 2.4. It can be a diaphragm located near the centroid, different kind of cross frames preventing relative movement of the top and bottom flanges, floor beams attached near the bottom tension flange or an attached deck to the top flange. The main principles can then differ and make up for a huge variety of torsional bracing systems.

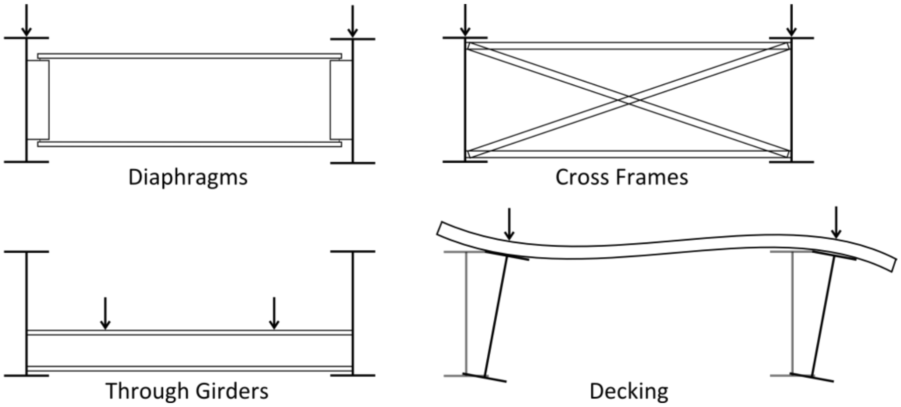

Figure 2.4 – Different types of torsional bracing systems. Reproduced from (Yura, 2001)

3 FORMWORK SYSTEMS

In this chapter some of the most common formwork systems will be described and analyzed. But only systems applicable to steel-concrete composite bridges will be described and focus will be on whether or not the system can be used as discrete lateral torsional bracing during concreting of the deck.

3.1 INTRODUCTION

3.1.1 DEFINITION

It can be hard to understand the difference between formwork and the other often used term falsework.

The company Groundforce Shorco (n.d.) gives a definition of formwork as; *"A structure which is usually temporary but can be whole or part permanent, it is used to contain poured concrete to mold it into required dimensions and support until it is able to support itself."*

Falsework is when dealing with situations where the supporting system is carrying a vertical load down to the ground. A definition, also by Groundforce Shorco (n.d.), could be; *"Falsework is any temporary structure, in which the main load bearing members are vertical and are used to support a permanent structure and associated elements during the erection until it is self-supporting."*

Clearly, there is no clear line between what formwork is and what falsework is, but at least formwork is used to contain poured concrete and further on everything used in this thesis will be referred to as formwork.

3.1.2 CONCEPT

Much is depending on an accurate formwork as M.K. Hurd (1995) would say. Forms must have the right dimensions, be rigid enough and maintain its position throughout the casting. A formwork filled with wet concrete has its weight at the top and is not basically a stable structure. One must have to think about ductility; what will happen if one member gives away? Is it easy enough to assemble, i.e. can the least skilled workmen be able to put it together?

On top of everything it needs to be time, cost and material effective.

3.1.3 FORMWORK HISTORY FOR STEEL-CONCRETE COMPOSITE BRIDGE

Before today's systems, various systems were used. The most common system was underslung beams attached beneath the bridge girders, which cantilevered outside of the edge of the bridge and supported a short falsework system to form the deck soffit. Erection of the underslung beams and dismantling was problematic and dangerous. Deflection of the cantilever beams often resulted in grout loss between the soffit and the bridge, something almost never seen with today's systems. Overslung systems of C frames were also used to cast bridge cantilevers as well as mobile gantries running on top of the bridge girders, or on a previously cast central section of bridge deck were also popular. Today this mobile method is still used on some of the larger bridges (Fryer, 2014).

3.2 EVALUATION OF FORMWORK SYSTEMS

Today various systems applicable to steel-concrete composite bridges can be found on the market. A fact is that many of them are similar to each other and the author wishes to give an overview of the different concepts availably on today's market.

It's hard to say exactly where and when the different systems was introduced because variants of them are always and have always been made up to fill the need of new, or at least, improved systems for more and more complex structures.

Four types of formwork systems applicable to composite bridges has been found to exists on the market today and the main types are

- Scaffolding system of modified steel pipes known as CUPLOK
- Top retrieved modular system
- Bottom retrieved modular system
- Mobile formwork wagons

3.2.1 CUPLOK SYSTEM

This system was first developed by Scaffolding Great Britain (SGB), today acquired by Harsco Infrastructure. It's used mostly in the UK but also by the Swedish scaffolding company Britek.

3.2.1.1 SYSTEM

The CUPLOK system is as simple as steel pipe sections of diameter 48.3 mm put together to form the supports to the timber parts of the formwork. The CUPLOK system can be used in many different formwork applications but Figure 3.1 shows it when used for steel-concrete composite bridges.

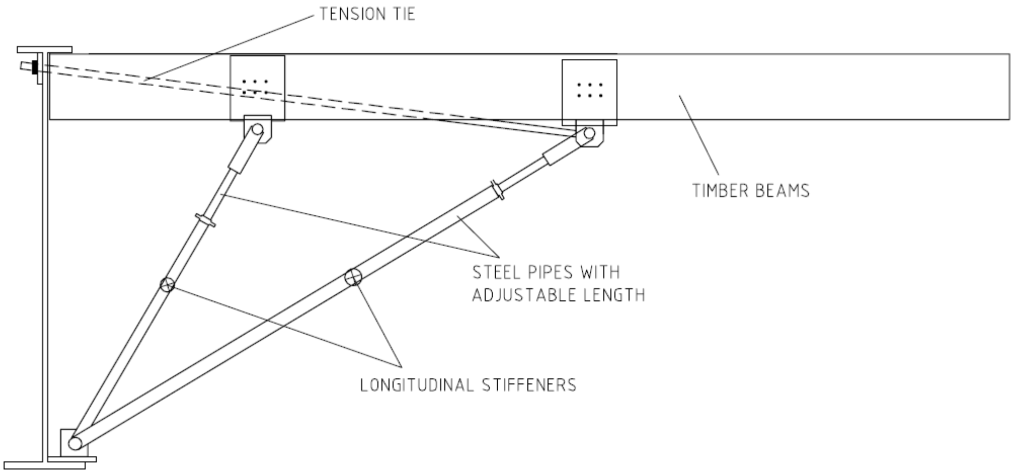

Figure 3.1 – Cantilever formwork part with CUPLOK system (BRITEK Ltd)

The steel pipes can easily, due to the threaded jacks, be adjusted in length to fit different projects and bridge girders. Neither does the supports have to be firmly fixed to the bottom flange and could instead be resting against the web at an adequate height. The timber beams are two parallel beams of rectangular shape with dimensions according to the need of the project. Those beams are not put directly next to each other and instead leave a small passage that allows for the tension ties to connect to the outermost steel pipe. The other end of the tension tie is then connected through the web of the beam. This tension tie is what actually holds the formwork at place, especially when the bottom support isn't resting in the bottom flange.

The system is also stabilized in the longitudinal direction, as seen in Figure 3.1, with steel pipes connected to cups located every 0.5 meter on the diagonal pipe sections, see Figure 3.2. This kind of connection can hold many intersecting pipes at one time and when the cops are hammered over the heels on the longitudinal steel pipes they lock and a rigid connection is made. CUPLOK has its name from this feature.

Figure 3.2 – CUPLOK components and the CUPLOK connection system (BRITEK Ltd)

The longitudinal spacing between the formworks depends on the dimensions of the cross section, i.e. spacing between the girders and also the extension of the cantilever parts. The thickness of the deck is also an important factor as the loading increases with the thickness. Most likely is that the spacing will be between 1.2-1.5 meters.

For a bridge with two main I-girders a system according to Figure 3.1 is often the case on each cantilever side. To hold the girders top flanges together, tension ties are used in between the girders as well, see Figure 3.3. Without these tension ties the girder would tend to twist because of the cantilever load hanging on the outside part of the girders.

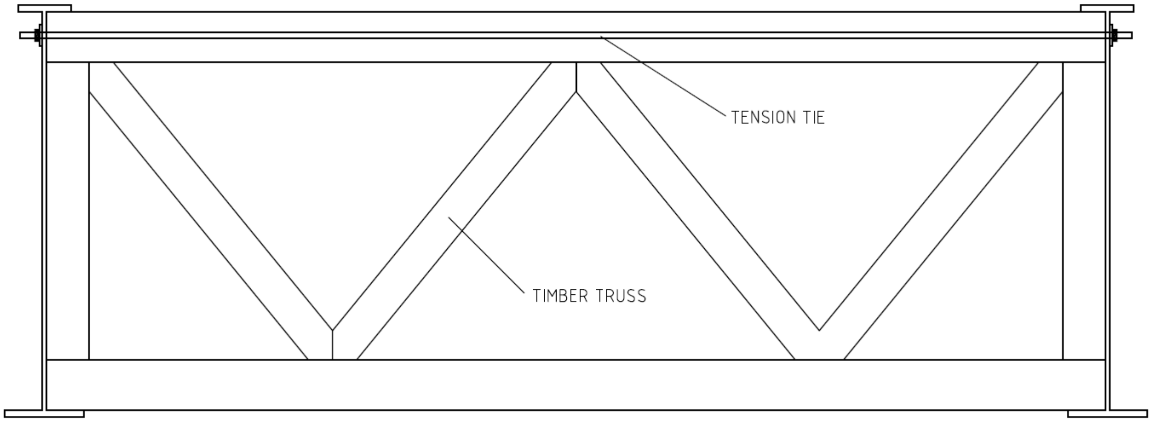

Figure 3.3 – Tension tie and timber truss interconnecting the main girders (BRITEK Ltd)

In Figure 3.3 the sometime used timber truss system can be seen. This timber truss system in combination with the cantilever part and the interconnecting tension ties make up for a statically stable system. The top flanges are not allowed any lateral displacements from the tension tie whereas the bottom flanges cannot be pushed inwards due to the intermediate truss restraining the movement.

Another way is to have a similar system as the cantilever one also in between the girders, see Figure 3.4.

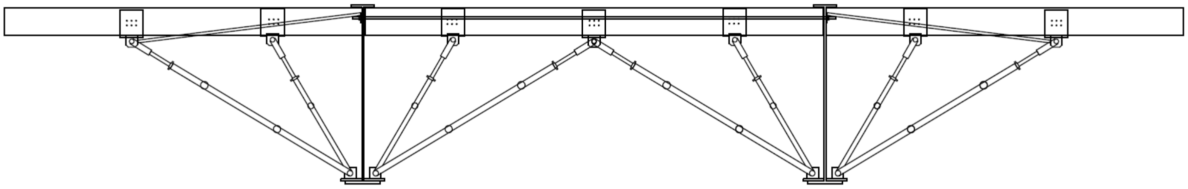

Figure 3.4 – CUPLOK system with both intermediate and cantilever parts (BRITEK Ltd)

When this system is used at least the intermediate formworks are resting on the bottom flanges.

This is also a statically stable system, but to be able to resist twist, i.e. lateral torsional buckling of the girders the formwork system must be connected to the girders and be able to take tension in the members. This is something they cannot do at their present appearance.

3.2.1.2 MODIFICATIONS TO SERVE AS LATERAL TORSIONAL BRACING

The system according to Figure 3.4 could serve as lateral torsional bracing, but it needs to be connected to the girders to be able to take both tension and compression at all stages of the casting of the concrete. One problem is that the threaded jack sections can only take compression without sliding out of its hold and another one is the lack of connections between the formworks and the girders.

The challenge is to make these alterations to the system with as small changes as possible. However, this is outside the scope of this thesis, but is at the same time analyzed in Mehri's ongoing PhD project.

In this thesis an assumption is made that the system can be modified and attached to the girders to work as lateral torsional bracing. The steel pipes are connected to the bottom flanges and the timber beams to the top flanges. The threaded jack sections are now also able to take tension without sliding out of its holds.

3.2.2 TOP RETRIEVED MODULAR SYSTEM

There are today many so called top retrieved modular systems on the market. According to Ian Fryer (2014) the top retrieved diagonal tie system was developed by him on a motorway project in South Wales in 1993. A mixture of RMD and SGB equipment was used at that time but 1995 he joined RMD and spent the year making the system better. Today the system goes under the name Paraslim and is provided by RMD Kwikform and used in the UK and Ireland, but has been used in the Middle East and Far East as well as Australia.

Although the system was developed by Ian many other companies has introduced their version of the system. To mention some of the biggest actors; Peri has a similar system called VARIOKIT Cantilever Bracket, Doka has a system called ParaTop that works the same and other companies like as A-Plant, Ischebeck and EFCO has similar systems. Heab Byggställningar AB is a Swedish reseller of the RMD Kwikform concepts. Further on in this chapter focus will be on the original Paraslim concept by Ian Fryer.

Paraslim is only used as cantilever part and RMD has therefore another concept called Webtie that is used between girders, which will also be explained.

3.2.2.1 SYSTEM

The top retrieved modular diagonal tie system known as Paraslim is a statically determinate system that is transported to the workspace in modules, illustrated in Figure 3.5.

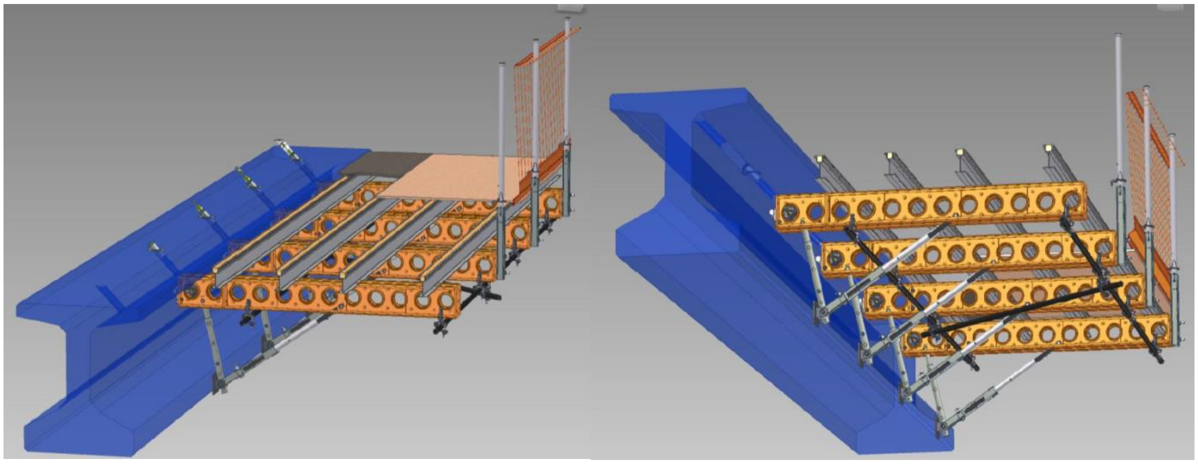

Figure 3.5 – Paraslim system attached to a concrete girder (RMD Kwikform, 2013)

The static forces can, according to Fryer (2014), be visualized by thinking of yourself carrying a long rectangular box with the short side against your body. In order to get the box to balance, your arms (the ties) have to take up a diagonal attitude and the face of the box rests against your torso. The distribution of compressive load between this face of the box and your body depends on the position of the items in the box in relation to your body and the point at which your arms support the underside of the box. Place too much load near your body and the remote end of the box tips up as the near end slides down your tummy. Place too much load remote from your body and the face of the box against your body slides upwards until the edge of the box catches under your chin.

The assembling is easy and can be performed with as little as two operatives and an engineer at a time. Modules of Paraslim are prefabricated on the ground before being crane handled into position. All adjustments, fixings and stripping are carried out safely from above the modules without the need to go beneath the deck slab; therefore the top retrieved name.

A section of a module can be seen in Figure 3.6.

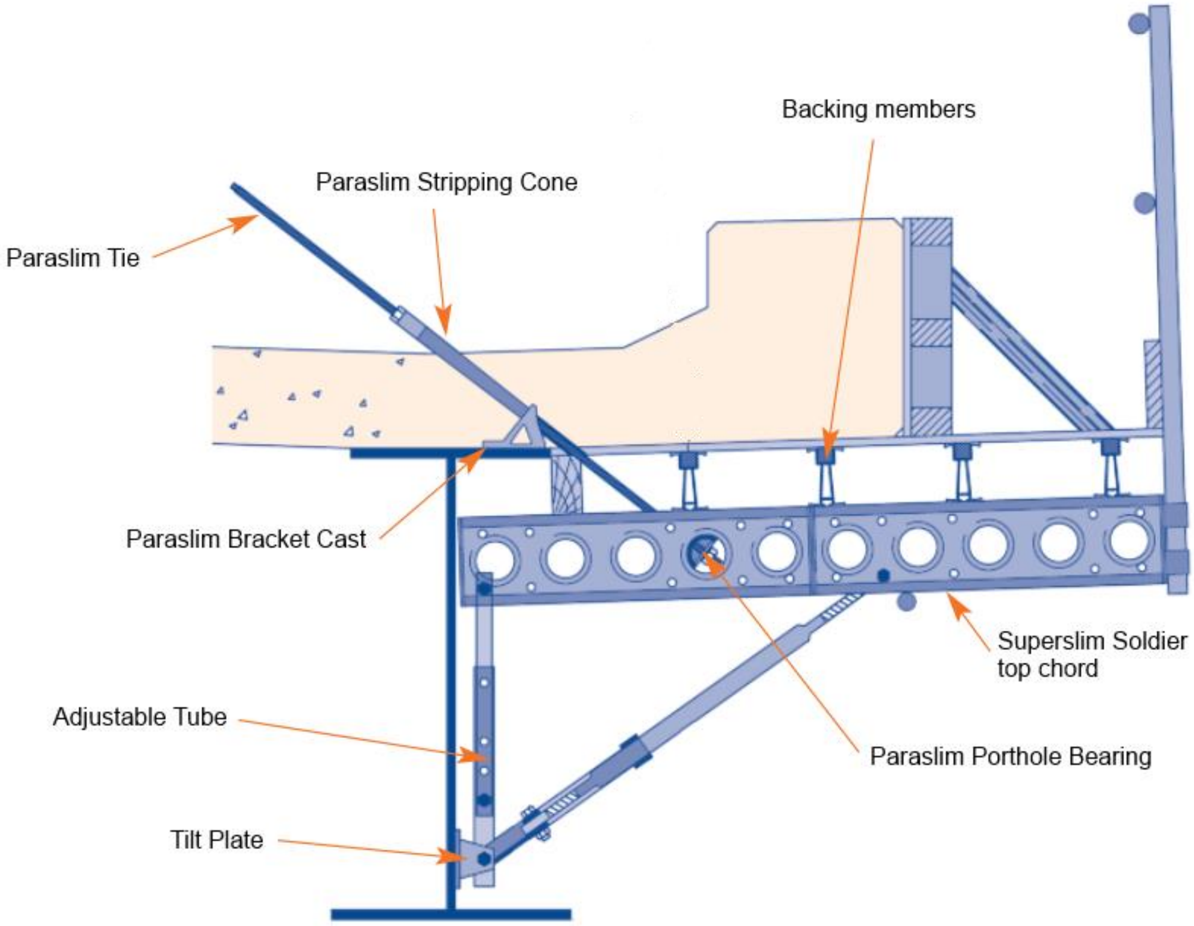

Figure 3.6 – Section of a Paraslim module attached to a steel girder. Modified figure from (RMD Kwikform, u.d.)

First a bracket is welded to the top flange of the girder and a porthole bearing positioned in an adequate hole of the Superslim Soldier beam. Then a module is lifted to place by crane and fixed to the girder using the bracket as an anchorage for the top mounted Paraslim tie attached to the porthole bearing. Four ties are holding each module at place and they can always be attached and stripped from above.

As the Paraslim concept is only applicable to cantilever parts RMD has another system called Webtie. This is as simple as a deck suspension system for the interior part of the formwork, see Figure 3.7.

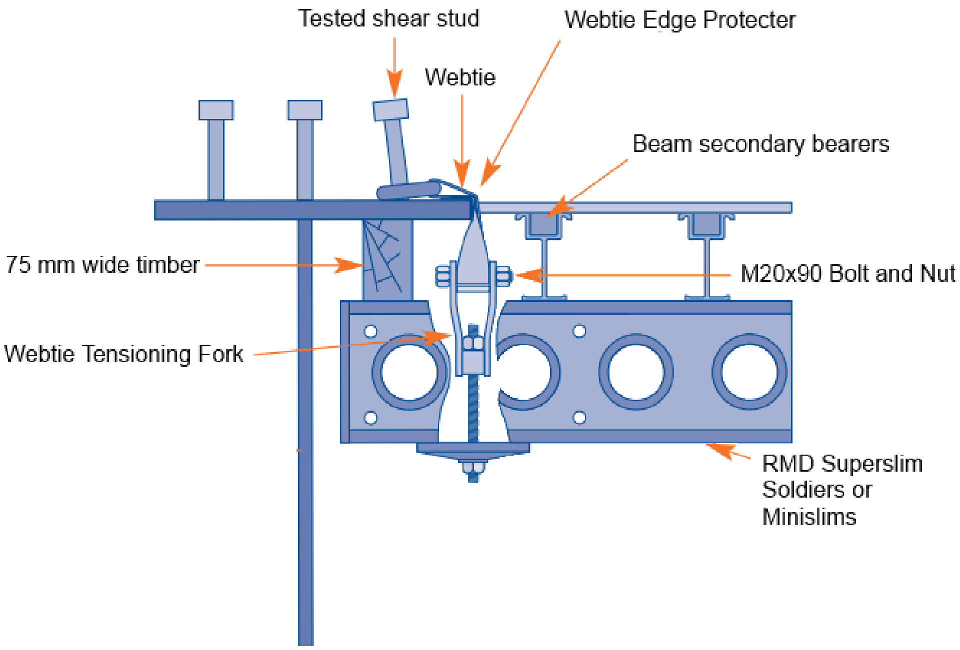

Figure 3.7 – Webtie system. Modified figure from (RMD Kwikform, u.d.)

The system can also be used as a saddle over an interior girder, see Figure 3.8.

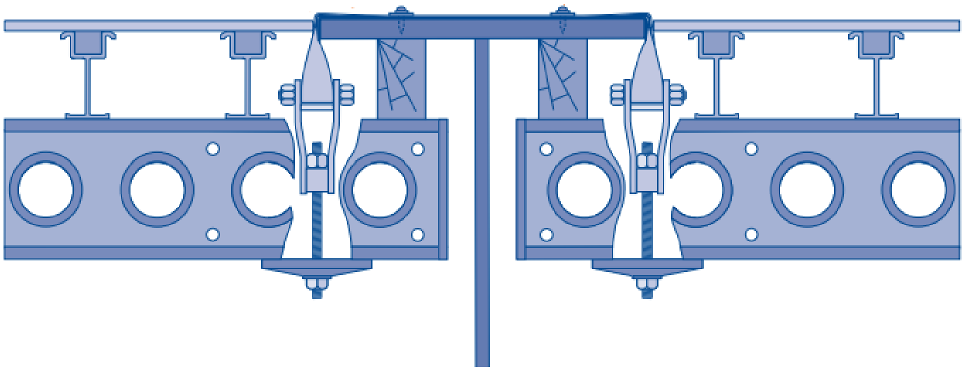

Figure 3.8 – Webtie system as a saddle over an interior girder. Modified figure from (RMD Kwikform, u.d.)

The Webtie system is holding the girders together while in a simple and time efficient way providing support for interior casting of the deck. No holes are made either to the flanges or to the web with Paraslim and Webtie system. When the deck is cast the webties are cut with a hot knife and the suspended beams can be stripped from below.

3.2.2.2 MODIFICATIONS TO SERVE AS LATERAL TORSIONAL BRACING

Due to that the interior parts only consists of a suspended tie system no alterations can be done to make the system work as lateral torsional bracing.

3.2.3 BOTTOM RETRIEVED MODULAR SYSTEM

When Fryer 1993 invented the top retrieved modular system he said to know nothing about that a similar, but bottom retrieved, system had been used by Symons and Dayton Superior in the USA for at least 20 years before him.

The author has tried to get in contact with them but without any success. What can be seen at their website is that their system called "C49 – Bridge Overhang Bracket", Figure 3.9, is very much similar to Paraslim and other top retrieved systems on the market.

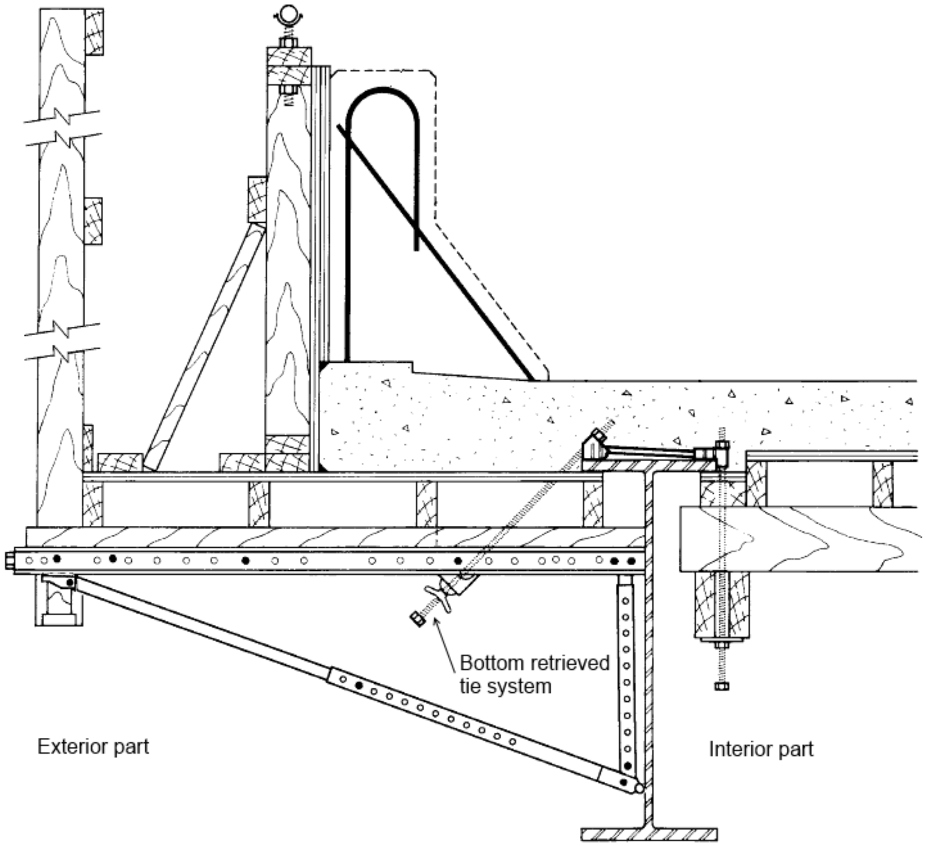

Figure 3.9 – Bottom retrieved modular system (C49 – Bridge Overhang Bracket) from Dayton Superior with shown interior and exterior parts. Modified figure from (Dayton Superior, 2014)

As with the top retrieved modular system, no alterations can be done to this system either to make it work as lateral torsional bracing.

3.2.4 MOBILE FORMWORK WAGONS

Another solution that the author just wants to mention is the use of mobile formwork wagons. These wagons can be put on top of the girders and moved along as moveable formwork. This can be both time and cost effective considering longer bridges where concrete is cast in many stages.

As lateral torsional bracing the wagon is of no good because it cannot cover the whole bridge at once.

3.3 CONCLUSIONS

With the in Section 3.2.1.2 mentioned modifications to an already existing and widely spread formwork solution, CUPLOK is a good alternative for further research on whether or not it could serve as lateral torsional bracing during the casing of the concrete.

4 FINITE ELEMENT MODELLING

Simulia Abaqus CAE is used for all of the numerical analyses. This is a widely used commercially finite element software and has been chosen mostly because it was used at the author's school and by his supervisor.

When using a finite element program it's of great importance to know what the best way to make an accurate model is. Mistakes in the input data such as interactions, mesh, material parameters, loads and boundary conditions can have big impacts on the results and therefore the modelling is described in detail in the following sections.

4.1 USED ANALYSIS METHODS

Two methods are being used within this thesis and they are linear eigen-value buckling analysis and non-linear incremental buckling analysis. Linear eigen-value buckling analyses are performed on perfectly straight beams and beam systems. For the non-linear incremental buckling analyses an initial imperfection has to be applied before any interesting effects of loading can be studied.

4.2 MATERIAL MODELLING

Within this section it's explained what materials are being used in the different analyses and how to model them in Abaqus.

4.2.1 STEEL

Steel is an isotropic elastic-plastic material with nominal values of yield strength f_y and ultimate tensile strength f_u for hot rolled structural steel shown in Table 4.1 (CEN, 1995).

Table 4.1 – Nominal values of yield strength and ultimate tensile strength

Standard and steel grade	Nominal thickness of the element			
	$t \leq 40$ mm		$40\text{ mm} < t \leq 80\text{ mm}$	
	f_y [N/mm^2]	f_u [N/mm^2]	f_y [N/mm^2]	f_u [N/mm^2]
S235	235	360	215	360
S355	355	510	335	470
S420M	420	520	390	500
S460M	460	540	430	530

Material parameters for steel can be found in Table 4.2 (CEN, 1995).

Table 4.2 – Structural steel material parameters

Modulus of elasticity	$E = 210$ GPa
Shear modulus	$G = \dfrac{E}{2(1+\nu)} \approx 81$ GPa
Poisson's ratio in elastic stage	$\nu = 0.3$

Figure 4.1 shows an elastic-plastic relationship allowing for strain hardening to be used for structural steel, based on Swedish regulations for Steel Structures (Boverket, 2003).

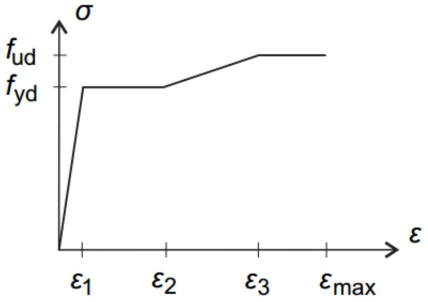

Figure 4.1 – Schematic stress-strain curve for steel. Reproduced from (Boverket, 2003).

Based on the schematic curve in Figure 4.1, equivalent curves can be made for the steel grades in Table 4.3, with the equations below. This resulted in the nominal curves in Figure 4.2.

$$\varepsilon_1 = \frac{f_{yd}}{E_d} \tag{4.1}$$

$$\varepsilon_2 = 0.025 - 5\frac{f_{ud}}{E_d} \tag{4.2}$$

$$\varepsilon_3 = 0.02 + 50\frac{f_{ud} - f_{yd}}{E_d} \tag{4.3}$$

$$\varepsilon_{max} = 0.6A_5 \tag{4.4}$$

Where A_5 is equal to 0.2.

Abaqus expects the stress-strain data to be entered as true stress and true plastic strain and the modulus of elasticity must correspond to the slope defined by the first point. To convert nominal stress to true stress the following equation should be used

$$\sigma_{tru} = \sigma_{nom}(1 + \varepsilon_{nom}) \tag{4.5}$$

Convert nominal strain to true strain using

$$\varepsilon_{tru} = \ln(1 + \varepsilon_{nom}) \tag{4.6}$$

To calculate the modulus of elasticity, divide the first nonzero true stress by the first nonzero true strain. Finally convert the true strain to true plastic strain, with use of the following equation

$$\varepsilon_{pl} = \varepsilon_{tru} - \frac{\sigma_{tru}}{E} \tag{4.7}$$

The curves for steel grade S235 and S355 are shown in Figure 4.2, but look similar for all steel grades.

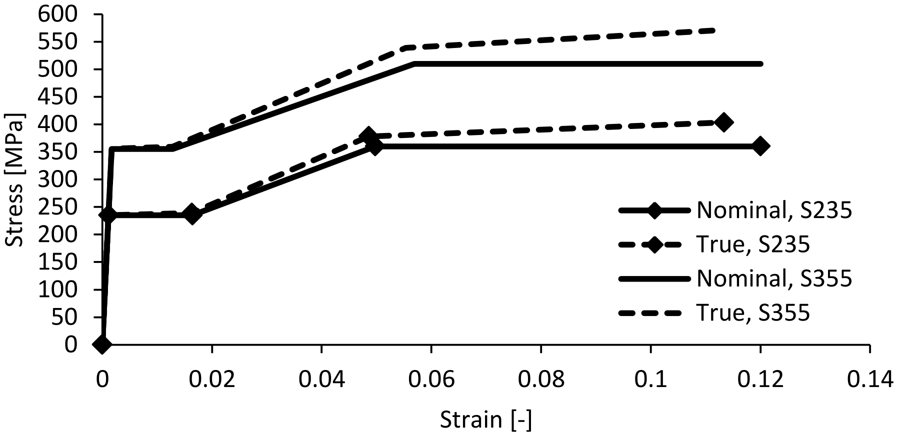

Figure 4.2 - Nominal and true stress – strain relationship of steel S235 and S355

Table 4.3 shows the input values of true stress and strain for all steel grades mentioned in Table 4.1.

Table 4.3 – Input of true stress and strain for material plasticity in Abaqus

Steel grade	True stress [Pa]	Plastic strain [Pa]	E-modulus [Pa]
S235	235262976	0.00000	2.104E+11
	238860714	0.01516	
	377914286	0.04677	
	403200000	0.11141	
S355	355600119	0.00000	2.105E+11
	359564286	0.01107	
	539021429	0.05278	
	571200000	0.11061	
S420M	420840000	0.00000	2.106E+11
	425300000	0.01052	
	542780952	0.04030	
	582400000	0.11056	
S460M	461007619	0.00000	2.107E+11
	465585714	0.00963	
	561085714	0.03787	
	604800000	0.11040	

4.2.2 TIMBER

According to Green et al. (1999) wood may be described as an orthotropic material. It has different unique mechanical properties in all three perpendicular axes, i.e. longitudinal, radial and tangential. The longitudinal axis L is parallel to the grain, the radial axis R is normal to the growth rings and the tangential axis T is perpendicular to the grain but tangent to the growth rings.

To describe the elastic properties of wood twelve constants are needed, but the moduli of elasticity and Poisson's ratios are related by Eq. (4.8), making only nine of them independent.

$$\frac{\mu_{ij}}{E_i} = \frac{\mu_{ji}}{E_j}, \quad i \neq j \quad i,j = L,R,T \tag{4.8}$$

The independent constants are three moduli of elasticity E, three Poisson's ratios μ and three moduli of rigidity G.

In the analyses timber has the strength class C24. According to K. B. Dahl (2009) all three moduli of elasticity is known for C24 as well as two of the three moduli of rigidity. An assumption that the C24 timber is made out of Norway spruce is made and the remaining properties are taken from that. Table 4.4 show the values from K. B. Dahl (2009) and the chosen combined values are the author's interpretation. Even though this may not be the completely right properties it has been shown that those values have a very small effect on the results when members are subjected to bending (Persson, 2010). In beam elements only E_L and the two parallel shear planes are being used.

Table 4.4 - Linear elastic orthotropic parameter values for various spruce species (E_i and G_{ij} in MPa)

Type	E_L	E_R	E_T	μ_{LR}	μ_{LT}	μ_{RL}	μ_{RT}	μ_{TL}	μ_{TR}	G_{LR}	G_{LT}	G_{RT}
C24	11000	370	370	-	-	-	-	-	-	690	690	-
Norway	10900	640	420	0.39	0.49	0.03	0.64	0.02	0.32	580	590	26
Combined	11000	370	370	0.39	0.49	0.03	0.64	0.02	0.32	690	690	26

Abaqus asks for directions 123, which are denoted by Figure 4.3, and values according to Table 4.5 are being used as input for engineering constants.

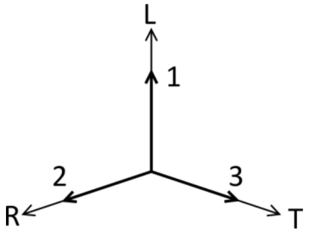

Figure 4.3 – Reference coordinate system 123 relative to principal material system LRT

Table 4.5 – Input values as engineering constants for elastic orthotropic material timber C24 ($E_i$and G_{ij} in MPa)

E_1	E_2	E_3	μ_{12}	μ_{13}	μ_{23}	G_{12}	G_{13}	G_{23}
11000	370	370	0.39	0.49	0.64	690	690	26

4.3 ELEMENT TYPES

To model the web and flanges of the main beams, shell elements with four nodes (S4R) are utilized. That is because a majority of the strain energy of the deformed state of the elements is in plane. Sufficiently fine meshing is being used.

For beams in the formwork, beam elements with six degree of freedoms (B31) were chosen. The formworks situated in between the beams are hinged at its fastening points and so are all formworks stiffened with longitudinal pipe sections.

4.4 LOADS

Load will be applied either to the beams as concentrated force at certain points, or by pressure applied to the top side of the upper flange or in a more realistic way, directly to the formworks as line loads.

5 NUMERICAL ANALYSIS OF LABORATORY TEST BEAMS

To investigate how the use of temporary formworks function as lateral torsional bracing and how big of an effect it has, two symmetrical I-beams will be modelled in Abaqus and stabilized with the use of different temporary formwork set-ups. Load will be applied both in a controlled way as two point loads to each beam and also in a similar way that real concrete load is applied, i.e. load applied directly to the formworks.

The beams used in the numerical analyses exist for real and are part of Mehri's ongoing PhD project and the author has had the privilege of lending his test set-up dimensions.

5.1 DESCRIPTION OF LABORATORY TEST BEAMS

As mentioned the two I-beams used in this analysis exists for real and are being subjected to four-point bending tests with different set-ups, such as intermediate only and intermediate and cantilever formworks combined. One part is to imitate a few of these test set-ups and in Abaqus make some conclusions whether or not the formworks could serve as lateral torsional bracing.

5.1.1 TEST BEAMS

The test beams are 15 meters long and 0.75 meter high with an intermediate distance of 2 meters. The shape of the beams can be seen in Figure 5.1 and the dimensions and material for the set-up can be found in Figure 5.2.

The beams are fixed in all directions at their lower flanges mid endpoints on the left hand side and fixed in the Y and Z direction at their lower flanges mid endpoints on the right hand side of the Figure 5.1. This makes the beams free to slide in the longitudinal direction at only one end. Both beams are fixed in the Z direction at the midpoint of the upper flanges endpoints. The boundary conditions are making the beams free to warp at the ends, but restrained from lateral twist.

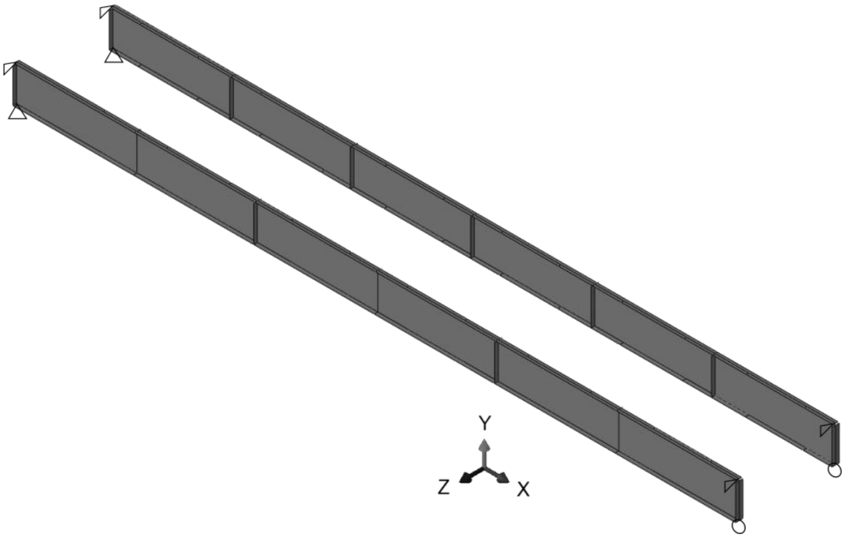

Figure 5.1 – Orientation and boundary conditions of laboratory test beams

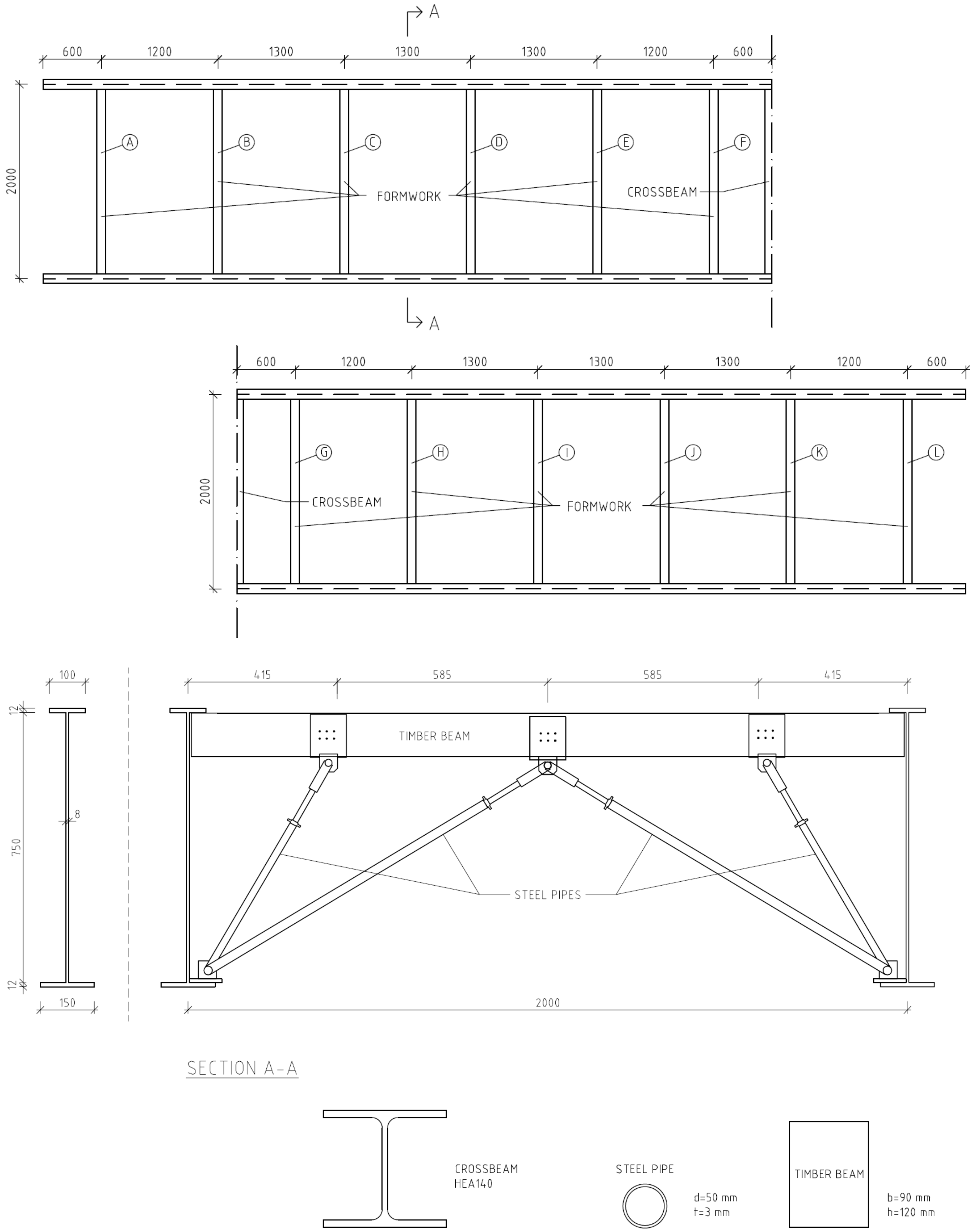

Figure 5.2 – Dimensions and notations of the laboratory test beams set-up (Mehri's PhD project & BRITEK LtD)

When the crossbeam is attached, it is located at mid height and mid length of the beams. All steel parts of the main beams have the strength class S355.

The plastic moment capacity, M_p, for a beam is equal to 801 kNm and almost every result is later on compared to this value.

5.1.2 FORMWORK

After evaluation of different formwork systems in Chapter 3, the result was that the CUPLOK system was the most suitable to be modified to work as discrete torsional bracing. Therefore, this system is chosen to be used in the further analyses within this thesis.

The formworks can be intermediate only, like in Figure 5.3, or more like when used in reality, both intermediate and cantilevered, see Figure 5.4.

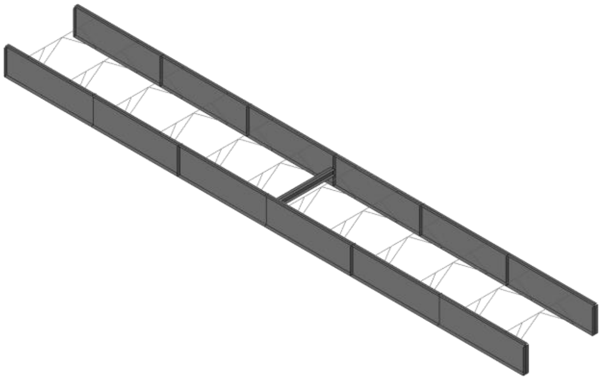

Figure 5.3 – Intermediate formwork

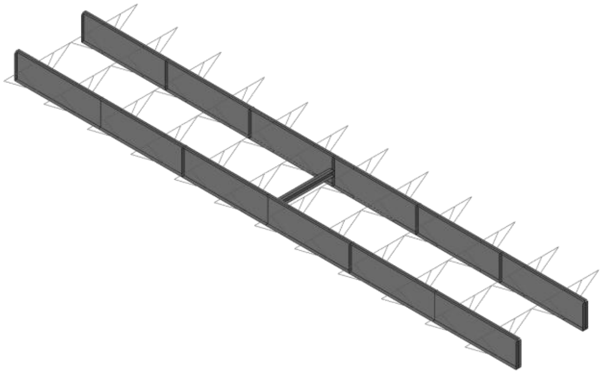

Figure 5.4 – Complete formwork set-up

Detailed dimensions and materials can be found in Figure 5.2 for the intermediate set-up and with the same longitudinal placement along the beam a complete formwork cross section look like Figure 5.5. Steel class S235 for the pipe sections and timber class C24 for the beams.

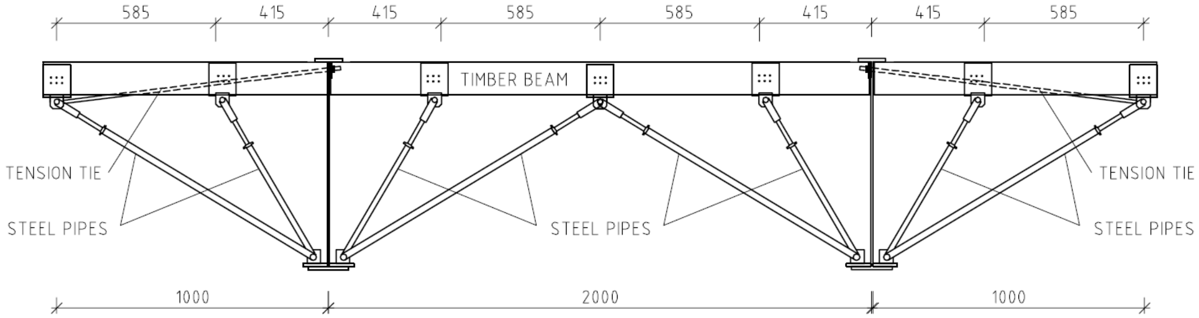

Figure 5.5 – Cross section of set-up with complete formwork attached (BRITEK Ltd)

Rebars are used as tension ties from the outermost point of the cantilevered formwork and run through the web of the beam to keep the cantilevered part at place. Rebars can also be used as tension ties in between the beams to restrain top flanges from lateral movement away from each other. Those can be assumed to have made more of an effect when the intermediate timber beams was not attached to the beams.

The cantilevered formwork part has been attached in two different ways during the modelling. First they were tied and fixed directly to the beams, but after a few run analyses it was discovered that a more efficient and realistic way to stabilize the system was to instead use the longitudinal stiffeners in between the formworks as fixed stabilizing elements, see Figure 5.6. Longitudinal stiffeners for the intermediate formworks are also applied to the system.

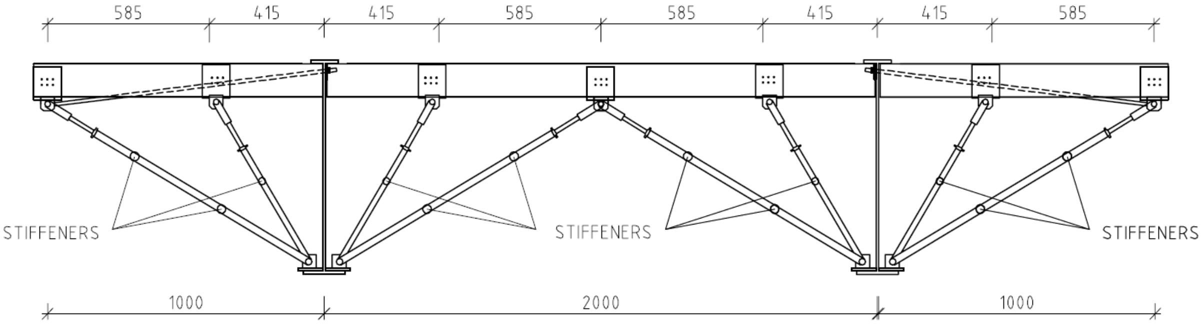

Figure 5.6 – Cross section with displayed longitudinal stiffeners attached between formworks (BRITEK Ltd)

The longitudinal stiffeners extend between the formworks and connect them with the rigid CUPLOK connection according to Figure 3.2.

In this way the cantilevers doesn't need to be fixed to the beams, as they were before, when instead the stiffeners are fixed between the cantilevered parts. The result is that all ties to the beams are hinged. Longitudinal stiffeners have the same cross section as the other pipe sections.

For all numerical analyses the simplified complete FE-model set-up can be seen in Figure 5.7. This figure can be used for a set-up with only intermediate formwork without cantilever parts as well, but then the cantilever formwork parts are removed. It can also be used for a system completely without longitudinal stiffeners if they are overseen.

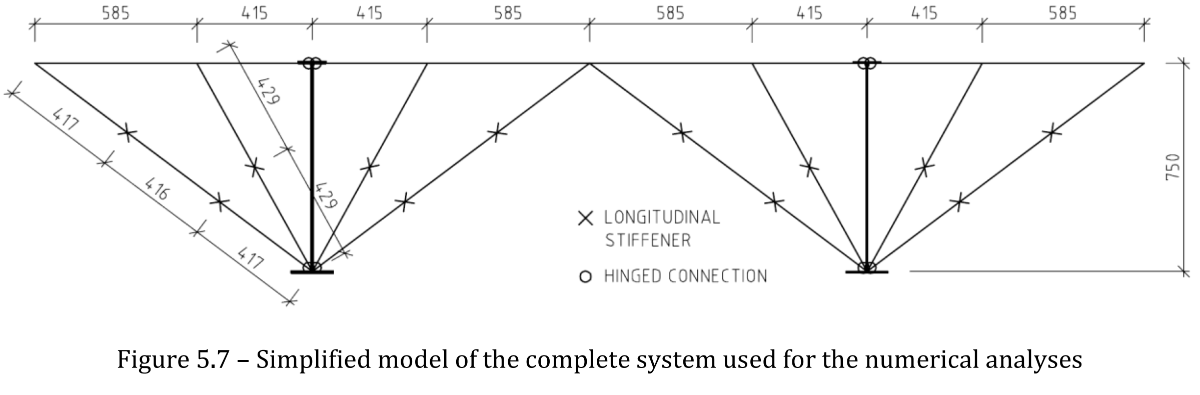

Figure 5.7 – Simplified model of the complete system used for the numerical analyses

The reader should remember that longitudinal stiffeners between the formworks are only applied when the complete set of formwork are analyzed with UDL applied directly to the top of the formworks, i.e. within Section 5.2.3.

5.2 ANALYSIS METHOD

Within this section the method for all laboratory test beam analyses are described.

One standard arrangement according to Figure 5.2 is being used and all alterations to this will be described. The standard arrangement consists of two main beams with initial imperfection L/500. Those are always connected with a HEA140 profile as crossbeam in the middle. Steel pipes in formworks are 50 mm in diameter.

5.2.1 LINEAR EIGENVALUE BUCKLING ANALYSES

First analyses will be linear eigenvalue buckling analyses to determine M_{cr} and mode-shapes for the following test set-ups. With load applied to the beams third point; the analyses are as follow.

1. Bare beams
2. Beams interconnected with a crossbeam at midpoint
3. Beams interconnected with formwork
4. Beams interconnected with formwork and crossbeam

5.2.2 INCREMENTAL BUCKLING ANALYSES OF BEAMS SUBJECTED TO CONCENTRATED FORCE

The first mode-shape in the first buckling analysis, with concentrated force applied to the bare beams third points, is saved and applied as an initial imperfection to the beams. This initial imperfection has the shape according to the bare beams in Figure 5.8, but with the largest nodal displacement equal to L/500, where L is the length of the span. No forces are introduced to the beams at this stage because of the initial imperfection.

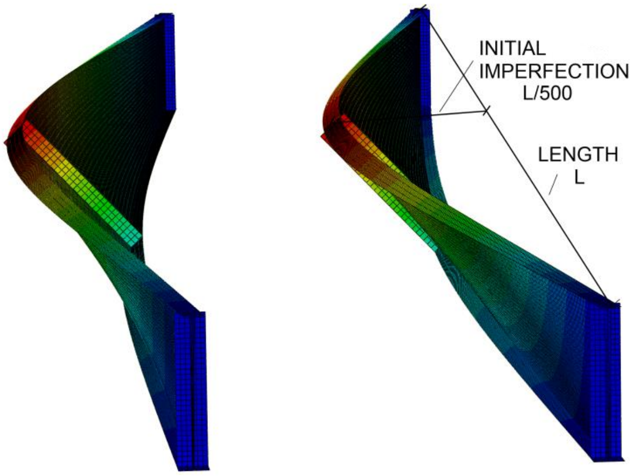

Figure 5.8 – Exaggerated shape of the initial imperfections of the beams before incremental loading

With the load applied in small increments the rotation of the beams can be measured until significant yielding occur. The rotations are calculated for every load increment, but are defined as zero at the beginning, even though there are initial imperfections.

The following analyses are being made and for every one of them, twist (θ) of the beam and displacement (u) of upper flange are measured for the beam with a top flange twisting inwards the system. Measured data are taken in L/4, L/2 and 3L/4 of the length, L, of the beam.

1. Bare beams
2. Beams interconnected with crossbeam

Standard set-up as described before is that the beams are interconnected with both formwork and crossbeam, but a comparison between having and not having a crossbeam attached is made after analysis 3 and 4.

3. Beams interconnected with formworks and crossbeam (standard set-up)
    a. Comparison between the twist and top flange displacement in both beams
    b. Forces in steel pipe sections and how they distribute along the length of the beams
4. Beams interconnected with formworks and no crossbeam
5. Beams interconnected with formwork and crossbeam but with initial imperfection of L/1000 instead of L/500
6. Beams interconnected with formwork and crossbeam but with steel pipes of diameter Ø25 mm instead of Ø50 mm

All steel pipe sections are reduced to Ø25 mm with thickness 2.5 mm; otherwise all is the same as standard set-up.

7. Beams interconnected with half the number of the formworks and attached crossbeam

In this analysis; formworks are only attached at B, D, F, G, I and K positions according to Figure 5.2 and formworks at all other positions has been excluded, i.e. only half the number of the formworks as previous analyses.

8. A comparison between the stiffness of set-up 1, 2 and 3.

5.2.3 INCREMENTAL BUCKLING ANALYSES OF BEAMS SUBJECTED TO UNIFORMLY DISTRIBUTED LOAD

More realistic and therefore more interesting is when the beams are subjected to uniformly distributed load (UDL), i.e. load applied to the top of the complete set of formworks. Now the load can be applied in the same way it would have been in-situ on a construction site.

Same procedure as in Section 5.2.2 is used concerning initial imperfections, initial shape and the way of incremental loading. Formworks are attached both with and without longitudinal stiffeners according to Figure 5.7. The following analyses are being made.

1. Beams interconnected with complete set of formwork according to Figure 5.5 and a crossbeam at midspan subjected to UDL to the formwork
2. Beams interconnected with complete set of formwork according to Figure 5.6 and a crossbeam at midspan subjected to UDL to the formwork
3. Same as 1, but now also with rebars as tension ties

Rebars with Ø16 mm c/c 2.5 m are used to hold the top flanges together. A total of five rebars are connected.

At last a comparison between the stiffness of a system with intermediate formworks, a system according to analysis 1 and a system according to analysis 2 is done.

5.3 ANALYSIS RESULTS

The results are presented in numerical order according to the section they were presented in in Section 5.2.

5.3.1 LINEAR EIGENVALUE BUCKLING ANALYSES

Analyses 1-4

Critical moments for different test set-ups are presented in Table 5.1 along with the slenderness ratio $\bar{\lambda}$ according to Eq. (5.1).

$$\bar{\lambda} = \sqrt{\frac{M_p}{M_{cr}}} \tag{5.1}$$

Table 5.1 – Results of buckling analyses and slenderness ratio

Analysis type	$\mathbf{M_{cr}}$ **(kNm)**	$\mathbf{M_{cr}/M_p}$	$\bar{\boldsymbol{\lambda}}$
Bare beams	22.7	2.8 %	5.94
Interconnected crossbeam	61.4	7.7 %	3.61
Interconnected formworks	519.5	64.8 %	1.24
Interconnected formworks and crossbeam	520.0	64.9 %	1.24

Buckling modes can be seen in Figure 5.9. Each of the bare beams top flanges buckle in half a sinusoidal shape and so does the beams interconnected with formwork. For the beams interconnected with just a crossbeam the first buckling shape is a full sinusoidal wave of the top flanges.

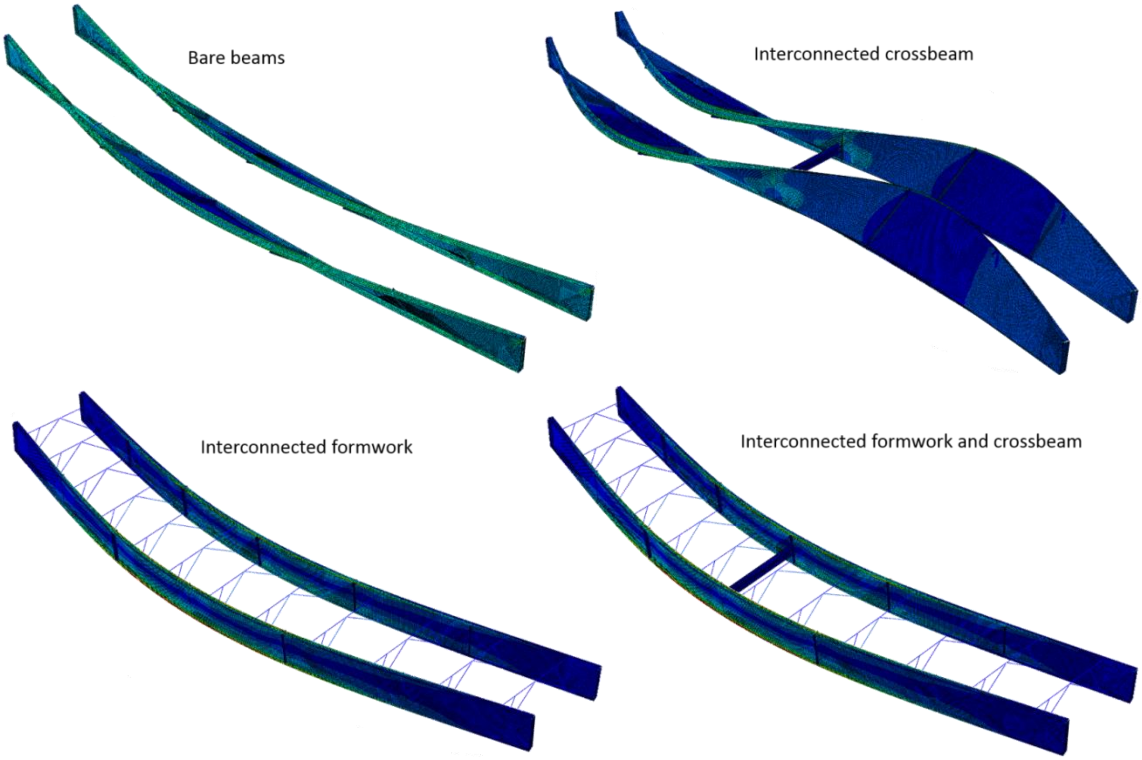

Figure 5.9 – First buckling mode of the different analysis set-ups

It can be seen that the critical moment is almost three times higher with a crossbeam attached, than it is for just the bare beams, but with formwork attached as discrete torsional bracing it is as much as 22 times higher. What can be seen is that when the formworks are attached the crossbeam has little to no effect at all.

5.3.2 INCREMENTAL BUCKLING ANALYSES OF BEAMS SUBJECTED TO CONCENTRATED FORCE

The beam that will be the most looked at is the beam with initial imperfections inclined inwards in the system; see the mode shape of the bare beams in Figure 5.9. This beam is henceforth referred to as the inwardly inclined beam.

Analysis 1

For bare beams subjected to concentrated forces at third points of the beams the twist and displacements of the inwardly inclined beam can be seen in Figure 5.10 and Figure 5.11 respectively.

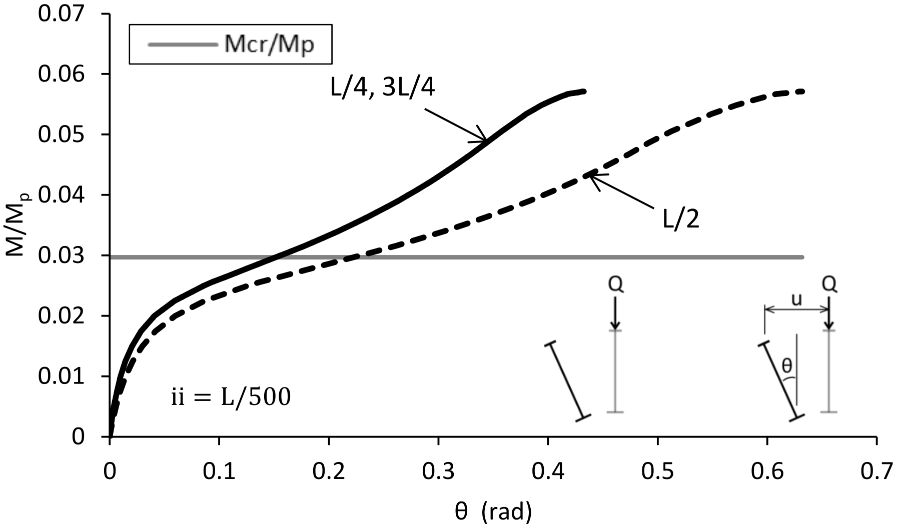

Figure 5.10 – Twist of the inwardly inclined beam subjected to concentrated force at third points

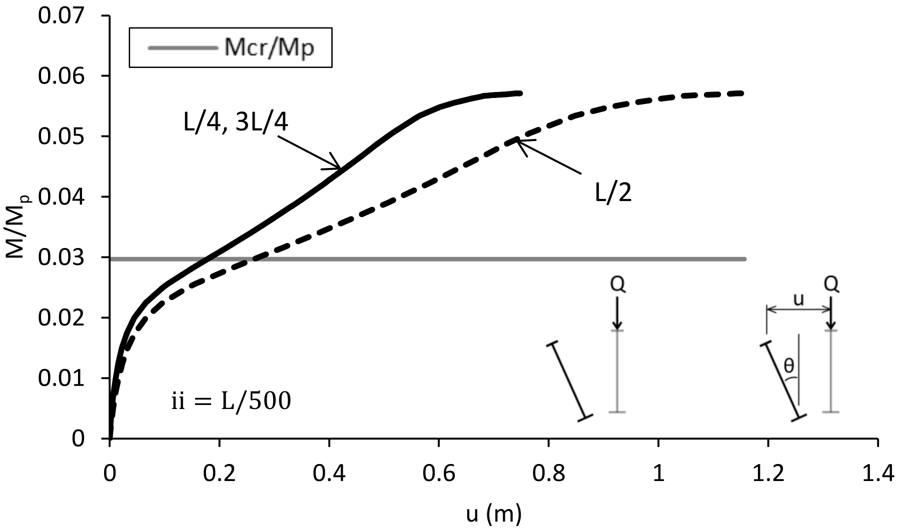

Figure 5.11 – Top flange displacement of the inwardly inclined beam subjected to concentrated force at third points

What can be seen here, and also shows in the mode-shapes, are that the twist is biggest in the middle and so are the displacements of the top flange. The beams buckle in half a sinusoidal wave. At first there is some resistance by the beams but when the loading approaches M_{cr} the speed of lateral torsional buckling increases.

Analysis 2
The inwardly inclined beam, for the beam system that is interconnected with a crossbeam, twist and translate according to Figure 5.12 and Figure 5.13 respectively.

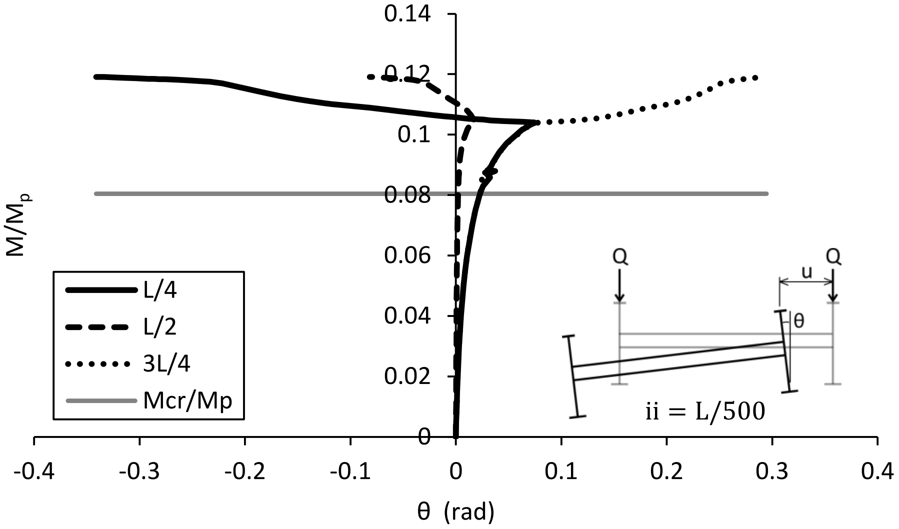

Figure 5.12 - Twist of the inwardly inclined beam connected with a crossbeam and subjected to concentrated force at third points

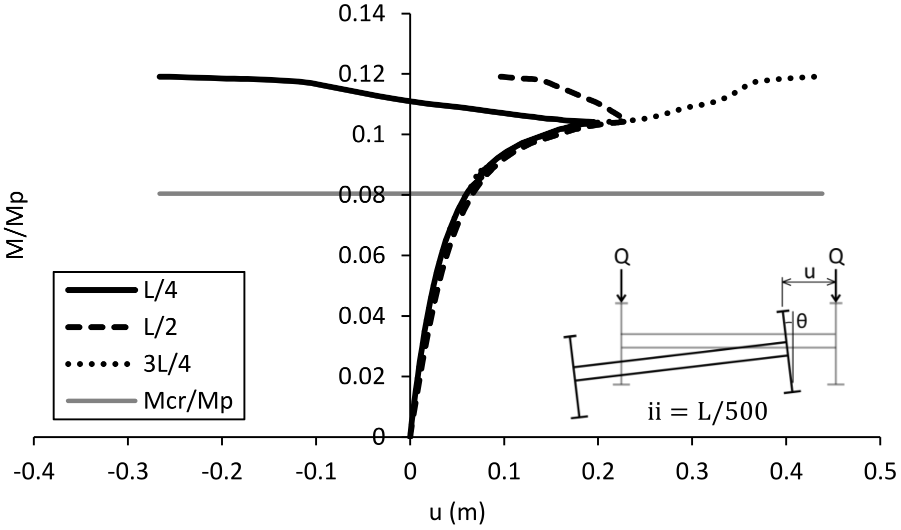

Figure 5.13 - Top flange displacement of the inwardly inclined beam connected with a crossbeam and subjected to concentrated force at third points

Figure 5.12 shows that when loading is under the critical load the twist is biggest in L/4 and 3L/4 and in the same direction. This is because the initial imperfection makes this the easiest direction for the flanges to move in initially. But when the load approaches the buckling load one of the flanges quickly changes direction and the buckled shape is the one of a full sinusoidal wave, as with the interconnected crossbeam in Figure 5.9.

Because the twist is nearly zero at the beams half point it's more interesting to look at the beams quarter points instead. Most of the figures and tables presented later on in this chapter have therefore focused on those points, but the maybe less interesting half point is also presented when relevant.

Analysis 3 (a)

Beams interconnected with a full set of formworks twist and displace according to Figure 5.14 and Figure 5.15 respectively. A comparison between the inwardly inclined and outwardly inclined beam are made and the curves for both beams are similar to the figures below, but the results and differences are easiest shown in Table 5.2.

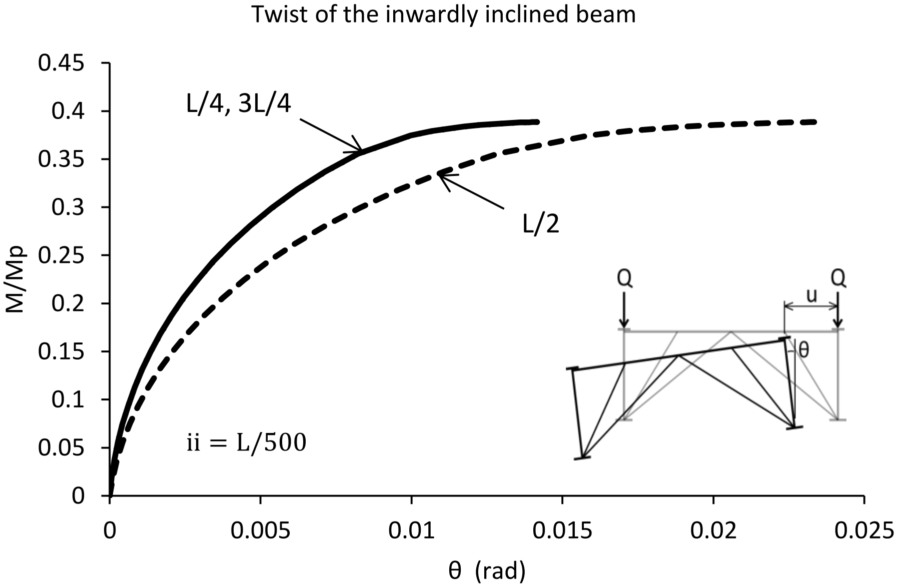

Figure 5.14 – Twist of the inwardly inclined beam connected with formworks and subjected to concentrated force at third points

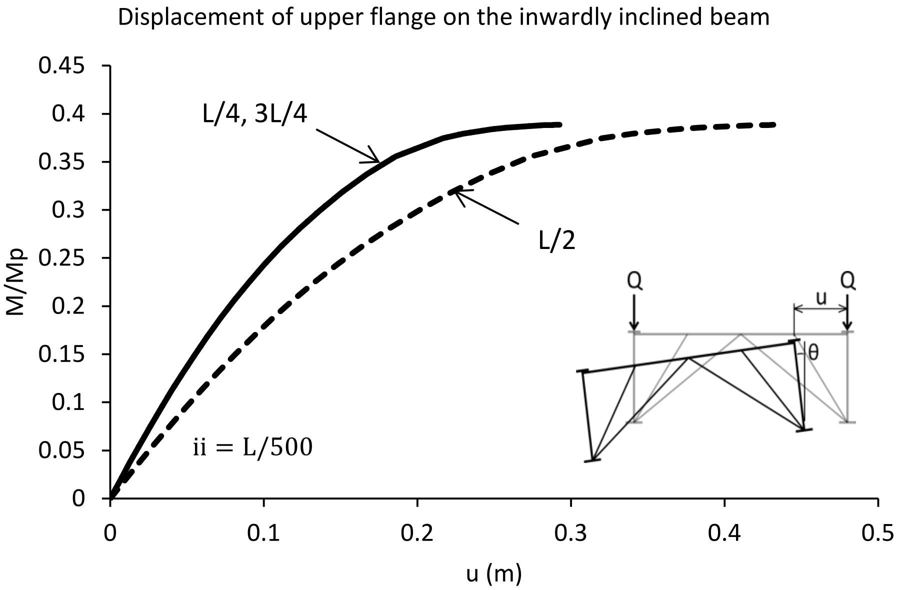

Figure 5.15 – Top flange displacement for the inwardly inclined beam connected with formworks and subjected to concentrated force at third points

As for the bare beams, even this set-up had a shape that looked like the corresponding mode shape from the buckling analysis, i.e., a mode shape of half a sinusoidal wave with the biggest twist and displacement in the middle of the beams.

Table 5.2 – Comparison of twist and displacement between the inwardly inclined and outwardly inclined beam

	θ (rad)		u (m)	
	L/4, 3L/4	L/2	L/4, 3L/4	L/2
Inwardly inclined beam	0,014	0,024	0,293	0,436
Outwardly inclined beam	0,019	0,027	0,292	0,436
Diff. (%)	37,2%	14,2%	-0,21%	0,05%

In Table 5.2 the difference in twist and displacement between the two parallel beams can be seen. The inwardly inclined beam twists significantly less than the outwardly inclined beam while the displacements between the two top flanges are almost the same. The biggest difference can be seen in the more movable quarter points.

This result is somewhat hard to understand and the author has no good answer.

Analysis 3 (b)
Results regarding forces in pipe sections and how they distribute along the length of the beam.

To make the results easy to illustrate, only a couple of figures displaying the forces in the pipe sections are being displayed for the most interesting formwork positions, explained below. The position of each formwork can be seen in Figure 5.2. Forces are displayed as the bracing force divided by the moment in the beam at the position of the formwork divided by the height of the beam; see Eq. (5.2) and Figure 5.16.

$$\frac{N_{brac}}{(M/h)} \tag{5.2}$$

The ratio M/h is always defined as positive, making it easy to see if a member is in tension (positive value) or in compression (negative value).

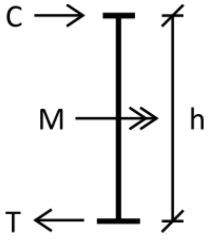

Figure 5.16 – Compression and tension in the flanges due to moment in the beam

Figure 5.17 shows the forces for formwork B, located quite close to the support, Figure 5.18 shows the forces for formwork D located near the quarter point and Figure 5.19 shows the forces for formwork F located closest to the middle of the beams.

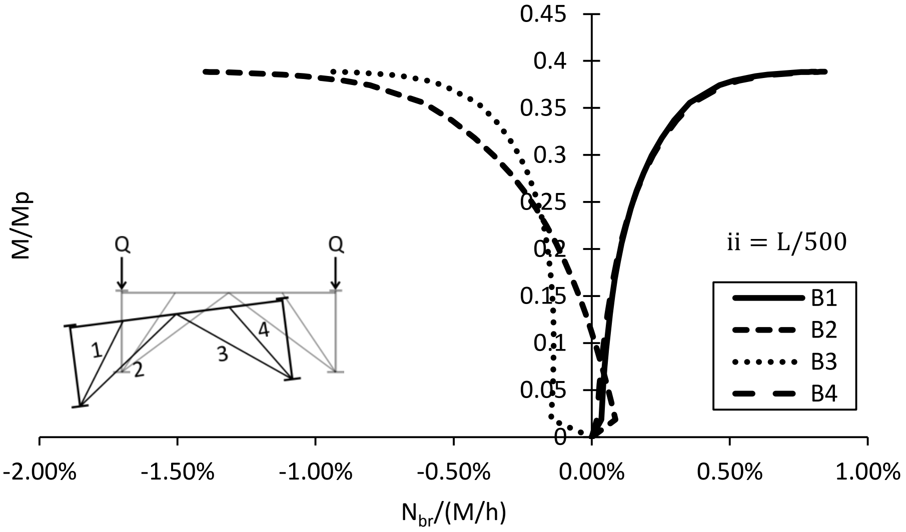

Figure 5.17 – Bracing forces in steel pipes in formwork B

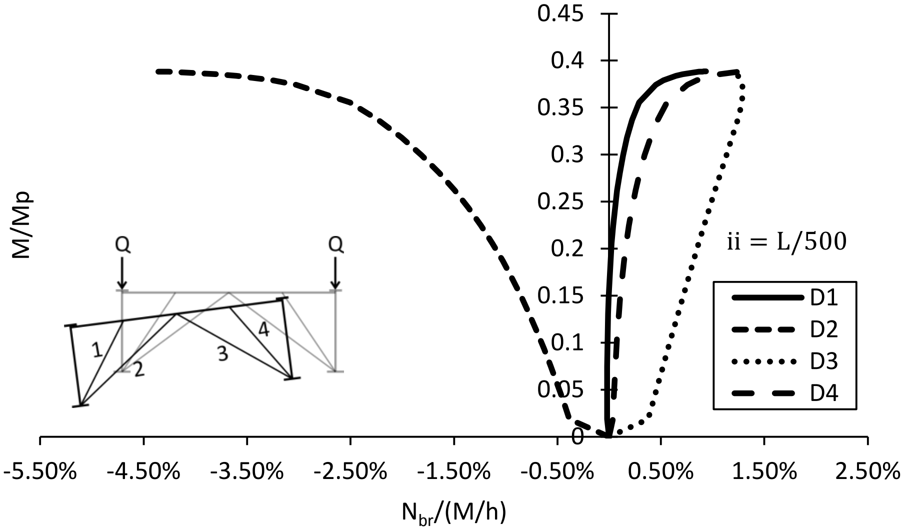

Figure 5.18 - Bracing forces in steel pipes in formwork D

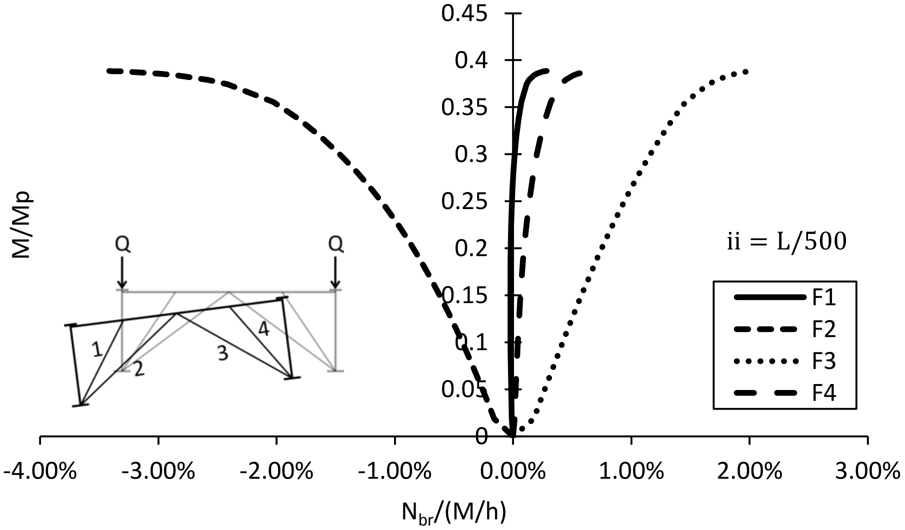

Figure 5.19 - Bracing forces in steel pipes in formwork F

Figure 5.20 - Figure 5.23 shows how the bracing forces in the different steel pipes changes along with their position on the beam. All formworks are represented in those figures.

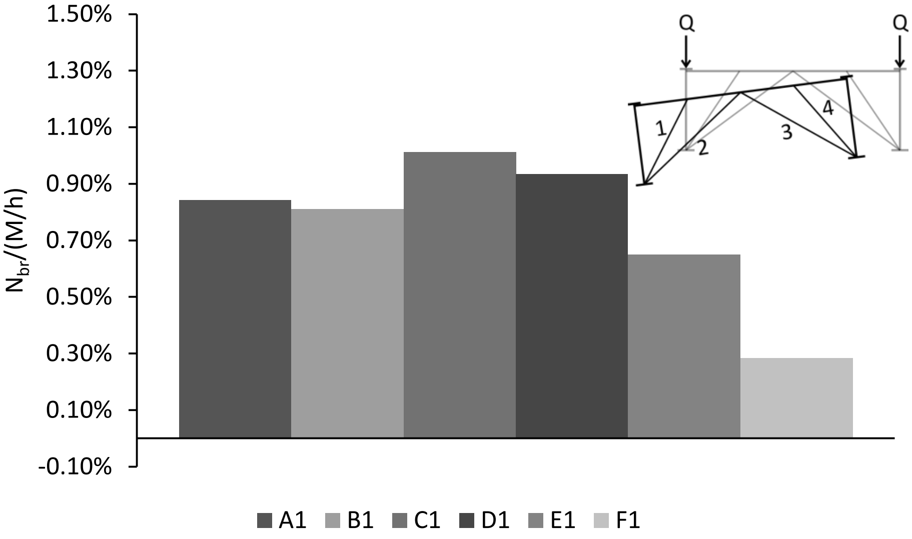

Figure 5.20 – Bracing forces in steel pipe 1 along half the length of the beam

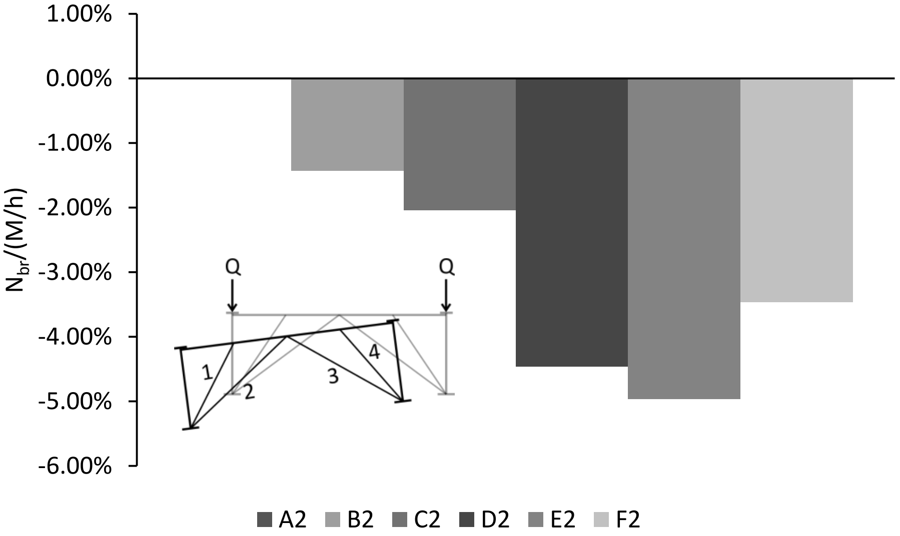

Figure 5.21 – Bracing forces in steel pipe 2 along half the length of the beam

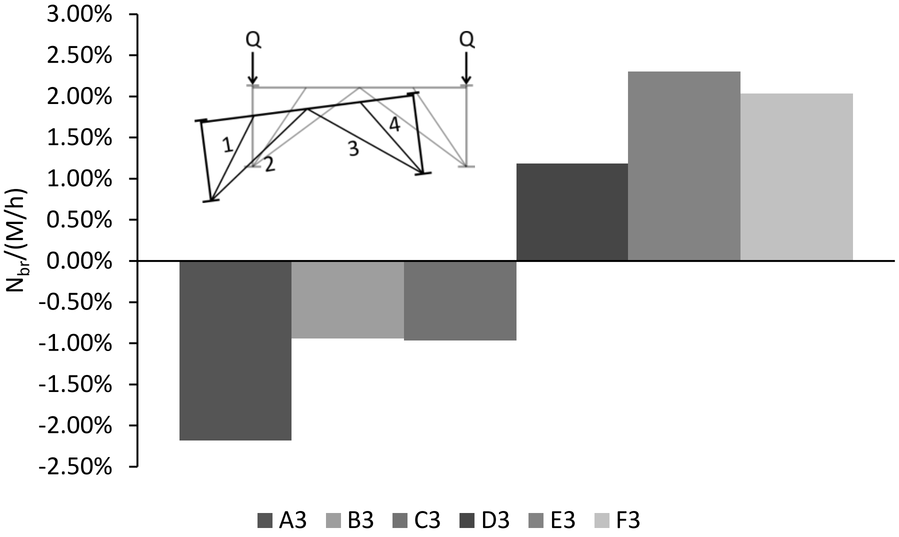

Figure 5.22 - Bracing forces in steel pipe 3 along half the length of the beam

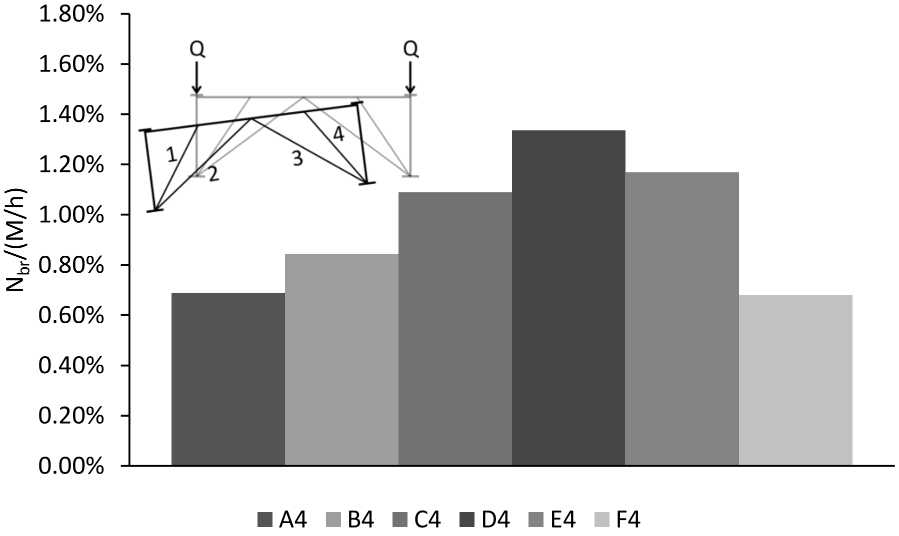

Figure 5.23 - Bracing forces in steel pipe 4 along half the length of the beam

A comparison between the two formworks closest to the middle is made and the result can be seen in Table 5.3. Formwork F and G are both located closest to the crossbeam with the crossbeam as a mirror plane.

Table 5.3 – Normal forces and differences between formwork F and G closest to the middle of the beams

	Normal forces (N)		
Pipe no.	Formwork F	Formwork G	Diff.
1	1180	1184	0.33 %
2	-14363	-14301	-0.43 %
3	8419	8360	-0.69 %
4	2816	2811	-0.18 %

Most often pipe number 1 and 4 are in tension while 2 and 3 are in compression. This can easiest be explained by thinking about the equilibrium. If the outermost pipes are in tension the inner pipes must be in compression to keep the system in equilibrium. The forces illustrated in Figure 5.22 are a bit odd and the author has no good explanation why the force goes from compression to tension the closer to the middle the elements are located. The forces are only due to twist in the system and it’s hard to understand exactly how the forces are distributed.

Worth to mention is that the highest stress in an element due to normal forces is 47 MPa, i.e. much less than the yielding strength.

From Table 5.3 the conclusion is that there is close to symmetry around the beams midpoints. Therefore the shown forces in formwork A can be said to be the same as formwork L, formwork B same as formwork K etc.

Analysis 4

The crossbeam is removed and all other input is the same as in the previous analysis, i.e. formworks attached to the beams. A comparison between the set-ups with and without crossbeam can be seen in Table 5.4 for the inwardly inclined beam quarter point and in Table 5.5 for the inwardly inclined beam midpoint.

Table 5.4 - Comparison in twist and top flange displacement at L/4 with and without a crossbeam attached

Load M/M_p	θ (rad) With crossbeam	θ (rad) Without crossbeam	Diff.	u (m) With crossbeam	u (m) Without crossbeam	Diff.
0.2	0.002	0.002	0.4 %	0.081	0.081	0.1 %
0.3	0.005	0.005	1.0 %	0.136	0.137	0.4 %
0.35	0.008	0.008	2.2 %	0.186	0.188	1.2 %

Table 5.5 - Comparison in twist and top flange displacement at midpoint with and without a crossbeam attached

Load M/M_p	θ (rad) With crossbeam	θ (rad) Without crossbeam	Diff.	u (m) With crossbeam	u (m) Without crossbeam	Diff.
0.2	0.004	0.004	-3.1 %	0.119	0.119	0.1 %
0.3	0.008	0.008	-5.2 %	0.201	0.202	0.5 %
0.35	0.013	0.012	-6.6 %	0.274	0.278	1.4 %

The twist and displacement can be said to be the same according to the tables above. The crossbeam has little effect on the system when formwork is attached.

Analysis 5

With initial imperfection according to the first mode shape of the bare girders with the biggest lateral displacement of L/1000 instead of L/500; the twist and displacements for the inwardly inclined beam are reduced which can be seen in Figure 5.24 and Figure 5.25 for the beam quarter point.

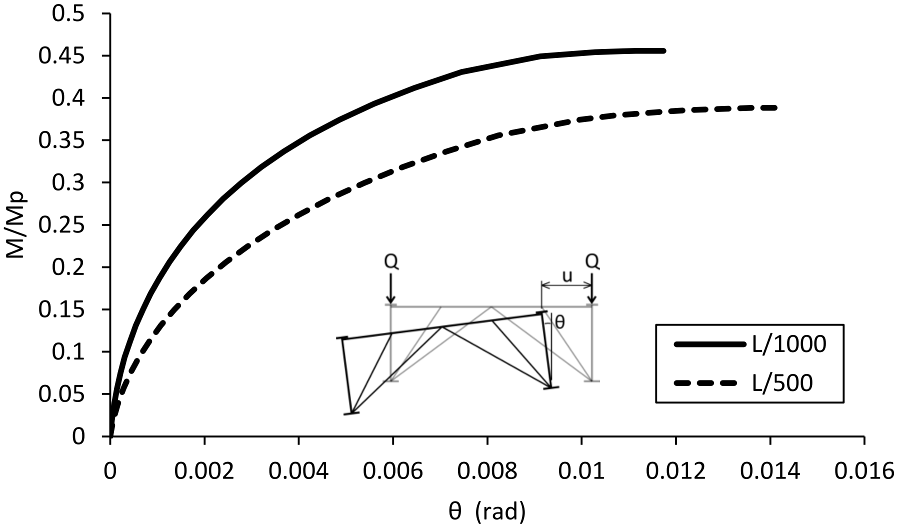

Figure 5.24 – Comparison of twist between initial imperfection L/1000 and L/500 at beam midpoint

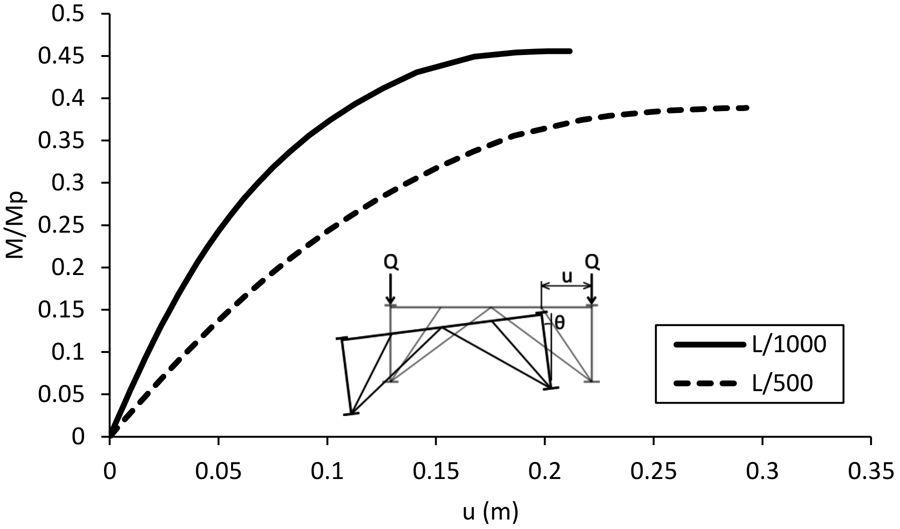

Figure 5.25 - Comparison of top flange lateral displacement between initial imperfection L/1000 and L/500 at beam quarter point

Table 5.6 shows the reduction in twist and displacement at the beam quarter point and Table 5.7 at the beam midpoint.

Table 5.6 – Differences between initial imperfection L/1000 and L/500 at beam quarter point

Load	θ (rad)			u (m)		
M/Mp	L/500	L/1000	Diff.	L/500	L/1000	Diff.
0.2	0.002	0.001	-48.9%	0.081	0.040	-50.0%
0.3	0.005	0.003	-48.4%	0.136	0.068	-50.1%
0.35	0.008	0.004	-48.5%	0.186	0.092	-50.7%

Table 5.7 – Differences between initial imperfection L/1000 and L/500 at beam midpoint

Load	θ (rad)			u (m)		
M/Mp	L/500	L/1000	Diff.	L/500	L/1000	Diff.
0.2	0.004	0.002	-49.0%	0.119	0.059	-50.0%
0.3	0.008	0.004	-49.2%	0.201	0.100	-50.1%
0.35	0.013	0.006	-49.9%	0.274	0.135	-50.7%

The reduction in twist and top flange displacement are almost 50 % for both the quarter point and the midpoint. If analyses were made for a larger amount of different initial imperfections, maybe a relationship could have been found between the degree of initial imperfection and the twist and top flange displacement of the beam.

Analysis 6

Figure 5.26 and Figure 5.27 shows a comparison between two different pipe cross-sections used for the formworks and Table 5.8 and Table 5.9 shows the difference between the two set-ups at the beam quarter point and midspan respectively for the inwardly inclined beam.

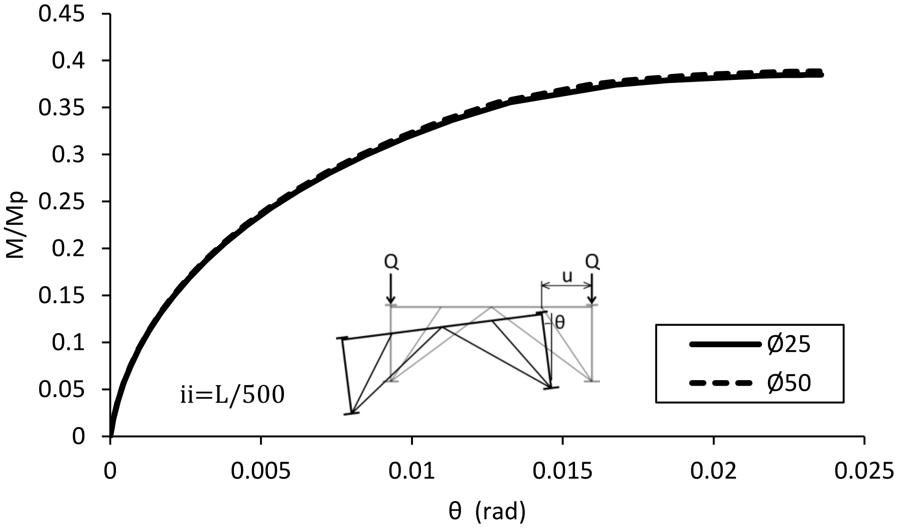

Figure 5.26 - Comparison of twist between steel pipe section Ø25 and steel pipe section Ø50 at beam quarter point

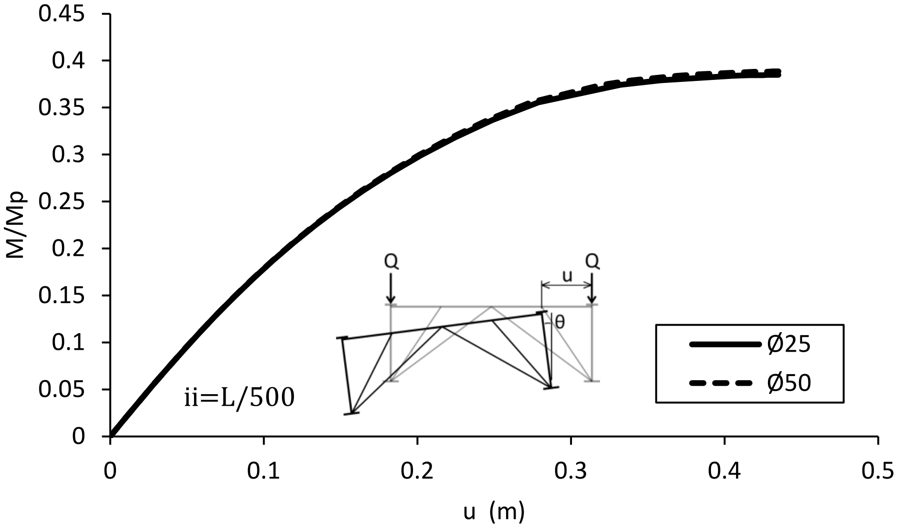

Figure 5.27 - Comparison of top flange lateral displacement between steel pipe section Ø25 and steel pipe section Ø50 at beam quarter point

Table 5.8 - Differences between steel pipe section Ø25 and steel pipe section Ø50 at beam quarter point

Load M/Mp	θ (rad) Ø50	θ (rad) Ø25	θ (rad) Diff.	u (m) Ø50	u (m) Ø25	u (m) Diff.
0.2	0.002	0.002	0.9%	0.081	0.081	0.4%
0.3	0.005	0.005	0.8%	0.136	0.138	0.9%
0.35	0.008	0.008	1.1%	0.186	0.189	1.8%

Table 5.9 - Differences between steel pipe section Ø25 and steel pipe section Ø50 at beam midpoint

Load M/Mp	θ (rad) Ø50	θ (rad) Ø25	θ (rad) Diff.	u (m) Ø50	u (m) Ø25	u (m) Diff.
0.2	0.004	0.004	1.5%	0.119	0.119	0.4%
0.3	0.008	0.008	2.0%	0.201	0.203	0.9%
0.35	0.013	0.013	3.1%	0.274	0.279	1.8%

It can be seen in Table 5.8 and Table 5.9 that the cross section of the steel pipes has a very small effect on the overall twist and top flange lateral displacement of the beam. The increase can be said to be little to none.

Analysis 7

Figure 5.28 and Figure 5.29 shows a comparison between the twist and top flange lateral displacement at beam quarter point for the cases with formworks in all positions, see Figure 5.2, compared to formworks only in position B, D, F, G, I and K. Figure 5.30 Figure 5.31 shows the same thing but for the beam midpoint. Both analyses concern the inwardly inclined beam.

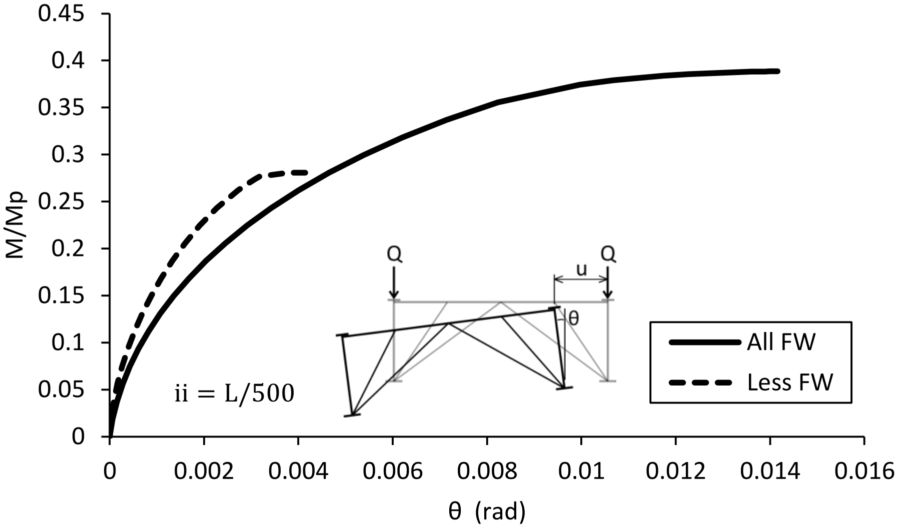

Figure 5.28 - Comparison of twist at beam quarter point for different formwork set-ups

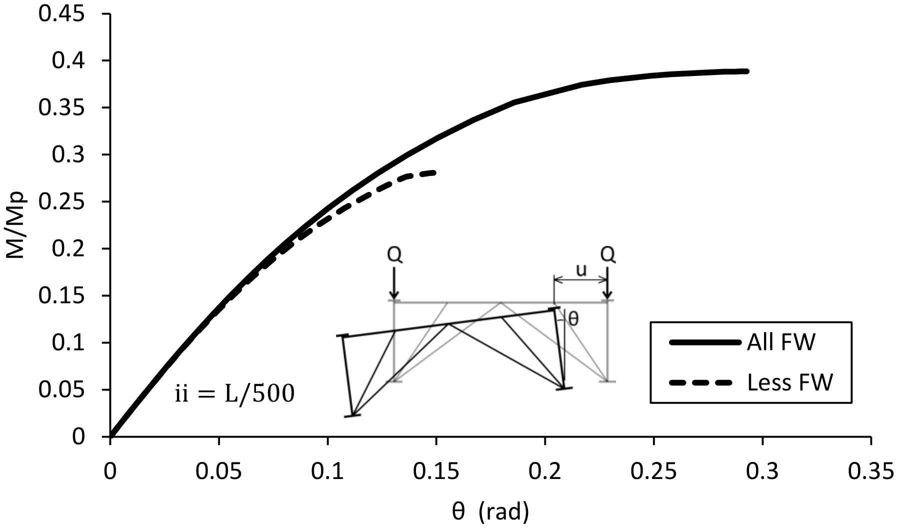

Figure 5.29 - Comparison of top flange displacements at beam quarter point for different formwork set-ups

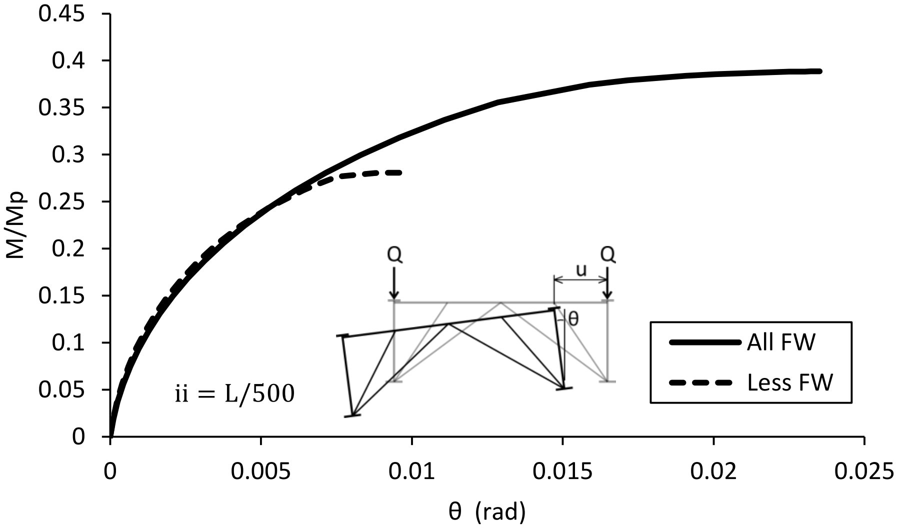

Figure 5.30 - Comparison of twist at beam midpoint for different formwork set-ups

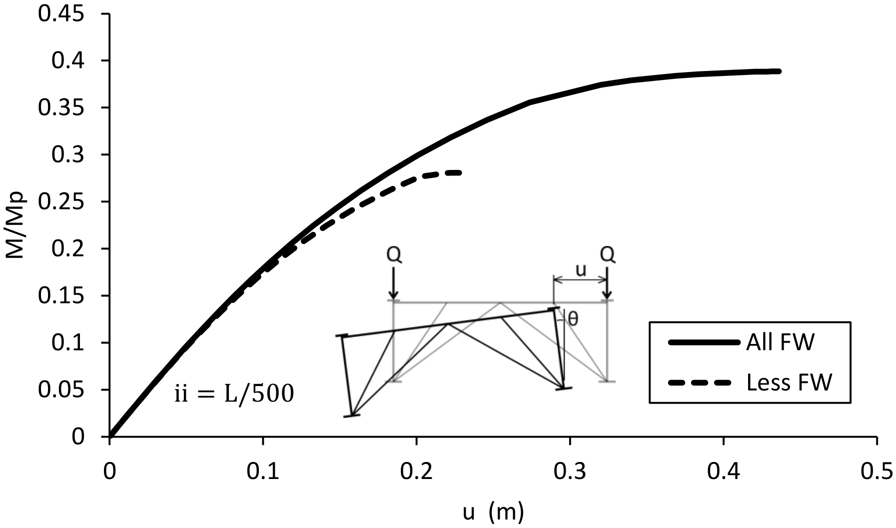

Figure 5.31 - Comparison of top flange displacements at midpoint for different formwork set-ups

It can be seen that the twist and top flange displacement follow almost the same curve until a certain point where no more load can be applied. Perhaps the stiffness of the system is the same until the load approaches the stage where the top flanges buckles in half sinusoidal waves between the bracing. With longer distance between the bracing points this occurs faster.

Analysis 8

Figure 5.32 shows how drastically the torsional stiffness increases from just the bare beams to beams interconnected with a crossbeam and finally beams interconnected with full formwork and crossbeam. Figure 5.33 shows the same thing but for top flange displacements. All values are taken at the quarter point of the inwardly inclined beam.

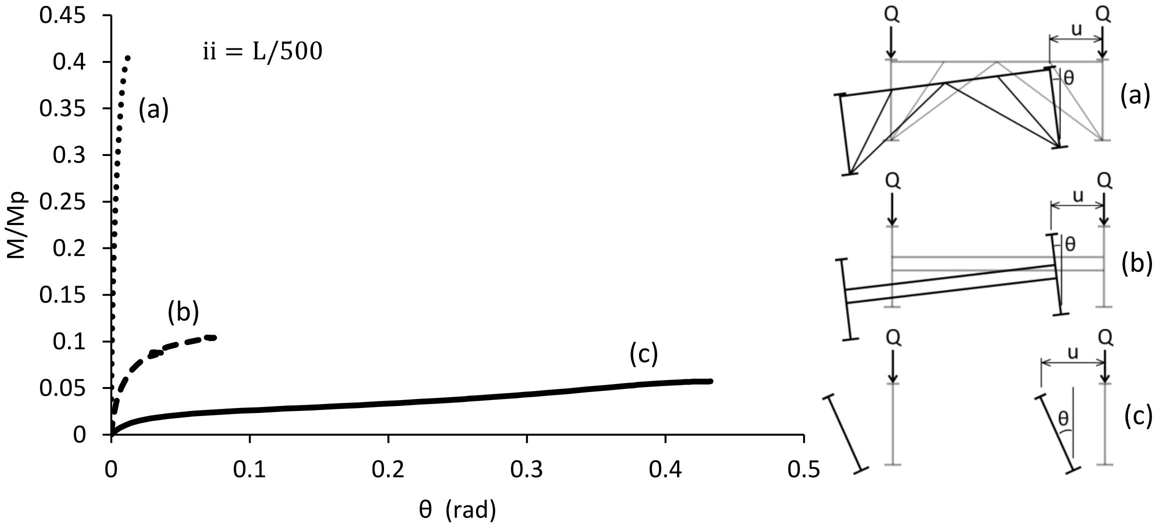

Figure 5.32 – Comparison between torsional stiffness (twist) for different set-ups

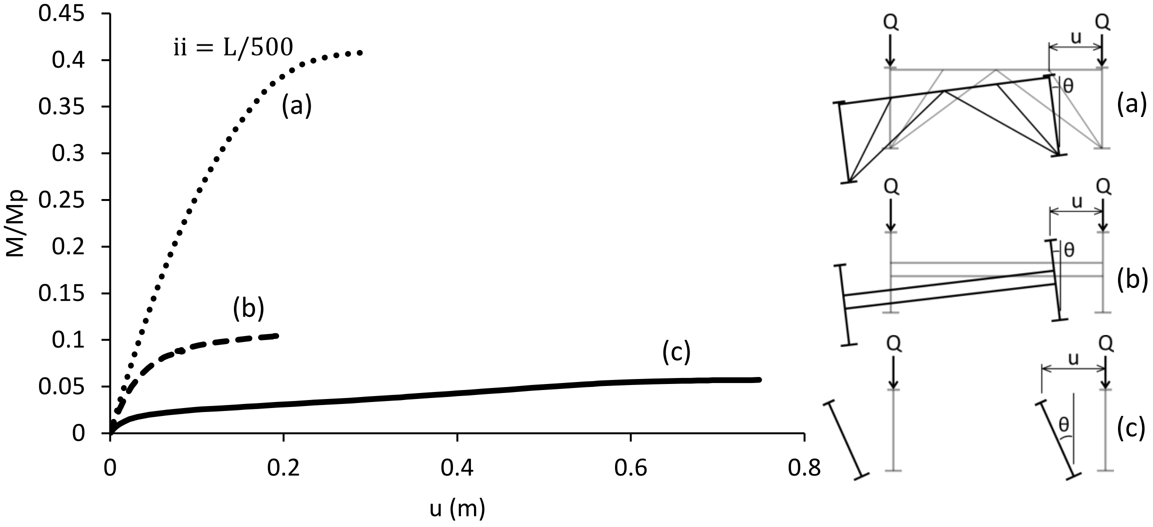

Figure 5.33 – Comparison between top flange displacements for different set-ups

5.3.3 INCREMENTAL BUCKLING ANALYSES OF BEAMS SUBJECTED TO UDL

Analysis 1

Figure 5.34 and Figure 5.35 shows the twist and top flange displacement of the most studied inwardly inclined beam. All loads have been applied through the top of the formwork.

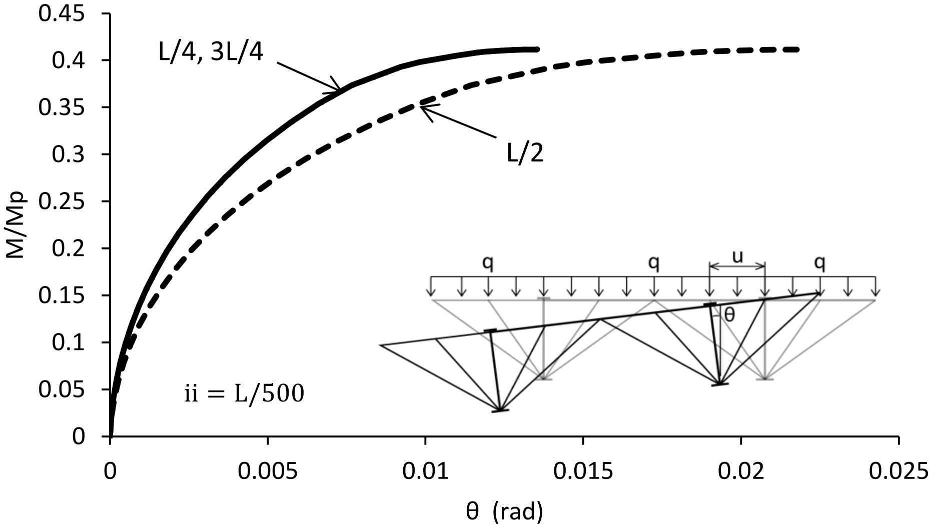

Figure 5.34 – Twist of the inwardly inclined beam when connected with formworks and subjected to UDL

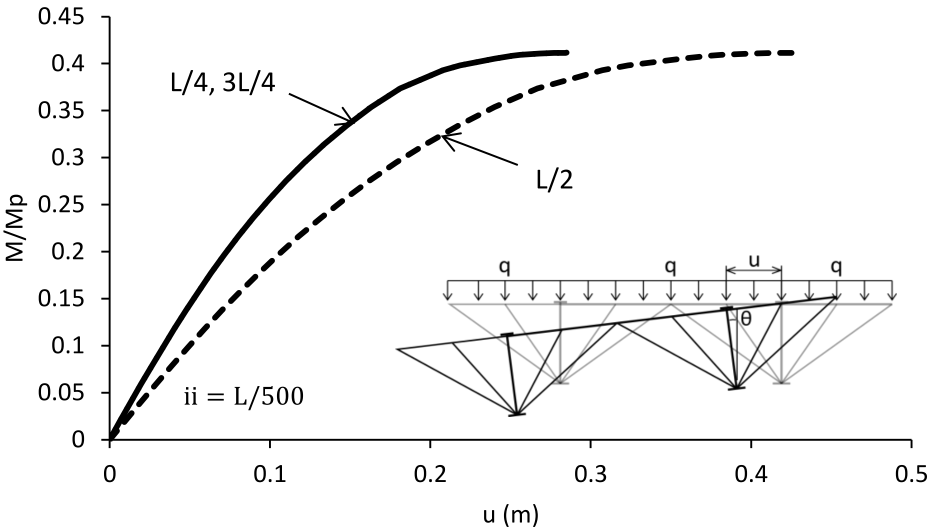

Figure 5.35 – Top flange displacement of the inwardly inclined beam when connected with formworks and subjected to UDL

The values differ a bit from the case with concentrated force applied to the beams third points and the differences can be seen in Table 5.10 for the beam quarter point and in Table 5.11 for the beam midspan.

Table 5.10 – Comparison between twist and top flange displacement at beam quarter point, for load applied as concentrated and as uniformly distributed to the formworks

Load M/Mp	θ (rad)			u (m)		
	Q@L/3	UDL	Diff.	Q@L/3	UDL	Diff.
0,2	0.002	0.002	-18.9 %	0.081	0.076	-6.0 %
0,3	0.005	0.004	-20.8 %	0.136	0.121	-11.0 %
0,35	0.008	0.007	-19.6 %	0.186	0.163	-12.2 %

Table 5.11 – Comparison between twist and top flange displacement at beam midspan, for load applied as concentrated and as uniformly distributed to the formworks

Load M/Mp	θ (rad)			u (m)		
	Q@L/3	UDL	Diff.	Q@L/3	UDL	Diff.
0,2	0,004	0,003	-24,9 %	0,119	0,112	-6,1 %
0,3	0,008	0,006	-25,4 %	0,201	0,179	-11,0 %
0,35	0,013	0,010	-23,8 %	0,274	0,240	-12,3 %

The differences shown in the tables above can somehow be explained due to the different moment gradient that come from the way of loading; i.e. concentrated force versus UDL.

Analysis 2

If the system of complete formwork is stiffened with longitudinal pipe sections, according to Figure 5.7, the twist and top flange displacement instead look like Figure 5.36 and Figure 5.37 respectively.

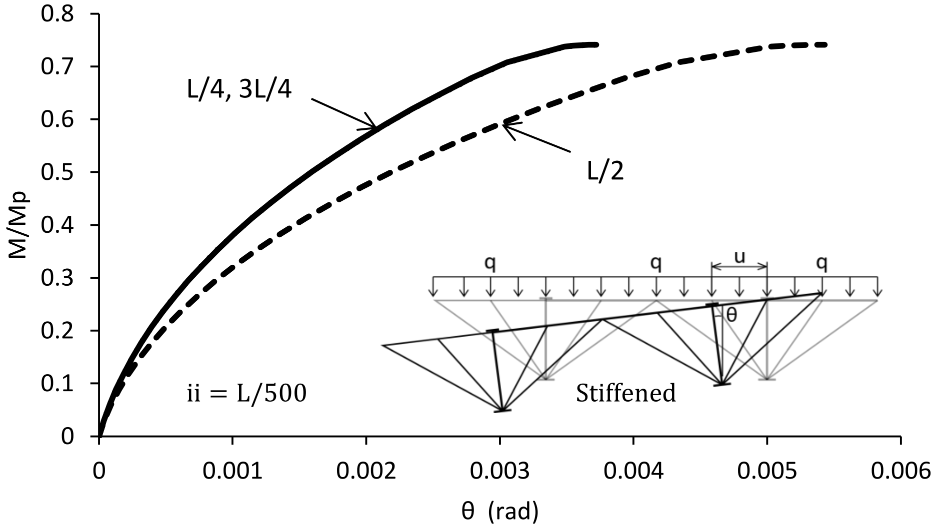

Figure 5.36 – Twist of beams connected with stiffened formworks and subjected to UDL

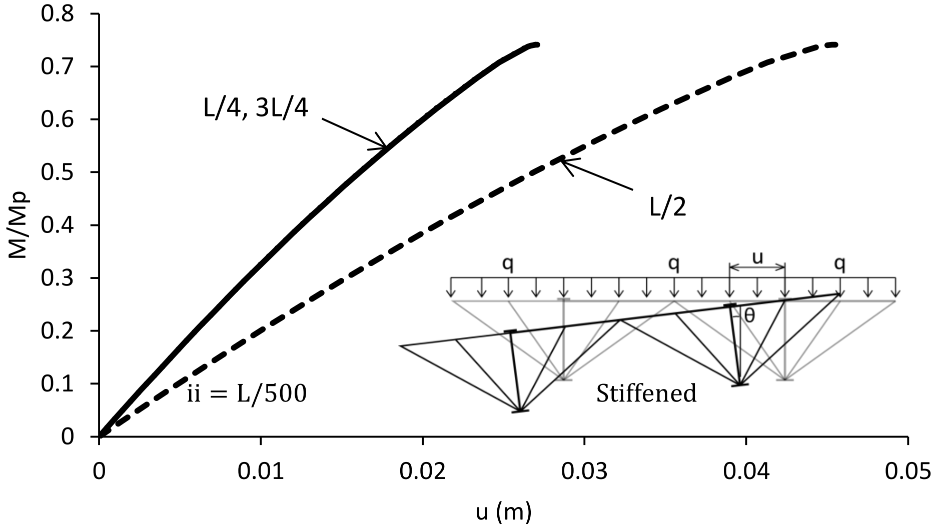

Figure 5.37 – Top flange displacement of beams connected with stiffened formworks and subjected to UDL

A comparison between the longitudinal stiffened and the longitudinal unstiffened system is made and the results can be seen in Table 5.12.

Table 5.12 – Comparison between the longitudinal stiffened and the longitudinal unstiffened system of complete formwork

	Without stiffeners	With stiffeners	Diff.
Maximum load (M/Mp)	0.410	0.740	80.1 %
Maximum twist (rad)	0.014	0.004	-72.5 %
Maximum displacement (m)	0.285	0.027	-90.5 %

Table 5.12 shows that there are huge differences between a system that is stiffened in the longitudinal direction and one that is not. At the same point that the maximum applied load is increased with 80 % the maximum twist is down almost 73 % and the maximum top flange displacement is down 90 %. A decrease of 90 % is similar to 1/10 of the displacement.

Analysis 3

If rebars are attached between the beams of the longitudinally unstiffened system, twist of the beam and displacement of the top flange for the inwardly inclined beam looks like Figure 5.38 and Figure 5.39 respectively. The longitudinally unstiffened system was chosen for this analysis because the intended stiffening impact was thought to be the biggest on a less stiff system.

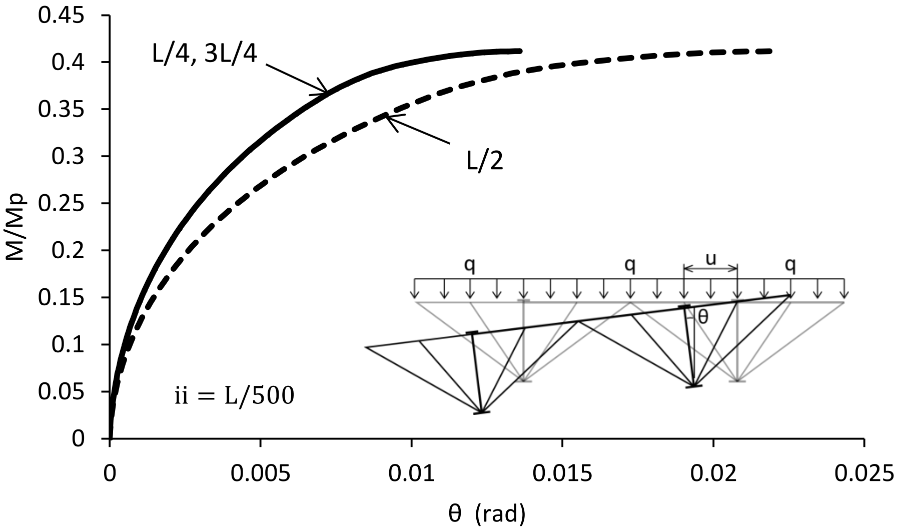

Figure 5.38 – Twist of beams connected with formworks and rebars and subjected to UDL

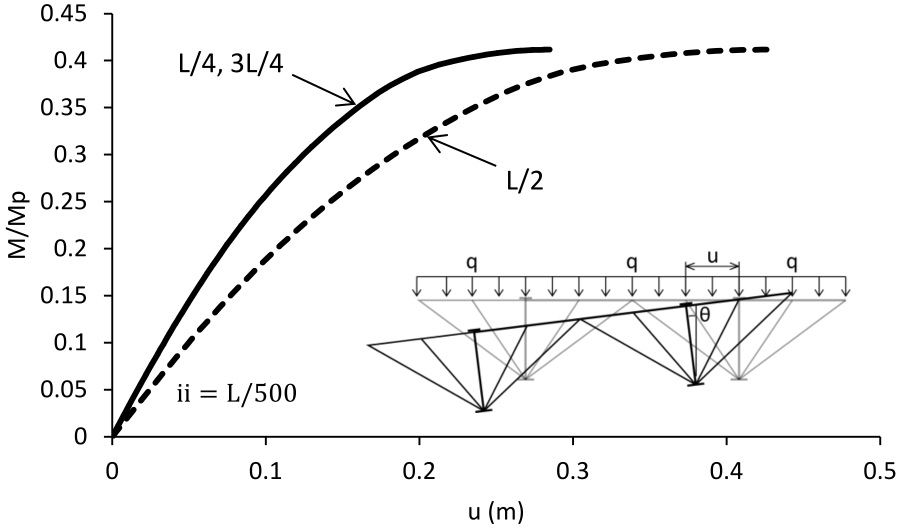

Figure 5.39 – Top flange displacement of beams connected with formworks and rebars and subjected to UDL

The difference between a system with and without rebars can be seen in Table 5.13 and the forces in the rebars can be seen in Figure 5.40.

Table 5.13 – Difference between a set-up with and without rebars connecting the beams

Load M/Mp	θ (rad)			u (m)		
	With	Without	Diff.	With	Without	Diff.
0.2	0.0025	0.0025	0.7 %	0.105	0.105	0.0 %
0.3	0.0073	0.0072	-0.3 %	0.197	0.197	0.0 %
0.35	0.0097	0.0098	1.2 %	0.237	0.240	1.3 %

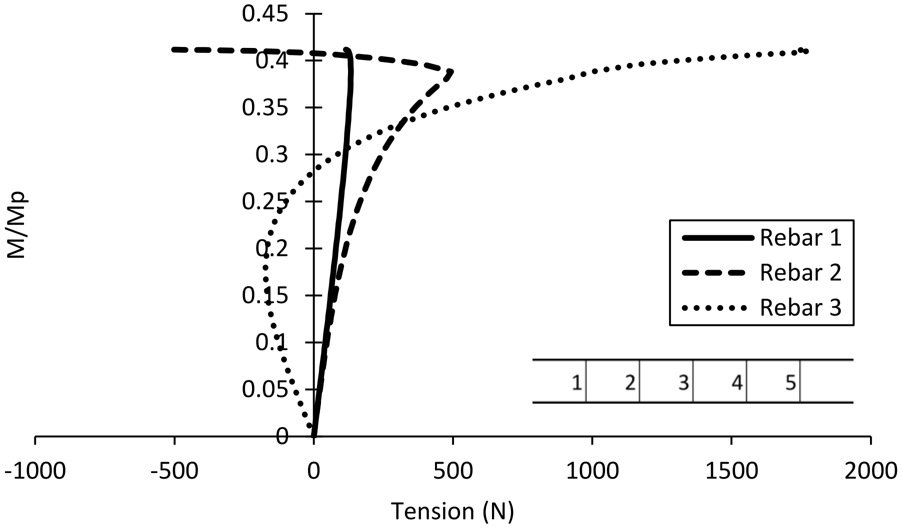

Figure 5.40 – Forces in the tension rebars

Figure 5.40 only show rebars 1-3 because of the previously shown symmetry in the system and therefore rebar 1 can be said to be loaded almost equally to 5 and 2 almost equally to 4. Rebar 1 is the one at the end and rebar 3 are situated in the middle right over the crossbeam. All negative values can be neglected when they aren't helping the flanges stay together. To make a conclusion; the rebars has no effect on the stabilization of this system and therefore even less effect on the stiffened system.

Analysis 4

A comparison of stiffness (twist) for three different systems can be seen in Figure 5.41 and the corresponding top flange displacements in Figure 5.42.

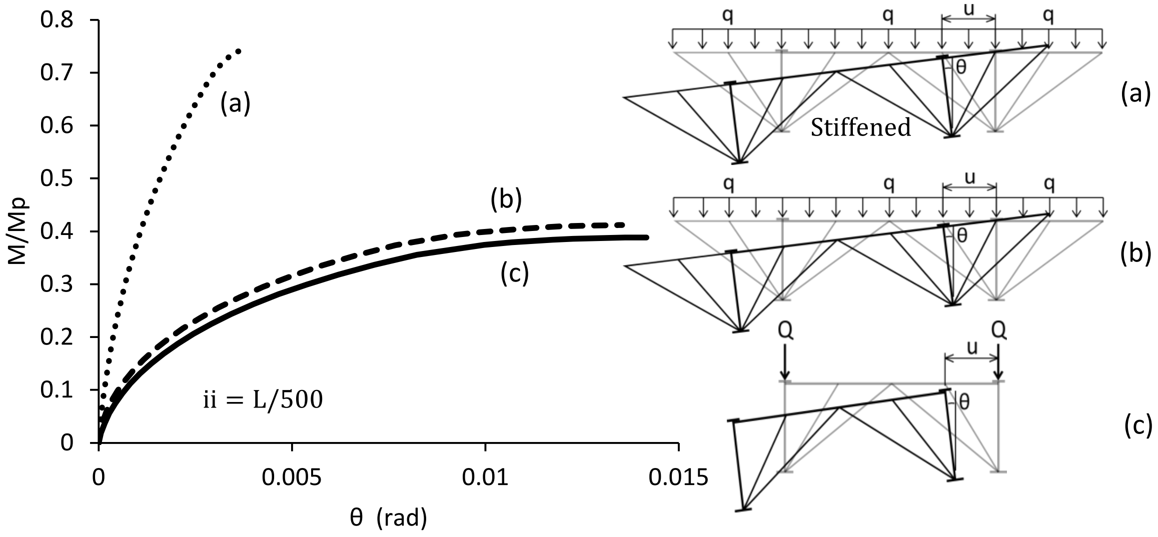

Figure 5.41 – Comparison between torsional stiffness (twist) for three different set-ups

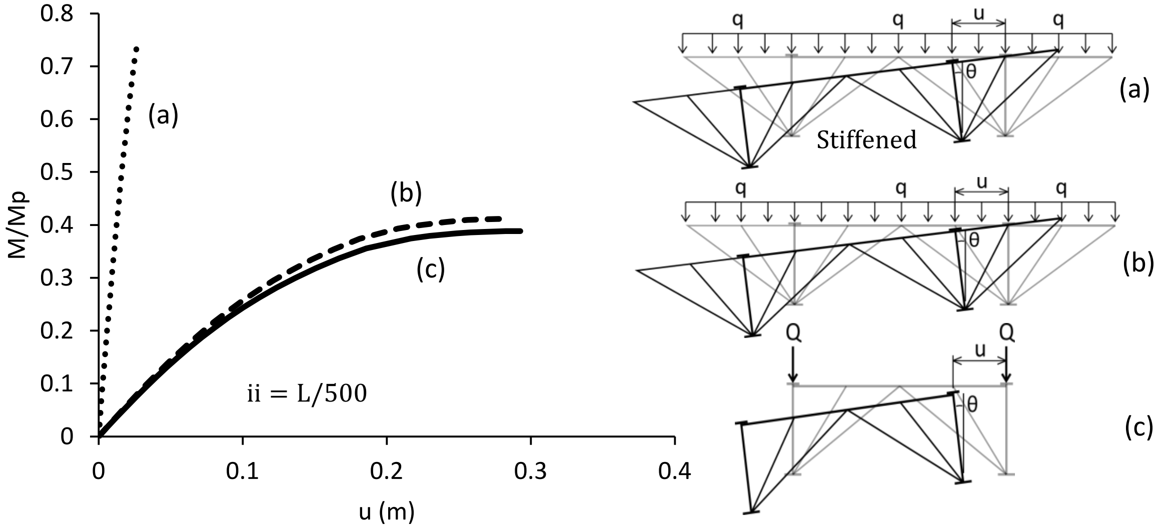

Figure 5.42 – Comparison between top flange displacements for three different set-ups

The first and less stiff system is the one with only intermediate and longitudinally unstiffened formwork attached between the beams. The second and only slightly more stiff system is the one with a longitudinally unstiffened complete set of formwork subjected to UDL. The huge increase is seen first when the complete formwork set-up are stiffened in the longitudinal direction. The longitudinally stiffeners are assumed to be completely clamped when attached between the formworks, which they almost are for real. If they are; they make up for a huge increase of stiffness in the system.

6 NUMERICAL ANALYSIS OF BRIDGE Y1504

Next bridge to be analyzed is a bridge that was under construction but collapsed during concreting of the deck. The aim is to investigate if there would have been an increase in the stiffness and stability of the bridge if CUPLOK temporary formworks had been attached as described earlier on.

6.1 DESCRIPTION OF Y1504

Y1504 was located over Sävarån in northwestern Sweden before it collapsed during construction.

6.1.1 MAIN GIRDER AND STEEL PARTS

The span is 65 meter long and the cross section consists of a trapezoidal 2 meter high box section, see Figure 6.1.

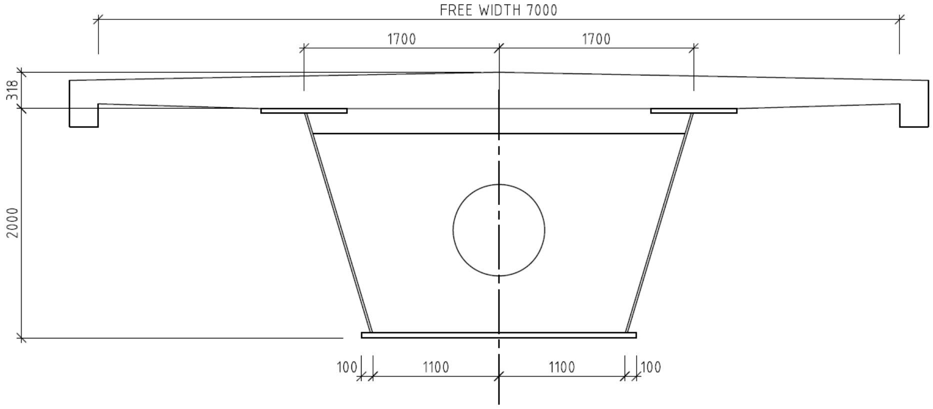

Figure 6.1 – Schematic cross section of the bridge Y1504

Y1504 consists of three different cross sections welded together according to Figure 6.2. The steel grade is S460M in flanges, S420M in webs and S355 in diaphragms. The 100 mm cantilevered part on the lower flange is used to simplify welding and to have somewhere to put the cantilever part of the temporary formworks.

In Abaqus the model is fixed in one of the lower corners and free to move in the longitudinal direction in the other three. All top flanges are restrained from moving in the transverse direction at the supports. These boundary conditions makes the girder free to warp at the ends, but restrained from lateral twist.

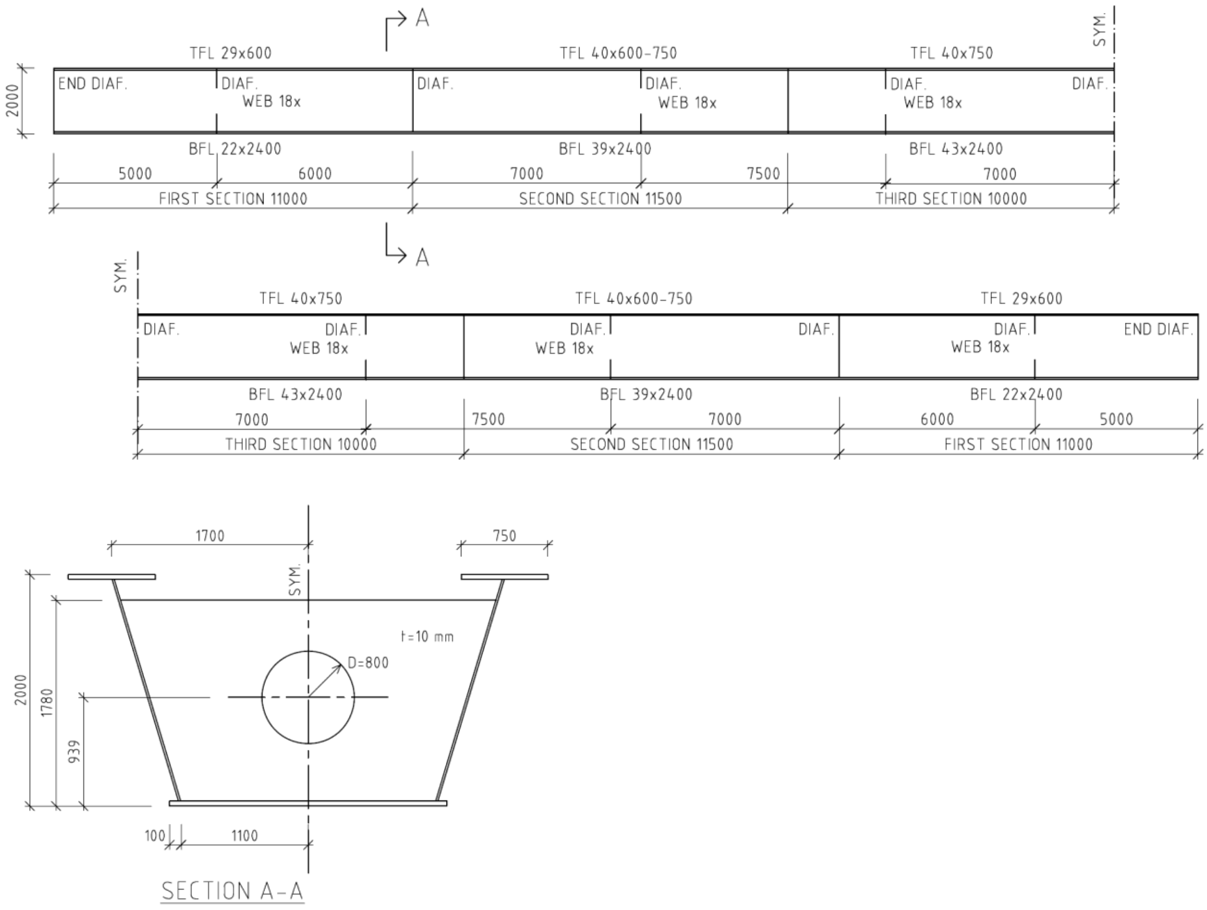

Figure 6.2 – Dimensions of Y1504 bridge

6.1.2 FORMWORK

Again the CUPLOK system from BRITEK is used as temporary formwork. For this analysis only intermediate formworks that are unstiffened in the longitudinal direction of the girder are attached. The set-up looks like Figure 6.3 and there are formworks attached every 1.5 meters. Steel pipes are of grade S235 and timber beam are of grade C24.

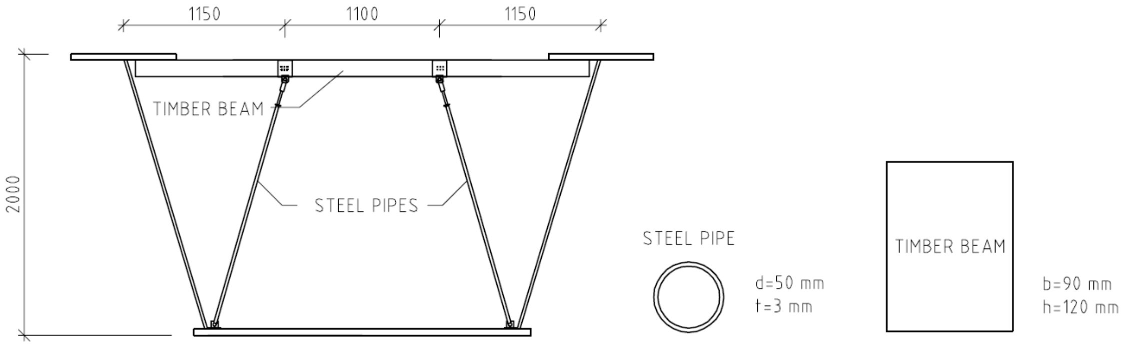

Figure 6.3 – Cross section of intermediate formwork attached (BRITEK Ltd)

6.2 ANALYSIS METHOD

Within this section the method for the numerical simulations are described. From the beginning the thought was that this would be the final bridge to look at, but as the result shown very little interesting things the decision was to pick yet another bridge for further analysis of the CUPLOK system. Therefore the analyses are not needed to be very comprehensive.

6.2.1 LINEAR EIGENVALUE BUCKLING ANALYSES

First thing to analyze is how the buckling capacity changes with and without the use of temporary formworks attached. For the calculation of M_{cr} load are uniformly distributed along the length of the flanges. The analyses are as follow.

1. Girder and diaphragms subjected to UDL
2. Girder and diaphragms with attached formworks subjected to UDL

After both analyses are run there is a comparison between them.

6.3 ANALYSIS RESULTS

The analysis results are presented within this section.

6.3.1 LINEAR EIGENVALUE BUCKLING ANALYSES

Analysis 1

With UDL applied to the top flanges the critical moment was calculated to 43180 kNm.

Analysis 2

With UDL applied to the top flanges and formwork attached every 1.5 meters the critical moment was calculated to 43163 kNm. The buckling mode is global torsional buckling and the mode shape can be seen in Figure 6.4.

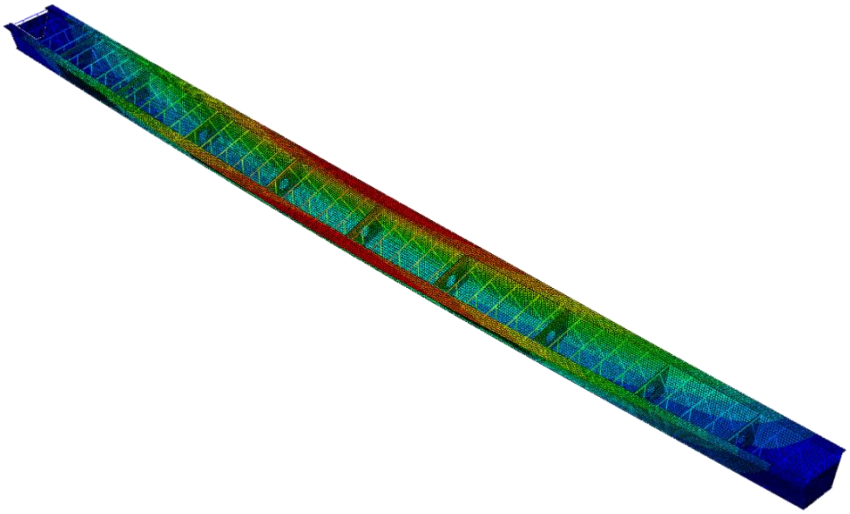

Figure 6.4 – Global torsional buckling of Y1504 with formwork attached

Comparison between results

The difference between the two analyses can be seen in Table 6.1.

Table 6.1 – Comparison between M_{cr} for a set-up with and without formwork attached

Analysis type	**M_{cr} (kNm)**	**Diff.**
Girder and diaphragms	43180	-
Girder and diaphragms with formwork	43163	-0.04 %

The result is that this kind of discrete torsional bracing, as the formworks provide, has no effect at all on the global torsional stiffness of the system. This is in line with the work performed by H. Mehri and R. Crocetti (2012) where a similar effect was to be seen.

Because of this result no further analyses are being made on the system.

7 NUMERICAL ANALYSIS OF BRIDGE OVER ROAD E6

Due to lack of results from the analyses of Bridge Y1504 this bridge was chosen to be modelled and analyzed as well. This is another I-girder bridge and the aim is to see if the results are similar for this real life bridge in comparison to the laboratory test beam bridge scenario.

7.1 DESCRIPTION OF BRIDGE OVER ROAD E6

Bridge over road E6 is a steel-concrete composite bridge crossing road E6 2.4 km north of traffic point Flädie in southern Sweden. The bridge has two spans with a diagonal support in the middle.

7.1.1 MAIN GIRDERS AND STEEL PARTS

The bridge consists of two 53.2 meters long symmetrical I-girders. Diaphragms are holding the beams together at support point. In between these points there are K-bracing every 6.65 meters. Dimensions can be seen in Figure 7.1. Both top and bottom flanges are 600 mm wide and 30 mm resp. 35 mm thick. The web is 15 mm thick.

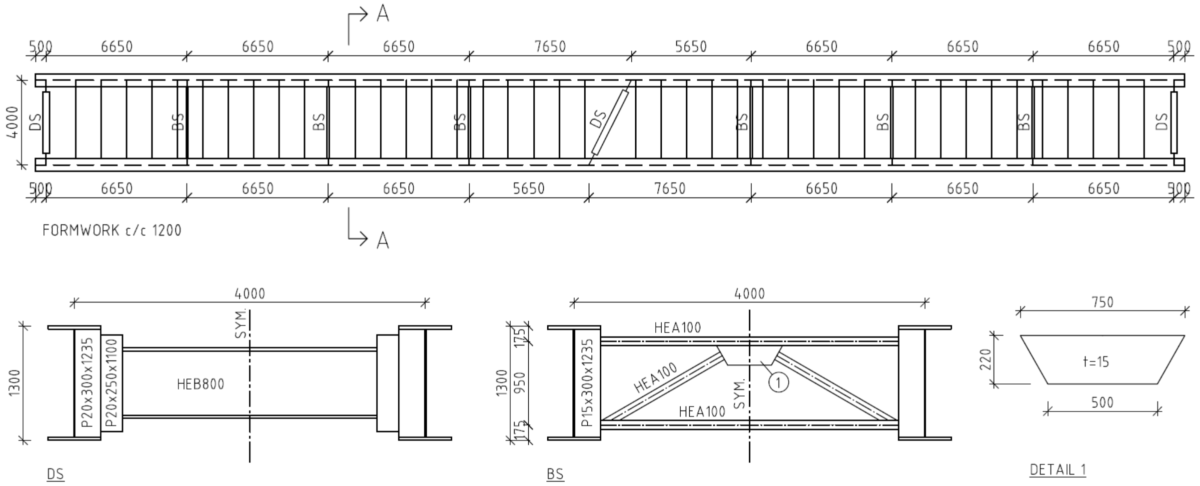

Figure 7.1 – Dimensions of Bridge over road E6

Main girders are of steel grade S460M and the rest of the steel parts are of grade S355.

Support points are right next to the diaphragms. The supports are fixed in the middle and free to move in the longitudinal direction at the ends. The beams only have support at the lower flanges.

Plastic moment capacity, M_p, of the beams are equal to 13 933 kNm and all results are in relation to this value.

7.1.2 FORMWORK

Formworks are attached every 1.2 meters according to the lines in Figure 7.1. Section A in the same figure looks like Figure 7.2.

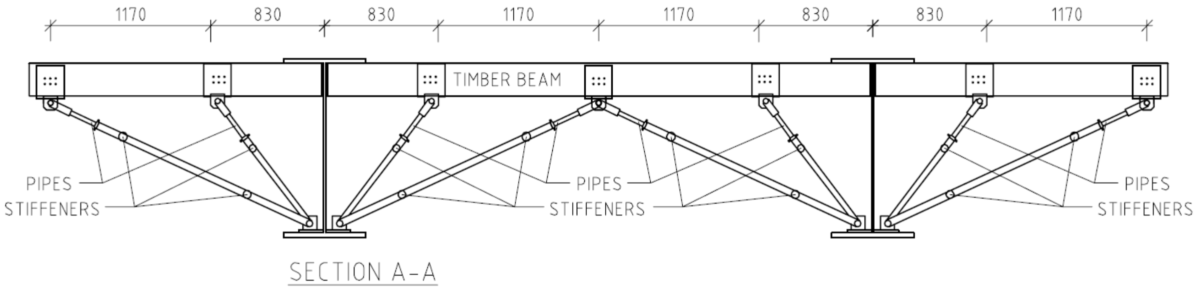

Figure 7.2 – Cross section of girders with attached formwork (BRITEK Ltd)

Dimensions of steel pipe sections and timber beam sections are the same as in previous chapters, i.e. diameter 50 mm with thickness 3 mm for the pipes and rectangular cross section of 90x120 mm^2 for the timber beams, with steel grade S235 and timber class C24 respectively. Longitudinal stiffeners of the same pipe section are used and they are completely clamped to the formworks at both ends.

The simplified set-up used in the numerical analyses can be seen in Figure 7.3 with the positions of the longitudinal stiffeners.

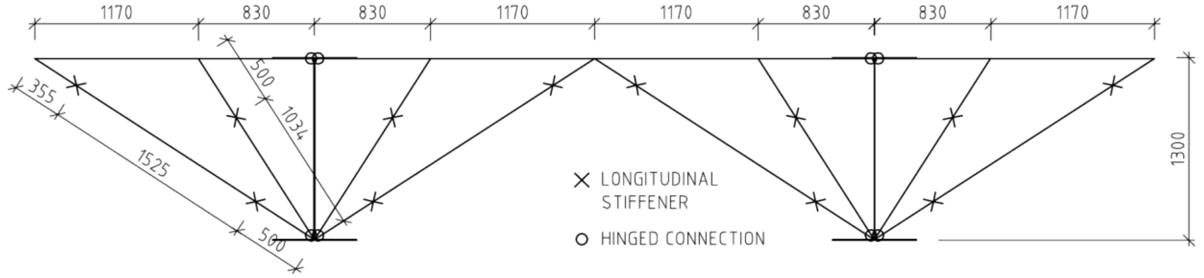

Figure 7.3 - Simplified model of the complete system used for the numerical analyses

7.2 ANALYSIS METHOD

Within this section the method for the numerical simulations are described.

Only one buckling analysis is done for this bridge and that is only to be able to view the first buckling mode and from that apply initial imperfections to forthcoming incremental analyses. The first positive buckling mode shape looks like Figure 7.4, where top flanges twist inwards the system at the longer span of each beam. No K-bracing are present at this stage to make the initial imperfections more realistic, compared to how real initial imperfections would have looked like.

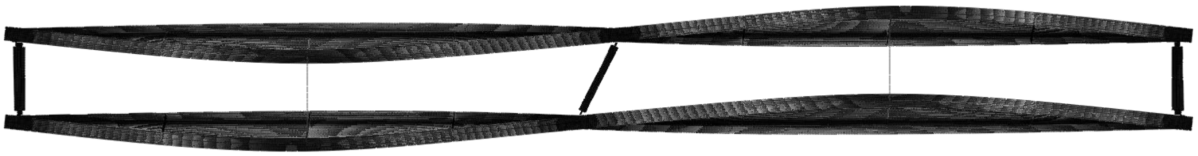

Figure 7.4 – First mode shape of beam system with bracing just at supports

Initial imperfection of L/500 at the most deflected place of the beams are applied, where L is the distance from an end support to the midpoint of the skew support in the middle. To the beams are then K-bracing attached as well. No stresses are introduced to any elements of the system at this stage. Load is then applied in increments, as pressure to the top flange for the case without formwork and as line loads directly to the formworks if they are present.

Analysis 1

To check for symmetry the twist and top flange displacement are measured at quarter points at each beam, i.e. in the middle of each span. This is made for the bridge without formwork attached, see Figure 7.5. Each beam has a longer and a shorter span and therefore the twist can be assumed to differ a bit between the spans. To see if there is any difference between the beams; twist and top flange displacement are measured at the quarter point in the longer span of each beam and then compared to each other.

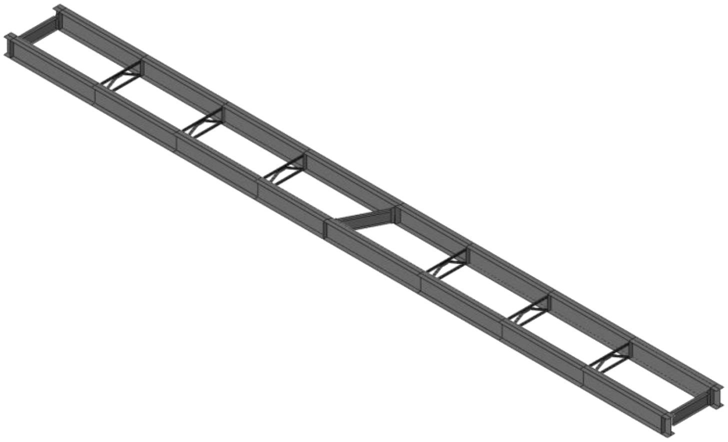

Figure 7.5 – FE-model of Bridge over road E6 without any formwork attached

Analysis 2

In this analysis formwork is attached to the beams in accordance to Figure 7.2 and the FE-assembly looks like Figure 7.6. Twist and top flange displacement is measured for one of the beams quarter points. Forces are measured in the in Figure 7.6 highlighted formworks A-D. Formwork A is close to an end support, B and D are almost in the middle of respective span and C is close to the middle support.

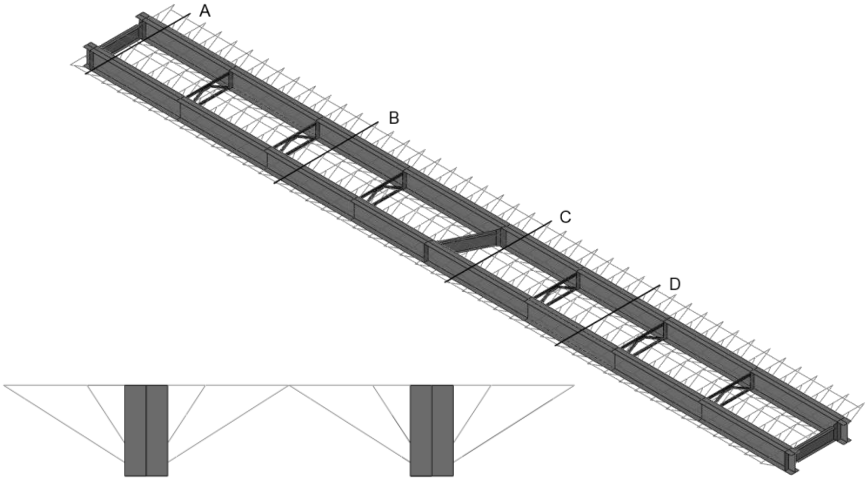

Figure 7.6 - FE-model of Bridge over road E6 with formwork attached incl. cross-section

Analysis 3

This is a comparison of twist and top flange displacement between the two systems; with and without formwork attached.

7.3 ANALYSIS RESULTS

Within Section 7.2 all analyses are described and within this section the appurtenant results are listed in the same order.

Analysis 1

Twist and top flange displacements for one beam can be seen in Figure 7.7 and Figure 7.8 respectively.

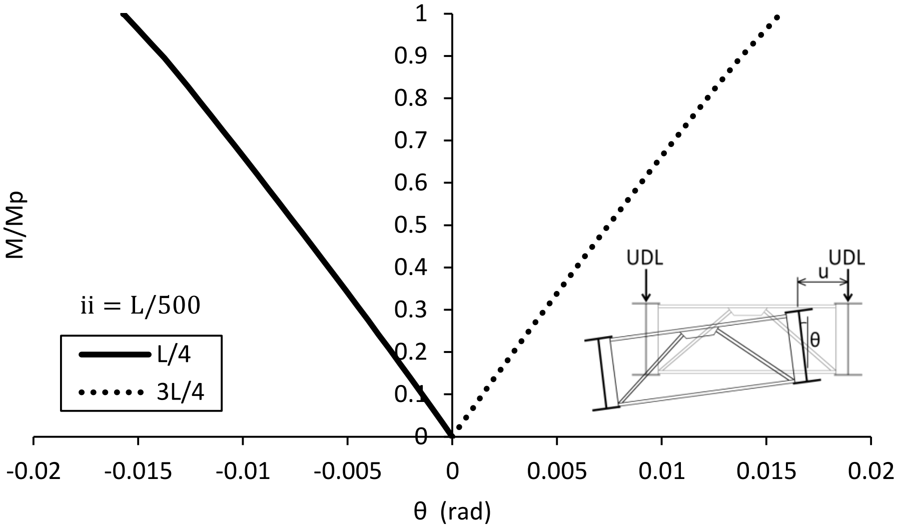

Figure 7.7 – Twist of a beam subjected to UDL along the top flanges

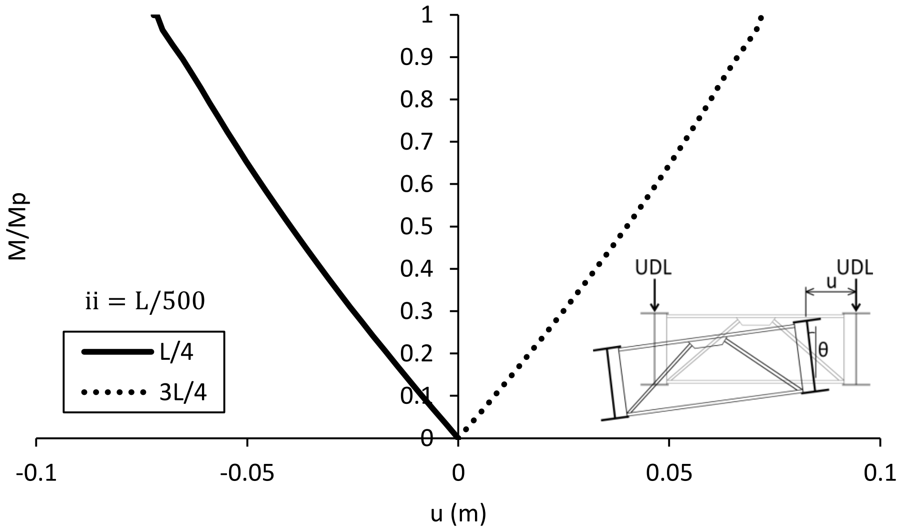

Figure 7.8 – Top flange displacement of a beam subjected to UDL along the top flanges

A comparison between the results can be seen in Table 7.1.

Table 7.1 – Comparison of twist and top flange displacement in the two spans

Load Ms/Mp	θ (rad) L/4	3L/4	Diff.	u (m) L/4	3L/4	Diff.
0.50	0.007	0.007	0.13 %	0.038	0.039	0.58 %
0.75	0.011	0.011	-0.07 %	0.055	0.055	0.72 %
1.00	0.015	0.015	-0.24 %	0.070	0.071	0.86 %

The twist and top flange displacement can be said to be about the same and the small difference can be explained because the two spans don't have equal length.

If only the longer spans of each beams are compared to each other twist and top flange displacement is shown in Table 7.2.

Table 7.2 - Comparison of twist and top flange displacement in the two longer spans for each beam

Load Ms/Mp	θ (rad) 1st beam	2nd beam	Diff.	u (m) 1st beam	2nd beam	Diff.
0.50	0.007	0.007	0.00 %	0.038	0.038	0.00 %
0.75	0.011	0.011	0.00 %	0.055	0.055	0.00 %
1.00	0.015	0.015	0.00 %	0.070	0.070	0.00 %

There are no differences between the two beams and therefore there is symmetry in the system.

Analysis 2

With a complete set of formwork attached; twist and top flange displacement for one of the equal beams quarter points looks like Figure 7.9 and Figure 7.10 respectively.

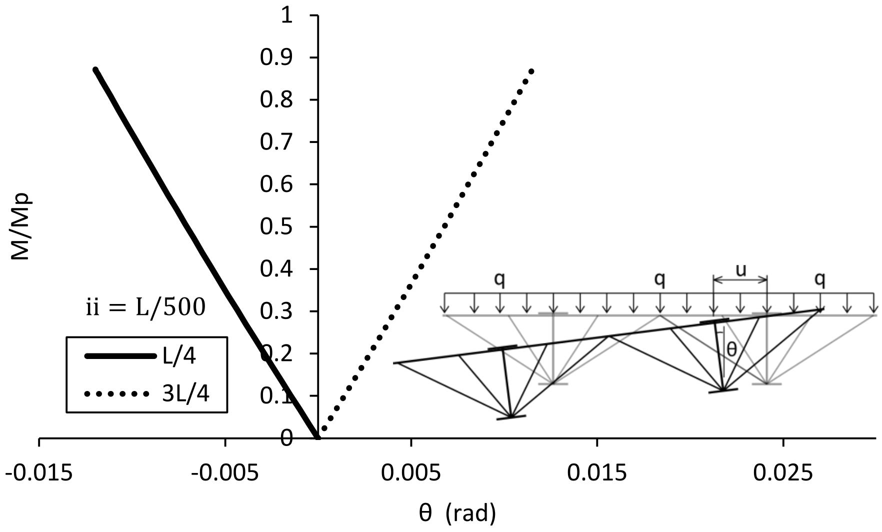

Figure 7.9 - Twist of beam subjected to UDL to the formworks

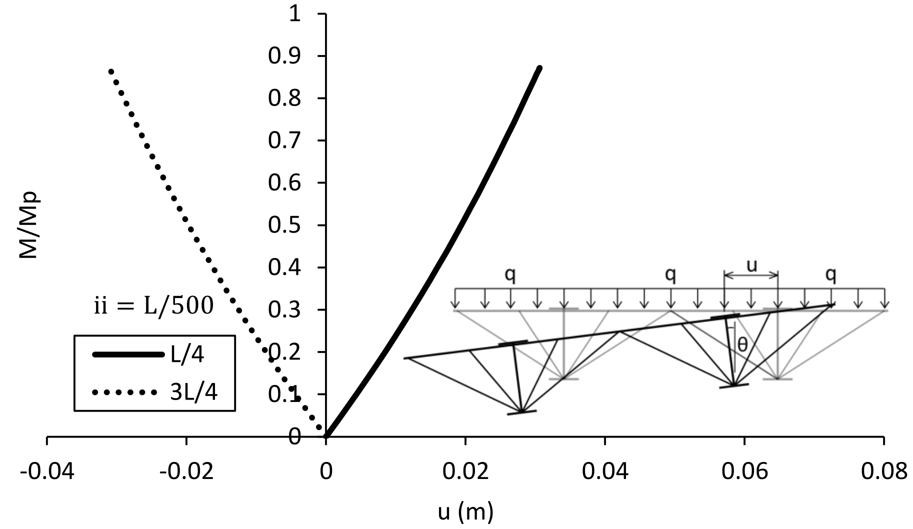

Figure 7.10 - Top flange displacement of beam subjected to UDL to the formworks

Twist of the beams is in the same direction as the bridge set-up without formwork attached, but the top flange displacements are mirrored in comparison. Figure 7.11 is a top view of the two systems and their shape, at exaggerated scales, after incremental loading. Noted is that the twist for both set-ups are in the opposite direction to the initial imperfection of the beams, as seen in Figure 7.4.

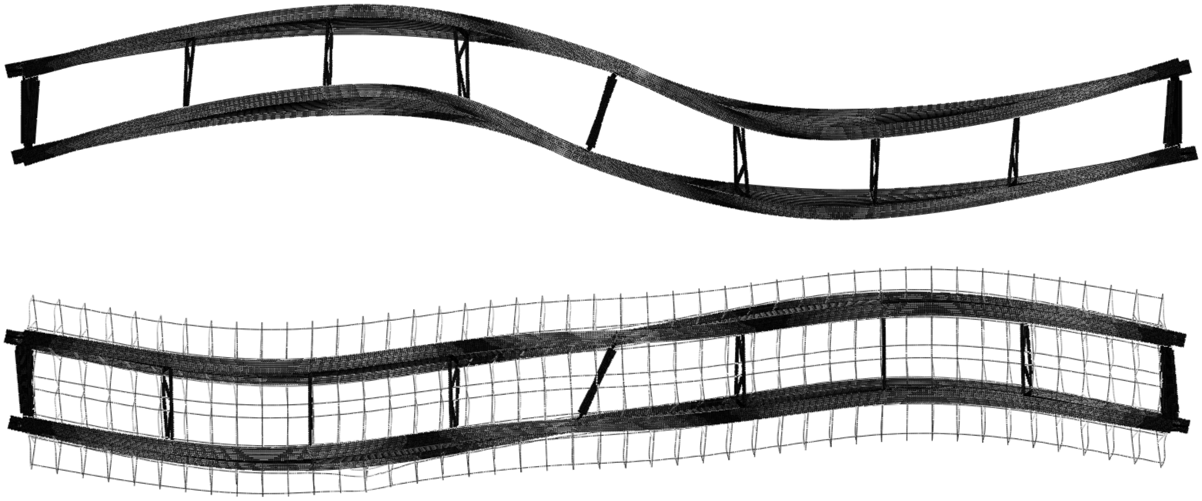

Figure 7.11 – Shapes at exaggerated scales after incremental loading for the bridge without and with formwork attached

Bracing forces in the steel pipes are measured at location A-D according to Figure 7.6 and the results can be seen in Figure 7.12-Figure 7.15.

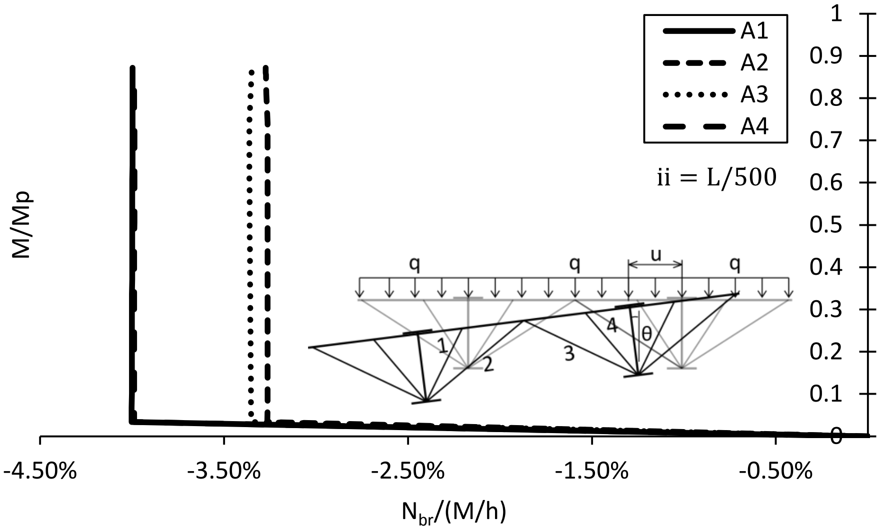

Figure 7.12 – Bracing forces in formwork A when subjected to UDL directly to the formwork

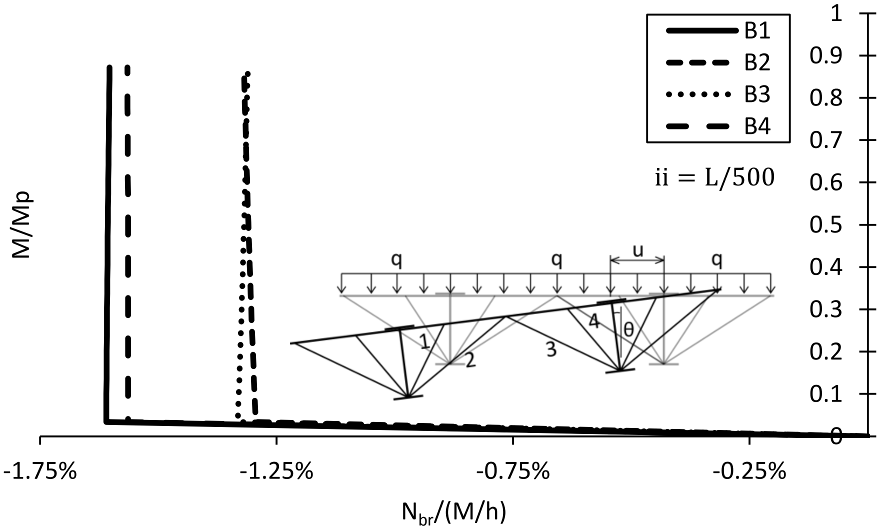

Figure 7.13 – Bracing forces in formwork B when subjected to UDL directly to the formwork

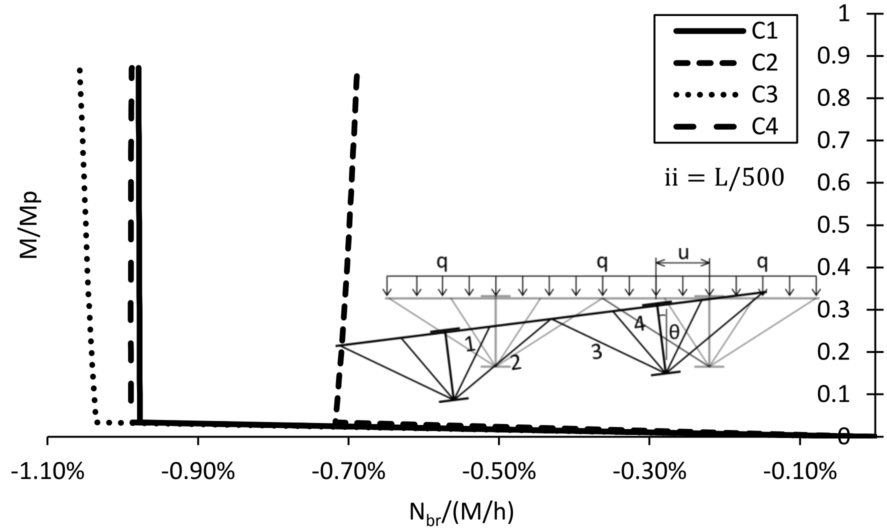

Figure 7.14 – Bracing forces in formwork C when subjected to UDL directly to the formwork

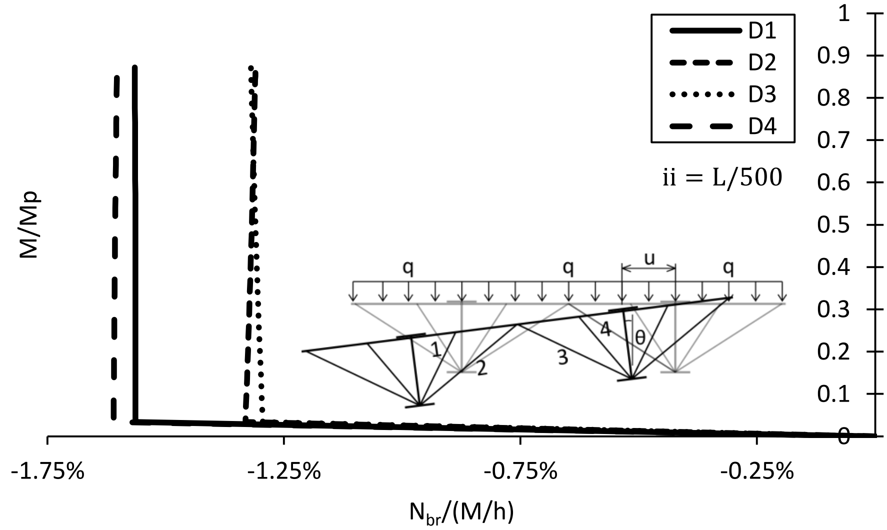

Figure 7.15 - Bracing forces in formwork D when subjected to UDL directly to the formwork

If bracing forces in formwork B are compared to formwork D it can once again be seen that there is symmetry in the system. The bracing forces are the same but they are mirrored because of that the longest span is also mirrored in the system.

Otherwise the bracing forces grow almost linear with the force applied and therefore the ratio is always almost the same for a section. The biggest normal stress in a member is 122 MPa.

Analysis 3

This is a comparison of twist and top flange displacement between the two systems; with and without formwork attached.

Figure 7.16 shows the comparison of twist and Figure 7.17 shows the comparison of top flange displacement, in the middle of the shorter span for one of the beams.

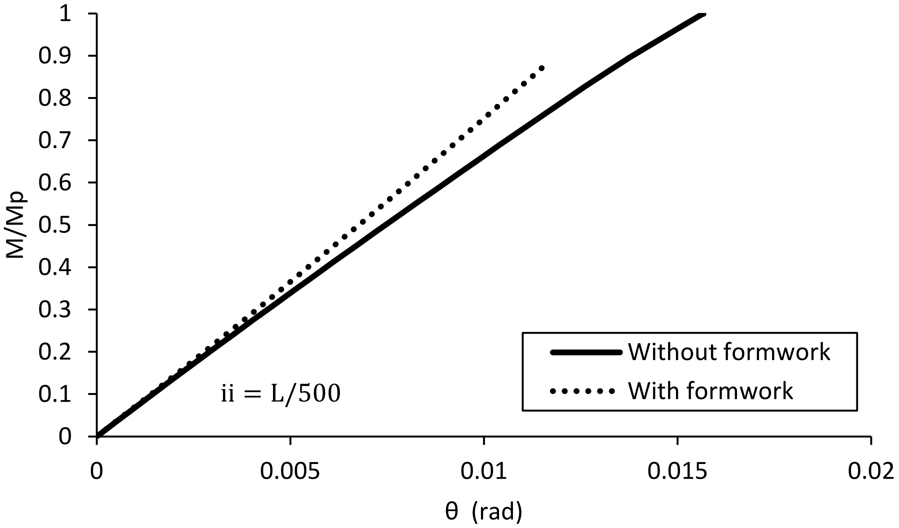

Figure 7.16 – Comparison of stiffness (twist) for the longer span of one beam with and without formwork attached

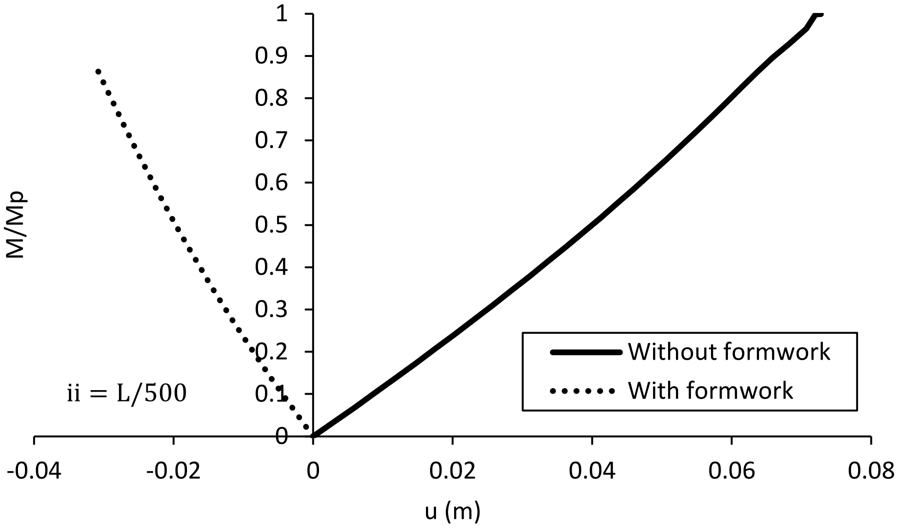

Figure 7.17 - Comparison of top flange displacement for the longer span of one beam with and without formwork attached

Top flange displacements in Figure 7.17 are as earlier discussed in opposite directions. To make a more readable figure the sign of the negative values has been switched in Figure 7.18. Otherwise all is the same as in Figure 7.17.

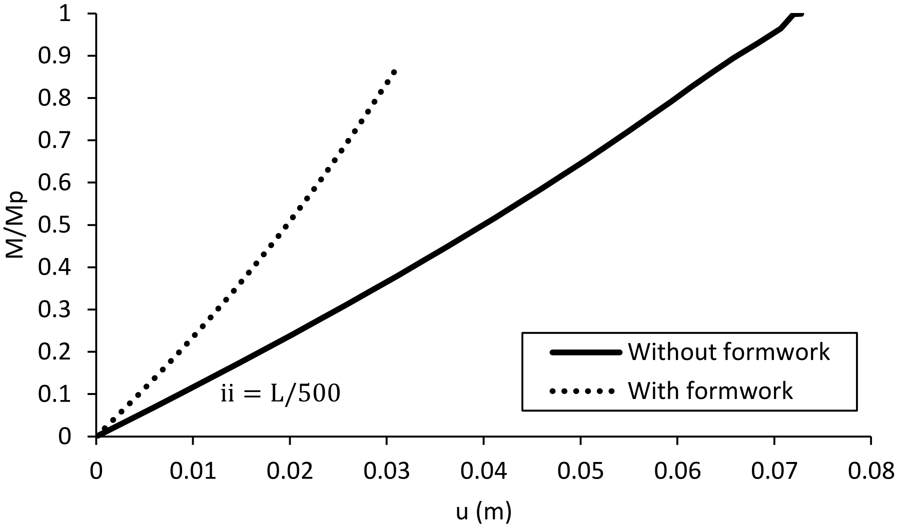

Figure 7.18 - Comparison of top flange displacement for the longer span of one beam with and without formwork attached (positive values for a simpler overview)

Table 7.3 shows the difference of twist and top flange displacements between the two systems with and without formwork attached.

Table 7.3 – Comparison of twist and top flange displacement between a system with and without formwork attached

Load M/M_p	θ (rad) Without formwork	θ (rad) With formwork	θ (rad) Diff.	u (m) Without formwork	u (m) With formwork	u (m) Diff.
0.4	0.0061	0.0055	-9.9 %	0.034	0.016	-51.2 %
0.6	0.0091	0.0082	-9.9 %	0.047	0.023	-50.8 %
0.8	0.0120	0.0107	-10.9 %	0.059	0.029	-50.7 %

An increase in stability can be seen for the system with formwork attached in comparison to the bridge set-up without formwork. It's not a very big difference in twist but on the other hand the lateral displacements decrease a lot.

Due to the quite bulky beams of the bridge the effect is not as big as expected from the results seen in the laboratory test beams; but there is still a clear stiffening effect to be seen.

8 CONCLUSION

8.1 SUMMARY OF RESULTS

The concluding results from this thesis are shortly summarized in this section:

- CUPLOK is a suitable temporary formwork system to be used as discrete torsional bracing during casting of the concrete after that it has been attached to the girders.
- The CUPLOK system has an increasing effect on the torsional stiffness when attached to twin I-girder systems.

In the following section the findings will be discussed more in detail.

8.2 DISCUSSION AND CONCLUSIONS

When different formwork systems were described only four different concepts could be found. CUPLOK was not the world's most widely spread system but definitely the only system suitable to be modified into torsional bracing.

Modifications had to be done to make the system able to be attached to the girders, as well as able to take tension in the otherwise loosely attached threaded jack section. Mehri will examine the opportunities to do so in his ongoing PhD project, but as thought today it is possible to do so.

For much of the time during this thesis it was thought that the longitudinal stiffeners between the diagonal steel pipes in the CUPLOK system wasn't having an increasing effect on the torsional stiffness of a system. Therefore some of the work above is done with them and some without them. The time for this thesis is up and no further analyses can be done to complement these sometimes maybe confusing analyses.

To start with the overall question; if there is any stiffening effect to be seen on a system with applied formwork, the answer is yes. Biggest effect could be seen on the very slender laboratory test beams and the discussion will begin with them.

While attached to the laboratory test beams some alterations were done to the modified CUPLOK system to see what differences different set-ups would make. The performed buckling analyses gave a quick indication that there sure is an effect; the critical moment was almost 22 times higher with only the interior and unstiffened formwork parts attached compared to the bare girders.

Forces in the steel pipe sections are at all times quite small but their distribution is hard to interpret and the author has no good explanation to why they distribute exactly as they does. It should be mentioned that those forces are the result of point loads applied to the third points of the girders and that this type of loading never exists as a real load.

When formwork is attached the presence of a crossbeam made no difference which could be assumed by looking at the small increase in critical moment compared to the system with formwork attached. Alternating the initial imperfection is having a huge effect on the system. When the initial imperfections are reduced by half so is the twist and top flange lateral displacement. The stability of the system depends highly on the degree of initial imperfection.

In this thesis an initial imperfection of L/500 has been used as standard. This initial imperfection is thought to represent imperfections existing in real girders due to that no element is completely straight. If accepted tolerances would be assumed less than L/500 in reality, then so would twist in the system and forces in the bracing be.

When the steel pipe cross section is heavily reduced twist and top flange displacements are still the same. This shows that the cross section chosen in the CUPLOK system could be smaller, but when the same formwork are being reused multiple times there are not really any big savings to be done. Better to have a robust system and one that easily could be used with larger bridges as well.

If the distance between formworks is increased the stiffness in the system is initially the same but when higher load was applied the stiffness went down. Maybe there are occasions when the distance can be increased but most often the distance would be the same for other reasons, i.e. the rest of the falsework has to have support at a certain distance to be able to bear the load from wet concrete.

When a complete set of longitudinally stiffened formwork are attached there was an increase in the maximum load possible to apply with 80 % and at the same time as a decrease in maximum twist of 70 % and maximum top flange displacement of 90 %. The system was now much stiffer and that is due to the clamped connections that is the cup-lock in the CUPLOK system.

Another thought is that if the formwork system is to be modified and screwed tight to the girders then there are no reasons to keep the tension ties. They do no further good and could be removed both on the interior and exterior part of the girders. This would make up for significantly less holes done to the web and somehow compensate for new holes possible needed to attach the formworks.

Bridge Y1504 was analyzed with only unstiffened interior formwork. At that time the author thought that only this part was stabilizing the system. Attached to this trapezoidal girder the system was shown to have no stabilizing effect at all.

Bridge over road E6 was chosen because it is an existing fully functional bridge similar to the laboratory test beams, but with less slender main girders and with two spans instead. The system was shown to be very stiff in itself but even then the complete set of formwork helped to stabilize the system further and the total twist was reduced by 10 % and the top flange displacement with 50 %.

UDL was for the bridge over Road E6 applied directly to the formworks, as load from real concrete would have been applied. It could be seen that there was never any tension in the steel pipe sections at any time of the loading. Maybe this would have been the case also for the laboratory test beams if a similar testing would have been done to them. If this could be shown to be the case no alterations to the threaded jack sections would be needed to make them able to take tension.

To sum it up many clear advantages can be seen with the use of temporary formworks as discrete torsional bracing. They may benefit economically, increasing the usable strength of structural members by limiting the out-of-plane deformations of bare steel girders, along with a safer construction process.

8.3 FURTHER RESEARCH

Further research can be done by means of actually testing the modified CUPLOK system on a real bridge.

As the laboratory test beams exists for real and are supposed to be subjected to similar testing by Mehri, during his ongoing PhD project, the results from laboratory testing could be compared to the results from the numerical analyses performed within this thesis.

If the numerical model can be verified to work the same as the laboratory test beams, computer models can be used for a variety of further analyses done with the system attached to different set-ups.

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