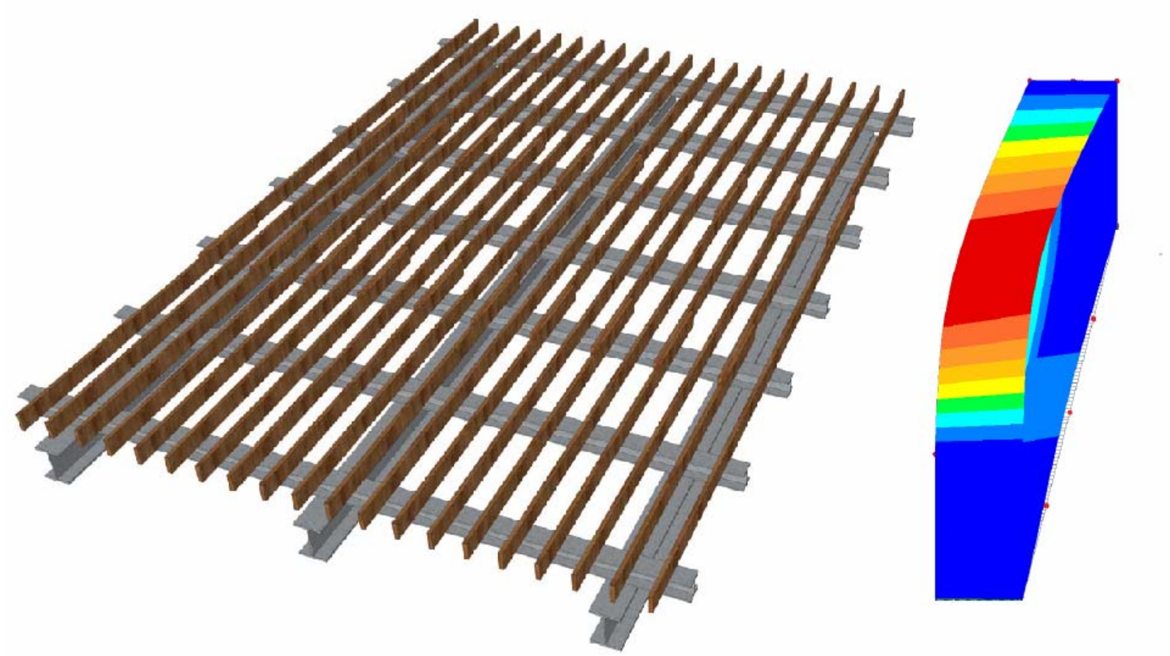
CHALMERS



Frictional Action between Beams in Formworks

Study on the Prevention of Lateral-torsional Buckling

Master of Science Thesis in the Master's Programme Structural Engineering and Building Performance Design

JOHAN ERIKSSON

Department of Civil and Environmental Engineering
Division of Structural Engineering
Steel and Timber Structures
CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden 2011
Master's Thesis 2011:8

MASTER'S THESIS 2011:8

Frictional Action between Beams in Formworks

Study on the Prevention of Lateral-torsional Buckling

Master of Science Thesis in the Master's Programme Structural Engineering and Building Performance Design

JOHAN ERIKSSON

Department of Civil and Environmental Engineering
Division of Structural Engineering
Steel and Timber Structures
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2011

Frictional Action between Beams in Formworks
Study on the Prevention of Lateral-torsional Buckling

Master of Science Thesis in the Master's Programme Structural Engineering and Building Performance Design
JOHAN ERIKSSON

Examensarbete / Institutionen för bygg- och miljöteknik,
Chalmers tekniska högskola 2011:8

Department of Civil and Environmental Engineering
Division of Structural Engineering
Steel and *Timber Structures*
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover:
Figures showing the type of structure analysed in this Master's Thesis and a deformed shape of an I-beam, corresponding to lateral-torsional buckling.

Chalmers Reproservice / Department of Civil and Environmental Engineering
Göteborg, Sweden 2011

Frictional Action between Beams in Formworks
Study on the Prevention of Lateral-torsional Buckling

Master of Science Thesis in the Master's Programme Structural Engineering and Building Performance Design
JOHAN ERIKSSON
Department of Civil and Environmental Engineering
Division of Structural Engineering
Steel and Timber Structures
Chalmers University of Technology

ABSTRACT

Bridge formwork, made of simply supported beam layers, is often constructed without structural joints between the layers because of the need for fast and easy construction and demolition. The capacity of steel beams must be calculated with respect to lateral-torsional buckling, which in some cases means that the utilization ratio is reduced down to 50 %. The most effective way to prevent lateral-torsional buckling of a simply supported I-beam is to laterally brace the upper flange of the beam. If there were structural joints between different beam layers in a frame work, the full bending resistance of the I-beam could be utilized. There is of course some friction between the structural members and that could be used in design as a kind of bracing.

The aim of this thesis work is to investigate the possibility of utilizing the frictional restrains between frame work beams as a mean of providing lateral bracing against lateral-torsional buckling

Many types of structural configurations and beam sizes have been analysed and therefore, this study is quantitative. Swedish building standards, as well as Eurocode, have been used in the analytical study. The results are then compared to those obtained from geometric nonlinear finite element analyses. The needed bracing forces and the influencing parameters are presented in the result section, where it is shown that the friction force capacity between the beams is too low. In addition to these results, factors that influence the lateral-torsional stability of structural steel work are presented and discussed. These include the effect of initial imperfection used in the finite element analyses. An interesting question was whether it would be possible to use lower initial imperfections if the manufacturing tolerances of a steel beam can be controlled. Another issue that is discussed is whether a higher friction coefficient can be assured between the beams in different form layers. If this is the case, how high must the friction coefficient be in order to prevent lateral-torsional buckling of a beam? This report discusses and answers these questions, among others. A simple hand calculation method to find out whether the friction force capacity is enough as bracing force will also be presented.

The general conclusion is that it is not recommended to rely on friction as a restrain, to prevent lateral-torsional buckling. More research work, in combination with experimental verification is needed in this field.

Key words: lateral-torsional buckling, friction, temporary works, formwork, bracing

Friktionsverkan mellan balkar i formbyggnader
Undersökning om förhindrande av vippning
Examensarbete inom Structural Engineering and Building Performance Design
JOHAN ERIKSSON
Institutionen för bygg- och miljöteknik
Avdelningen för Konstruktionsteknik
Stål- och träbyggnad
Chalmers tekniska högskola

SAMMANDRAG

Formbyggnad för broar, byggda av fritt upplagda lager av balkar, är ofta byggda utan fasta förband mellan balklagren på grund av behovet av snabb och lätt uppbyggning och rivning. Stålbalkars kapacitet måste beräknas med hänsyn till vippning, vilket i vissa fall betyder att utnyttjandegraden reduceras ned till 50 %. Det mest effektiva sättet att förhindra en fritt upplagd I-balk från att vippa är att staga balkens överfläns i sidled. Om det fanns fasta förband mellan balklagren, skulle I-balkens fulla böjkapacitet kunna utnyttjas. Det finns förstås friktion mellan konstruktionens delar och den skulle kunna användas vid dimensionering som en sorts sidostagning.

Syftet med det här examensarbetet är att undersöka möjligheten att utnyttja den återhållande effekten av friktion mellan balkar i en konstruktion som ett sätt att motverka vippning.

Många typer av konstruktionskonfigurationer och balkstorlekar har analyserats och därför, den här undersökningen är kvantitativ. Svenska byggstandarder, och även Eurokod, har använts i den analytiska studien. Resultaten jämförs med resultat från geometriska icke-linjära finita element analyser. Sidostagskraften som behövs och parametrar som påverkar presenteras i resultatkapitlet, som visar att friktionskraftskapaciteten mellan balkarna är för låg. Utöver dessa resultat presenteras och diskuteras faktorer som påverkar vippningsstabiliteten för stålkonstruktioner. Inkluderat i det är effekten av vilken initialimperfektion som används i finita element analyserna. En intressant fråga är om det skulle vara möjligt att använda en lägre initialimperfektion om tillverkningstoleranserna för en stålbalk kan kontrolleras. En annan fråga som diskuteras är om en högre friktionskoefficient kan säkerställas mellan balkarna i olika lager. Om det är fallet, hur hög måste friktionskoefficienten vara för att förhindra vippning av en balk? Den här rapporten diskuterar och svarar på dessa frågar, bland andra. En enkel handberäkningsmetod för att ta reda på huruvida friktionskraftskapaciteten är tillräcklig som sidostagkraft kommer också att presenteras.

Den allmänna slutsatsen är att det inte är rekommenderat att lita på friktionen som ett sätt att motverka vippning. Mer forskningsarbete, i kombination med experimentella försök behövs inom detta område.

Nyckelord: vippning, friktion, temporära konstruktioner, formbyggnad, stag

Contents

Preface

The scope of this study was to evaluate the possibility to use static friction, between grid layer beams in temporary structures, as stabilizing effect. The Master's Thesis was carried out in cooperation with *Ramböll Sverige AB* and *Chalmers University of Technology, Department of Civil and Environmental Engineering, Division of Structural Engineering* during the autumn 2010.

Firstly, I would like to direct my gratitude to my supervisor, Bridge engineer Christer Carlsson at Ramböll Sverige AB, who has been helpful, when it comes to practical as well as theoretical knowledge in this subject. Furthermore, he has inspired me with his interest in the topics studied. The help from my examiner Docent Mohammad Al-Emrani at Chalmers University of Technology has been essential, especially when modelling with finite element software. I would like to thank him for his interest in and positive approach to the subject. Thanks to my opponents Jacob Hellgren and Ludwig Lundberg for their comments and support.

I have obtained a great deal of help from several employees of Ramböll's Bridge and Tunnel Department. Especially I would like to thank Emelie Carlstedt for her assistance with the finite element software and to Leonardo Canales for our fruitful discussions on the subject.

Finally, I want to thank my family and friends, especially my fiancé Moa Langemark, who has been supportive and patient in my work.

It has been stimulating and educative to work with this Master's Thesis, since both Ramböll and Chalmers have shown great interest in the progress and the result of the analyses. I hope that the result of the study can be useful and that this Master's Thesis will shed more light on this topic.

Stockholm January 2011

Johan Eriksson

Notations

Roman letters

A	Area
b	Width
C_1, C_2	Coefficients used when calculating the critical moment
DY	Displacement in Y-direction, LUSAS
d	Deflection
E	Modulus of elasticity
F,P	Force
Fy	Needed bracing force
F_μ	Friction force [Fmy]
G	Shear modulus
I	Moment of inertia
I_t	S:t Venant's torsion constant
I_w	Warping constant
f_y	Yield strength of steel
L	Length
l_1	Distance between bracing points
M	Bending moment
N	Normal force
q	Distributed load
s_{brac}	Distance between bracings
W,Z	Bending resistance

Greek letters

α_{LT}	Imperfection factor [alfa_LT]
γ_{M1}	Partial factor with respect to instability
γ_m	Partial factor with regard to material uncertainties [gamma_m]
γ_n	Partial factor with respect to safety class [gamma_n]
γ_μ	Partial factor with respect to friction coefficient [gamma_my]
η_c	Form factor, depending on steel section class
λ_b	Slenderness factor [lambda]
μ	Friction coefficient [my]
χ_{LT}	Reduction factor with regard to lateral-torsional buckling [chei_LT]
ω_b	Reduction factor with regard to lateral-torsional buckling, BSK [w_b]

1 Introduction

When casting concrete in various types of construction work, there is always a need to use some kind of temporary structure that keeps the concrete in place until it hardens. The formwork is an important part of the total production cost and therefore, any solution that results in a more cost-effective production of the formwork will also result in savings in the production costs of the whole project. The demands and functions put on formworks for concrete casting are in general:

- it has to carry the dead weight of the concrete without excessive deformations
- it has to be fast and easy to both build and demolish
- it has to be able to form the concrete structure

Especially, the formwork of a concrete bridge is subjected to very high loads and is often used in outdoor environments. The purpose and requirement of a bridge is to overpass some obstacle and therefore the formwork has to overpass the same obstacle, although it is often possible to have some temporary intermediate supports during the construction time. Steel and timber are the most common materials used in bridge formwork but also aluminium, engineered wood products and composite materials are being used.

1.1 Problem description

The formwork of a bridge superstructure, soffit formwork, is often constructed as a number of simply supported grid structures. Depending on geometrical properties, the loads to be carried by the form and production and installation cost aspects, the number of beams in each grid and the number of grid layers vary from case to case. Two different examples are shown in Figure 1-1 and Figure 1-2. Timber beams are often used to form the top layer of the form, with a surface composed of flat timber board or tongued boards.

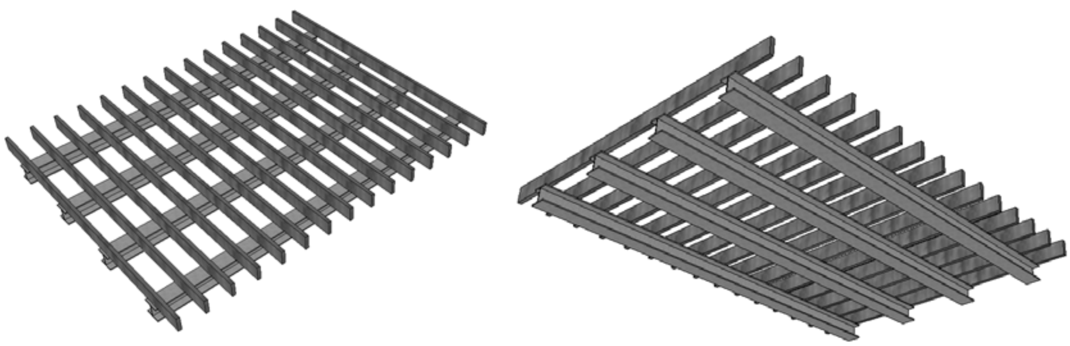


Figure 1-1 Secondary timber beams resting on simply supported steel beams.

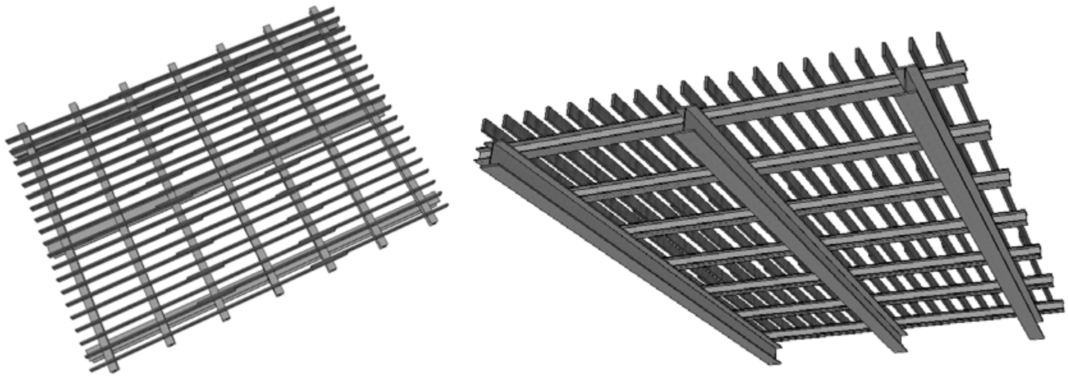


Figure 1-2 Three layers grid structure.

In most cases, there are no structural connections between beams in different grid layers. The main reason for omitting these connections is the wish to have a formwork which is fast and easy to build and demolish. The primary and, in some cases secondary, steel beams of the formwork are designed to carry the ultimate load and provide the required stiffness. As structural connections, in general, are omitted between different elements in the grid structure, the risk of lateral-torsional instability of the steel beams needs to be considered. One effective method to prevent lateral-torsional buckling is to laterally stabilize the beam at some discrete points along the span, which would be the case if the different beam layers were fully connected to each other, see Figure 1-3. In the real structure, however, the friction between the orthogonal elements will provide some restrain against lateral-torsional buckling. Whether this restrain, provided by friction, can be utilized as an advantage or not, depends on several factors that need to be identified and evaluated. But perhaps the friction between the members is enough to prevent lateral-torsional buckling.

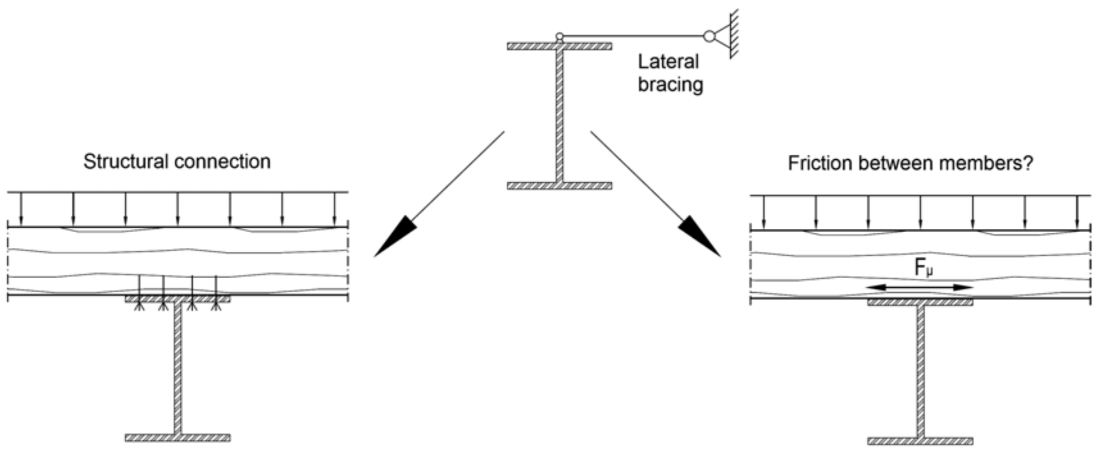


Figure 1-3 Methods to prevent lateral-torsional buckling.

1.2 Aim of the study

The aim of the Master's Thesis was to investigate whether the restrain provided by the friction between steel and timber can be utilized in design to prevent lateral-torsional instability in formwork grid structures. Concerning this, the questions and objectives below was identified, and they have been answered in the report.

- What friction coefficients can be used for the connections between steel-steel and steel-timber respectively?
- What bracing force is needed to prevent lateral-torsional buckling and is the friction force large enough?
- Model the formwork with different materials, dimensions, loads, span lengths etc. and analyse the structural behaviour regarding lateral-torsional buckling.
- If the friction force can be sufficient to prevent lateral-torsional buckling the aim is to find a simple method to take it into account in design.

1.3 Method

A literature study was made in order to gain good understanding of the lateral-torsional buckling phenomenon and methods to prevent it. The study has also considered the frictional properties between steel and wood. To gain good theoretical and practical understanding of how to design and construct formwork, a combination of interviews with professionals, study of examples and reading of literature concerning formwork has been made.

To investigate the interaction between steel and timber deeper, especially with respect to preventing lateral-torsional buckling of a steel beam, several finite element analyses have been performed and compared to analytical calculations.

1.4 Limitations

The studies conducted in this Master's Thesis are only relevant to temporary works. Any long-term effects have not been taken into consideration. The formworks treated in this report were idealized in such manner that, the study involved only failure of one beam layer and the other parts of the structure were assumed to be stable. Only steel beams with dimensions commonly used in bridge formwork were treated. In addition, only formwork structures composed of steel and timber members were treated.

2 Background Study

2.1 General description of formwork

In order to get the correct definitions from the beginning, a list is set up with common concepts:

- *Temporary works*, or temporary structures, are set up to aid the construction of a permanent building or structure, and will be dismantled and removed when the permanent works are completed. Temporary works are also used for inspection, maintenance and repair work.

- *Scaffolding* is a temporary structure used to support material and people during the construction or repair of a structure or building.

- *Falsework* is a temporary structure used to support a permanent structure while it is not self-supporting.

- *Formwork* is a temporary structure, or partially or completely permanent structure, used to contain and shape the wet concrete until the concrete structure is self-supporting. Falsework supports the formwork.

Formworks are divided into supporting formwork, also called wall formwork, and bearing formwork, also called soffit formwork, depending on the type of loading it is subjected with, Nilsson et al. (1985).

2.1.1 Supporting formwork

Supporting formwork is used when casting walls or columns and it consists of a face material that is in direct contact with the concrete and some bearers that support the face material. The face material is nailed on wailings that rests on vertical studs, called soldiers, see Figure 2-1. Materials most frequently used in formwork structures are timber and plywood because of economic reasons, availability and workability but steel, aluminium and plastic materials are common for reusable forms, Ratay (2008).

To resist the external horizontal loads some kind of lateral bracing is needed and that is commonly steel props that are attached to the soldiers and to a permanent structure or the ground. The structure also needs formwork ties to keep them together when casting the concrete, i.e. resisting the concrete pressure, Nilsson et al. (1985), see Figure 2-1. The most common types of formwork ties is the through tie, which is a bar in a plastic cover so that it can be reused, and the lost tie system that leaves the tie rod moulded in the concrete, Pallett (2003).

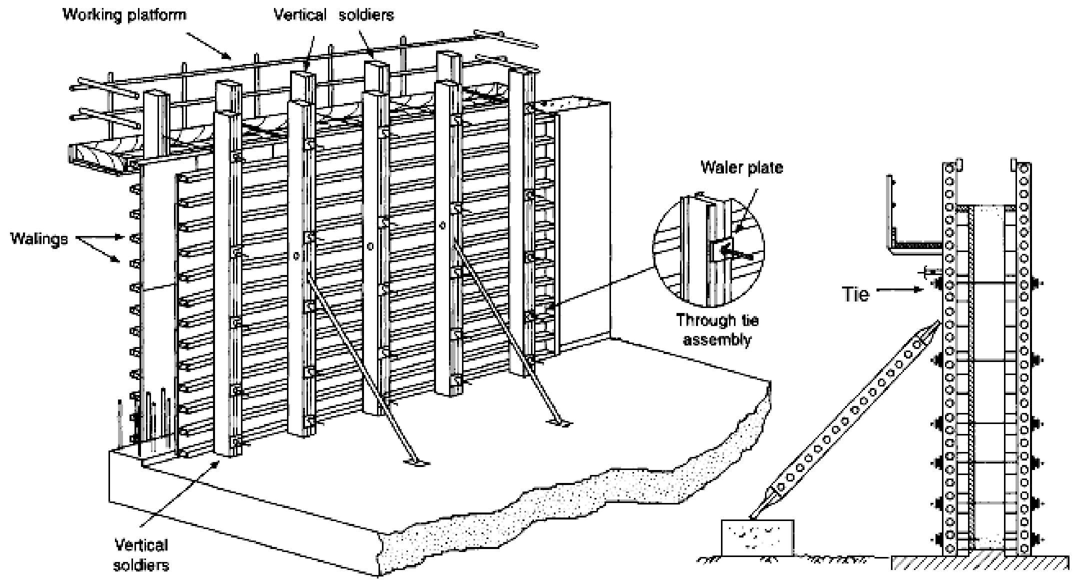


Figure 2-1 Example of wall formwork, Pallett (2003).

Figure 2-2 Formwork structure of a large bridge, Rmd Kwikform News (2010).

2.1.2 Bearing formwork

Bearing formwork, or soffit formwork, is used when casting slabs or beams and it consists, like the supporting formwork, of a face material and a system of bearers. The soffit formwork rests on a falsework system, often tower systems of tubular steel props, Nilsson et al. (1985). Figure 2-2 shows an example of an advanced falsework and formwork system. In this Master's Thesis the traditional way of constructing bridge soffit formwork is considered, with timber face material and wailings and steel beam layers, see Figure 2-3. The primary beams of the formwork are simply supported on the top of the falsework. Other frequently used decking systems consist of aluminium beams, engineered timber composite beams and large steel truss beams. The face material is in most cases, due to economical reasons, made of flat timber board, like plywood, but to give the visible concrete a wood-like surface tongued boards are often used. In buildings, the face material sometimes becomes a part of the permanent structure and reusable steel frames are common. But bridges, though, are often too irregular to use the same formwork twice. To form the sides of the slabs and beams, edge formwork is needed and the edge form is similar to a supporting form.

Figure 2-3 Common bridge formwork, Birsta, Sundsvall. Steel primary beams, timber secondary beams and tongued board face material. The formwork rests on towers made of tubular steel props.

2.1.3 Design of formwork

The contractor is in most cases responsible for the design and construction of the formwork. At this time of writing there are in Sweden no particular design codes for formwork, but there are a few commonly used documents treating falsework and formwork:

- Handbook of formwork construction, Nilsson et al. (1985).
- BKR 2010, Boverket (2010) that is the set of rules for construction in Sweden but applies mainly to permanent structures. BKR 2010 refers to the design handbooks BSK 2007 Boverket (2007) and BBK 2004 Boverket (2004).

Since there are no particular codes of design, the engineers use their experience and rules of thumb, with some help from the handbooks and Swedish design codes. This implies that the formwork is designed similarly to a permanent structure, but usually not as carefully. In bridge formwork, Carlsson[1] means that the design depends much on what building material the contractor has and wants to reuse, but of course it also depends on the geometrical conditions, for example where it is possible to place supports and what the available construction height is.

According to Nilsson et al. (1985) the main topics when designing bearing formwork are to determine what kind of static system to use in the calculations, for example how to take friction, nailing and sheet action into account. Another issue is the loading and how to treat the concrete placement load, which depends on factors like height of the form, the concrete pouring rate of rise and the concrete type, Pallett (2003). An uneven concrete pouring may cause shock loads on the formwork and if the concrete is slow-flowing there may be local accumulations.

In the future, the European Standards will replace the national standards. The following European Standards treat falsework and formwork:

- SS-EN 12812:2008 Falsework - Performance requirements and general design, Swedish Standards Institute (2008c) determines requirements for falsework and formwork

- SS-EN 12811-1:2004 Part I: Scaffolds - Performance requirements and general design, Swedish Standards Institute (2005), and SS-EN 12811-2:2004 Part II: Information on materials, Swedish Standards Institute (2008b).

In SS-EN 12812:2008 the falsework is divided into two classes, Class A and Class B. Class A treats simple structures with the limitations:

a) slabs have a cross-sectional area not exceeding 0,3 m^2 per metre width of slab
b) beams have a cross-sectional area not exceeding 0,5 m^2
c) the clear span of beams and slabs does not exceed 6,0 m
d) the height to the underside of the permanent structure does not exceed 3,5 m

Class B treats the other structures and is divided in B1, for which the structure has to be designed according to Eurocode as a permanent structure, and B2, which allows the simplifications in design described in SS-EN 12812:2008. The designer can make a choice between Class B1 and B2 because, according to Swedish Standards Institute (2008c), “Class B2 uses a simpler design method than Class B1 to achieve the same level of safety”.

2.1.4 Short note on formwork failures

A lot of structure failures occur because of collapses of falsework and formwork. A research of 85 major falsework collapses, both building and bridge falsework, performed by Hadipriono and Wang (1986) showed that about half of the failures occurred during pouring of the concrete, see Figure 2-4. For bridges, common causes of collapse were improper steel tower shoring and horizontal shoring of beams, see Figure 2-5. Inadequate review of falsework design and lack of inspection during concreting were common procedural causes.

[1] Christer Carlsson, supervisor Ramböll, meeting on 2010-08-31.

Figure 2-4 Concrete pouring.

Figure 2-5 Tower collapse due to broken cross-bracings, Surdahl et al. (2010).

2.2 Frictional behaviour of steel and timber

Tribology is the science and technology of interactive surfaces in relative motion and includes the branches friction, lubrication and wear, Szeri (2008). A friction force appears when two surfaces are in contact with each other and there is a force that attempts to move one surface relative to the other, see Figure 2-6. The friction force always opposes the motion. If there is some layer between the surfaces, for example a liquid, the friction force, that opposes the movement, will be much smaller, which is due to lubrication. Wear is defined as loss of substance from a surface that rubs against another. The friction is the most important branch of tribology for the aim of this Master's Thesis and will be described further in the following sections.

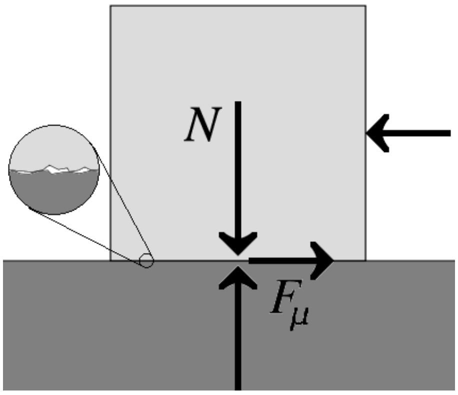


Figure 2-6 Friction between two bodies.

2.2.1 The laws of friction

The friction laws were first published in 1699 when Guillaume Amontons described his observations on solid surfaces in sliding contact, Krim and Family (2000). However, Leonardo da Vinci begun the modern study of friction as early as in the fourteenth century, but the generalizations of the friction phenomenon are named Amonton's laws of friction. Charles Augustin de Coulomb later verified and contributed to the laws of friction. The first law of friction is that the friction force is proportional to the normal force, see equation (1).

$$F_{\mu} = \mu \cdot N \tag{1}$$

μ friction coefficient

N normal force

The second law states that the friction force is independent of the apparent contact area. The third law, Coulomb's law, states that the friction is independent of the sliding velocity. With these generalizations it seems like friction is a simple phenomenon, but the frictional behaviour depends on many different factors.

The apparent area of contact is in fact not the same as the real contact area. Some materials have rough surfaces and, even if a surface appears smooth and flat, there are always some microscopic irregularities, Bowden and Tabor (1950). Those irregularities create many small contact points, asperities, between the surfaces and the total shear capacity of these asperities is, in theory, equal to the friction force. A higher normal force induces more contact points between asperities and that is why the friction force is independent of the apparent contact area. But in most cases there are some particles or layers of other materials between the surfaces they work like a lubricant, and it is more or less the frictional properties between the surfaces and the lubricant that determine the friction coefficient. Micro scale and nano scale theories are explained further in Mo et al. (2009) and Gerde and Marder (2001) but are unnecessarily advanced for the purpose of this Master's Thesis. Other factors that might influence the frictional behaviour are for example temperature, vibrations, applied load and even more factors that are listed in Blau (2001).

With all the influencing factors it is very complicated to exactly estimate the real friction coefficient between materials. Tabulated friction coefficients from different sources can have differing values for the same specific material because the friction coefficient depends on the conditions of the testing. Often additional friction testing under authentic conditions is required to find a useful friction coefficient. In this Master's Thesis the friction force is supposed to be used as a bracing force against lateral-torsional buckling in a formwork structure, see Figure 2-7. The surrounding conditions will not be known and the surfaces will most certainly not be clean and dry, which means that the frictional behaviour is hard to predict. It is an engineering judgement whether to reduce the friction coefficient with a safety factor or to not use the friction force at all, Pallett et al. (2002).

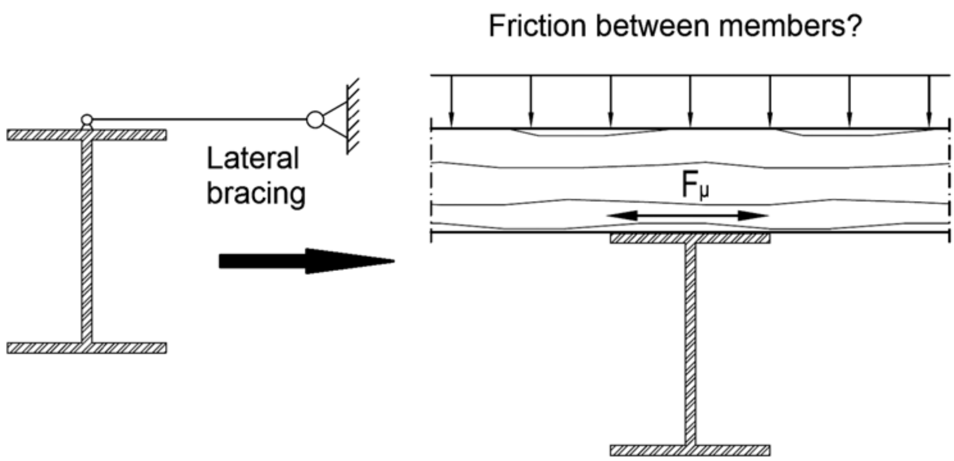


Figure 2-7 Perhaps can friction between structural members prevent lateral-torsional buckling.

There are two kinds of friction: static friction and kinetic, or sliding, friction. The friction force that work against the beginning of a movement is the static friction force and during the movement the kinetic friction acts, Blau (2001). The static friction coefficient is often about 20 percent higher than the kinetic friction coefficient, Rabinowicz (2008). As a stabilizing force to prevent lateral-torsional buckling of beams it is the static friction force that is of interest, because if it comes to sliding it is already too late to prevent the failure. In this Master's Thesis friction properties between metals and between timber and metal are pertinent.

The friction between two metal surfaces is in most cases dependent on the material film between the surfaces, as mentioned above. Metals that are exposed to the air gets a thin film of oxide, Bowden (1952). With pressures that are common in structural joints, the friction coefficient that is measured is the one between the surface films. At much higher pressure the asperities of the surfaces will connect metal to metal and the friction coefficient will be higher, Nolle and Richardson (1974).

Wood is structurally more complex and much softer than metal. It is an anisotropic material that is composed by fibres and has different properties depending on fibre direction. It absorbs water and has different moisture content depending on the surroundings and the mechanical properties changes with the moisture content, Atack and Tabor (1958). In Mckenzie and Karpovich (1968) and Guan et al. (1983) the friction between metal and wood has been investigated with focus on the sliding friction between a metal saw blade and wood in a milling machine, in Bejo et al. (2000) the friction in certain structural joints is investigated and in Svensson et al. (2009) the friction in the chip refining process is studied. These publications mainly focus on kinetic friction but adhesion and lubrication are the two most important mechanisms, even under static conditions. The friction coefficient between metal and wood depends on the moisture content, fibre direction, resin content and metal roughness among others. In particular friction between steel-steel and steel-timber are of interest in this report and the next section will give reasonable values of the friction coefficients.

2.2.2 Friction coefficients

A research was performed at The University of Birmingham to find values of the static friction coefficient between materials that are commonly used in temporary works, Pallett et al. (2002). The research treated types of structures and building materials, that are alike the ones in this Master's Thesis. Under the assembly, and even in use, of temporary works the lateral stability often rely on friction between the members and that is the same friction that might be useful as stabilizing force against lateral-torsional buckling. The aim of the research was, besides to establish useful friction coefficients, to verify the friction coefficients in the British and European temporary works design standards, Gorst et al. (2003).

As described in Section 2.2.1 there are a lot of factors that influence the friction and the measured values of friction coefficients vary widely. In design calculations it is reasonable to use the most unfavourable measured value of the friction coefficient. In Table 2-1 values of the static friction coefficients between steel-steel and steel-timber connections are listed. The static friction coefficients may be used as a lower bound value according to Gorst et al. (2003). As a comparison to the tabulated values of the friction coefficients there is in Rabinowicz (2008) explained that for normal walking a human need a friction coefficient value of more than 0.20.

Table 2-1 Static friction coefficients from Gorst et al. (2003). "Para" and "perp" means parallel and perpendicular to the fibre direction of the timber.

Static friction coefficient		Steel			Timber			
					Softwood		Hardwood	
		Plain unrusted	Plain rusted	Galva-nised	Para	Perp	Para	Perp
Steel	Plain unrusted	0.3	0.4	0.3	0.3	0.4	0.4	0.5
	Plain rusted	0.4	0.4	0.3	-	-	0.6	-
	Galva-nised	0.3	0.3	0.2	0.4	0.5	0.5	0.5

In SS-EN 12812:2008 Swedish Standards Institute (2008c) there are tabulated values of friction coefficient to be used in static equilibrium calculations of global and local stability. Those friction coefficients are listed in Table 2-2, and there are only small differences between the values in Table 2-1. According to Table 2-1 some friction coefficients, in the case of timber-steel, are lower, than in Table 2-2.

Table 2-2 Friction coefficients from Swedish Standards Institute (2008c).

Building material combination	Friction coefficient	
	Maximum	Minimum
Wood/steel	1.2	0.5
Steel/steel	0.8	0.2

Paragraph 9.5.10 in SS-EN 12812:2008 states:

> "Friction coefficients can be obtained from several different sources. Where friction coefficients are expressed as minimum and maximum values, the minimum coefficient shall be used if the frictional resistance is stabilising, and the maximum coefficient shall be used if the frictional resistance is destabilizing."
> Swedish Standards Institute (2008c)

2.3 Structural instability of steel beams

The loss of the stability equilibrium corresponds to the maximum load carrying capacity for many structural members, Hjelmstad (2005). Generally, it is a slender member that is subjected to compression that becomes unstable when its critical load is reached. At this critical load, the member deforms dramatically, and the direction of deformation changes, without any or little increase of load. The structure can not practically be loaded above the critical load without bracing, Al-Emrani et al. (2007). There are different instability phenomenon such as buckling of axially loaded columns, local buckling of a plate, sideways buckling of frames and lateral-torsional buckling of beams, Lui (2008).

2.3.1 Lateral-torsional buckling

A beam that is loaded by bending moment in the stiff direction may, for a load that is less than the bending capacity, lose its stability equilibrium and laterally bend, in the weak direction, and twist, Statens Stålbyggnadskommitté (1973). The beam has reached a critical point. The instability phenomenon is related to buckling of axially loaded member, because the compressed flange buckles laterally and the rest of the beam follows, see Figure 2-8. The risk for lateral-torsional buckling (LTB) is higher for beams that have small moments of inertia in the lateral direction and have a small torsional capacity, Scalzi (2008).

The LTB strength can be increased by using lateral bracing, which prevents the beam from moving laterally, and torsional bracing, which prevents the twisting of the beam, Nguyen et al. (2010). According to Statens Stålbyggnadskommitté (1973) and Höglund (1994) the most effective way to prevent LTB of a double flanged beam, or at least increase the critical moment, is to laterally brace the compression flange, see Figure 2-9.

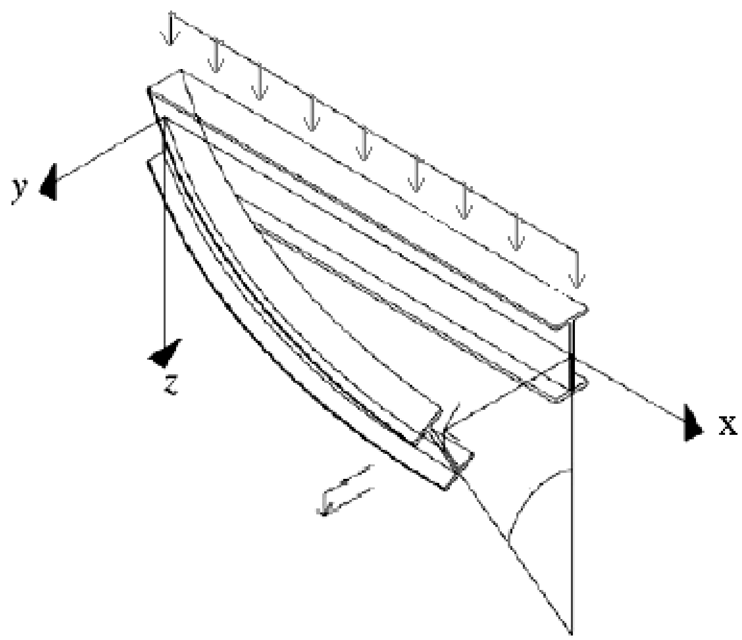


Figure 2-8 Lateral-torsional buckling of a steel I-beam, Rebelo et al. (2009).

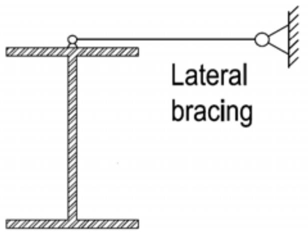
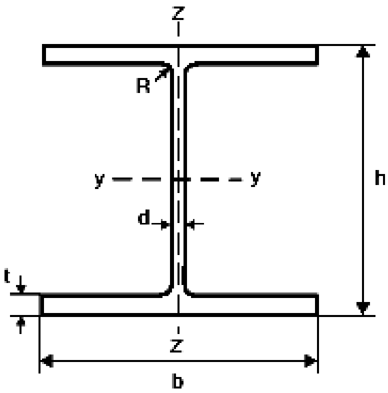


Figure 2-9 Lateral bracing of the compressed flange.

In the type of soffit formwork structures that concerns this Master's Thesis HEB steel primary beams are commonly used, Carlsson[2], which are double flanged hot-rolled beams. A speciality with HEB beams is that for HEB size 300 mm and larger, the width of the beam remains constant, see Table 2-3. It means that the moment of inertia around the y-axis, the strong direction, increases with increasing section height but the moment of inertia around the z-axis, the weak direction, increases much less because of the constant width. This makes larger HEB beams relatively more prone to LTB, and the section can not be fully utilized regarding bending capacity. If the secondary beams of a formwork structure can be used as lateral bracing members for the primary HEB beams, due to the friction between the members, there might be a more optimal use of the HEB beams, which is an improvement both economically and in aspects of material usage.

Table 2-3 HEB section data from Tibnor Ab (2006).

	h	b	t	d	R
HEB 100	100	100	10,0	6,0	12
HEB 120	120	120	11,0	6,5	12
HEB 140	140	140	12,0	7,0	12
HEB 160	160	160	13,0	8,0	15
HEB 180	180	180	14,0	8,5	15
HEB 200	200	200	15,0	9,0	18
HEB 220	220	220	16,0	9,5	18
HEB 240	240	240	17,0	10,0	21
HEB 260	260	260	17,5	10,0	24
HEB 280	280	280	18,0	10,5	24
HEB 300	300	300	19,0	11,0	27
HEB 320	320	300	20,5	11,5	27
HEB 340	340	300	21,5	12,0	27
HEB 360	360	300	22,5	12,5	27
HEB 400	400	300	24,0	13,5	27
HEB 450	450	300	26,0	14,0	27
HEB 500	500	300	28,0	14,5	27
HEB 550	550	300	29,0	15,0	27
HEB 600	600	300	30,0	15,5	27
	mm	mm	mm	mm	mm



[2] Christer Carlsson, supervisor Ramböll, meeting on 2010-08-31.

2.3.2 Design for lateral-torsional buckling

Lateral-torsional buckling (LTB) can be divided in two branches that are free and restrained LTB, Statens Stålbyggnadskommitté (1973). Restrained LTB means that the beam has one or more bracing points along the span. In both the Swedish design code and the Eurocode an approach with reduced bending moment capacity due to LTB is used, but there are some differences.

The Swedish design handbook BSK 2007, Boverket (2007), takes LTB into account by a factor that reduces the bending moment capacity for the compressed edge, see equation (2).

$$M_{Rcd} = \omega_b \eta_c W_c f_{yd} \tag{2}$$

ω_b reduction factor regarding LTB

η_c form factor with respect to compressed edge, depending on the section class

W_c bending resistance with respect to compressed edge

f_{yd} design yield stress

If the condition in equation (3) is fulfilled the beam is prevented from LTB, i.e. $\omega_b = 1$.

$$\frac{l_1}{b_{tot}} \leq \left(0{,}6 - 0{,}2\frac{M_2}{M_1} - 0{,}1\left(\frac{M_2}{M_1}\right)^2 \right)\sqrt{\frac{E_k}{f_{yk}}} \tag{3}$$

l_1 distance between the bracing points

b_{tot} total width of the rectangular compressed flange

M_1 highest bending moment within the observed beam section

M_2 moment in the opposite end of the observed beam section, see Figure 2-10

E_k characteristic E-modulus

f_{yk} characteristic yield stress

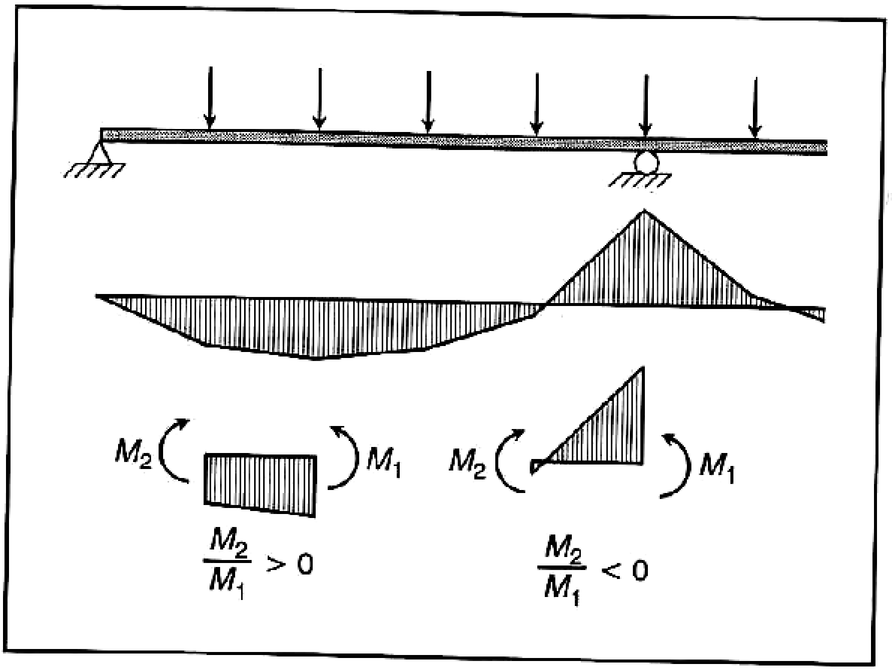


Figure 2-10 Illustration of M_1 and M_2, Höglund (1994).

If the condition in equation (3) is not fulfilled the reduction factor ω_b needs to be calculated. The method in paragraph 6:2442 in BSK 2007 is valid for beams with U- or I-sections. The reduction factor depends on the slenderness of the beam, equation (4), and for a hot-rolled beam the reduction factor is calculated with equation (5).

$$\lambda_b = \sqrt{\frac{\eta_c W_c f_{yk}}{M_{cr}}} \tag{4}$$

$$\omega_b = \frac{1{,}02}{\sqrt{1+\lambda_b^4}} \le 1{,}0 \tag{5}$$

λ_b slenderness of the beam

M_{cr} elastic critical moment for LTB, see Appendix E

In BSK 2007 a reference is made to Höglund (1994) that a ridge that acts like lateral bracing can be design according to K18:45. It prescribes a design connection force of the attachment between the beam and the bracing member as in equation (6) and a member that braces several beams can be designed for a normal force as in equation (7). There is no information about whether, if there is more than one bracing point, every connection must be designed for this force, but it can probably be assumed that an adaptation to the actual compressive flange stress can be made the same way as described below, in Bro 2004.

$$F_{con} = 0{,}01 A_f f_{yd} \tag{6}$$

$$N_{brace} = \left(0{,}2n + 0{,}8\sqrt{n}\right) F_{con} \tag{7}$$

A_f area of the braced beam flange

n number of beams that is braced

The Swedish handbook for bridges Bro 2004, Vägverket (2004), prescribes a slightly different design connection force of the attachment, see equation (8). If the full resistance against LTB is not utilized the bracing force may be reduced in proportion to the utilized resistance.

$$F_{con} = 0{,}015 A_f f_{yd} \tag{8}$$

An older Swedish code for steel structures, Statens Stålbyggnadskommitté (1970), also prescribes a different design connection force of the attachment, see equation (9).

$$F_{con} = 0{,}017 A_f f_{yd} \tag{9}$$

In SS-EN 1993-1-1:2005, Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for buildings, paragraph 6.3.2, Swedish Standards Institute (2008a), the design bending moment capacity with respect to LTB is calculated with equation (10).

$$M_{b,Rd} = \chi_{LT} W_y \frac{f_y}{\gamma_{M1}} \tag{10}$$

χ_{LT} reduction factor regarding LTB

W_y bending resistance with respect to compressed edge, depending on the section class

f_y yield stress

γ_{M1} partial coefficient with respect to instability

If one of the conditions in equation (11) or (12) is fulfilled no check for LTB is required.

$$\bar{\lambda}_{LT} \leq \bar{\lambda}_{LT,0} \tag{11}$$

$$\frac{M_{Ed}}{M_{cr}} \leq \bar{\lambda}_{LT,0}^2 \tag{12}$$

$\bar{\lambda}_{LT}$ non-dimensional slenderness factor for LTB

$\bar{\lambda}_{LT,0}$ value of the plateau length for buckling curves of hot-rolled sections

M_{Ed} design moment

M_{cr} elastic critical moment for LTB, see Appendix E

SS-EN 1993-1-1:2005 presents one general case and one special case of design check of LTB, Rebelo et al. (2009). For hot-rolled sections, the special case, the reduction factor is calculated with equation (13) - (15).

$$\chi_{LT} = \frac{1}{\Phi_{LT} + \sqrt{\Phi_{LT}^2 - \beta\bar{\lambda}_{LT}^2}} \quad \begin{cases} \chi_{LT} \leq 1 \\ \chi_{LT} \leq \dfrac{1}{\bar{\lambda}_{LT}^2} \end{cases} \tag{13}$$

$$\Phi_{LT} = 0{,}5\left(1 + \alpha_{LT}\left(\bar{\lambda}_{LT} - \bar{\lambda}_{LT,0}\right) + \beta\bar{\lambda}_{LT}^2\right) \tag{14}$$

$$\bar{\lambda}_{LT} = \sqrt{\frac{W_y f_y}{M_{cr}}} \tag{15}$$

β correction factor for buckling curves of hot-rolled sections

α_{LT} imperfection factor

In SS-EN 1993-1-1:2005, paragraph 6.3.5.2, the design connection force of the attachment between the beam and the bracing member should be calculated as equation (16). The bracing member should be controlled for a force at every bracing point as described in equation (17).

$$F_{con} = \frac{2{,}5}{100} N_{f,Ed} = 0{,}025 N_{f,Ed} \tag{16}$$

$$Q_m = 1{,}5\alpha_m \frac{N_{f,Ed}}{100} = 0{,}015\alpha_m N_{f,Ed} \tag{17}$$

$N_{f,Ed}$ the force in the compressed flange of the beam

α_m reduction factor according to paragraph 5.3.3, Swedish Standards Institute (2008a)

3 Methodology

One of the aims of this Master's Thesis was to model the formwork with different materials, dimensions, loads, span lengths etc. and analyze the structural behaviour, especially regarding lateral-torsional buckling, see Section 1.2. To fulfil this aim, firstly analytical calculations were performed in a schematic manner, to treat many different structure configurations, and secondly some of the structure configurations were modelled and analysed with nonlinear analysis with the finite element software LUSAS. Several different structure configurations, likely to be used in bridge formwork structures, were set up and numbered according to Table 3-1. The span length and distance between bracing points were combined in totally 21 different structure configurations and the calculations were performed for HEB steel beams of 4 different sizes, HEB 200, HEB 300, HEB 400 and HEB 500.

Table 3-1 Structure numbering. It is vital to understand the difference between the structure configurations, because this system was used all through the Master's Thesis.

Variable	Number	Explanation
Material	1.x.x	timber beam on steel beam
	2.x.x	steel beam on steel beam
Span	x.1.x	span length 5 m
	x.2.x	span length 10 m
	x.3.x	span length 15 m
Distance between bracing	1.x.1	distance between timber wailings/bracing points 0,3 m
	1.x.2	distance between timber wailings/bracing points 0,35 m
	1.x.3	distance between timber wailings/bracing points 0,4 m
Distance between bracing	2.x.1	distance between secondary steel beams/bracing points 1 m
	2.x.2	distance between secondary steel beams/bracing points 1,5 m
	2.x.3	distance between secondary steel beams/bracing points 2 m
	2.x.4	distance between secondary steel beams/bracing points 2,5 m

There were different ways to distribute the secondary beams on the primary beams. In the case of timber beam on steel beam there was always one secondary beam exactly at mid-span, and the distribution of the others followed as shown in Figure 3-1. In the case of steel beam on steel beam there were different load alternatives: one alternative when a secondary beam was placed exactly at mid-span and another alternative when two secondary beams were placed with the mid-span in the middle of them, see Figure 3-2.

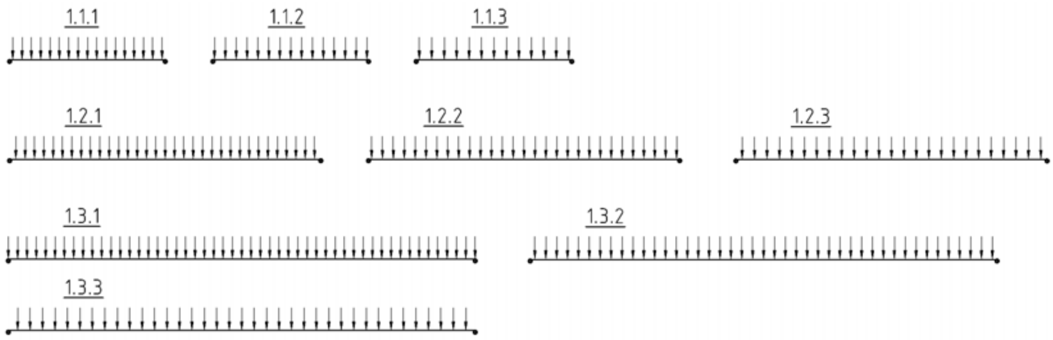


Figure 3-1 *Distribution of secondary beams in the case of secondary timber beams on steel beam.*

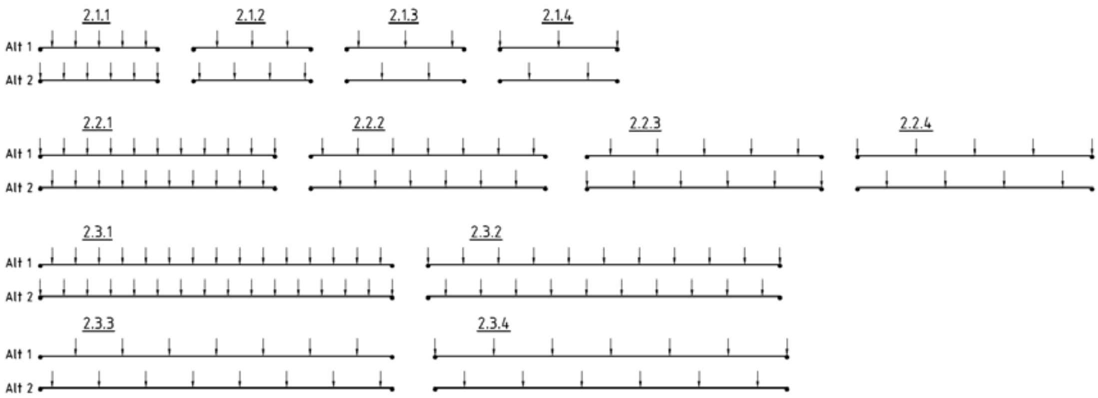


Figure 3-2 *Distribution of secondary beams in the case of secondary steel beams on steel beam.*

3.1 Analytical calculations

The purpose of the analytical calculations was to analyse the structural behaviour, analyse if the friction force was enough to prevent lateral-torsional buckling and to use them as verification to the finite element analyses. In Appendix A the analytical calculations are presented. At first an explaining part was made in MathCAD and after that the analyses of the different structure configurations were made in Excel. Both the Swedish standard BSK 2007, Boverket (2007), and SS-EN 1993-1-1:2005, Eurocode 3, Swedish Standards Institute (2008a), were used parallel in the analytical calculations. The calculations were divided into five sections that were performed for every structure configuration.

- *Input data.*

  In this first section information about the steel material, the friction coefficient between the members and geometric properties of the current structure configuration was set up. The minimum values from Table 2-2 were used as friction coefficients, but were much reduced by a partial factor, $\gamma_{\mu} = 2$. The reduction of the friction coefficient is motivated by the high insecurity when it comes to friction. This section also contained the cross-sectional data for the HEB beams, taken from engineering tables.

- *a) Beam analysis - take no bracings into account - free LTB.*

The beams in the current structure configuration were analysed as if there were no bracings present. The beam was considered free to LTB and the load-bearing capacity was calculated by using BSK 2007, equations (2), (4) and (5) and Eurocode 3, equations (10), (13), (14) and (15), see Section 2.3.2. This beam analysis regarding lateral-torsional buckling was founded on the theoretical elastic critical moment for which an ideal beam with no imperfections will LTB.

Three different ways to calculate the critical moment of a beam were compared in Appendix E. The three methods were taken from StBK-K2, Statens Stålbyggnadskommitté (1973), NCCI (Non Contradictory Complementary Information), The Steel Construction Institute (2005), and the software LTBeam created by CTICM (Centre Technique Industriel de la ,Construction Métallique). With the method from StBK-K2 the calculated critical moment differed from the other two methods presented, as can be seen in Appendix E. The method from NCCI was chosen and used in the analytical calculations, to calculate the elastic critical moment, and in a few cases the software LTBeam was used.

For the different structure configurations the distance between the secondary beams varied and in most cases the distance was much smaller than the span length, see Figure 3-1 and Figure 3-2. In those cases the analysis was simplified such that the beam was loaded with a uniformly distributed load. In the few other cases where the ratio between centre distance of the secondary beams and the span length was too big, the beam was analysed with the correct number of concentrated loads. See for example Figure 3-2 structure configurations 2.1.3 and 2.1.4. The load distribution, or the moment distribution, and the point of action of the loads had a big influence on the elastic critical moment, as well as the support conditions, among others.

The elastic critical moment was used in the BSK 2007 and Eurocode 3 formulations, which differed a bit from each other, and the beams load bearing capacities with regard to bending were calculated for the different standards respectively. Eurocode 3 gave a higher load bearing capacity than the Swedish standard because in BSK 2007 there was a partial factor γ_n, with regard to the safety class, that reduced the design yield strength. This safety margin was, in Eurocode, put on the load combination instead. This means that it seemed like the beam could carry much less load when designing with BSK 2007, but it evens out.

- *b) Beam analysis - take friction into account as bracing force - prevented LTB.*

In this section the friction between the analysed beams and the secondary grid layer was, as the title implies, taken into account as bracing of the top flange.

The ultimate load bearing capacities with regard to bending of the beams were calculated as if they were fully braced against LTB, i.e. the reduction factors for LTB were put equal to one.

For the structure configurations, for which the loading was simplified as a uniformly distributed load, as explained above, the corresponding concentrated load from one single secondary beam was calculated. That concentrated load was multiplied with the reduced friction coefficient to find the friction force capacity of the connection. The friction force was compared to the maximum design connection force for BSK 2007, see equation (6), and for Eurocode 3, see equation (16), Section 2.3.2. The maximum design connection force is valid for connections near a point where the yielding stress is reached, i.e. near mid-span of a simply supported beam. If the friction force capacity was higher than the maximum design connection force, the beam won't laterally move at that connection.

But in both BSK 2007 and Eurocode 3 there were other conditions that must be fulfilled, to make the assumption that the beams were fully braced against LTB, see equation (3) respective equations (11) and (12), Section 2.3.2. If these conditions were fulfilled and the friction force capacity was higher than the maximum design connection force, the friction was enough to prevent the beam from LTB.

- *c) Beam analysis - deformation limit.*

The deformations are often crucial for formwork beams and in the analytical calculations a reasonable and common limit of the vertical deformation was used. The maximum deflection was limited to the smallest value of L/300 or 50 mm, in accordance with Carlsson[3]. The maximum load with regard to the maximum deflection was calculated in the fourth section. Also the deflection, corresponding to the loads from section a) and b), was calculated and compared to the maximum load corresponding to the deflection limit. If the calculated deflection from section a) and b) was higher than the maximum deflection, the design load for that particular structure configuration and beam size was limited due to deflection. If, on the other hand, the loads from section a) and/or b) passed the deflection test, the ultimate design load for that particular structure configuration and beam size was limited either by the load from section a), free LTB, or if, and only if, the friction force was enough to prevent the beam from LTB, the load from section b), prevented LTB, was the ultimate design load, see Figure 3-3.

- *d) Beam analysis - The design load.*

The load-bearing capacities of the current structure configuration and beam sizes were listed and associated to their limitation. From the tables in section *d)* it was clear whether it was either deflection, free LTB or prevented LTB that was the limitation of the maximum load bearing capacity.

---

[3] Christer Carlsson, supervisor Ramböll

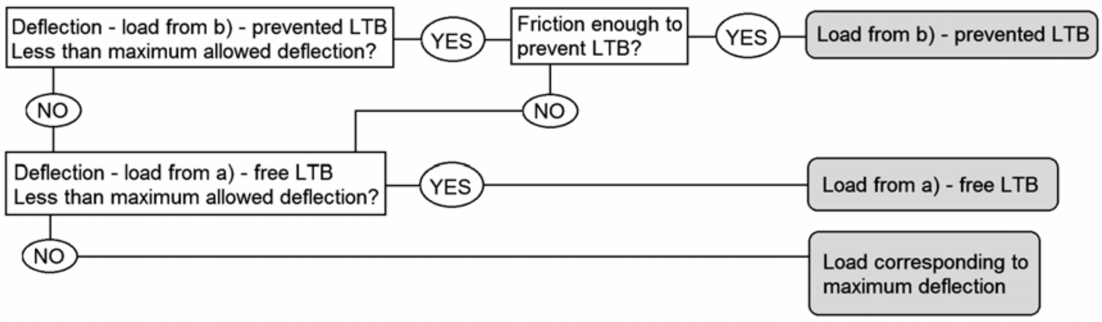


Figure 3-3 Schematic figure of how the ultimate design load was chosen.

3.1.1 Reasonable loads for bridge formwork

The load bearing capacities for the different structure configurations and beam sizes that were obtained from the analytical calculations were only the maximum capacity of that specific case. It had no relation to what are reasonable real loads for a bridge formwork structure. To decide which structure configurations that had a reasonable load bearing capacity and could be of practical use, an interval was calculated, see Appendix B. The structure configurations that had a load bearing capacity within this interval were analysed further with finite element software.

3.2 Analysis with finite element software

The structure configurations and beam sizes that were chosen for further analysis were modelled with the finite element software LUSAS, which is a quite general three-dimensional structural analysis system. This section describes the schematic way of which these analyses were performed. Although the structure configurations and beam sizes differed with respect to span length, distance between secondary beams and cross-sectional dimensions of the HEB beams, principally the same methodology was used. The purpose of the FEM analyses was to extract the needed bracing force to prevent the beam from LTB, from the results. The needed bracing forces extracted from FEM analysis were presumably more similar to the real needed bracing forces than the ones calculated analytically. This because of in the finite element model more properties of the analysed structure were taken into account, than in the equations (6) and (16), Section 2.3.2. In the analytical calculations both the Swedish standard BSK 2007, Boverket (2007), and SS-EN 1993-1-1:2005, Eurocode 3, Swedish Standards Institute (2008a), were used, but in the finite element analysis only Eurocode 3 was used.

The finite element analysis of each structure configuration and beam size was divided into four main parts. At first the geometry was drawn and the cross-sectional and material properties were assigned to the model and also correct boundary conditions for the particular structure configuration. Secondly an initial linear analysis was performed to check that the model behaviour was satisfactory. The third step was an eigenvalue buckling analysis, to find the mode for lateral-torsional buckling of the beam, and at last a geometric and material nonlinear analysis was performed.

3.2.1 Geometry, mesh, material and boundary conditions

In LUSAS simple beam elements can be used, but for such elements boundary conditions and loading can only be applied to the centre line of the beam. A beams structural behaviour, when it comes to lateral-torsional buckling, is highly dependent on the load application point, the support condition and where at the cross-section the bracings are placed, as described in Section 3.1. Therefore the HEB beams were modelled with steel plates that were drawn as an I-cross-section and this way the supports and loads could be applied anywhere on the beam. When drawing the flanges and the web, the translations between the plates were not curved, as for a hot-rolled section, but it had very little effect on the final result. The beams were modelled with web stiffeners over the supports, because most bridge formwork structures, of the types treated in this Master's Thesis, have web stiffeners, according to Carlsson[4]. The structures were modelled with the X-direction along the beam and Y- and Z-direction horizontally respectively vertically in the cross-section of the beam, see Figure 3-4.

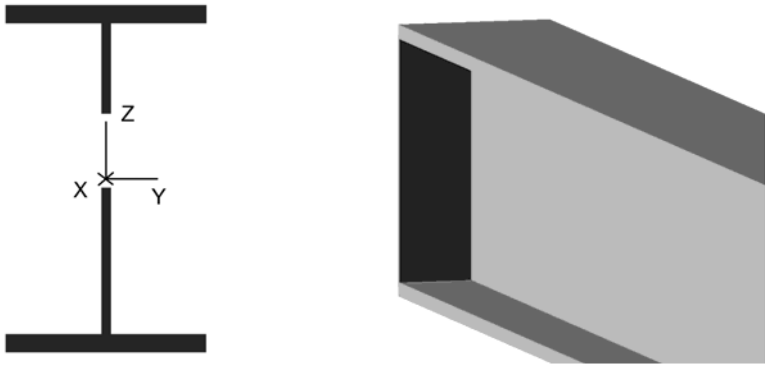


Figure 3-4 Beam cross-section and end web stiffener from finite element model.

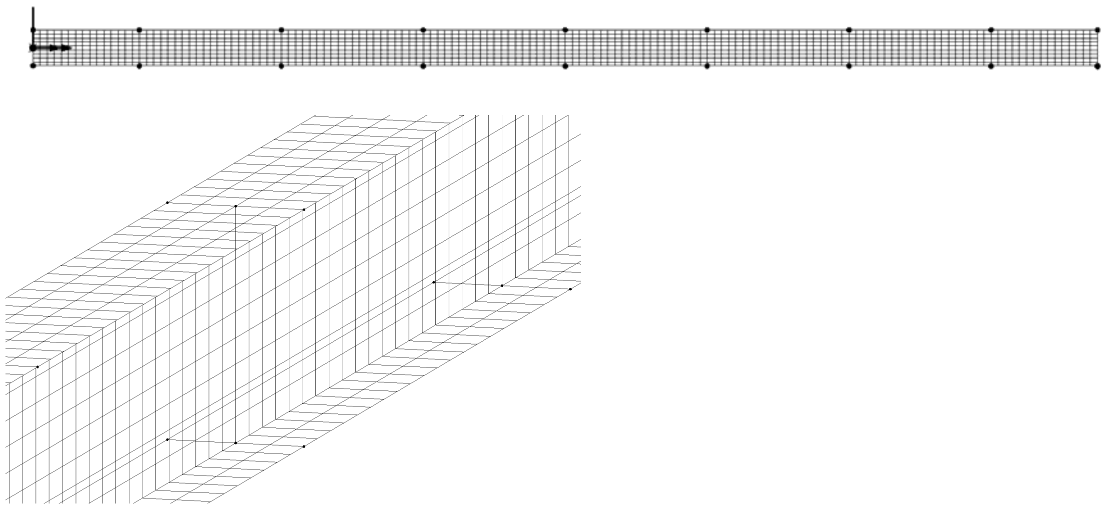


Figure 3-5 Meshed finite element model of a HEB beam.

[4] Christer Carlsson, supervisor Ramböll

The beam parts were meshed with quadrilateral thin shell elements with eight nodes. The elements are called Semiloof Curved Thin Shell Elements in LUSAS and they have the element name QSL8. They can be used for nonlinear analyses and are based on a Kirchhoff hypothesis, Lusas (2010c). The mesh size was chosen so that it was approximately ten elements per meter, in each direction, see Figure 3-5. After that the thickness and material properties of the beam parts were assigned. For the web and flanges the thickness was of course the same as for the corresponding HEB beam, and for the web stiffeners an appropriate thickness for each case was used, usually the same as the web thickness. Most important was that the stiffener did not buckle before LTB occurs.

The boundary conditions differed between the structure configurations but similar for all of them was that the beam was simply supported at both ends. The degrees of freedom in X, Y and Z were fixed for the support called “Fixed bearing” and Y and Z were fixed for the support called “Rolling bearing”. The boundary conditions that differ between different structure configurations were the lateral bracings of the top flange. A support with the Y degree of freedom fixed, called “Lateral support”, functioned as the frictional connection between the primary and secondary beams in the grid structure. The Lateral supports were assigned to the centre of the top flange with centre distance along the beam depending on the structure configuration. The Lateral supports were assigned to only one node, in order to simplify the post-processing of the analysis.

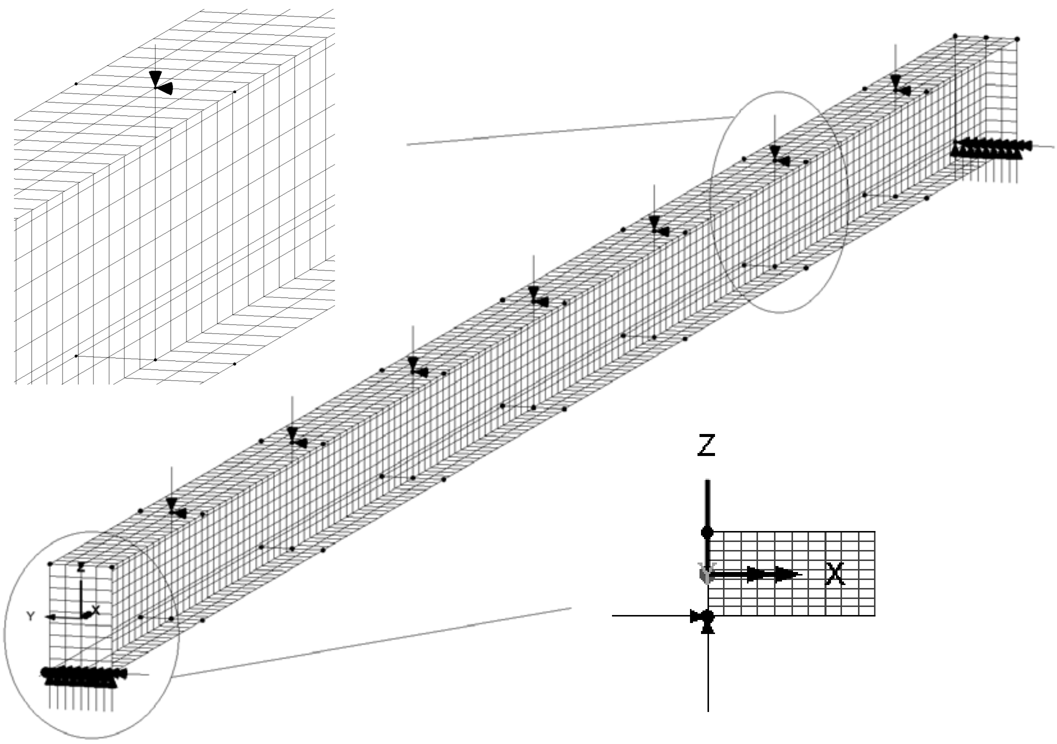


Figure 3-6 Beam with assigned concentrated loads and the boundary conditions “Fixed bearing” at the left end, “Rolling bearing” at the right end and “Lateral support” at the same points as the concentrated loads.

The load on the beam was in the analytical calculations often simplified as an evenly distributed line load, but in LUSAS there was no reason to make this simplification. The loading in the finite element model was concentrated loads acting in the Z-direction on the top flange of the beam, at the same points as the Lateral supports. It was more alike the real loading on the beam, than using evenly distributed loading. In Figure 3-6 an example of a finite element model, with assigned boundary conditions and load, is shown.

3.2.2 Initial linear analysis

After the model geometry, material and boundary properties had been created and assigned an initial linear analysis was performed to make sure the model behaved as expected. For each structure configuration and beam size an ultimate load had been calculated analytically, as described in Section 3.1, and also the corresponding mid-span deflection. This ultimate load from the analytical calculations, which in most cases was an evenly distributed load, was transformed into concentrated loads and the initial analysis was performed in LUSAS. A global equilibrium control that the total reaction forces of the supports were equal to the applied load was made. Also the deformed shape was checked to be as expected, the maximum mid-span deflection was compared to the calculated deflection and maximum stresses were checked to be approximately the same as the yield strength of the steel, which was used in the analytical calculations.

3.2.3 Eigenvalue buckling analysis

When performing a nonlinear buckling analysis the initial structure must, in this case, have an imperfection, otherwise the nonlinear analysis output will be the same as for a linear analysis. The reaction forces at the Lateral supports, i.e. the needed bracing force, would have been equal to zero if the nonlinear analysis would be performed without imperfections. The real structural members are not ideal but they have imperfections that will give rise to second order effects, and because of the imperfections the member will fail before it reaches the theoretical elastic critical moment. The most unfavourable imperfection in this case, with regard to lateral bracing forces, was the deformed shape of the buckling mode corresponding to lateral-torsional buckling of the beam, without any lateral bracings.

In LUSAS there is a type of analysis that computes the different buckling modes of a structure, called Eigenvalue buckling analysis. This analysis was used to find the buckling mode corresponding to LTB, which for the beams analysed in this Master's Thesis, generally was the lowest global buckling mode. For each buckling mode there was a corresponding load multiplication factor. The load factor was multiplied to the applied load to get the specific load the buckling mode was associated to. The applied load on the structure, when the eigenvalue buckling analysis was performed, was put equal to 1 kN, and therefore the load factor itself was equal to the buckling load in kN. For this load the structure lost its stability and buckled and it corresponded, in the case of LTB, to the elastic critical moment, see Section 3.1.

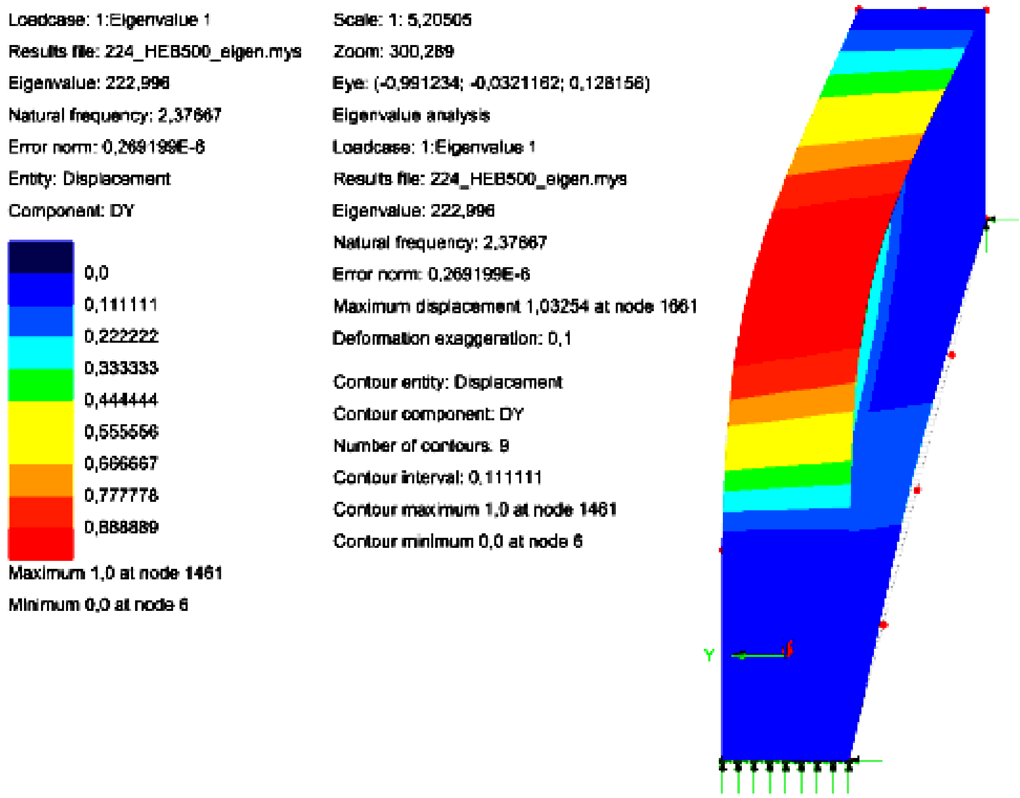


Figure 3-7 Example of deformed shape. Structure 2.2.4 HEB 500.

The useful output from this eigenvalue analysis was the deformed shape and the load factor, see Figure 3-7. The displacements, stresses and reaction forces among others were of no practical use because they were relative to the unit normalised eigenvector used by LUSAS, Lusas (2010a). As can be seen in Figure 3-7, the maximum displacement DY was equal to 1 meter. In this case meter was the unit used when modelling in LUSAS, and therefore the maximum displacement was 1 meter, because of the unit normalisation. In other words, for any applied load the maximum displacement in each direction would always be 1. The deformed shape was accurate for the buckling load but the values of the displacements were unusable. To use the deformed shape in a nonlinear analysis the deformations needed to be scaled down to a reasonable value and this is described in Section 3.2.4.

For each structure configuration and beam size an output report, for the eigenvalue analysis, was generated containing information about the geometry, mesh and used element type, material, supports, loading and eigenvalues. These reports are not published, but can be presented by contacting the author.

3.2.4 Nonlinear buckling analysis

To use a linear analysis the deformations must be small and the material must have elastic properties, Lusas (2010d). Geometrical nonlinearities occur when the deformations are big enough to give major secondary effects on the structure, and the undeformed model can not accurately be used in analysis anymore, as the load increases. One example, when there are significant changes in the structure, is when a beam buckles lateral-torsional. The structure will at some point reach a critical load when the structure loses its stability and this will not be found with a linear analysis. With material nonlinearity means for example the plastic yielding of metals. The material has approximate elastic properties up to a limiting stress and after that the stress in the material can not increase anymore, only the deformations increase.

To take geometrical and material nonlinearities into account, a nonlinear finite element analysis must be performed. A nonlinear analysis can simply be explained as a series of linear analyses that for each new step has a new load factor and an updated stiffness matrix, due to the deformed shape from the step before. It is an iterative process that continues until, in the case of buckling, the structure loses its stability. There are many ways to perform a nonlinear analysis in LUSAS and only the procedure that was used in this Master's Thesis is described. The nonlinear analysis concept that was used is called incremental-iterative method. For further reading see Lusas (2010d).

As mentioned in Section 3.2.3 the deformed shape from the eigenvalue was used as a starting structure in the nonlinear analysis, though the deformations needed to be scaled down to a reasonable level. In SS-EN 1993-1-1:2005 Section 5.3.2(b), Swedish Standards Institute (2008a), an initial imperfection of L/250 is prescribed to be used for the HEB beams treated in this Master's Thesis, where L is the span length of the beam. The initial imperfection L/250 was implemented in the finite element model and in LUSAS it was made with the deformed mesh factor, Lusas (2010d). When using the deformed mesh factor, the maximum displacements from the eigenvalue analysis were equal to the prescribed value of the initial imperfection, L/250.

The boundary condition called Lateral support, shown in Figure 3-6, was assigned with correct distances depending on the structure configurations. At those supports there arose reaction forces that later could be compared to the friction force capacity, between primary and secondary beams. Also the yield strength of the steel was assigned to the structure. In LUSAS there are several nonlinear controls that must be set up before starting a nonlinear analysis, like the load incrementation, the convergence criterions and a few other functions that help the convergence of the solution. The automatic load incrementation was set up by a starting load multiplication factor, a maximum total load factor and a maximum change of load step. The applied concentrated loads, described in Section 3.2.1, were all set to 1 kN, which meant that the load multiplication factor would be equal to the real applied load in kN. The values of the starting, maximum and change of the load factor depended on the structure configuration, i.e. what the actual load-bearing capacity the actual structure configuration and beam size had. This could be found in the analytical calculations, see Appendix A.

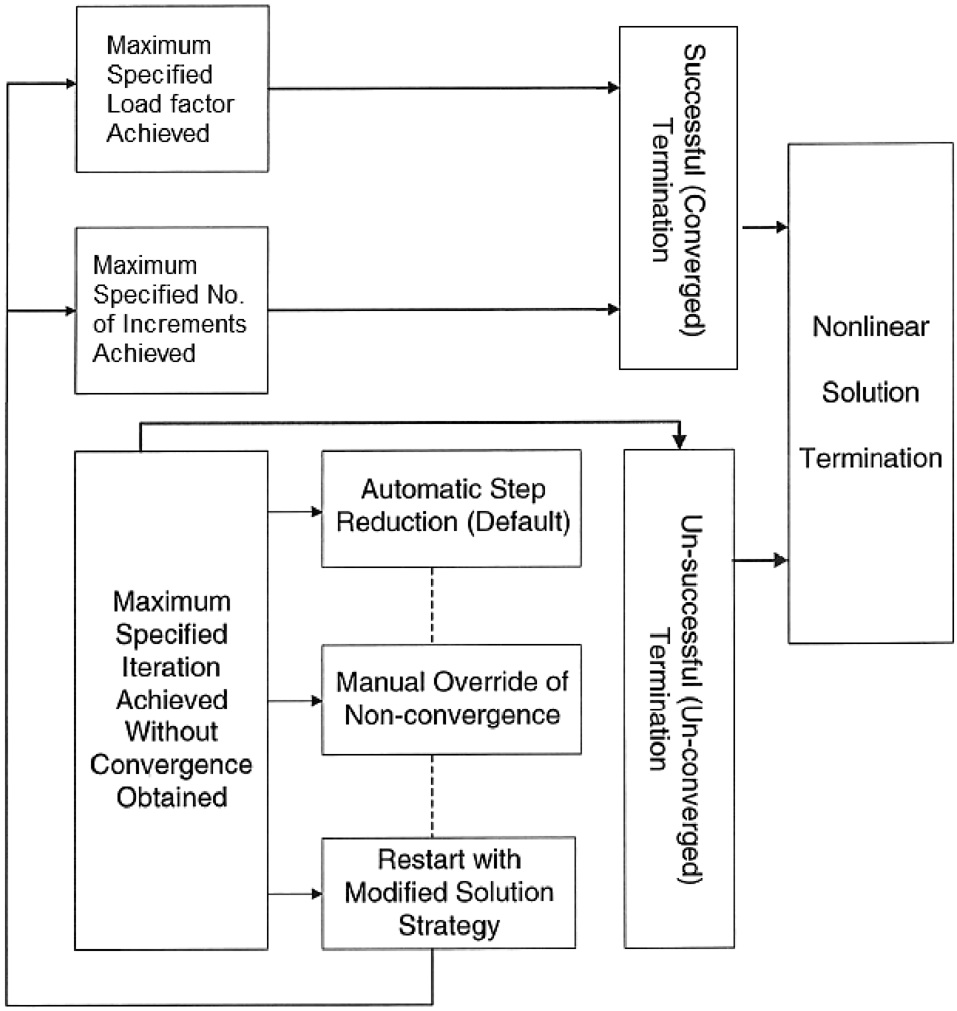


Figure 3-8 Scheme for LUSAS solution termination, Lusas (2010f).

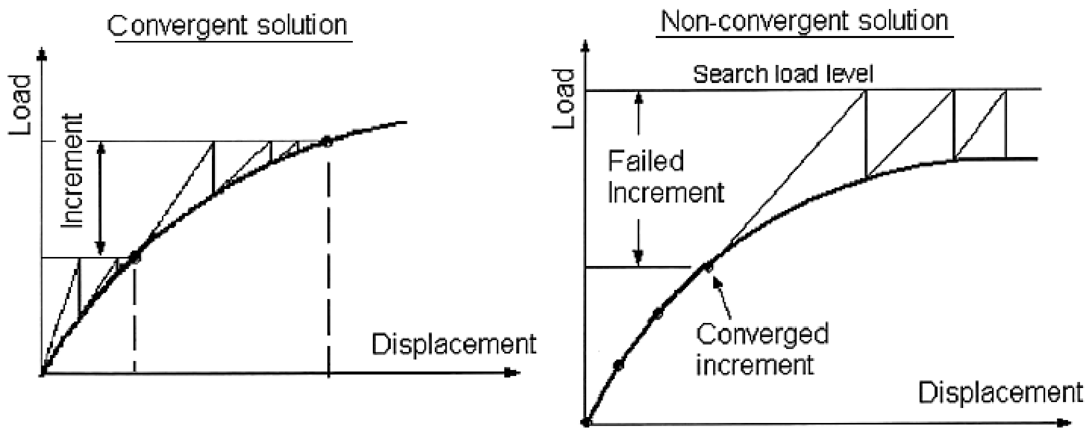


Figure 3-9 Examples of a solution that converges and not converges, Lusas (2010e) and Lusas (2010f).

The nonlinear analysis continues until some solution termination criterion has been reached, see Figure 3-8. For each load increment an iterative analysis is performed until the increment converges or not converges, see Figure 3-9. If the increment converges the load factor increases and the iterative process starts over. Six different convergence criterions can be set up in LUSAS, Lusas (2010f). They are set up so that the analyses give satisfying and reasonable results. In addition to the convergence criterion a maximum number of load increments and a maximum number of iterations per increment can be set up. If the solution does not converge before the maximum number of iterations, for a specific load increment, different assisting functions in LUSAS starts to interfere. There is a function called Automatic step reduction that, if the load increment does not converge, reduces the load increment to a lower load factor and attempts to get convergence, see Figure 3-10. The change of load factor may affect the function of the Automatic step reduction because if the load step is too high the solution might fail to converge, even if the load step is reduced. Another function called the Arc-length solution method improves the convergence behaviour if there is a limit point, Lusas (2010f), see Figure 3-11. If the solution fails to converge after all or if the maximum number of load increments has been reached, the nonlinear analysis stops.

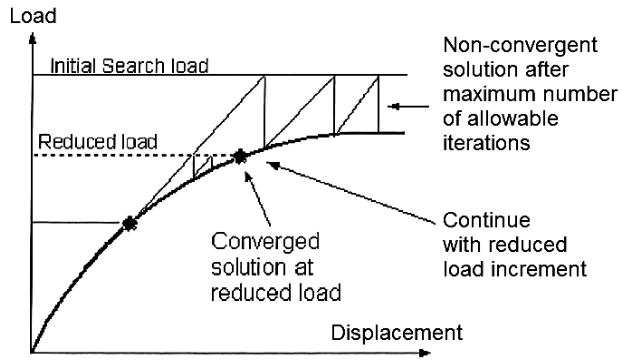


Figure 3-10 The step-reduction function in LUSAS, Lusas (2010f).

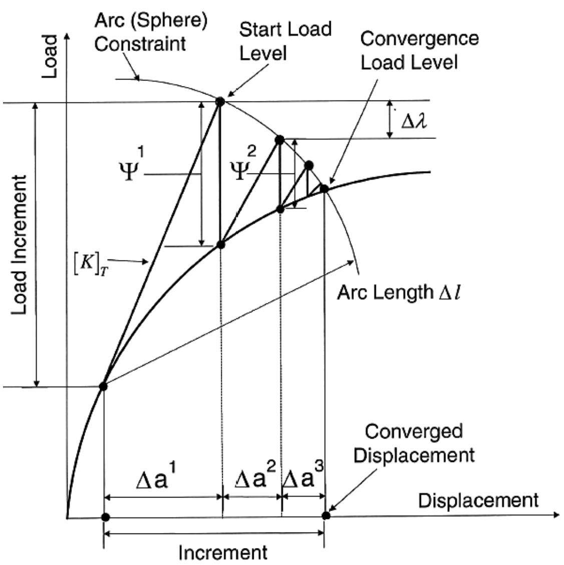


Figure 3-11 The arc-length solution method, Lusas (2010f).

A load-deflection graph was plotted for each analysis with maximum vertical deflection on the x-axis and the load factor on the y-axis, see Figure 3-12 for an example. The load for which the structure would fail was not automatically output, Lusas (2010b), but in the graph it was in most cases quite clear, for which load the structure would fail. Each dot in the graph represented one load increment and the output from the analysis was presented with separate output data belonging to each load increment. For example for every load increment the reaction forces at the Lateral supports could be extracted. For each structure configuration and beam size an output report, for the nonlinear analysis, was generated containing information about the material, loads and reaction forces from a few chosen load increments. It also contained some figures of the stress state, deformation and the load-deflection curve. These reports are not published, but can be presented by contacting the author.

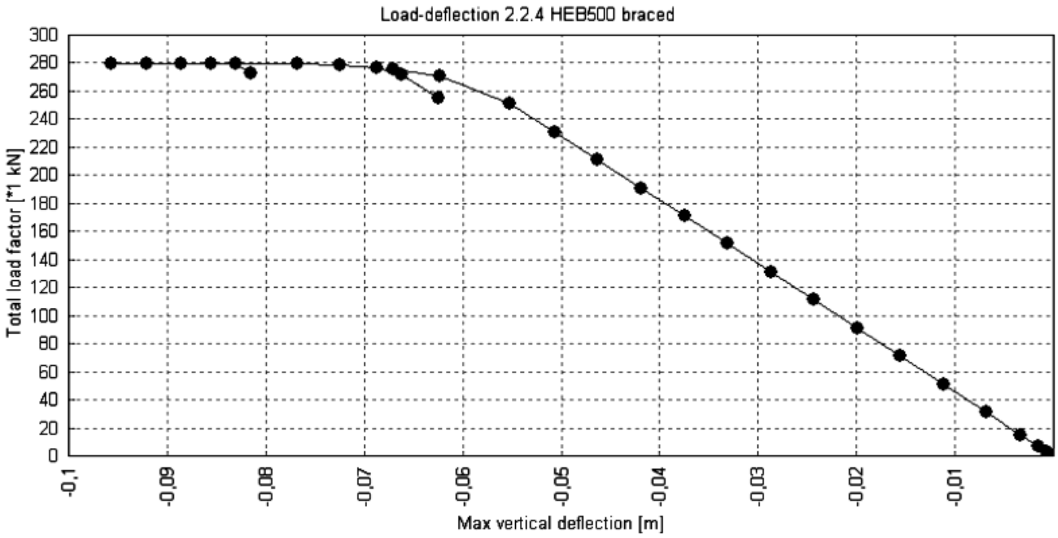


Figure 3-12 Example of load-deflection graph. Structure 2.2.4 HEB 500.

4 Result

Appendix A contains the analytical calculations and in Appendix B the reasonable load interval was calculated. Appendix C and Appendix D present the result from the finite element analyses. All the results in this chapter were taken from these appendices. Principally the same calculations and studies were carried out on all the structure configurations and beam sizes, which mean that there were many graphs that appear similar. In the following sections the results will be described and important issues highlighted.

4.1 The analytical calculations

All the structure configurations that were set up, see Table 3-1, were analysed according to Section 3.1 and Appendix A. Under the sections *d) Beam analysis - The design load*, in Appendix A, the design loads for the different structure configurations and beam sizes were listed, together with information from which demand that were the limitation. The design loads and limitations were listed both for BSK 2007 and Eurocode 3, and the results often differed between the standards. The results showed that for HEB 200 and HEB 300 it was always deflection that limited the design load, except for HEB 300 structure 2.1.4 load alternative 1, a beam with only one point load in mid-span. For the structure configurations that have 15 meters span length it was always deflection that was the limitation. For the 10 meters configurations it was, for the Eurocode 3 case, always deflection that limited the design load. For the BSK case it was deflection that was the limitation in most cases, except for the HEB 500 beams. They passed the deflection demands for the load corresponding to free lateral-torsional buckling, i.e. the load calculated under the sections *a) Beam analysis - take no bracings into account - free LTB*. Only for span length 5 meters there were some structure configurations and beam sizes for which full bending capacity could be utilized, i.e. friction enough to prevent LTB.

If ignoring the deflection demand and study the result from sections *b) Beam analysis - take friction into account as bracing force - prevented LTB*, it can be seen that it was only in a few cases the friction force capacity was higher than the maximum design connection force, according to BSK 2007 respective Eurocode 3. For the structure configurations, with secondary timber beams and with many bracing points, the friction was not enough for any structure configuration and beam size according to Eurocode 3, but according to BSK the friction force capacity was higher than the maximum design connection force for some of the structures with span length 5 meters. The short span length allowed for a higher load-bearing capacity, i.e. higher friction force capacity. For the structure configurations with secondary steel beams the distance between the bracings were higher, and from that followed a higher load per bracing point, which allowed for a higher friction force capacity. In the analytical calculations the trend was that the fewer bracing points the higher friction capacity and the higher chance to meet the maximum design connection force demand. In Section 4.1.1 the structure configurations and beam sizes that fell into a reasonable load interval are presented and more results will be presented for those structures.

4.1.1 Reasonable load interval

Section 3.1.1 describes that in Appendix B an interval of reasonable loads was developed. The interval was $12{,}5 \leq q \leq 125$ kN/m, and it was used to sort out which structure configurations and beam sizes that were to be analysed by finite element analysis. The structure configurations and beam sizes that were chosen are shown in Table 4-1. Some of the selected configurations were not analysed because they were similar to each other and the result would have been approximately the same. The results for these selected configurations, both from the analytical calculations, Appendix A, and the finite element analysis, Appendix C and Appendix D, are presented in Section 4.2.

Table 4-1 Structure configurations and beam sizes chosen for finite element analysis. The coloured fields mean that it falls inside the interval. The solid fields were analysed and the striped fields were omitted.

	HEB200	HEB300	HEB400	HEB500
1.1.1				
1.1.2				
1.1.3				
1.2.1				
1.2.2				
1.2.3				
1.3.1				
1.3.2				
1.3.3				

= FE analysis
= omitted

	HEB200	HEB300	HEB400	HEB500
2.1.1				
2.1.2				
2.1.3				
2.1.4				
2.2.1				
2.2.2				
2.2.3				
2.2.4				
2.3.1				
2.3.2				
2.3.3				
2.3.4				

4.2 The finite element analysis

The output data from the finite element analysis contains a large amount of variables, but only a few are of interest to this Master's Thesis. The model and output files from LUSAS and the eigenvalue and nonlinear output reports are not included in this report. Contact the author to get them. The output data of interest to this Master's Thesis was extracted and put together in two appendices, Appendix C and Appendix D, that present the essential data in tables and graphs. Straightforward comparison and evaluation of the result was possible, both between the different structure configurations and beam sizes and between the finite element analyses and the analytical calculations.

4.2.1 Presentation and analysis of results

Appendix C, timber beams on steel beams, and Appendix D, steel beams on steel beams, includes excel documents with different graphs visualising the results from the finite element analysis for each structure configuration and beam size.

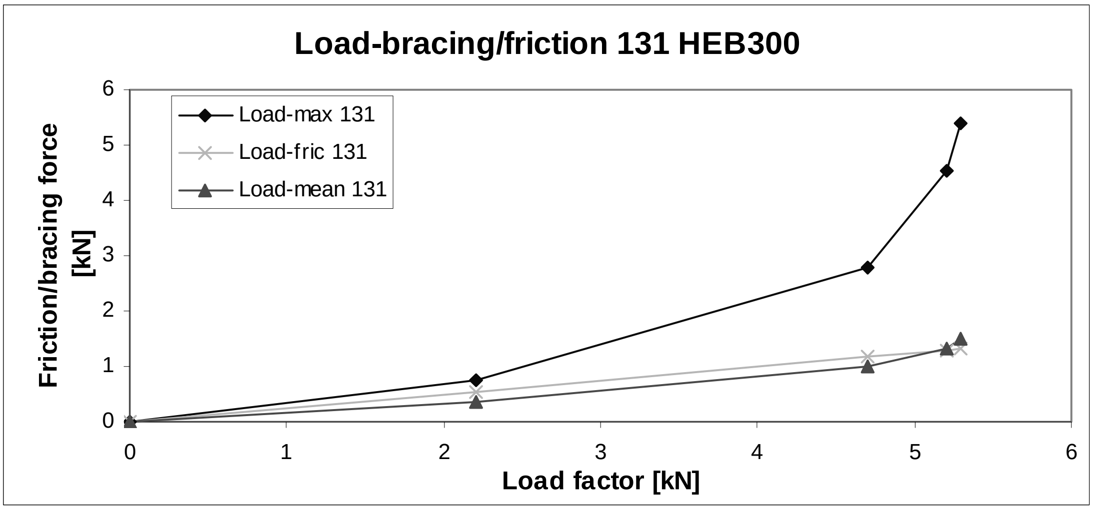


Figure 4-1 *Example of a graph showing the maximum and mean needed bracing force and the friction capacity. Structure 1.3.1 HEB 300.*

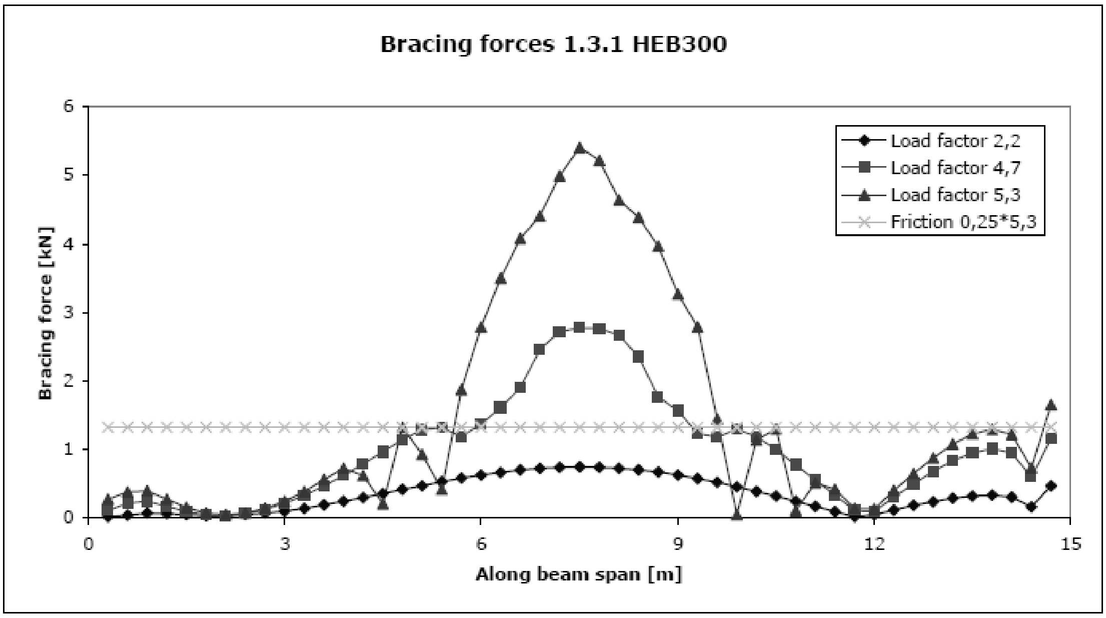


Figure 4-2 *Example of a graph showing the distribution of the needed bracing forces at different bracing points along the span length of the beam. Structure 1.3.1 HEB 300.*

The same types of graphs were used for all different structure configurations. The first graph, on each page in Appendix C and Appendix D, shows three curves; the maximum needed bracing force, the mean needed bracing force and the friction capacity. The curves were plotted in relation to the applied load, or the load factor. See Figure 4-1 for an example. The needed bracing forces were output from the finite element analysis and the friction capacity was calculated according to equation (1), Section 2.2.1, with the same friction coefficients as in the analytical calculations, i.e. 0,25 between timber and steel and 0,1 between steel and steel. The next graph, on each page in Appendix C and Appendix D, shows the load-deflection curve, see Figure 3-12 and Section 3.2.4. The third graph, on each page in Appendix C and Appendix D, shows the distribution of the needed bracing force in every braced point along the span length of the beam. A few different lines corresponding to different levels of the applied load, or load factor, were plotted in the graph and also a line with the friction capacity. See Figure 4-2 for an example. Below the third graph there was an extract of key parameters from the analytical calculations, such as calculated maximum load and the design connection force. The maximum design connection force was presented both according to BSK 2007, equation (6), and Eurocode 3, equation (16), see Section 2.3.2. These parameters can be compared to the corresponding parameters from the finite element analysis output.

In the graphs of the type shown in Figure 4-1 it was clear whether the friction force capacity was enough, i.e. higher, than the needed bracing force. The friction capacity must be compared to the maximum needed bracing force. The mean needed bracing force was merely plotted to show that there was a quite large variation, between the needed bracing forces in different points along the beam. That variation of the needed bracing force along the beam was also shown in the types of graphs, like the one shown in Figure 4-2. For loads that were equal to approximately half of the ultimate load, the distribution had a parabolic like shape. For loads that were near the ultimate load, the shape of the distribution changed and a more distinct increase, of the needed bracing force, was formed around mid-span. This was valid for most of the structure configurations and beam sizes. For some of the steel beams on steel beam configuration, where the distance between the bracing points was high and there were only a few bracing points along the beam, there was no clear shape of the force distribution. But the increase near mid-span, for the ultimate load, could still be observed. The line that showed the friction force capacity corresponds to the ultimate load, and the fact that it in many cases was above some of the lines does not mean that the capacity was enough. The friction capacity can only be compared to the ultimate load, i.e. the same load that was used to calculate it.

To get an overview of the result a summarising table, of some key parameters, was made, see Table 4-2. Only the structure configurations and beam sizes that were chosen for finite element analysis were included. The parameters were collected both from the analytical calculations, Appendix A, and the results of the finite element analysis, Appendix C and Appendix D. According to the analytical calculations, sections *d) Beam analysis - The design load*, in Appendix A, the deflection limited the maximum load for all of the structure configurations and beam sizes that were chosen for finite element analysis. But the deflection limit was overlooked and focus was put on whether the friction force capacity was enough to prevent LTB.

The column “Load-prevent LTB” contains the ultimate load of the beam, for beams that were assumed to be fully braced against lateral-torsional buckling. The calculated ultimate loads from sections *b) Beam analysis - take friction into account as bracing force - prevented LTB* in the analytical calculations, Appendix A, when using Eurocode 3, were put beside the ultimate loads from the finite element analysis. The distributed loads used in the analytical calculations were transformed into corresponding concentrated loads. In Figure 4-3 and Figure 4-4 the loads from column “Load-prevent LTB” were plotted to compare the analytically calculated loads to the numerically found load from the finite element analysis. In some cases there are small differences, but in general they are in very good agreement.

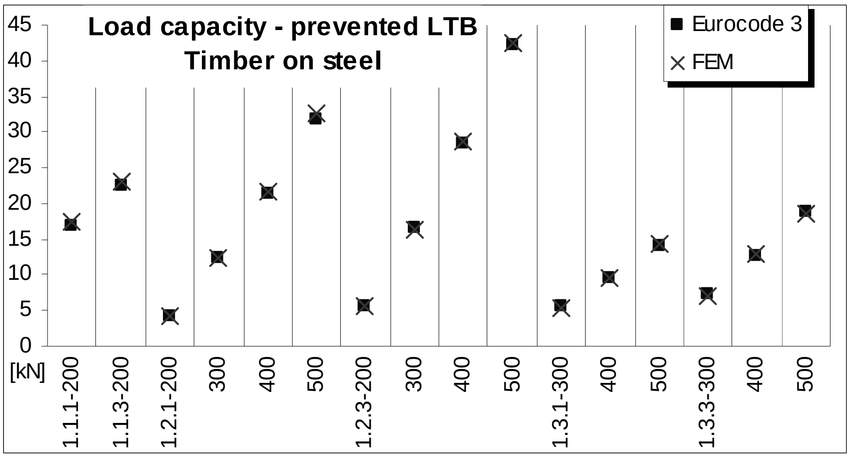


Figure 4-3 Comparison of loads from the analytical calculations and the finite element analysis. Secondary timber beams on steel beams. From the column "Load-prevent LTB" in Table 4-2.

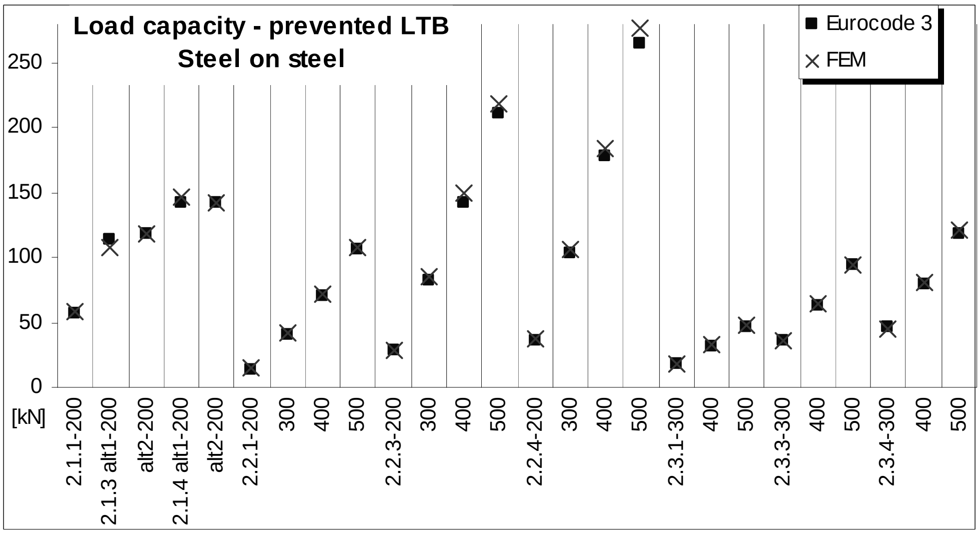


Figure 4-4 Comparison of loads from the analytical calculations and the finite element analysis. Secondary steel beams on steel beams. From the column "Load-prevent LTB" in Table 4-2.

One aim of this Master's Thesis was to find out whether the friction force capacity, between the primary and secondary beams, was enough to prevent the beam from lateral-torsional buckling. Table 4-2, column "Friction enough as bracing?", holds the answer to that question. From the analytical calculations, Appendix A, the result from section *b) Beam analysis - take friction into account as bracing force - prevented LTB*, both according to BSK 2007 and Eurocode 3, were collected. Both the answer to the question, "Friction enough as bracing force?", and the ratio between the friction force capacity F_{μ} and the maximum design connection force, $F_{con.\max}$, for BSK and for Eurocode 3, were put in to the table. From the finite element analysis the same

Table 4-2 For each structure number and beam size that were analysed by the finite element method different parameter are collected from the results. Some are taken from the analytical calculations, Appendix A, and some from the finite element analysis results, Appendix C and Appendix D. The parameters taken from the finite element analysis are named "FE". "Fy.max" means maximum needed bracing force.

Structure	HEB size	Load-prevent LTB EC3 [kN/m]	Load-prevent LTB EC3 [kN]	Load-prevent LTB FE [kN]	Friction EC3	EC3 $F_\mu/F_{con.max}$	Friction BSK 2007	BSK 2007 $F_\mu/F_{con.max}$	Friction FE	FE $F_\mu/F_{y.max}$	FE Fy.max [kN]
1.1.1	200	56,6	17,0	17,5	No	21%	No	43%	No	54%	8,1
1.1.3	200	56,6	22,6	23,0	No	27%	No	57%	No	59%	9,7
1.2.1	200	14,1	4,2	4,2	No	5%	No	11%	No	31%	3,3
	300	41,1	12,3	12,4	No	8%	No	16%	No	33%	9,4
	400	71,1	21,3	21,6	No	11%	No	22%	No	55%	9,8
	500	105,8	31,7	32,5	No	14%	No	29%	No	62%	13,1
1.2.3	200	14,1	5,7	5,7	No	7%	No	14%	No	25%	5,7
	300	41,1	16,5	16,4	No	10%	No	22%	No	41%	10,0
	400	71,1	28,4	28,6	No	14%	No	30%	No	59%	12,2
	500	105,8	42,3	42,4	No	18%	No	38%	No	81%	13,1
1.3.1	300	18,3	5,5	5,3	No	3%	No	7%	No	25%	5,4
	400	31,6	9,5	9,5	No	5%	No	10%	No	36%	6,5
	500	47,0	14,1	14,3	No	6%	No	13%	No	45%	8,0
1.3.3	300	18,3	7,3	7,0	No	5%	No	10%	No	27%	6,5
	400	31,6	12,6	12,8	No	6%	No	13%	No	33%	9,6
	500	47,0	18,8	18,7	No	8%	No	17%	No	54%	8,7
2.1.1	200	56,6	56,6	59,0	No	27%	No	57%	No	50%	11,8
2.1.3	200	56,6	113,2	107,9	No	55%	Yes	114%	No	53%	20,5
alt1&2	200	-	117,9	118,9	No	57%	Yes	119%	No	75%	15,8
2.1.4	200	-	141,5	146,8	No	69%	Yes	143%	No	78%	18,8
alt1&2	200	-	141,5	142,5	No	69%	Yes	143%	No	78%	18,4
2.2.1	200	14,1	14,1	14,3	No	7%	No	14%	No	8%	17,4
	300	41,1	41,1	41,5	No	10%	No	22%	No	16%	25,2
	400	71,1	71,1	71,7	No	14%	No	30%	No	29%	24,6
	500	105,8	105,8	108,5	No	18%	No	38%	No	45%	24,3
2.2.3	200	14,1	28,3	28,4	No	14%	No	29%	No	22%	12,9
	300	41,1	82,3	84,8	No	21%	No	44%	No	31%	27,0
	400	71,1	142,1	150,0	No	29%	No	60%	No	43%	35,1
	500	105,8	211,6	218,5	No	37%	No	76%	No	57%	38,3
2.2.4	200	14,1	35,4	36,9	No	17%	No	36%	No	16%	23,1
	300	41,1	102,9	105,8	No	26%	No	55%	No	26%	40,2
	400	71,1	177,7	184,9	No	36%	No	75%	No	40%	46,4
	500	105,8	264,6	276,9	No	46%	No	95%	No	52%	53,4
2.3.1	300	18,3	18,3	17,8	No	5%	No	10%	No	10%	17,2
	400	31,6	31,6	32,2	No	6%	No	13%	No	16%	19,6
	500	47,0	47,0	48,0	No	8%	No	17%	No	25%	19,3
2.3.3	300	18,3	36,6	35,2	No	9%	No	19%	No	11%	32,0
	400	31,6	63,2	63,8	No	13%	No	27%	No	18%	35,3
	500	47,0	94,1	93,8	No	16%	No	34%	No	26%	35,6
2.3.4	300	18,3	45,7	44,9	No	12%	No	24%	No	12%	37,5
	400	31,6	79,0	80,7	No	16%	No	33%	No	20%	40,9
	500	47,0	117,6	120,6	No	20%	No	42%	No	29%	41,9

parameters were taken, $F_\mu / F_{y.\max}$, and also the maximum needed bracing forces, $F_{y.max}$, were put into the last column of Table 4-2. These results are visualised in different ways in the following graphs, at first for the cases of secondary timber beams on steel beam.

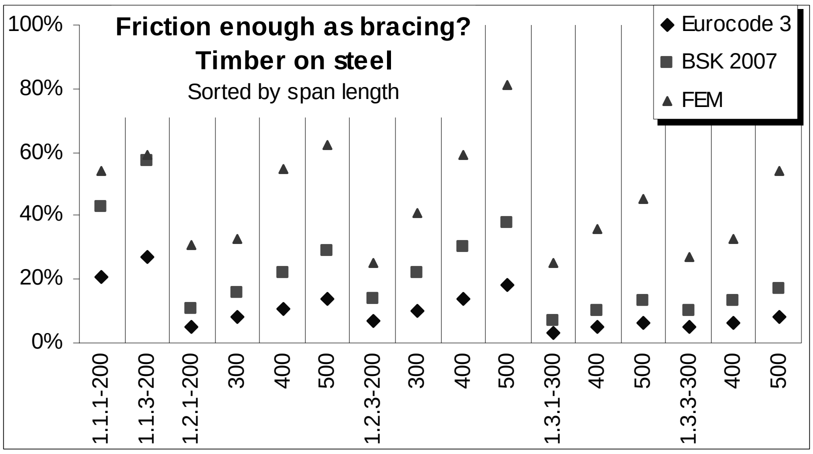


Figure 4-5 Sorted by span length. Secondary timber beams on steel beams. Ratio between the friction capacity and the maximum design connection force (Eurocode 3 and BSK 2007, $F_\mu / F_{con.\max}$) and the ratio between friction capacity and maximum needed bracing force (FEM $F_\mu / F_{y.\max}$), see Table 4-2.

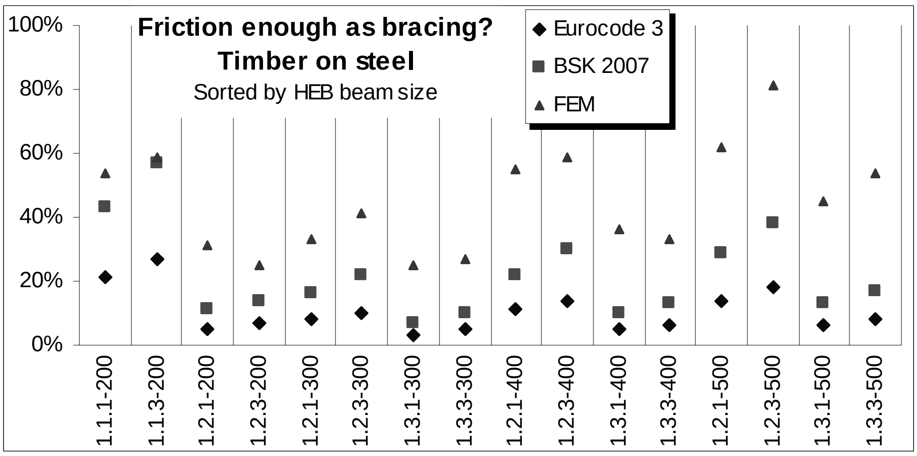


Figure 4-6 Sorted by HEB beam size. See Figure 4-5 for further explanation.

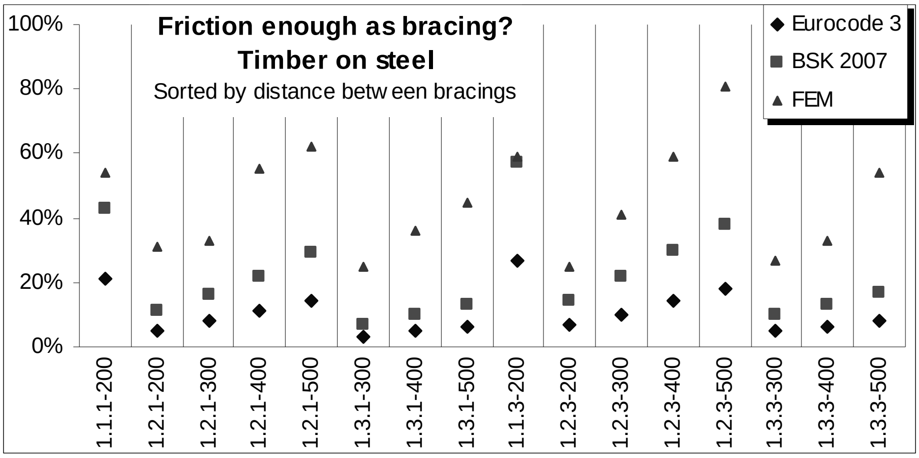


Figure 4-7 *Sorted by distance between bracings. See Figure 4-5 for further explanation.*

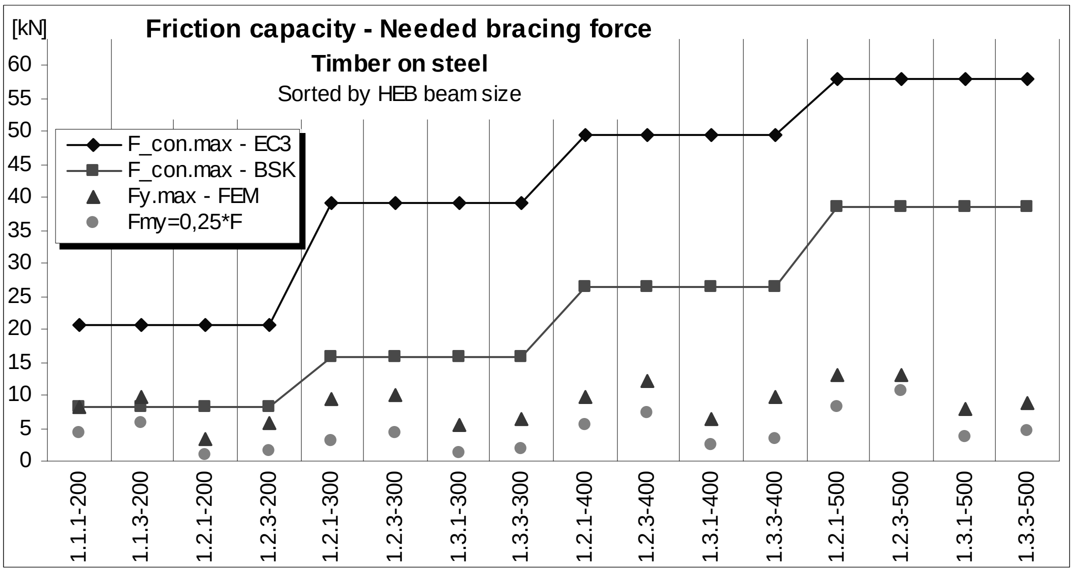


Figure 4-8 *Sorted by HEB beam size. Secondary timber beams on steel beams. The maximum design connection force according to Table 4-3 in comparison to the maximum needed bracing force, Fy.max, from the finite element analyses. The friction force capacity, Fmy, which was calculated as 0,25*F, where F was the ultimate load, was also included.*

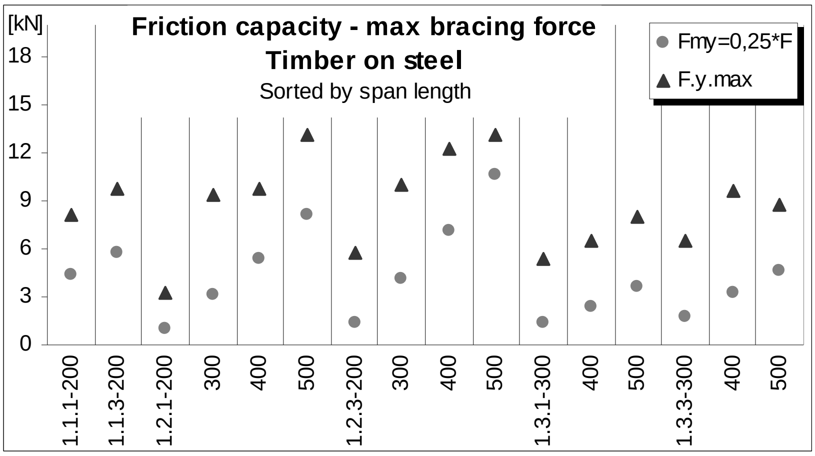


Figure 4-9 The graph shows the friction force capacity, Fmy, and the maximum needed bracing force, Fy.max, i.e. similar to Figure 4-8 but sorted by span length.

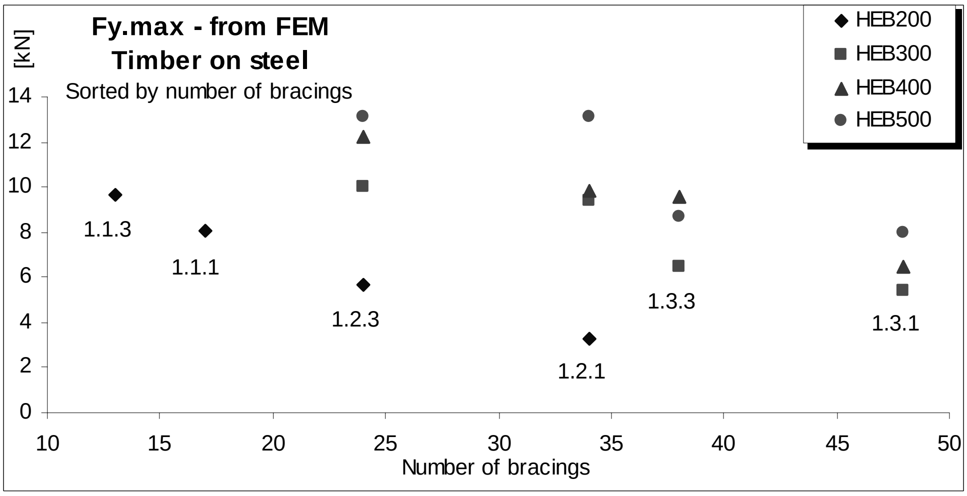


Figure 4-10 Secondary timber beams on steel beams. Maximum needed bracing force, Fy.max, from the finite element analysis for different HEB beam sizes. Sorted by number of bracing points along the beam.

In Figure 4-5 to Figure 4-7 the ratios between the friction force capacity and the maximum design connection force from the analytical calculations, both for Eurocode 3 and BSK 2007, were plotted in comparison to the ratios between the friction capacity and the maximum needed bracing force, from the finite element analysis. The structure configurations with secondary timber beams were treated. For ratios below 100% the friction force capacity was to low to work as a lateral bracing.

The BSK ratio was always higher than the Eurocode 3 ratio and that was of course because the maximum design connection force was higher according to Eurocode 3 than BSK, see Table 4-3. The FEM ratio was, in the case of timber on steel beams, higher than the ratios from the analytical calculations. It means that according to the finite element analysis the friction capacity was closer to the needed bracing force and/or the maximum needed bracing force was lower than the maximum design connection force from BSK and Eurocode 3. This was more clearly shown in Figure 4-8, where the maximum needed bracing force from the finite element analysis were plotted together with the maximum design connection force from BSK and Eurocode 3. Also the friction force capacity was plotted. In Figure 4-9 the friction capacity and maximum needed bracing force was plotted in a different scale and sorted by span length instead. In this graph it was easier to see the difference between the friction capacity and the maximum needed bracing force.

The maximum design connection force was a percentage of the maximum compressive force in the beam flange, and that force was of course higher the larger flange size, if the yield strength of the steel was kept constant, see Table 4-3. The Eurocode 3 maximum design connection force seems very conservative, when looking at Figure 4-8, but the BSK maximum design connection force seems more reasonable. Figure 4-2 showed that the needed bracing forces decreased closer to the ends of the beam. The Eurocode 3 and probably the BSK 2007 method, see equation (16) and equation (6), Section 2.3.2, take this effect into account by taking the variation of the stress in the compressed flange, which follows the moment distribution, into account. The design connection force will vary approximately like in Figure 4-2, with the maximum design connection force at mid-span of the beam.

Table 4-3 The maximum design connection forces according to equation (6) respective (16), Section 2.3.2.

HEB	**F_con.max** [kN] BSK	**F_con.max** [kN] EC3
200	8,25	20,6
300	15,7	39,2
400	26,4	49,5
500	38,5	57,8

One trend in Figure 4-5, which was sorted in the order span length, distance between bracings and HEB beam size, was that the ratio increases with increasing HEB beam size, within a structure configuration. In Figure 4-6, where the ratios were sorted in the order HEB beam size, span length and distance between bracings, the plot was more scattered but one tendency was that the ratio was, within each HEB beam size, higher for a shorter span length. It could also be interpreted that, for the same span length the ratio was higher for a larger beam size. Figure 4-7 presents the ratios sorted in the order distance between bracings, span length and HEB beam size. The trend that the ratio increased with beam size persisted.

When studying Figure 4-9 it seemed like the friction force capacity and the maximum needed bracing force followed each other. Increasing the beam size meant higher needed bracing force, but it also meant that the structure could carry a higher load, which increased the friction force capacity. If both the friction capacity and the needed bracing force increased, the ratio increased. That was because of the relative difference became smaller and it might be part of an explanation to why the ratios tended to increase for increasing HEB beam size. Another type of graph was shown in Figure 4-10, where the maximum needed bracing forces, from the finite element analysis, were plotted against the number of bracing points. In the graph it was clear, with some exceptions, that the more bracing points the lower needed bracing force, i.e. the total bracing force was spread over more points.

To sum up the trends found in the case of timber on steel beams, the HEB beam size seemed to be most important for the needed bracing force. The second most important factor seemed to be the number of bracing points. The following graphs visualise the results for the cases of secondary steel beams on steel beam, in a similar way as above. After those results have been described and analysed, a summary will follow.

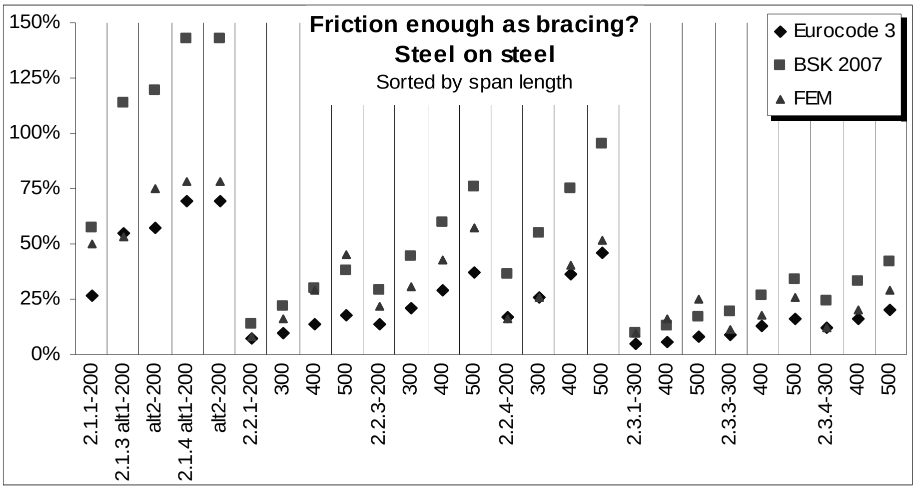


Figure 4-11 Sorted by span length. Secondary steel beams on steel beams. Ratio between the friction capacity and the maximum design connection force (Eurocode 3 and BSK 2007, $F_{\mu}/F_{con.\max}$) and the ratio between friction capacity and maximum needed bracing force (FEM, $F_{\mu}/F_{y.\max}$), see Table 4-2.

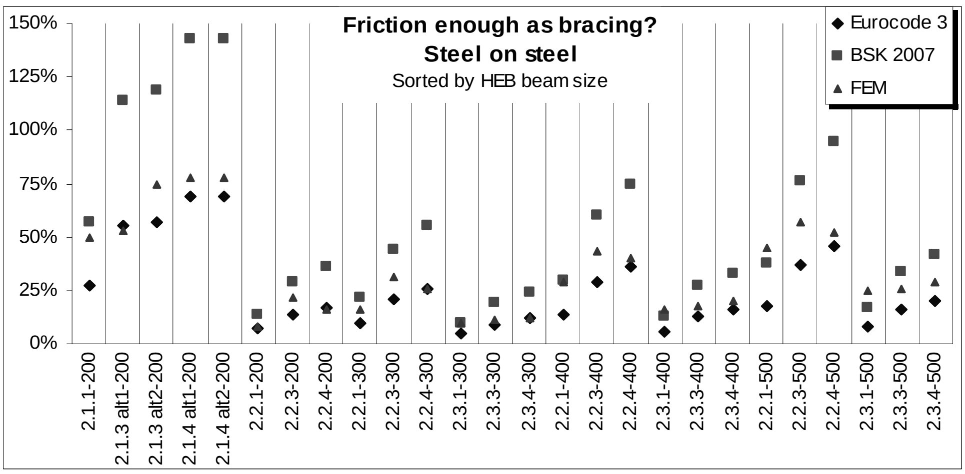


Figure 4-12 Sorted by HEB beam size. See Figure 4-11 for further explanation.

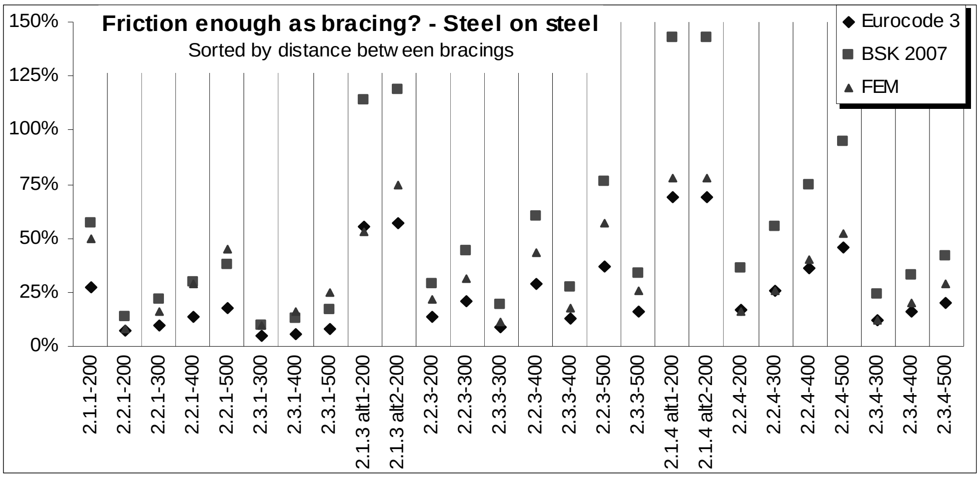


Figure 4-13 Sorted by distance between bracings. See Figure 4-11 for further explanation.

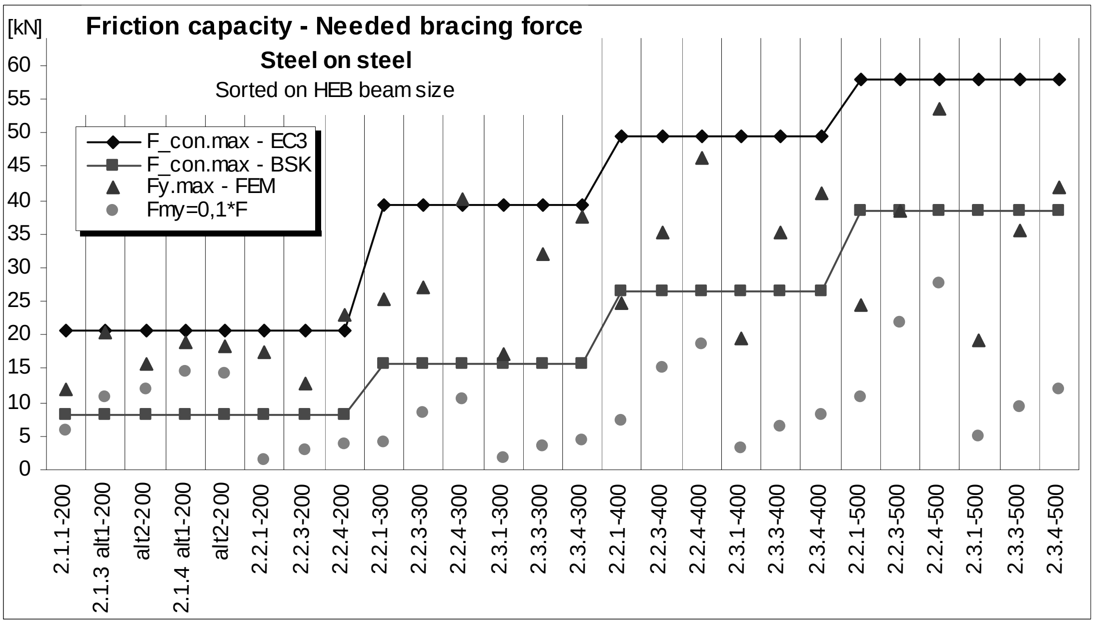


*Figure 4-14 Sorted by HEB beam size. Secondary steel beams on steel beams. The maximum design connection force according to Table 4-3 in comparison to the maximum needed bracing force, Fy.max, from the finite element analyses. The friction force capacity, Fmy, which was calculated as 0,1*F, where F was the ultimate load, is also included.*

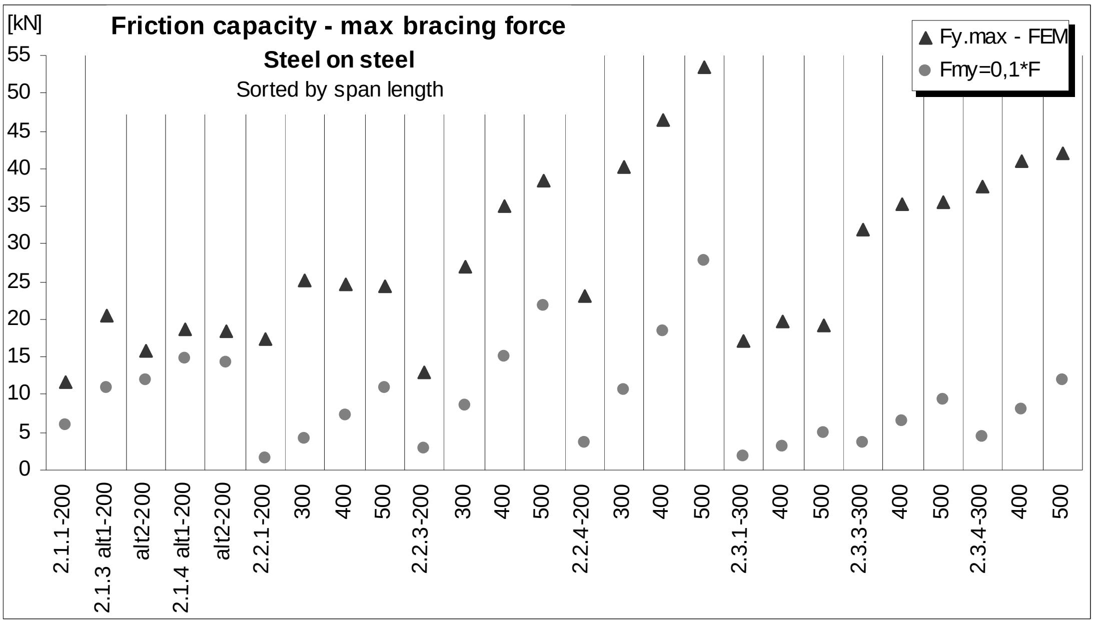


Figure 4-15 The graph shows the friction force capacity, Fmy, and the maximum needed bracing force, Fy.max, i.e. similar to Figure 4-14 but sorted by span length.

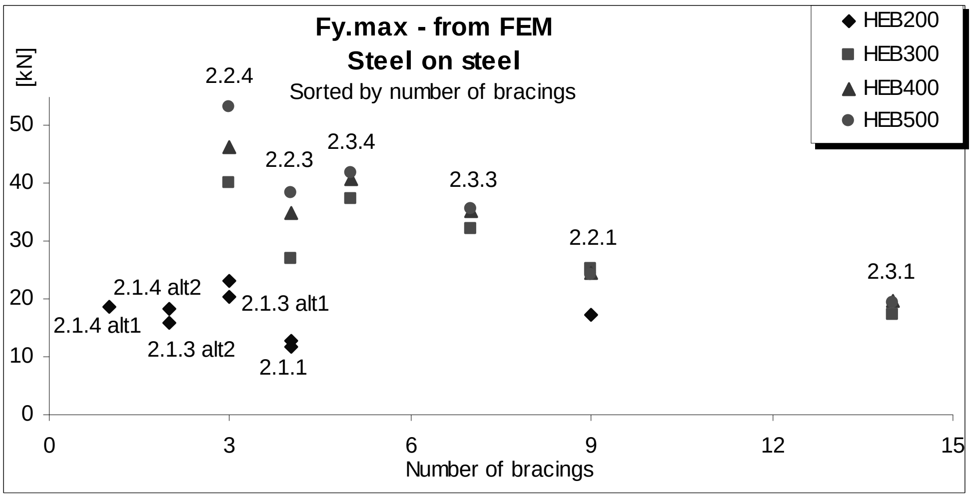


Figure 4-16 Secondary steel beams on steel beams. Maximum needed bracing force, Fy.max, from the finite element analysis for different HEB beam sizes. Sorted by number of bracing points along the beam.

In Figure 4-11 to Figure 4-13 the ratios between the friction force capacity and the maximum design connection force respective maximum needed bracing force were presented, for the structure configurations with secondary steel beams on steel beam. In contrast to the timber on steel beam case the ratios from the finite element analysis was not higher than the ratios connected to BSK and Eurocode 3, rather somewhere between BSK and Eurocode 3 ratios. Figure 4-14 shows the friction force capacity, the maximum needed bracing force from the finite element analyses and the maximum design connection force according to Eurocode 3 and BSK. In the case of timber on steel beam the BSK and Eurocode 3 maximum design connection forces seemed quite conservative, but in this case, steel on steel beam, the needed bracing force from the finite element analysis was much higher and the maximum design connection forces did not seem so conservative anymore. In a few cases the maximum needed bracing force was even higher than the maximum design connection force according to Eurocode 3. In Figure 4-15 the friction capacity and maximum needed bracing force was plotted in a different scale, and it was sorted by span length instead. In this graph it was easier to see the difference between the friction capacity and needed bracing force and Figure 4-15 and Figure 4-9 were quite alike.

In Figure 4-11 to Figure 4-13, where the ratios were plotted and sorted in different ways, the same trends could be found, as for the timber on steel beam case. For increasing HEB beam size the ratios increased and also a lower span length seemed to increase the ratio. The structure configurations 2.1.3 and 2.1.4 were special, because they only have one, two or three bracing points. In the analytical calculations, according to BSK 2007, the friction capacity was enough to prevent LTB, but according to both Eurocode 3 and the result from the finite element analysis the ratio was below 100%.

In Figure 4-15 it could be seen, like in the case of timber on steel beam, that the friction force capacity and the maximum needed bracing force followed each other and increasing the beam size meant higher needed bracing force and it also meant that the structure could carry a higher load, which increased the friction force capacity. If they both increase, the ratio between them increases, because of the decreased relative difference between them. Also the graph presented in Figure 4-16 showed similar trends as the equivalent timber on steel graph, more bracing points meant lower needed bracing force, although the results were a bit more scattered in this case.

The trends found in the case of secondary steel beams on steel beam were in most cases similar to the ones found in the case of timber on steel. An important difference was that for the case of secondary timber beams the maximum design connection force, according to Eurocode 3 and BSK 2007, seemed conservative but not for the steel on steel case. The BSK 2007 maximum design connection force was even lower than the needed bracing force according to the finite element analysis.

Both the cases, timber on steel and steel on steel, demonstrated that the standards Eurocode 3 and BSK 2007 did not agree fully with the finite element analysis results. The analytical calculations, according to EC3 and BSK, had the trend that the friction force capacity was closer to the maximum design connection force, i.e. higher ratio, when there were only a few bracing points along the beam. That was reasonable because with fewer bracing points, which also were the loading points, the concentrated load on each point was higher and hence the friction force capacity became higher. The friction capacity was compared to the maximum design connection force, which had the same value regardless the number of bracing points and thus the ratio increased with fewer bracing points. The finite element analysis showed the trend that the ratio between the friction force capacity and the maximum needed bracing force was lower with fewer bracing points. This was visualised in Figure 4-17, where both the ratios corresponding to Eurocode 3 and BSK increased when the number of bracing points decreased, but not the ratios corresponding to the finite element results.

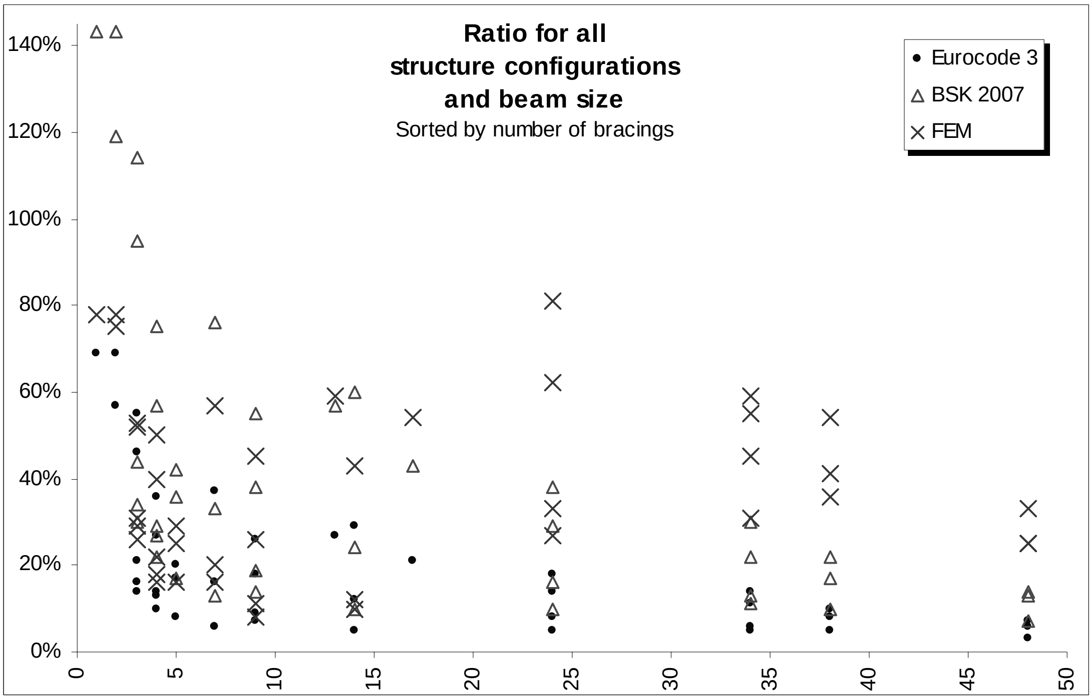


Figure 4-17 Ratio between the friction capacity and the maximum design connection force (Eurocode 3 and BSK 2007, $F_{\mu}/F_{con.\max}$) and the ratio between friction capacity and maximum needed bracing force (FEM, $F_{\mu}/F_{y.\max}$), see Table 4-2. Sorted by the number of bracing points along the beam.

4.3 Summary of the results

It was quite clear that the results showed that the friction force, between primary and secondary beams in these types of formwork, is not sufficient to be utilized as a rigid bracing against lateral-torsional buckling. In addition the results showed that the standards Eurocode 3 and BSK 2007 in some cases did not agree with the finite element results very well. In the case of secondary timber beams the maximum design connection force, according to Eurocode 3 and BSK 2007, seemed conservative but for the case of secondary steel beams they seemed more reasonable. The Swedish design code BSK maximum design connection force was even lower than the needed bracing force according to finite element analysis. The finite element analysis showed that the maximum needed bracing force appeared near mid-span and that the other bracing points were subjected to a much smaller load. In Eurocode 3 this phenomenon was taken into account by using the actual stress in the compressed flange, which follows the moment distribution, see equation (16) Section 2.3.2. Probably the BSK 2007 formulation shall be used the same way, with the actual compressed flange stress. For all of the structure configurations the trend was that for more bracing points the needed bracing force became smaller, according to the finite element results, see Figure 4-10 respective Figure 4-16. In BSK and Eurocode 3 this effect was not taken into account.

5 Discussion

If all the analysed beams were limited by the maximum deflection demand, was it really useful to perform all the analyses for loads much higher than the maximum deflection load?

The deflection demands can, because of several reasons, be changed so that the ultimate load-bearing capacity instead will be the limiting design load. The beam might be precambered to prevent a big deflection or there might be some wooden blocks put in between the beam layers.

In many of the graphs, like the one in Figure 4-2, from the finite element analysis results, see Appendix C and Appendix D, it could be seen that it was only at the midmost bracing points that the needed bracing forces exceeded the friction force capacity. How can that be interpreted? How much have the load-bearing capacity in fact increased, if some of the bracing points still hold?

It means that the midmost bracing points would slip, but there would still be some left, closer to the beam ends, that would withhold. The beam would probably hold for a load somewhere between the load corresponding to free lateral-torsional buckling and the load corresponding to a fully braced beam. How high that load would be could not be derived from the analyses performed in this Master's Thesis. To find that load some kind of friction joints must be used in the finite element analysis, which would take much longer time per analysis. The friction joints could take the static and kinetic friction into account and a more realistic load-bearing capacity could be found. Another method could be that after an analysis, like the kind of analyses performed in this Master's Thesis, all of the bracing points which exceeded the limiting friction capacity, were removed and a new analysis was started and so on in an iterative process.

The results from the finite element analyses showed that for more bracing points the needed bracing force became smaller. Why is this not taken into account in the standards?

The results showed that the Eurocode 3 design connection force was reasonable to use as a design connection force, because for some of the structure configurations and beam sizes the maximum needed bracing force was that high. It seems that the BSK 2007 design connection force was too low to use generally, at least according to Figure 4-14. The Eurocode 3, and probably also the BSK 2007, design connection force took into account that the needed bracing force was lower nearer the beam ends by using the actual compressed flange stress. Neither Eurocode 3 nor BSK 2007 took the number of bracing points into account. It would be good with some extra rules regarding the design connection forces.

Why was the friction coefficient reduced that much? Would not the friction coefficient in fact be much higher?

As described in Section 2.2 there are a lot of factors that influence the friction between two surfaces. It is complicated to estimate the friction coefficient and it depends on the surrounding conditions, which are hard to control. For example there might be some moisture between the beams and it may freeze, which means that the real friction coefficient will be that between for example timber and ice. There is a high uncertainty, which means that to use the friction in design there is need for a high safety margin. In this Master's Thesis the friction coefficient values used were taken from the standard SS-EN 12812:2008, see Table 2-2, minimum values. These values were then reduced by the partial factor $\gamma_{\mu}=2$. This partial factor should perhaps be higher or perhaps be lower, to give a reasonable safety margin. The purpose of using this factor was to show that the friction coefficient must be reduced to be used in design. The purpose of the Master's Thesis was to evaluate whether the friction was enough to prevent lateral-torsional buckling of a beam, and it was the value of the friction coefficient that was of importance, not how it was calculated.

If a higher friction coefficient could be assured how much higher must it be to prevent LTB?

The friction coefficients used in the calculations were for timber-steel connections $\mu = 0{,}5$ and for steel-steel connections $\mu = 0{,}2$. They were reduced by a partial factor to $\mu_d = 0{,}25$ respectively $\mu_d = 0{,}1$.

To answer this discussion point the needed friction coefficients were, in the analytical calculations, Appendix A, changed to fulfil the demands of the maximum design connection force, according to BSK 2007 and Eurocode 3. Only the structure configurations and beam sizes that fall into the reasonable load interval, see Section 4.1.1, were considered. For the structure configurations with secondary timber beams the design friction coefficient needed to fulfil the demands was $\mu_d = 7{,}25$. It means that before reduction with the partial factor $\gamma_{\mu} = 2$ the needed friction coefficient was $\mu = 14{,}5$. For the structure configurations with secondary steel beams the needed design friction coefficient was $\mu_d = 2{,}25$ and before reduction $\mu = 4{,}5$. These needed friction coefficients were several times higher than the friction coefficients prescribed in Table 2-2, and it indicates that according to the analytical calculations there is need for structural connections to prevent LTB, at least for many of the structure configurations and beam sizes.

In the results from the finite element analysis, Appendix C and Appendix D for secondary timber respectively secondary steel beams, the friction coefficient was changed to increase the friction force capacity. For the case of secondary timber beams the friction coefficient needs to be $\mu_d = 1{,}1$ and for the case of secondary steel beams the friction coefficient needs to be $\mu_d = 1$, to prevent LTB. For the finite element analysis the needed friction coefficient for the timber-steel case actually fell inside the interval given in Table 2-2, but keep in mind that the needed values above were design values. The unreduced friction coefficients need to be two times as high, to keep the safety margin.

These values of the needed friction coefficients were based on that every structure configuration and beam size must fulfil the demand, which was why the values were that high. Some structures did not need such high coefficients, but still they needed a higher friction coefficient than was used in the analyses performed in this Master's Thesis. In some cases it might be possible to assure a high enough friction coefficient, but careful controls must be made.

In the case of timber beams on steel beams, will not the contact pressure between the timber and the steel make the timber deform and create an edge, which would withhold the steel beam from LTB?

In some cases this would probably occur, but the effects from it can not be used in design because it can not be proved that the timber really would be deformed in such way. Perhaps some timber beams would resist much higher compressive stresses than others, regardless of the design compression stress capacity. In those cases there would not be an edge and no withholding effect.

If the tolerance for the steel manufacturing is lowered somehow, a smaller initial imperfection might be used in the finite element analyses. What changes if the initial imperfection is reduced?

A few additional finite element analyses were performed to try this variation of initial imperfection. HEB 200, 300, 400 and 500 were analysed for structure configuration 1.2.3, which had secondary timber beams with centre distance 0,4 meters and a 10 meters span length. The results were presented in graphs in Appendix F and the graphs were of the same type like the one shown in Figure 4-2. For each HEB beam size three graphs were presented and they corresponded to different sizes on the initial imperfection of the beam. As was explained in Section 3.2.4 according to Eurocode 3 the initial imperfection, in LUSAS called deformed mesh factor, was L/250. The first graph, on each page in Appendix F, corresponded to L/250, the middle graph corresponded to L/500 and the last L/2000.

As could be seen in Appendix F the ultimate load, used to calculate the friction force capacity, was approximately the same independent of the change in initial imperfection, but the needed bracing force decreased for a lower value of the initial imperfection. The middle graphs, L/500, showed that friction force capacity was enough to prevent lateral-torsional buckling for the beam sizes HEB 500 and almost for HEB 400. For L/2000 the friction capacity was enough for all of the HEB beam sizes. If the tolerances could be limited, so that the value L/2000 can be used as the initial imperfection, the friction capacity would be enough to prevent lateral-torsional buckling, at least for this specific structure configuration.

5.1 Conclusion

The questions and objectives of this Master's Thesis will be commented in this section.

What friction coefficients can be used for the connections between steel-steel and steel-timber respectively?

There are several sources for friction coefficients but the ones used in this Master's Thesis was, as discussed above, taken from the standard SS-EN 12812:2008, Swedish Standards Institute (2008c). In Table 2-2 the friction coefficients were listed for steel-steel surfaces and timber-steel surfaces respectively. The minimum values were of interest when it came to favourable effects, like stabilizing a beam from LTB.

What bracing force is needed to prevent lateral-torsional buckling and is the friction force large enough? Model the formwork with different materials, dimensions, loads, span lengths etc. and analyse the structural behaviour regarding lateral-torsional buckling.

The needed bracing force, or the design connection force, for bracing the upper flange of a beam, for the types of structure configurations and beams sizes treated in this Master's Thesis, was calculated with equation (6) respectively equation (16) according to *BSK 2007*, Boverket (2007), respectively *SS-EN 1993-1-1:2005, Eurocode 3*, Swedish Standards Institute (2008a), see Section 2.3.2. The values of the design connection forces are a percentage of the normal force in the upper flange. Eurocode 3, and probably BSK 2007, takes the variation of the stress in the compressed flange, due to the moment distribution, into account, which means that the design connection force depends on beam size and where, along the beam, the bracing point is put.

According to the finite element analyses the needed bracing force depended on beam cross-section size, span length, number of bracings and varied quite much along the beam. The maximum needed bracing force was found near mid-span of the beam and closer to the edges the needed bracing force was much lower. For the structure configurations with only a few bracing points the needed bracing force sometimes reached the same level as the maximum design connection force according to Eurocode 3. The number of bracing points was not considered in BSK 2007 and Eurocode 3, but the finite element results showed that the needed bracing force decreased with more bracing points.

The friction force, corresponding to the ultimate load, was calculated between the beam layers and compared to the needed bracing force. For the structure configurations and beam sizes chosen for their reasonable load-bearing capacity, the friction force capacity was not enough according to the finite element analysis. As discussed above there are favourable effects that were not taken into account in the analyses. These effects are, though, very uncertain and are not recommended to take into account. The friction between the beam layers will possibly have a favourable effect for the load-bearing capacity. The beam will not be free to LTB, but will have an ultimate load-bearing capacity somewhere between free LTB capacity and prevented LTB capacity. The analyses performed in this Master's Thesis cannot conclude the real load-bearing capacity of such a beam.

The conclusion is that the friction force capacity between beams, in the sort of structures treated in this Master's Thesis, is not enough to prevent the beam from lateral-torsional buckling. The possible favourable effects of the friction are hard to prove and use in design. Based on the results from the analyses performed in this Master's Thesis, it is not recommended to take the friction into account when designing for lateral-torsional buckling.

If the friction force can be sufficient to prevent lateral-torsional buckling the aim is to find a simple method to take it into account in design.

As described above the friction force capacity is not enough, but nevertheless, the method used in the analytical calculations, Appendix A, is simple and fast to perform. The friction force capacity is found by multiplying the concentrated load, from the secondary layer, with the friction coefficient. The friction force capacity can be compared to the design connection force and instantly the comparison shows if or if not the friction force capacity is enough.

5.2 Future research

This Master's Thesis concludes that the friction force capacity is not enough, but leaves some questions that are suggested for future research in this matter. In this Master's Thesis quantitative analyses have been performed and many different structure configurations and beam sizes have been analysed. To find the answer to the question: *How much has the capacity been increased?* a few structure configurations must be analysed more qualitative. For example analyses with friction joints between the beam layers might give better results, but will take longer time. Analyses regarding the difference between different initial imperfections, and how that affects the needed bracing force, are also a more qualitative form of analysis. This type of analysis was made for one structure configuration, as discussed above, but more analyses must be performed. Another issue is the reduction of the friction coefficients. In this Master's Thesis a partial factor was used, to show that the friction coefficient must be reduced. But it was not evaluated how much the friction coefficients must be reduced to give a reasonable safety margin. It is also suggested that some full-scale lab tests are performed, to compare with the finite element results.

6 References

Al-Emrani, M., Engström, B., Johansson, M. & Johansson, P. (2007): *Bärande konstruktioner*. Course literature. (Load-bearing structures. In Swedish.) Avdelningen för konstruktionsteknik, Chalmers tekniska högskola, Publication no. 2007:17, Göteborg

Atack, D. & Tabor, D. (1958): The Friction of Wood. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences,* Vol. 246, No. 1247, 1958, pp. 539-555.

Bejo, L., Lang, E. M. & Fodor, T. (2000): Friction coefficients of wood-based structural composites. *Forest Products Journal,* Vol. 50, No. 3, 2000, pp. 39-43.

Blau, P. J. (2001): The significance and use of the friction coefficient. *Tribology International,* Vol. 34, No. 9, 2001, pp. 585-591.

Bowden, F. P. (1952): Introduction to the Discussion: The Mechanism of Friction. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences,* Vol. 212, No. 1111, 1952, pp. 440-449.

Bowden, F. P. & Tabor, D. (1950): *The Friction and Lubrication of Soldis,* Oxford University Press, Oxford

Boverket (2004): *Boverkets handbok om betongkonstruktioner.* (Boverket's handbook of concrete structures. In Swedish), Boverket, Karlskrona

Boverket (2007): *Boverkets handbok om stålkonstruktioner.* (Boverket's handbook of steel structures. In Swedish), Boverket, Karlskrona

Boverket (2010): *Regelsamling för konstruktion, BKR 2010.* (Set of rules for construction. In Swedish), Boverket, Karlskrona

Gerde, E. & Marder, M. (2001): Friction and fracture. *Nature,* Vol. 413, No. 6853, 2001, pp. 285-288.

Gorst, N. J. S., J., W. S., Pallett, P. F. & Clark, L. A. (2003): *Friction in temporary works*. Research report. Shool of Engineering, The University of Birmingham, Health and Safety Executive, Publication no. 071, Birmingham

Guan, N., Thunell, B. & Lyth, K. (1983): On the friction between steel and some common swedish wood species. *European Journal of Wood and Wood Products,* Vol. 41, No. 2, 1983, pp. 55-60.

Hadipriono, F. C. & Wang, H.-K. (1986): Analysis of Causes of Falsework Failures in Concrete Structures. *Journal of Construction Engineering and Management,* Vol. 112, No. 1, 1986, pp. 112-121.

Hjelmstad, K. D. (2005): *Fundamentals of Structural Mechanics,* University of Illinois, Urbana-Champaign, Illinois

Höglund, T. (1994): *Dimensionering av stålkonstruktioner - Utdrag ur Handboken Bygg Kapitel 18 och 19,* C E Fritzes AB, Stockholm

Krim, J. & Family, F. (2000): Origin of friction. *AccessScience*, McGraw-Hill Companies

Lui, E. M. (2008): Structural stability. *AccessScience*, McGraw-Hill Companies

Lusas (2010a): *Application Examples Manual (Bridge, Civil & Structural),* LUSAS, Kingston Upon Thames, London, pp. 249-265

Lusas (2010b): *Customer support note - Buckling Analysis,* LUSAS, Kingston Upon Thames, London

Lusas (2010c): *Element Reference Manual,* LUSAS, Kingston Upon Thames, London, pp. 291-298

Lusas (2010d): *Modeller Reference Manual,* LUSAS, Kingston Upon Thames, London, pp. 50-51, 291-303

Lusas (2010e): *Module ADV-N1 Introduction to Nonlinear analysis,* LUSAS, Kingston Upon Thames, London

Lusas (2010f): *Module ADV-N2 Nonlinear Solution Procedures & Control,* LUSAS, Kingston Upon Thames, London

Mckenzie, W. M. & Karpovich, H. (1968): The frictional behaviour of wood. *Wood Science and Technology,* Vol. 2, No. 2, 1968, pp. 139-152.

Mo, Y., Turner, K. T. & Szlufarska, I. (2009): Friction laws at the nanoscale. *Nature,* Vol. 457, No. 7233, 2009, pp. 1116-1119.

Nguyen, C. T., Moon, J., Le, V. N. & Lee, H.-E. (2010): Lateral-torsional buckling of I-girders with discrete torsional bracings. *Journal of Constructional Steel Research,* Vol. 66, No. 2, 2010, pp. 170-177.

Nilsson, M., Jorborg, N., Löfling, P. & Farkas, I. (1985): *Handbok i formbyggnad : för anläggnings- och husbyggnadsarbeten,* (Handbook of formwork construction. In Swedish), Byggförbundet, Stockholm

Nolle, H. & Richardson, R. S. H. (1974): Static friction coefficients for mechanical and structural joints. *Wear,* Vol. 28, No. 1, 1974, pp. 1-13.

Pallett, P., Gorst, N., Clark, L. & Thomas, D. (2002): Friction resistance in temporary works materials. *Concrete,* Vol. 36, No. 6, 2002, pp. 12-15.

Pallett, P. F. (2003): Formwork and falsework. *Advanced Concrete Technology Set,* 2003, pp. 3-27.

Rabinowicz, E. (2008): Friction. *AccessScience*, McGraw-Hill Companies

Ratay, R. T. (2008): Temporary structure. *AccessScience,* McGraw-Hill Companies

Rebelo, C., Lopes, N., Simões Da Silva, L., Nethercot, D. & Vila Real, P. M. M. (2009): Statistical evaluation of the lateral-torsional buckling resistance of steel I-beams, Part 1: Variability of the Eurocode 3 resistance model. *Journal of Constructional Steel Research,* Vol. 65, No. 4, 2009, pp. 818-831.

Rmd Kwikform News (2010): *Twin success for RMD Kwikform Iberica.* [Electronic]. Edson Evers PR, Stafford, United Kingdom. Availible: http://www.rmdkwikformnews.co.uk/topics/country/spain/ [2011-01-26]

Scalzi, J. B. (2008): Loads, transverse. *AccessScience,* McGraw-Hill Companies

Statens Stålbyggnadskommitté (1970): *Stålbyggnadsnorm 70,* (Code for Steel Structures 70. In Swedish), AB Svensk Byggtjänst, Stockholm

Statens Stålbyggnadskommitté (1973): *StBK-K2 Knäckning, vippning och buckling,* (Buckling, lateral-torsional buckling and local buckling. In Swedish), AB Svensk Byggtjänst, Stockholm

Surdahl, R., Miller, D. & Glenn, V. (2010): *The Positive Legacy of a Bridge Collapse.* [Electronic]. United States Department of Transportation, Washington, USA. Availible: http://www.fhwa.dot.gov/publications/publicroads/10mar/04.cfm [2011-01-26]

Swedish Standards Institute (2005): *SS-EN 12811-1:2004 Part I: Scaffolds - Performance requirements and general design.* SIS Förlag AB, Stockholm

Swedish Standards Institute (2008a): *SS-EN 1993-1-1:2005, Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for buildings.* SIS Förlag AB, Stockholm

Swedish Standards Institute (2008b): *SS-EN 12811-2:2004 Part II: Information on materials.* SIS Förlag AB, Stockholm

Swedish Standards Institute (2008c): *SS-EN 12812:2008, Falsework - Performance requirements and general design.* SIS Förlag AB, Stockholm

Svensson, B. A., Nyström, S., Gradin, P. A. & Höglund, H. (2009): Frictional testing of wood--Initial studies with a new device. *Tribology International*, Vol. 42, No. 1, 2009, pp. 190-196.

Szeri, A. Z. (2008): Tribology. *AccessScience*, McGraw-Hill Companies

The Steel Construction Institute (2005): *Elastic critical moment for lateral torsional buckling*, SCI, Berkshire

Tibnor Ab (2006): *Handelsstål - Sortiment, toleranser och produktion.* [Electronic]. Tibnor AB, Solna. Availible: http://www.tibnor.se/web/Handelsstal_1.aspx [2010-09-30]

Vägverket (2004): *Vägverkets allmänna tekniska beskrivning för nybyggande och förbättring av broar. Bro 2004.* (Vägverket's general technical description for construction and improvement of bridges. In Swedish), Svensk Byggtjänst, Stockholm

Appendix A Analytical Calculations of Different Structure Configurations

This Appendix includes the explaining MathCAD document and the excel document that contains the analytical calculations of all the different structure configurations and beam sizes.

First read through the MathCAD document to understand the formulations used in excel. In excel the formulations are hidden and only the input data and the answers appear.

In the excel document principally the same calculation repeats with different input data for the different structure configurations.

Analytical calculations of different structure configurations

Input data

For description of the notations, see Excel

<u>BSK 2007:</u>

$$f_{yd} = \frac{f_{yk}}{\gamma_n \cdot \gamma_m}$$

$$\mu_d = \frac{\mu}{\gamma_n \cdot \gamma_\mu}$$

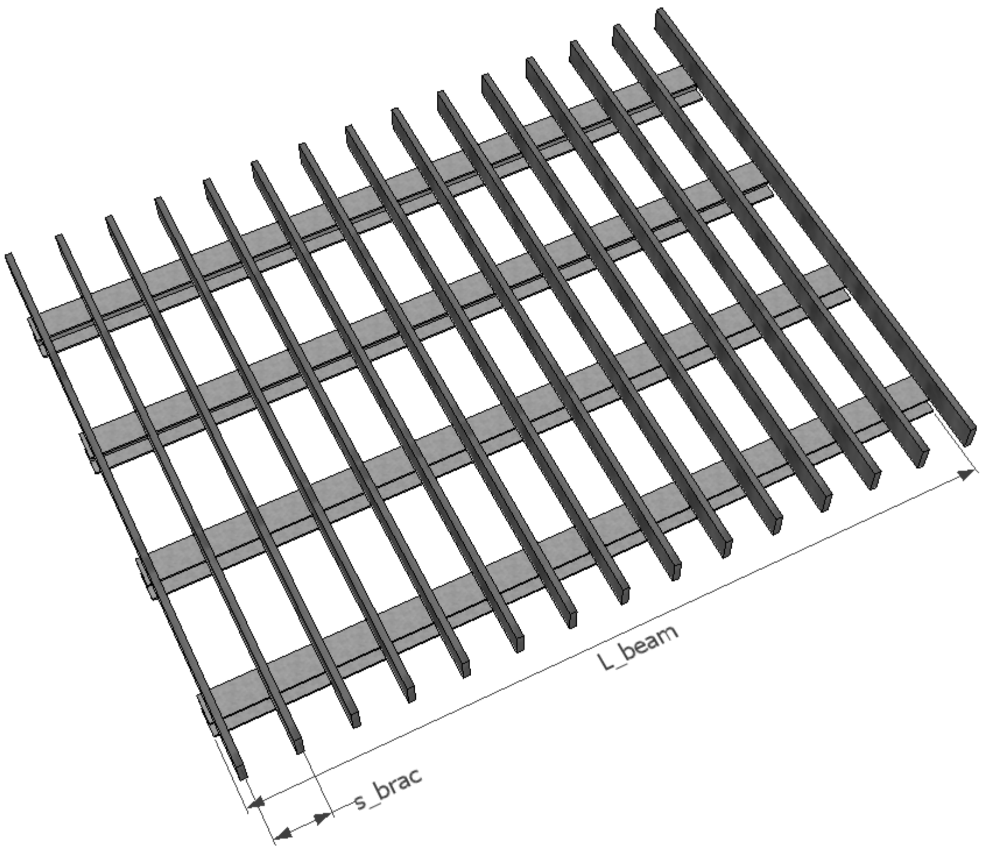
<u>Eurocode 3:</u>

$$f_{yd} = \frac{f_{yk}}{\gamma_m}$$

In Eurocode there is no safety parameter but the safety is put in the load factors instead

$$\mu_d = \frac{\mu}{\gamma_\mu}$$

The other input data can be found in the excel document, and is partly dependant on the structure configurations. There is also an explanation of the numbering of structure configurations.



a) Beam analysis - take no bracings into account - free LTB

$$M_{cr} = C_1 \cdot \frac{\pi^2 \cdot E \cdot I_y}{L^2} \left[\sqrt{\frac{I_w}{I_y} + \frac{L^2 \cdot G \cdot I_t}{\pi^2 \cdot E \cdot I_y} + \left(C_2 \cdot z_g\right)^2} - C_2 \cdot z_g \right]$$ (NCCI, SN003a-EN-EU)

C_1	C_2						
1,127	0,454	for evenly distributed load and simply supported ends					
1,348	0,63	for midspan point load and simply supported ends					

The software LTBeam is used for other load cases

$$\lambda = \sqrt{\frac{W_{pl} \cdot f_{yk}}{M_{cr}}}$$ slenderness factor $\lambda = \lambda_b = \lambda_{LT}$

<u>BSK 2007:</u>

$$M_{Rd} = \omega_b \cdot \eta_c \cdot W_c \cdot f_{yd} = \omega_b \cdot Z_x \cdot f_{yd}$$

η_c - form factor for bending

$$\eta_c = \frac{Z_x}{W_x}$$ Section class 1 for hot-rolled sections with $f_{yk} \leq 275$ MPa, according to BSK 07, 6:211

Z_x - plastic bending resistance (W_{pl})

W_c - elastic bending resistance (W_x)

$$\omega_b = \frac{1.02}{\sqrt{1 + \lambda_b^{\ 4}}} \leq 1$$

<u>Eurocode 3:</u>

$$M_{Rd} = \chi_{LT} \cdot W_{pl} \cdot f_{yd}$$

$$\chi_{LT} = \frac{1}{\Phi_{LT} + \sqrt{\Phi_{LT}^{\ 2} - \beta \cdot \lambda_{LT}^{\ 2}}} \leq \begin{pmatrix} 1.0 \\ \dfrac{1}{\lambda_{LT}^{\ 2}} \end{pmatrix}$$

$$\Phi_{LT} = 0.5\left[1 + \alpha_{LT} \cdot \left(\lambda_{LT} - \lambda_{LT.0}\right) + \beta \cdot \lambda_{LT}^{\ 2}\right]$$

$\alpha_{LT} := 0.34$ buckling curve b for hot-rolled I-section with $h/b \leq 2$

$\lambda_{LT.0} := 0.4$ $\beta := 0.75$ National values, Sweden

Put $M_{Ed} = M_{Rd}$ and solve for q_d (in some cases point loads, P_d, is calculated)

- Distributed load: $$q_d = \frac{8 \cdot M_{Rd}}{L_{beam}^{\ 2}}$$
- One point load: $$P_d = \frac{4 \cdot M_{Rd}}{L_{beam}}$$
- Two point loads: $$P_d = \frac{2 \cdot M_{Rd}}{L_{beam} - s_{brac}}$$

b) Beam analysis - take friction into account as bracing force - prevented LTB

BSK 2007:

$$M_{Rd} = \omega_b \cdot Z_x \cdot f_{yd}$$

$\omega_b := 1$ the beam is assumed to be fully braced

Put M_{Ed} = M_{Rd} and solve for q_d (in some cases point loads, P_d, is calculated)

- Distributed load
- One point load
- Two point loads

$$q_d = \frac{8 \cdot M_{Rd}}{L_{beam}^2} \qquad P_d = \frac{4 \cdot M_{Rd}}{L_{beam}} \qquad P_d = \frac{2 \cdot M_{Rd}}{L_{beam} - s_{brac}}$$

Load from one secondary beam and corresponding friction force

$$Q_{brac} = q_d \cdot s_{brac} \qquad F_\mu = \mu_d \cdot Q_{brac}$$

Maximum design connection force according to BSK 2007

$$F_{con.max} = 0.01 \cdot A_f \cdot f_{yd}$$

May full bracing be assumed?

$$\frac{s_{brac}}{b} \le \left[0.6 - 0.2 \cdot \frac{M_2}{M_1} - 0.1 \cdot \left(\frac{M_2}{M_1}\right)^2\right] \cdot \sqrt{\frac{E_k}{f_{yk}}}$$

This test assumes that the bracing points are fully connected!

(In Excel, left side and right side)

Moment distribution for simply supported beam with evenly distributed load

$$M(x) = \frac{q_d \cdot L_{beam} \cdot x}{2} - \frac{q_d \cdot x^2}{2}$$

Example:

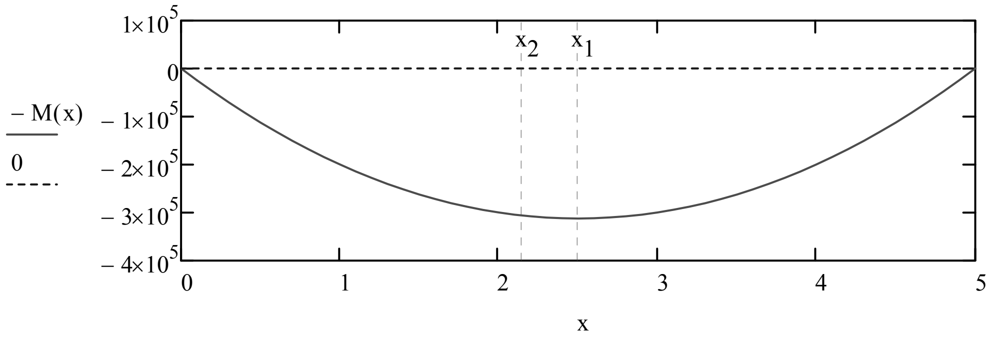
$L_{beam} := 5m$ $\quad x := 0m, 0.1m .. L_{beam}$ $\quad s_{brac} := 0.35m$

$q_d := 100 \frac{kN}{m}$ $\quad M(x) := \frac{q_d \cdot L_{beam} \cdot x}{2} - \frac{q_d \cdot x^2}{2}$

$E_k := 210GPa$ $\quad f_{yk} := 275MPa$ $\quad b := 300mm$

$x_1 := \frac{L_{beam}}{2} = 2.5\,m$ $\quad M_1 := M(x_1) = 312.5 \cdot kN \cdot m$

$x_2 := \frac{L_{beam}}{2} - s_{brac} = 2.15\,m$ $\quad M_2 := M(x_2) = 306.375 \cdot kN \cdot m$



$$test := \begin{cases} 0 & \text{if } \dfrac{s_{brac}}{b} > \left[0.6 - 0.2\cdot\dfrac{M_2}{M_1} - 0.1\cdot\left(\dfrac{M_2}{M_1}\right)^2\right]\cdot\sqrt{\dfrac{E_k}{f_{yk}}} \\ 1 & \text{if } \dfrac{s_{brac}}{b} \le \left[0.6 - 0.2\cdot\dfrac{M_2}{M_1} - 0.1\cdot\left(\dfrac{M_2}{M_1}\right)^2\right]\cdot\sqrt{\dfrac{E_k}{f_{yk}}} \end{cases} = 1$$

if 1 the beam is fully braced

Eurocode 3:

$$M_{Rd} = \chi_{LT}\cdot W_{pl}\cdot f_{yd}$$

$\chi_{LT} := 1$ the beam is assumed to be fully braced

Put $M_{Ed} = M_{Rd}$ and solve for q_d (in some cases point loads, P_d, is calculated)

- Distributed load

$$q_d = \frac{8\cdot M_{Rd}}{L_{beam}^2}$$

- One point load

$$P_d = \frac{4\cdot M_{Rd}}{L_{beam}}$$

- Two point loads

$$P_d = \frac{2\cdot M_{Rd}}{L_{beam} - s_{brac}}$$

Load from one secondary beam and corresponding friction force

$$Q_{brac} = q_d\cdot s_{brac} \qquad F_\mu = \mu_d\cdot Q_{brac}$$

Design connection force according to Eurocode 3

$$F_{con} = 0.025\cdot N_{f.Ed}$$

$$F_{con.max} = 0.025\cdot A_f\cdot f_{yd}$$

Valid for connections at, or near, a point where the yielding stress is reached, i.e. near mid-span for a simply supported beam.

May full bracing be assumed?

$\lambda \le \lambda_{LT.0}$ or $\dfrac{M_{Ed}}{M_{cr}} \le \lambda_{LT.0}^2$

For the cases of assuming distributed load the bracing are assumed to be distributed too, which gives very high M_{cr}. It means that full bracing can be assumed.

c) Beam analysis - deformation limit

$$d = \frac{5 \cdot q_d \cdot L^4}{384 \cdot E \cdot I}$$ distributed load

$$d_{mid} = \frac{P_d \cdot L^3}{48E \cdot I}$$ one point load

$$d_{mid} = 2 \cdot \frac{P_d \cdot b \cdot \left(3 \cdot L^2 - 4 \cdot b^2\right)}{48 \cdot E \cdot I}$$ two point loads (b = distance from load to nearest support)

Maximum deflection, d_{max}, is often limited by either 50 mm or $L_{beam}/300$

This gives a maximum load q_d resp. P_d due to deflection limitation.

The deflection corresponding to the loads from part a) and b) is calculated and compared to the maximum deflection.

If 'not OK' the maximum load is limited by the deflection

If 'OK' the maximum load is either the load from a) or, if the friction force is enough to prevent LTB, the load from b).

d) Beam analysis - The maximum load

The maximum load $q_{d.max}$ resp. P_{d_max} for Structure x.x.x is taken from either a), b) or c).

Analytical calculations of different structure configurations

Structure numbering

Variable	Number	Explanation
Material	1.x.x	timber beam on steel beam
	2.x.x	steel beam on steel beam

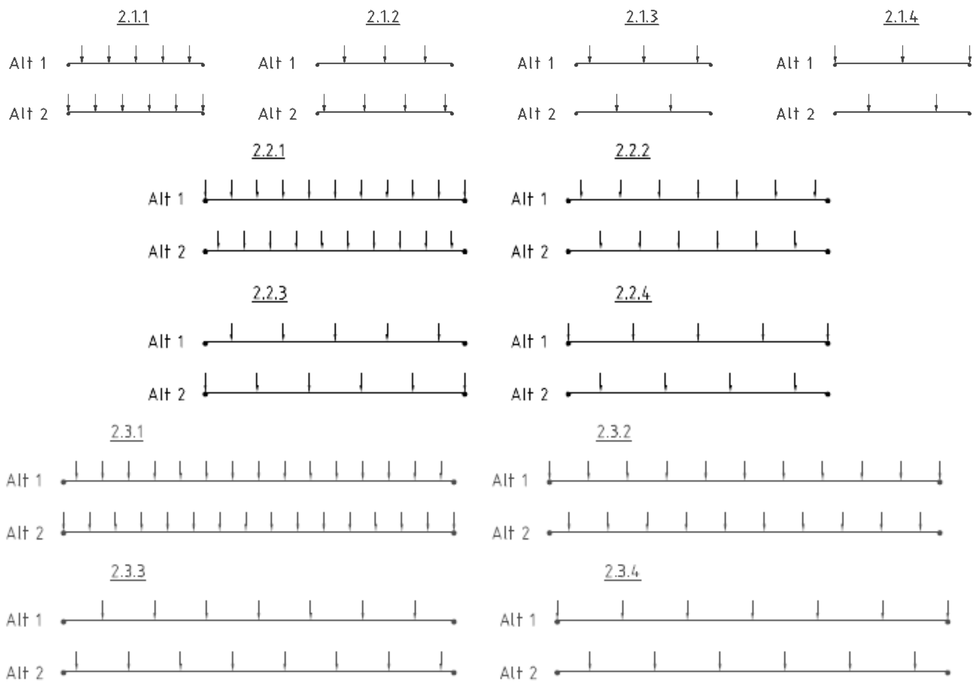
Span	x.1.x	span length 5 m
	x.2.x	span length 10 m
	x.3.x	span length 15 m

Distance between bracing	1.x.1	distance between timber wailings/bracing points 0,3 m
	1.x.2	distance between timber wailings/bracing points 0,35 m
	1.x.3	distance between timber wailings/bracing points 0,4 m

Distance between bracing	2.x.1	distance between secondary steel beams/bracing points 1 m
	2.x.2	distance between secondary steel beams/bracing points 1,5 m
	2.x.3	distance between secondary steel beams/bracing points 2 m
	2.x.4	distance between secondary steel beams/bracing points 2,5 m

Analytical calculations
Front page

Below the Structures starting with 2.x.x, i.e. steel on steel, is shown. The loads can be treated like distributed loads in most of the cases but sometimes they must be treated as point loads.

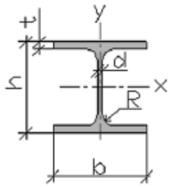


Structure number 1.1.1

Timber beam on steel beam, span length 5 m, centre distance bracings 0,3 m

Input data

gamma_n	1,2		partial factor with regard to safety class (Safety class 3), only BSK 2007
gamma_m	1		partial factor with regard to uncertainties in determining resistance
gamma_my	2		partial factor with regard to friction
f_yk	275	[MPa]	characteristic yield stress
f_yd	229	[MPa]	design yield stress, only BSK 2007
E_k	210	[GPa]	Young modulus
G_k	80,77	[Gpa]	shear modulus
my	0,5		friction coefficient between steel and timber
my_db	0,21		BSK 2007, design friction coefficient between steel and timber
my_de	0,25		Eurocode 3, design friction coefficient between steel and timber
L_beam	5	[m]	beam span length
s_brac	0,3	[m]	distance between timber wailings/bracing points



HEB **h** [mm]	**b** [mm]	**t_flange** [mm]	**I_x** [10^6x mm^4]	**Z_x** [10^3x mm^3]	**W_x** [10^3x mm^3]	**I_y** [10^6x mm^4]	**I_t** [10^6 x mm^4]	**I_w** [10^9 x mm^6]
200	200	15	56,96	643	570	20,03	0,595	171
300	300	19	251,7	1870	1680	85,63	1,86	1690
400	300	24	576,8	3230	2880	108,2	3,57	3820
500	300	28	1072	4810	4290	126,2	5,4	7020

I_x, I_y	moment of inertia
W_x, Z_x	elastic and plastic bending restistance
I_t	S:t Venants torsion constant
I_w	warping constant

Structure number 1.1.1

a) Beam analysis - take no bracings into account - free LTB

						BSK 2007		
HEB	**z_g** [mm]	**C_1**	**C_2**	**M_cr** [kNm]	**lambda**	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]
200	100	1,127	0,454	287	0,78	0,87	128,0	41,0
300	150	1,127	0,454	1162	0,67	0,93	399,7	127,9
400	200	1,127	0,454	1863	0,69	0,92	681,5	218,1
500	250	1,127	0,454	2576	0,72	0,91	1000,2	320,1

		Eurocode 3: Design of steel structures - Part 1-1					
HEB	**lambda_0**	**beta**	**alfa_LT**	**phei_LT**	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]
200	0,4	0,75	0,34	0,80	0,83	146,0	46,7
300	0,4	0,75	0,34	0,71	0,89	456,0	145,9
400	0,4	0,75	0,34	0,73	0,87	776,7	248,5
500	0,4	0,75	0,34	0,75	0,86	1139,3	364,6

M_cr	elastic critical moment with regard to LTB
lambda	slenderness factor regarding LTB
w_b	reduction factor regarding LTB
z_g	the distance between the shear centre and the load application point
C_1, C_2	coefficients depending on the loading and support conditions
lamda_0	value of the plateau length for buckling curves of hot-rolled sections
beta	correction factor for buckling curves of hot-rolled sections
alfa_LT	imperfection factor
phei_LT	help factor
chei_LT	reduction factor regarding LTB

Structure number 1.1.1

b) Beam analysis - take friction into account as bracing force - prevented LTB

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	47,2	14,1	2,9	6,9	43%	not OK
300	1	428,5	137,1	41,1	8,6	13,1	66%	not OK
400	1	740,2	236,9	71,1	14,8	16,5	90%	not OK
500	1	1102,3	352,7	105,8	22,0	19,3	115%	OK

May full bracing be assumed?

x_1 2,5 [m] M_1 highest bending moment in the observed beam section
x_2 2,2 [m] M_2 bending moment in the opposite end of the observed beam section

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	147,4	145,2	1,5	8,4	OK
300	428,5	422,4	1,0	8,4	OK
400	740,2	729,5	1,0	8,4	OK
500	1102,3	1086,4	1,0	8,4	OK

Q_brac concentrated load from one beam
F_my friction force capacity
F_con.max design connection force BSK for connection near mid-span
F_con.max design connection force Eurocode 3 for connection near mid-span

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	56,6	17,0	4,2	20,6	21%	not OK
300	1	514,3	164,6	49,4	12,3	39,2	31%	not OK
400	1	888,3	284,2	85,3	21,3	49,5	43%	not OK
500	1	1322,8	423,3	127,0	31,7	57,8	55%	not OK

Full bracing can be assumed, see description in Mathcad

Structure number 1.1.1

c) Beam analysis - deformation limit

$$d\_max = \min \begin{cases} L/300 = 16,7 \\ 50,0 \end{cases} = 16,7 \text{ [mm]}$$

d deflection
d_max maximum deflection

With regard to maximum deflection

HEB	**q_d** [kN/m]
200	24,5
300	108,3
400	248,1
500	461,0

- If 'not OK' the maximum load is limited by the deflection

- If 'OK' the maximum load is either the load from a) or, if the demands in b) are fullfilled, the load from b).

From a) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	41,0	27,9	167%	not OK
300	127,9	19,7	118%	not OK
400	218,1	14,7	88%	OK
500	320,1	11,6	69%	OK

From a) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	46,7	31,8	191%	not OK
300	145,9	22,5	135%	not OK
400	248,5	16,7	100%	not OK
500	364,6	13,2	79%	OK

From b) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	47,2	32,1	192%	not OK
300	137,1	21,1	127%	not OK
400	236,9	15,9	95%	OK
500	352,7	12,8	77%	OK

From b) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	56,6	38,5	231%	not OK
300	164,6	25,3	152%	not OK
400	284,2	19,1	115%	not OK
500	423,3	15,3	92%	OK

Structure number 1.1.1

d) Beam analysis - The design load

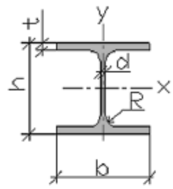
BSK 2007		
HEB	**q_d max** [kN/m]	**Limited by**
200	24,5	c) Deflection
300	108,3	c) Deflection
400	218,1	a) Free LTB
500	352,7	b) Prevented LTB

Eurocode 3: Design of steel structures - Part 1-1		
HEB	**q_d max** [kN/m]	**Limited by**
200	24,5	c) Deflection
300	108,3	c) Deflection
400	248,1	c) Deflection
500	364,6	a) Free LTB

Structure number 1.1.2
Timber beam on steel beam, span length 5 m, centre distance bracings 0,35 m

Input data

gamma_n	1,2		partial factor with regard to safety class (Safety class 3), only BSK 2007
gamma_m	1		partial factor with regard to uncertainties in determining resistance
gamma_my	2		partial factor with regard to friction
f_yk	275	[MPa]	characteristic yield stress
f_yd	229	[MPa]	design yield stress, only BSK 2007
E_k	210	[GPa]	Young modulus
G_k	80,77	[Gpa]	shear modulus
my	0,5		friction coefficient between steel and timber
my_db	0,21		BSK 2007, design friction coefficient between steel and timber
my_de	0,25		Eurocode 3, design friction coefficient between steel and timber
L_beam	5	[m]	beam span length
s_brac	0,35	[m]	distance between timber wailings/bracing points



HEB **h** [mm]	**b** [mm]	**t_flange** [mm]	**I_x** [10^6x mm^4]	**Z_x** [10^3x mm^3]	**W_x** [10^3x mm^3]	**I_y** [10^6x mm^4]	**I_t** [10^6 x mm^4]	**I_w** [10^9 x mm^6]
200	200	15	56,96	643	570	20,03	0,595	171
300	300	19	251,7	1870	1680	85,63	1,86	1690
400	300	24	576,8	3230	2880	108,2	3,57	3820
500	300	28	1072	4810	4290	126,2	5,4	7020

I_x, I_y	moment of inertia
W_x, Z_x	elastic and plastic bending restistance
I_t	S:t Venants torsion constant
I_w	warping constant

Structure number 1.1.2

a) Beam analysis - take no bracings into account - free LTB

						BSK 2007		
HEB	**z_g** [mm]	**C_1**	**C_2**	**M_cr** [kNm]	**lambda**	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]
200	100	1,127	0,454	287	0,78	0,87	128,0	41,0
300	150	1,127	0,454	1162	0,67	0,93	399,7	127,9
400	200	1,127	0,454	1863	0,69	0,92	681,5	218,1
500	250	1,127	0,454	2576	0,72	0,91	1000,2	320,1

	Eurocode 3: Design of steel structures - Part 1-1						
HEB	**lambda_0**	**beta**	**alfa_LT**	**phei_LT**	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]
200	0,4	0,75	0,34	0,80	0,83	146,0	46,7
300	0,4	0,75	0,34	0,71	0,89	456,0	145,9
400	0,4	0,75	0,34	0,73	0,87	776,7	248,5
500	0,4	0,75	0,34	0,75	0,86	1139,3	364,6

M_cr	elastic critical moment with regard to LTB
lambda	slenderness factor regarding LTB
w_b	reduction factor regarding LTB
z_g	the distance between the shear centre and the load application point
C_1, C_2	coefficients depending on the loading and support conditions
lamda_0	value of the plateau length for buckling curves of hot-rolled sections
beta	correction factor for buckling curves of hot-rolled sections
alfa_LT	imperfection factor
phei_LT	help factor
chei_LT	reduction factor regarding LTB

Structure number 1.1.2

b) Beam analysis - take friction into account as bracing force - prevented LTB

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	47,2	16,5	3,4	6,9	50%	not OK
300	1	428,5	137,1	48,0	10,0	13,1	77%	not OK
400	1	740,2	236,9	82,9	17,3	16,5	105%	OK
500	1	1102,3	352,7	123,5	25,7	19,3	134%	OK

May full bracing be assumed?

x_1	2,5	[m]	M_1	highest bending moment in the observed beam section
x_2	2,15	[m]	M_2	bending moment in the opposite end of the observed beam section

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	147,4	144,5	1,8	8,5	OK
300	428,5	420,1	1,2	8,5	OK
400	740,2	725,7	1,2	8,5	OK
500	1102,3	1080,7	1,2	8,5	OK

Q_brac	concentrated load from one beam
F_my	friction force capacity
F_con.max	design connection force BSK for connection near mid-span
F_con.max	design connection force Eurocode 3 for connection near mid-span

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	56,6	19,8	5,0	20,6	24%	not OK
300	1	514,3	164,6	57,6	14,4	39,2	37%	not OK
400	1	888,3	284,2	99,5	24,9	49,5	50%	not OK
500	1	1322,8	423,3	148,1	37,0	57,8	64%	not OK

Full bracing can be assumed, see description in Mathcad

Structure number 1.1.2

c) Beam analysis - deformation limit

d_max=	min	{	L/300=	16,7	=	16,7	[mm]	d	deflection
				50,0				d_max	maximum deflection

With regard to maximum deflection

HEB	**q_d** [kN/m]
200	24,5
300	108,3
400	248,1
500	461,0

- If 'not OK' the maximum load is limited by the deflection

- If 'OK' the maximum load is either the load from a) or, if the demands in b) are fullfilled, the load from b).

From a) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	41,0	27,9	167%	not OK
300	127,9	19,7	118%	not OK
400	218,1	14,7	88%	OK
500	320,1	11,6	69%	OK

From a) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	46,7	31,8	191%	not OK
300	145,9	22,5	135%	not OK
400	248,5	16,7	100%	not OK
500	364,6	13,2	79%	OK

From b) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	47,2	32,1	192%	not OK
300	137,1	21,1	127%	not OK
400	236,9	15,9	95%	OK
500	352,7	12,8	77%	OK

From b) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	56,6	38,5	231%	not OK
300	164,6	25,3	152%	not OK
400	284,2	19,1	115%	not OK
500	423,3	15,3	92%	OK

Structure number 1.1.2

d) Beam analysis - The design load

BSK 2007		
HEB	**q_d max** [kN/m]	**Limited by**
200	24,5	c) Deflection
300	108,3	c) Deflection
400	236,9	b) Prevented LTB
500	352,7	b) Prevented LTB

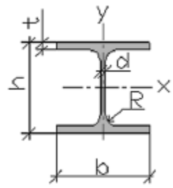
Eurocode 3: Design of steel structures - Part 1-1		
HEB	**q_d max** [kN/m]	**Limited by**
200	24,5	c) Deflection
300	108,3	c) Deflection
400	248,1	c) Deflection
500	364,6	a) Free LTB

Structure number 1.1.3

Timber beam on steel beam, span length 5 m, centre distance bracings 0,4 m

Input data

gamma_n	1,2		partial factor with regard to safety class (Safety class 3), only BSK 2007
gamma_m	1		partial factor with regard to uncertainties in determining resistance
gamma_my	2		partial factor with regard to friction
f_yk	275	[MPa]	characteristic yield stress
f_yd	229	[MPa]	design yield stress, only BSK 2007
E_k	210	[GPa]	Young modulus
G_k	80,77	[Gpa]	shear modulus
my	0,5		friction coefficient between steel and timber
my_db	0,21		BSK 2007, design friction coefficient between steel and timber
my_de	0,25		Eurocode 3, design friction coefficient between steel and timber
L_beam	5	[m]	beam span length
s_brac	0,4	[m]	distance between timber wailings/bracing points



HEB **h** [mm]	**b** [mm]	**t_flange** [mm]	**I_x** [10^6x mm^4]	**Z_x** [10^3x mm^3]	**W_x** [10^3x mm^3]	**I_y** [10^6x mm^4]	**I_t** [10^6 x mm^4]	**I_w** [10^9 x mm^6]
200	200	15	56,96	643	570	20,03	0,595	171
300	300	19	251,7	1870	1680	85,63	1,86	1690
400	300	24	576,8	3230	2880	108,2	3,57	3820
500	300	28	1072	4810	4290	126,2	5,4	7020

I_x, I_y	moment of inertia
W_x, Z_x	elastic and plastic bending restistance
I_t	S:t Venants torsion constant
I_w	warping constant

Structure number 1.1.3

a) Beam analysis - take no bracings into account - free LTB

						BSK 2007		
HEB	**z_g** [mm]	**C_1**	**C_2**	**M_cr** [kNm]	**lambda**	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]
200	100	1,127	0,454	287	0,78	0,87	128,0	41,0
300	150	1,127	0,454	1162	0,67	0,93	399,7	127,9
400	200	1,127	0,454	1863	0,69	0,92	681,5	218,1
500	250	1,127	0,454	2576	0,72	0,91	1000,2	320,1

	Eurocode 3: Design of steel structures - Part 1-1						
HEB	**lambda_0**	**beta**	**alfa_LT**	**phei_LT**	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]
200	0,4	0,75	0,34	0,80	0,83	146,0	46,7
300	0,4	0,75	0,34	0,71	0,89	456,0	145,9
400	0,4	0,75	0,34	0,73	0,87	776,7	248,5
500	0,4	0,75	0,34	0,75	0,86	1139,3	364,6

M_cr	elastic critical moment with regard to LTB
lambda	slenderness factor regarding LTB
w_b	reduction factor regarding LTB
z_g	the distance between the shear centre and the load application point
C_1, C_2	coefficients depending on the loading and support conditions
lamda_0	value of the plateau length for buckling curves of hot-rolled sections
beta	correction factor for buckling curves of hot-rolled sections
alfa_LT	imperfection factor
phei_LT	help factor
chei_LT	reduction factor regarding LTB

Structure number 1.1.3

b) Beam analysis - take friction into account as bracing force - prevented LTB

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	47,2	18,9	3,9	6,9	57%	not OK
300	1	428,5	137,1	54,9	11,4	13,1	87%	not OK
400	1	740,2	236,9	94,7	19,7	16,5	120%	OK
500	1	1102,3	352,7	141,1	29,4	19,3	153%	OK

May full bracing be assumed?

x_1 2,5 [m] M_1 highest bending moment in the observed beam section
x_2 2,1 [m] M_2 bending moment in the opposite end of the observed beam section

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	147,4	143,6	2,0	8,6	OK
300	428,5	417,6	1,3	8,6	OK
400	740,2	721,3	1,3	8,6	OK
500	1102,3	1074,1	1,3	8,6	OK

Q_brac concentrated load from one beam
F_my friction force capacity
F_con.max design connection force BSK for connection near mid-span
F_con.max design connection force Eurocode 3 for connection near mid-span

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	56,6	22,6	5,7	20,6	27%	not OK
300	1	514,3	164,6	65,8	16,5	39,2	42%	not OK
400	1	888,3	284,2	113,7	28,4	49,5	57%	not OK
500	1	1322,8	423,3	169,3	42,3	57,8	73%	not OK

Full bracing can be assumed, see description in Mathcad

Structure number 1.1.3

c) Beam analysis - deformation limit

d_max= min { L/300= 16,7 = 16,7 [mm]
50,0

d deflection
d_max maximum deflection

With regard to maximum deflection

HEB	**q_d** [kN/m]
200	24,5
300	108,3
400	248,1
500	461,0

- If 'not OK' the maximum load is limited by the deflection

- If 'OK' the maximum load is either the load from a) or, if the demands in b) are fullfilled, the load from b).

From a) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	41,0	27,9	167%	not OK
300	127,9	19,7	118%	not OK
400	218,1	14,7	88%	OK
500	320,1	11,6	69%	OK

From a) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	46,7	31,8	191%	not OK
300	145,9	22,5	135%	not OK
400	248,5	16,7	100%	not OK
500	364,6	13,2	79%	OK

From b) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	47,2	32,1	192%	not OK
300	137,1	21,1	127%	not OK
400	236,9	15,9	95%	OK
500	352,7	12,8	77%	OK

From b) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	56,6	38,5	231%	not OK
300	164,6	25,3	152%	not OK
400	284,2	19,1	115%	not OK
500	423,3	15,3	92%	OK

Structure number 1.1.3

d) Beam analysis - The design load

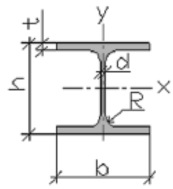
BSK 2007		
HEB	**q_d max** [kN/m]	**Limited by**
200	24,5	c) Deflection
300	108,3	c) Deflection
400	236,9	b) Prevented LTB
500	352,7	b) Prevented LTB

Eurocode 3: Design of steel structures - Part 1-1		
HEB	**q_d max** [kN/m]	**Limited by**
200	24,5	c) Deflection
300	108,3	c) Deflection
400	248,1	c) Deflection
500	364,6	a) Free LTB

Structure number 1.2.1
Timber beam on steel beam, span length 10 m, centre distance bracings 0,3 m

Input data

gamma_n	1,2		partial factor with regard to safety class (Safety class 3), only BSK 2007
gamma_m	1		partial factor with regard to uncertainties in determining resistance
gamma_my	2		partial factor with regard to friction
f_yk	275	[MPa]	characteristic yield stress
f_yd	229	[MPa]	design yield stress, only BSK 2007
E_k	210	[GPa]	Young modulus
G_k	80,77	[Gpa]	shear modulus
my	0,5		friction coefficient between steel and timber
my_db	0,21		BSK 2007, design friction coefficient between steel and timber
my_de	0,25		Eurocode 3, design friction coefficient between steel and timber
L_beam	10	[m]	beam span length
s_brac	0,3	[m]	distance between timber wailings/bracing points



HEB **h** [mm]	**b** [mm]	**t_flange** [mm]	**I_x** [10^6x mm^4]	**Z_x** [10^3x mm^3]	**W_x** [10^3x mm^3]	**I_y** [10^6x mm^4]	**I_t** [10^6 x mm^4]	**I_w** [10^9 x mm^6]
200	200	15	56,96	643	570	20,03	0,595	171
300	300	19	251,7	1870	1680	85,63	1,86	1690
400	300	24	576,8	3230	2880	108,2	3,57	3820
500	300	28	1072	4810	4290	126,2	5,4	7020

I_x, I_y	moment of inertia
W_x, Z_x	elastic and plastic bending restistance
I_t	S:t Venants torsion constant
I_w	warping constant

Structure number 1.2.1

a) Beam analysis - take no bracings into account - free LTB

						BSK 2007		
HEB	**z_g** [mm]	**C_1**	**C_2**	**M_cr** [kNm]	**lambda**	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]
200	100	1,127	0,454	145	1,10	0,65	95,3	7,6
300	150	1,127	0,454	524	0,99	0,73	312,0	25,0
400	200	1,127	0,454	819	1,04	0,69	511,8	40,9
500	250	1,127	0,454	1095	1,10	0,65	717,0	57,4

	Eurocode 3: Design of steel structures - Part 1-1						
HEB	**lambda_0**	**beta**	**alfa_LT**	**phei_LT**	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]
200	0,4	0,75	0,34	1,08	0,64	112,5	9,0
300	0,4	0,75	0,34	0,97	0,71	362,8	29,0
400	0,4	0,75	0,34	1,02	0,67	599,0	47,9
500	0,4	0,75	0,34	1,07	0,64	845,5	67,6

M_cr	elastic critical moment with regard to LTB
lambda	slenderness factor regarding LTB
w_b	reduction factor regarding LTB
z_g	the distance between the shear centre and the load application point
C_1, C_2	coefficients depending on the loading and support conditions
lamda_0	value of the plateau length for buckling curves of hot-rolled sections
beta	correction factor for buckling curves of hot-rolled sections
alfa_LT	imperfection factor
phei_LT	help factor
chei_LT	reduction factor regarding LTB

Structure number 1.2.1

b) Beam analysis - take friction into account as bracing force - prevented LTB

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	11,8	3,5	0,7	6,9	11%	not OK
300	1	428,5	34,3	10,3	2,1	13,1	16%	not OK
400	1	740,2	59,2	17,8	3,7	16,5	22%	not OK
500	1	1102,3	88,2	26,5	5,5	19,3	29%	not OK

May full bracing be assumed?

x_1	5	[m]	M_1	highest bending moment in the observed beam section
x_2	4,7	[m]	M_2	bending moment in the opposite end of the observed beam section

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	147,4	146,8	1,5	8,3	OK
300	428,5	427,0	1,0	8,3	OK
400	740,2	737,5	1,0	8,3	OK
500	1102,3	1098,3	1,0	8,3	OK

Q_brac	concentrated load from one beam
F_my	friction force capacity
F_con.max	design connection force BSK for connection near mid-span
F_con.max	design connection force Eurocode 3 for connection near mid-span

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	14,1	4,2	1,1	20,6	5%	not OK
300	1	514,3	41,1	12,3	3,1	39,2	8%	not OK
400	1	888,3	71,1	21,3	5,3	49,5	11%	not OK
500	1	1322,8	105,8	31,7	7,9	57,8	14%	not OK

Full bracing can be assumed, see description in Mathcad

Structure number 1.2.1

c) Beam analysis - deformation limit

d_max=	min	{	L/300=	33,3	=	33,3	[mm]	d	deflection
				50,0				d_max	maximum deflection

With regard to maximum deflection

HEB	q_d [kN/m]
200	3,1
300	13,5
400	31,0
500	57,6

- If 'not OK' the maximum load is limited by the deflection

- If 'OK' the maximum load is either the load from a) or, if the demands in b) are fullfilled, the load from b).

From a) - BSK 2007

HEB	q_d [kN/m]	d [mm]	d / d_max	
200	7,6	83,0	249%	not OK
300	25,0	61,5	184%	not OK
400	40,9	44,0	132%	not OK
500	57,4	33,2	100%	OK

From a) - Eurocode 3

HEB	q_d [kN/m]	d [mm]	d / d_max	
200	9,0	98,0	294%	not OK
300	29,0	71,5	214%	not OK
400	47,9	51,5	155%	not OK
500	67,6	39,1	117%	not OK

From b) - BSK 2007

HEB	q_d [kN/m]	d [mm]	d / d_max	
200	11,8	128,3	385%	not OK
300	34,3	84,5	253%	not OK
400	59,2	63,7	191%	not OK
500	88,2	51,0	153%	not OK

From b) - Eurocode 3

HEB	q_d [kN/m]	d [mm]	d / d_max	
200	14,1	154,0	462%	not OK
300	41,1	101,3	304%	not OK
400	71,1	76,4	229%	not OK
500	105,8	61,2	184%	not OK

Structure number 1.2.1

d) Beam analysis - The design load

BSK 2007		
HEB	**q_d max** [kN/m]	**Limited by**
200	3,1	c) Deflection
300	13,5	c) Deflection
400	31,0	c) Deflection
500	57,4	b) Free LTB

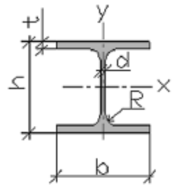
Eurocode 3: Design of steel structures - Part 1-1		
HEB	**q_d max** [kN/m]	**Limited by**
200	3,1	c) Deflection
300	13,5	c) Deflection
400	31,0	c) Deflection
500	57,6	c) Deflection

Structure number 1.2.2

Timber beam on steel beam, span length 10 m, centre distance bracings 0,35 m

Input data

gamma_n	1,2		partial factor with regard to safety class (Safety class 3), only BSK 2007
gamma_m	1		partial factor with regard to uncertainties in determining resistance
gamma_my	2		partial factor with regard to friction
f_yk	275	[MPa]	characteristic yield stress
f_yd	229	[MPa]	design yield stress, only BSK 2007
E_k	210	[GPa]	Young modulus
G_k	80,77	[Gpa]	shear modulus
my	0,5		friction coefficient between steel and timber
my_db	0,21		BSK 2007, design friction coefficient between steel and timber
my_de	0,25		Eurocode 3, design friction coefficient between steel and timber
L_beam	10	[m]	beam span length
s_brac	0,35	[m]	distance between timber wailings/bracing points



HEB **h** [mm]	**b** [mm]	**t_flange** [mm]	**I_x** [10^6x mm^4]	**Z_x** [10^3x mm^3]	**W_x** [10^3x mm^3]	**I_y** [10^6x mm^4]	**I_t** [10^6 x mm^4]	**I_w** [10^9 x mm^6]
200	200	15	56,96	643	570	20,03	0,595	171
300	300	19	251,7	1870	1680	85,63	1,86	1690
400	300	24	576,8	3230	2880	108,2	3,57	3820
500	300	28	1072	4810	4290	126,2	5,4	7020

I_x, I_y moment of inertia
W_x, Z_x elastic and plastic bending restistance
I_t S:t Venants torsion constant
I_w warping constant

Structure number 1.2.2

a) Beam analysis - take no bracings into account - free LTB

						BSK 2007		
HEB	**z_g** [mm]	**C_1**	**C_2**	**M_cr** [kNm]	**lambda**	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]
200	100	1,127	0,454	145	1,10	0,65	95,3	7,6
300	150	1,127	0,454	524	0,99	0,73	312,0	25,0
400	200	1,127	0,454	819	1,04	0,69	511,8	40,9
500	250	1,127	0,454	1095	1,10	0,65	717,0	57,4

		Eurocode 3: Design of steel structures - Part 1-1						
HEB		**lambda_0**	**beta**	**alfa_LT**	**phei_LT**	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]
200		0,4	0,75	0,34	1,08	0,64	112,5	9,0
300		0,4	0,75	0,34	0,97	0,71	362,8	29,0
400		0,4	0,75	0,34	1,02	0,67	599,0	47,9
500		0,4	0,75	0,34	1,07	0,64	845,5	67,6

M_cr elastic critical moment with regard to LTB
lambda slenderness factor regarding LTB
w_b reduction factor regarding LTB
z_g the distance between the shear centre and the load application point
C_1, C_2 coefficients depending on the loading and support conditions
lamda_0 value of the plateau length for buckling curves of hot-rolled sections
beta correction factor for buckling curves of hot-rolled sections
alfa_LT imperfection factor
phei_LT help factor
chei_LT reduction factor regarding LTB

Structure number 1.2.2

b) Beam analysis - take friction into account as bracing force - prevented LTB

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	11,8	4,1	0,9	6,9	13%	not OK
300	1	428,5	34,3	12,0	2,5	13,1	19%	not OK
400	1	740,2	59,2	20,7	4,3	16,5	26%	not OK
500	1	1102,3	88,2	30,9	6,4	19,3	33%	not OK

May full bracing be assumed?

x_1 5 [m] M_1 highest bending moment in the observed beam section

x_2 4,65 [m] M_2 bending moment in the opposite end of the observed beam section

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	147,4	146,6	1,8	8,3	OK
300	428,5	426,4	1,2	8,3	OK
400	740,2	736,6	1,2	8,3	OK
500	1102,3	1096,9	1,2	8,3	OK

Q_brac concentrated load from one beam

F_my friction force capacity

F_con.max design connection force BSK for connection near mid-span

F_con.max design connection force Eurocode 3 for connection near mid-span

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	14,1	5,0	1,2	20,6	6%	not OK
300	1	514,3	41,1	14,4	3,6	39,2	9%	not OK
400	1	888,3	71,1	24,9	6,2	49,5	13%	not OK
500	1	1322,8	105,8	37,0	9,3	57,8	16%	not OK

Full bracing can be assumed, see description in Mathcad

Structure number 1.2.2

c) Beam analysis - deformation limit

$$d\_max = \min \begin{cases} L/300 = 33,3 \\ 50,0 \end{cases} = 33,3 \text{ [mm]}$$

d deflection

d_max maximum deflection

With regard to maximum deflection

HEB	**q_d** [kN/m]
200	3,1
300	13,5
400	31,0
500	57,6

- If 'not OK' the maximum load is limited by the deflection

- If 'OK' the maximum load is either the load from a) or, if the demands in b) are fullfilled, the load from b).

From a) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	7,6	83,0	249%	not OK
300	25,0	61,5	184%	not OK
400	40,9	44,0	132%	not OK
500	57,4	33,2	100%	OK

From a) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	9,0	98,0	294%	not OK
300	29,0	71,5	214%	not OK
400	47,9	51,5	155%	not OK
500	67,6	39,1	117%	not OK

From b) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	11,8	128,3	385%	not OK
300	34,3	84,5	253%	not OK
400	59,2	63,7	191%	not OK
500	88,2	51,0	153%	not OK

From b) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	14,1	154,0	462%	not OK
300	41,1	101,3	304%	not OK
400	71,1	76,4	229%	not OK
500	105,8	61,2	184%	not OK

Structure number 1.2.2

d) Beam analysis - The design load

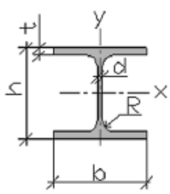
BSK 2007		
HEB	**q_d max** [kN/m]	**Limited by**
200	3,1	c) Deflection
300	13,5	c) Deflection
400	31,0	c) Deflection
500	57,4	b) Free LTB

Eurocode 3: Design of steel structures - Part 1-1		
HEB	**q_d max** [kN/m]	**Limited by**
200	3,1	c) Deflection
300	13,5	c) Deflection
400	31,0	c) Deflection
500	57,6	c) Deflection

Structure number 1.2.3
Timber beam on steel beam, span length 10 m, centre distance bracings 0,4 m

Input data

gamma_n	1,2		partial factor with regard to safety class (Safety class 3), only BSK 2007
gamma_m	1		partial factor with regard to uncertainties in determining resistance
gamma_my	2		partial factor with regard to friction
f_yk	275	[MPa]	characteristic yield stress
f_yd	229	[MPa]	design yield stress, only BSK 2007
E_k	210	[GPa]	Young modulus
G_k	80,77	[Gpa]	shear modulus
my	0,5		friction coefficient between steel and timber
my_db	0,21		BSK 2007, design friction coefficient between steel and timber
my_de	0,25		Eurocode 3, design friction coefficient between steel and timber
L_beam	10	[m]	beam span length
s_brac	0,4	[m]	distance between timber wailings/bracing points



HEB **h** [mm]	**b** [mm]	**t_flange** [mm]	**I_x** $[10^6 x\ mm^4]$	**Z_x** $[10^3 x\ mm^3]$	**W_x** $[10^3 x\ mm^3]$	**I_y** $[10^6 x\ mm^4]$	**I_t** $[10^6\ x\ mm^4]$	**I_w** $[10^9\ x\ mm^6]$
200	200	15	56,96	643	570	20,03	0,595	171
300	300	19	251,7	1870	1680	85,63	1,86	1690
400	300	24	576,8	3230	2880	108,2	3,57	3820
500	300	28	1072	4810	4290	126,2	5,4	7020

I_x, I_y	moment of inertia
W_x, Z_x	elastic and plastic bending restistance
I_t	S:t Venants torsion constant
I_w	warping constant

Structure number 1.2.3

a) Beam analysis - take no bracings into account - free LTB

						BSK 2007		
HEB	**z_g** [mm]	**C_1**	**C_2**	**M_cr** [kNm]	**lambda**	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]
200	100	1,127	0,454	145	1,10	0,65	95,3	7,6
300	150	1,127	0,454	524	0,99	0,73	312,0	25,0
400	200	1,127	0,454	819	1,04	0,69	511,8	40,9
500	250	1,127	0,454	1095	1,10	0,65	717,0	57,4

	Eurocode 3: Design of steel structures - Part 1-1						
HEB	**lambda_0**	**beta**	**alfa_LT**	**phei_LT**	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]
200	0,4	0,75	0,34	1,08	0,64	112,5	9,0
300	0,4	0,75	0,34	0,97	0,71	362,8	29,0
400	0,4	0,75	0,34	1,02	0,67	599,0	47,9
500	0,4	0,75	0,34	1,07	0,64	845,5	67,6

M_cr elastic critical moment with regard to LTB
lambda slenderness factor regarding LTB
w_b reduction factor regarding LTB
z_g the distance between the shear centre and the load application point
C_1, C_2 coefficients depending on the loading and support conditions
lamda_0 value of the plateau length for buckling curves of hot-rolled sections
beta correction factor for buckling curves of hot-rolled sections
alfa_LT imperfection factor
phei_LT help factor
chei_LT reduction factor regarding LTB

Structure number 1.2.3

b) Beam analysis - take friction into account as bracing force - prevented LTB

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	11,8	4,7	1,0	6,9	14%	not OK
300	1	428,5	34,3	13,7	2,9	13,1	22%	not OK
400	1	740,2	59,2	23,7	4,9	16,5	30%	not OK
500	1	1102,3	88,2	35,3	7,3	19,3	38%	not OK

May full bracing be assumed?
x_1 5 [m] M_1 highest bending moment in the observed beam section
x_2 4,6 [m] M_2 bending moment in the opposite end of the observed beam section

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	147,4	146,4	2,0	8,4	OK
300	428,5	425,8	1,3	8,4	OK
400	740,2	735,5	1,3	8,4	OK
500	1102,3	1095,2	1,3	8,4	OK

Q_brac concentrated load from one beam
F_my friction force capacity
F_con.max design connection force BSK for connection near mid-span
F_con.max design connection force Eurocode 3 for connection near mid-span

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	14,1	5,7	1,4	20,6	7%	not OK
300	1	514,3	41,1	16,5	4,1	39,2	10%	not OK
400	1	888,3	71,1	28,4	7,1	49,5	14%	not OK
500	1	1322,8	105,8	42,3	10,6	57,8	18%	not OK

Full bracing can be assumed, see description in Mathcad

Structure number 1.2.3

c) Beam analysis - deformation limit

d_max= min { L/300= 33,3 = 33,3 [mm]
50,0

d deflection
d_max maximum deflection

With regard to maximum deflection

HEB	q_d [kN/m]
200	3,1
300	13,5
400	31,0
500	57,6

- If 'not OK' the maximum load is limited by the deflection

- If 'OK' the maximum load is either the load from a) or, if the demands in b) are fullfilled, the load from b).

From a) - BSK 2007

HEB	q_d [kN/m]	d [mm]	d / d_max	
200	7,6	83,0	249%	not OK
300	25,0	61,5	184%	not OK
400	40,9	44,0	132%	not OK
500	57,4	33,2	100%	OK

From a) - Eurocode 3

HEB	q_d [kN/m]	d [mm]	d / d_max	
200	9,0	98,0	294%	not OK
300	29,0	71,5	214%	not OK
400	47,9	51,5	155%	not OK
500	67,6	39,1	117%	not OK

From b) - BSK 2007

HEB	q_d [kN/m]	d [mm]	d / d_max	
200	11,8	128,3	385%	not OK
300	34,3	84,5	253%	not OK
400	59,2	63,7	191%	not OK
500	88,2	51,0	153%	not OK

From b) - Eurocode 3

HEB	q_d [kN/m]	d [mm]	d / d_max	
200	14,1	154,0	462%	not OK
300	41,1	101,3	304%	not OK
400	71,1	76,4	229%	not OK
500	105,8	61,2	184%	not OK

Structure number 1.2.3

d) Beam analysis - The design load

BSK 2007		
HEB	**q_d max** [kN/m]	**Limited by**
200	3,1	c) Deflection
300	13,5	c) Deflection
400	31,0	c) Deflection
500	57,4	b) Free LTB

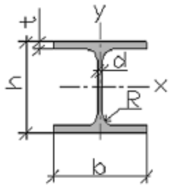
Eurocode 3: Design of steel structures - Part 1-1		
HEB	**q_d max** [kN/m]	**Limited by**
200	3,1	c) Deflection
300	13,5	c) Deflection
400	31,0	c) Deflection
500	57,6	c) Deflection

Structure number 1.3.1

Timber beam on steel beam, span length 15 m, centre distance bracings 0,3 m

Input data

gamma_n	1,2		partial factor with regard to safety class (Safety class 3), only BSK 2007
gamma_m	1		partial factor with regard to uncertainties in determining resistance
gamma_my	2		partial factor with regard to friction
f_yk	275	[MPa]	characteristic yield stress
f_yd	229	[MPa]	design yield stress, only BSK 2007
E_k	210	[GPa]	Young modulus
G_k	80,77	[Gpa]	shear modulus
my	0,5		friction coefficient between steel and timber
my_db	0,21		BSK 2007, design friction coefficient between steel and timber
my_de	0,25		Eurocode 3, design friction coefficient between steel and timber
L_beam	15	[m]	beam span length
s_brac	0,3	[m]	distance between timber wailings/bracing points



HEB **h** [mm]	**b** [mm]	**t_flange** [mm]	**I_x** [10^6x mm^4]	**Z_x** [10^3x mm^3]	**W_x** [10^3x mm^3]	**I_y** [10^6x mm^4]	**I_t** [10^6 x mm^4]	**I_w** [10^9 x mm^6]
200	200	15	56,96	643	570	20,03	0,595	171
300	300	19	251,7	1870	1680	85,63	1,86	1690
400	300	24	576,8	3230	2880	108,2	3,57	3820
500	300	28	1072	4810	4290	126,2	5,4	7020

I_x, I_y	moment of inertia
W_x, Z_x	elastic and plastic bending restistance
I_t	S:t Venants torsion constant
I_w	warping constant

Structure number 1.3.1

a) Beam analysis - take no bracings into account - free LTB

						BSK 2007		
HEB	**z_g** [mm]	**C_1**	**C_2**	**M_cr** [kNm]	**lambda**	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]
200	100	1,127	0,454	99	1,34	0,50	73,3	2,6
300	150	1,127	0,454	351	1,21	0,58	246,7	8,8
400	200	1,127	0,454	546	1,28	0,53	395,4	14,1
500	250	1,127	0,454	724	1,35	0,49	539,8	19,2

		Eurocode 3: Design of steel structures - Part 1-1						
HEB		**lambda_0**	**beta**	**alfa_LT**	**phei_LT**	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]
200		0,4	0,75	0,34	1,33	0,50	89,1	3,2
300		0,4	0,75	0,34	1,19	0,57	295,0	10,5
400		0,4	0,75	0,34	1,26	0,54	476,9	17,0
500		0,4	0,75	0,34	1,35	0,50	657,0	23,4

M_cr	elastic critical moment with regard to LTB
lambda	slenderness factor regarding LTB
w_b	reduction factor regarding LTB
z_g	the distance between the shear centre and the load application point
C_1, C_2	coefficients depending on the loading and support conditions
lamda_0	value of the plateau length for buckling curves of hot-rolled sections
beta	correction factor for buckling curves of hot-rolled sections
alfa_LT	imperfection factor
phei_LT	help factor
chei_LT	reduction factor regarding LTB

Structure number 1.3.1

b) Beam analysis - take friction into account as bracing force - prevented LTB

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	5,2	1,6	0,3	6,9	5%	not OK
300	1	428,5	15,2	4,6	1,0	13,1	7%	not OK
400	1	740,2	26,3	7,9	1,6	16,5	10%	not OK
500	1	1102,3	39,2	11,8	2,4	19,3	13%	not OK

May full bracing be assumed?

x_1 7,5 [m] M_1 highest bending moment in the observed beam section
x_2 7,2 [m] M_2 bending moment in the opposite end of the observed beam section

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	147,4	147,1	1,5	8,3	OK
300	428,5	427,9	1,0	8,3	OK
400	740,2	739,0	1,0	8,3	OK
500	1102,3	1100,5	1,0	8,3	OK

Q_brac concentrated load from one beam
F_my friction force capacity
F_con.max design connection force BSK for connection near mid-span
F_con.max design connection force Eurocode 3 for connection near mid-span

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	6,3	1,9	0,5	20,6	2%	not OK
300	1	514,3	18,3	5,5	1,4	39,2	3%	not OK
400	1	888,3	31,6	9,5	2,4	49,5	5%	not OK
500	1	1322,8	47,0	14,1	3,5	57,8	6%	not OK

Full bracing can be assumed, see description in Mathcad

Analytical calculations
1.3.1

Structure number 1.3.1

c) Beam analysis - deformation limit

d_max= min { L/300= 50,0 = 50,0 [mm]
50,0

d deflection
d_max maximum deflection

With regard to maximum deflection

HEB	**q_d** [kN/m]
200	0,9
300	4,0
400	9,2
500	17,1

- If 'not OK' the maximum load is limited by the deflection

- If 'OK' the maximum load is either the load from a) or, if the demands in b) are fullfilled, the load from b).

From a) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	2,6	143,7	287%	not OK
300	8,8	109,4	219%	not OK
400	14,1	76,5	153%	not OK
500	19,2	56,2	112%	not OK

From a) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	3,2	174,6	349%	not OK
300	10,5	130,8	262%	not OK
400	17,0	92,3	185%	not OK
500	23,4	68,4	137%	not OK

From b) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	5,2	288,7	577%	not OK
300	15,2	190,0	380%	not OK
400	26,3	143,2	286%	not OK
500	39,2	114,8	230%	not OK

From b) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	6,3	346,5	693%	not OK
300	18,3	228,0	456%	not OK
400	31,6	171,9	344%	not OK
500	47,0	137,7	275%	not OK

Structure number 1.3.1

d) Beam analysis - The design load

BSK 2007		
HEB	**q_d max** [kN/m]	**Limited by**
200	0,9	c) Deflection
300	4,0	c) Deflection
400	9,2	c) Deflection
500	17,1	c) Deflection

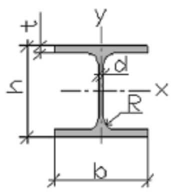
Eurocode 3: Design of steel structures - Part 1-1		
HEB	**q_d max** [kN/m]	**Limited by**
200	0,9	c) Deflection
300	4,0	c) Deflection
400	9,2	c) Deflection
500	17,1	c) Deflection

Structure number 1.3.2

Timber beam on steel beam, span length 15 m, centre distance bracings 0,35 m

Input data

gamma_n	1,2		partial factor with regard to safety class (Safety class 3), only BSK 2007
gamma_m	1		partial factor with regard to uncertainties in determining resistance
gamma_my	2		partial factor with regard to friction
f_yk	275	[MPa]	characteristic yield stress
f_yd	229	[MPa]	design yield stress, only BSK 2007
E_k	210	[GPa]	Young modulus
G_k	80,77	[Gpa]	shear modulus
my	0,5		friction coefficient between steel and timber
my_db	0,21		BSK 2007, design friction coefficient between steel and timber
my_de	0,25		Eurocode 3, design friction coefficient between steel and timber
L_beam	15	[m]	beam span length
s_brac	0,35	[m]	distance between timber wailings/bracing points



HEB **h** [mm]	**b** [mm]	**t_flange** [mm]	**I_x** [10^6x mm^4]	**Z_x** [10^3x mm^3]	**W_x** [10^3x mm^3]	**I_y** [10^6x mm^4]	**I_t** [10^6 x mm^4]	**I_w** [10^9 x mm^6]
200	200	15	56,96	643	570	20,03	0,595	171
300	300	19	251,7	1870	1680	85,63	1,86	1690
400	300	24	576,8	3230	2880	108,2	3,57	3820
500	300	28	1072	4810	4290	126,2	5,4	7020

I_x, I_y	moment of inertia
W_x, Z_x	elastic and plastic bending restistance
I_t	S:t Venants torsion constant
I_w	warping constant

Structure number 1.3.2

a) Beam analysis - take no bracings into account - free LTB

HEB	z_g [mm]	C_1	C_2	M_cr [kNm]	lambda	BSK 2007 w_b	BSK 2007 M_Rd [kNm]	BSK 2007 q_d [kN/m]
200	100	1,127	0,454	99	1,34	0,50	73,3	2,6
300	150	1,127	0,454	351	1,21	0,58	246,7	8,8
400	200	1,127	0,454	546	1,28	0,53	395,4	14,1
500	250	1,127	0,454	724	1,35	0,49	539,8	19,2

HEB	Eurocode 3: Design of steel structures - Part 1-1 lambda_0	beta	alfa_LT	phei_LT	chei_LT	M_Rd [kNm]	q_d [kN/m]
200	0,4	0,75	0,34	1,33	0,50	89,1	3,2
300	0,4	0,75	0,34	1,19	0,57	295,0	10,5
400	0,4	0,75	0,34	1,26	0,54	476,9	17,0
500	0,4	0,75	0,34	1,35	0,50	657,0	23,4

M_cr elastic critical moment with regard to LTB
lambda slenderness factor regarding LTB
w_b reduction factor regarding LTB
z_g the distance between the shear centre and the load application point
C_1, C_2 coefficients depending on the loading and support conditions
lamda_0 value of the plateau length for buckling curves of hot-rolled sections
beta correction factor for buckling curves of hot-rolled sections
alfa_LT imperfection factor
phei_LT help factor
chei_LT reduction factor regarding LTB

Structure number 1.3.2

b) Beam analysis - take friction into account as bracing force - prevented LTB

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	5,2	1,8	0,4	6,9	6%	not OK
300	1	428,5	15,2	5,3	1,1	13,1	9%	not OK
400	1	740,2	26,3	9,2	1,9	16,5	12%	not OK
500	1	1102,3	39,2	13,7	2,9	19,3	15%	not OK

May full bracing be assumed?
x_1 7,5 [m] M_1 highest bending moment in the observed beam section
x_2 7,15 [m] M_2 bending moment in the opposite end of the observed beam section

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	147,4	147,0	1,8	8,3	OK
300	428,5	427,6	1,2	8,3	OK
400	740,2	738,6	1,2	8,3	OK
500	1102,3	1099,9	1,2	8,3	OK

Q_brac concentrated load from one beam
F_my friction force capacity
F_con.max design connection force BSK for connection near mid-span
F_con.max design connection force Eurocode 3 for connection near mid-span

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	6,3	2,2	0,6	20,6	3%	not OK
300	1	514,3	18,3	6,4	1,6	39,2	4%	not OK
400	1	888,3	31,6	11,1	2,8	49,5	6%	not OK
500	1	1322,8	47,0	16,5	4,1	57,8	7%	not OK

Full bracing can be assumed, see description in Mathcad

Structure number 1.3.2

c) Beam analysis - deformation limit

d_max= min { L/300= 50,0 = 50,0 [mm]
50,0

d deflection
d_max maximum deflection

With regard to maximum deflection

HEB	**q_d** [kN/m]
200	0,9
300	4,0
400	9,2
500	17,1

- If 'not OK' the maximum load is limited by the deflection

- If 'OK' the maximum load is either the load from a) or, if the demands in b) are fullfilled, the load from b).

From a) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	2,6	143,7	287%	not OK
300	8,8	109,4	219%	not OK
400	14,1	76,5	153%	not OK
500	19,2	56,2	112%	not OK

From a) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	3,2	174,6	349%	not OK
300	10,5	130,8	262%	not OK
400	17,0	92,3	185%	not OK
500	23,4	68,4	137%	not OK

From b) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	5,2	288,7	577%	not OK
300	15,2	190,0	380%	not OK
400	26,3	143,2	286%	not OK
500	39,2	114,8	230%	not OK

From b) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	6,3	346,5	693%	not OK
300	18,3	228,0	456%	not OK
400	31,6	171,9	344%	not OK
500	47,0	137,7	275%	not OK

Structure number 1.3.2

d) Beam analysis - The design load

BSK 2007		
HEB	**q_d max** [kN/m]	**Limited by**
200	0,9	c) Deflection
300	4,0	c) Deflection
400	9,2	c) Deflection
500	17,1	c) Deflection

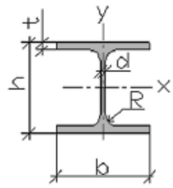
Eurocode 3: Design of steel structures - Part 1-1		
HEB	**q_d max** [kN/m]	**Limited by**
200	0,9	c) Deflection
300	4,0	c) Deflection
400	9,2	c) Deflection
500	17,1	c) Deflection

Structure number 1.3.3

Timber beam on steel beam, span length 15 m, centre distance bracings 0,4 m

Input data

gamma_n	1,2		partial factor with regard to safety class (Safety class 3), only BSK 2007
gamma_m	1		partial factor with regard to uncertainties in determining resistance
gamma_my	2		partial factor with regard to friction
f_yk	275	[MPa]	characteristic yield stress
f_yd	229	[MPa]	design yield stress, only BSK 2007
E_k	210	[GPa]	Young modulus
G_k	80,77	[Gpa]	shear modulus
my	0,5		friction coefficient between steel and timber
my_db	0,21		BSK 2007, design friction coefficient between steel and timber
my_de	0,25		Eurocode 3, design friction coefficient between steel and timber
L_beam	15	[m]	beam span length
s_brac	0,4	[m]	distance between timber wailings/bracing points



HEB **h** [mm]	**b** [mm]	**t_flange** [mm]	**I_x** [10^6x mm^4]	**Z_x** [10^3x mm^3]	**W_x** [10^3x mm^3]	**I_y** [10^6x mm^4]	**I_t** [10^6 x mm^4]	**I_w** [10^9 x mm^6]
200	200	15	56,96	643	570	20,03	0,595	171
300	300	19	251,7	1870	1680	85,63	1,86	1690
400	300	24	576,8	3230	2880	108,2	3,57	3820
500	300	28	1072	4810	4290	126,2	5,4	7020

I_x, I_y	moment of inertia
W_x, Z_x	elastic and plastic bending restistance
I_t	S:t Venants torsion constant
I_w	warping constant

Structure number 1.3.3

a) Beam analysis - take no bracings into account - free LTB

						BSK 2007		
HEB	**z_g** [mm]	**C_1**	**C_2**	**M_cr** [kNm]	**lambda**	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]
200	100	1,127	0,454	99	1,34	0,50	73,3	2,6
300	150	1,127	0,454	351	1,21	0,58	246,7	8,8
400	200	1,127	0,454	546	1,28	0,53	395,4	14,1
500	250	1,127	0,454	724	1,35	0,49	539,8	19,2

		Eurocode 3: Design of steel structures - Part 1-1						
HEB		**lambda_0**	**beta**	**alfa_LT**	**phei_LT**	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]
200		0,4	0,75	0,34	1,33	0,50	89,1	3,2
300		0,4	0,75	0,34	1,19	0,57	295,0	10,5
400		0,4	0,75	0,34	1,26	0,54	476,9	17,0
500		0,4	0,75	0,34	1,35	0,50	657,0	23,4

M_cr	elastic critical moment with regard to LTB
lambda	slenderness factor regarding LTB
w_b	reduction factor regarding LTB
z_g	the distance between the shear centre and the load application point
C_1, C_2	coefficients depending on the loading and support conditions
lamda_0	value of the plateau length for buckling curves of hot-rolled sections
beta	correction factor for buckling curves of hot-rolled sections
alfa_LT	imperfection factor
phei_LT	help factor
chei_LT	reduction factor regarding LTB

Structure number 1.3.3

b) Beam analysis - take friction into account as bracing force - prevented LTB

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	5,2	2,1	0,4	6,9	6%	not OK
300	1	428,5	15,2	6,1	1,3	13,1	10%	not OK
400	1	740,2	26,3	10,5	2,2	16,5	13%	not OK
500	1	1102,3	39,2	15,7	3,3	19,3	17%	not OK

May full bracing be assumed?

x_1 7,5 [m] M_1 highest bending moment in the observed beam section
x_2 7,1 [m] M_2 bending moment in the opposite end of the observed beam section

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	147,4	146,9	2,0	8,3	OK
300	428,5	427,3	1,3	8,3	OK
400	740,2	738,1	1,3	8,3	OK
500	1102,3	1099,2	1,3	8,3	OK

Q_brac concentrated load from one beam
F_my friction force capacity
F_con.max design connection force BSK for connection near mid-span
F_con.max design connection force Eurocode 3 for connection near mid-span

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	6,3	2,5	0,6	20,6	3%	not OK
300	1	514,3	18,3	7,3	1,8	39,2	5%	not OK
400	1	888,3	31,6	12,6	3,2	49,5	6%	not OK
500	1	1322,8	47,0	18,8	4,7	57,8	8%	not OK

Full bracing can be assumed, see description in Mathcad

Structure number 1.3.3

c) Beam analysis - deformation limit

d_max= min { L/300= 50,0 = 50,0 [mm]
50,0

d deflection
d_max maximum deflection

With regard to maximum deflection

HEB	**q_d** [kN/m]
200	0,9
300	4,0
400	9,2
500	17,1

- If 'not OK' the maximum load is limited by the deflection

- If 'OK' the maximum load is either the load from a) or, if the demands in b) are fullfilled, the load from b).

From a) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	2,6	143,7	287%	not OK
300	8,8	109,4	219%	not OK
400	14,1	76,5	153%	not OK
500	19,2	56,2	112%	not OK

From a) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	3,2	174,6	349%	not OK
300	10,5	130,8	262%	not OK
400	17,0	92,3	185%	not OK
500	23,4	68,4	137%	not OK

From b) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	5,2	288,7	577%	not OK
300	15,2	190,0	380%	not OK
400	26,3	143,2	286%	not OK
500	39,2	114,8	230%	not OK

From b) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	6,3	346,5	693%	not OK
300	18,3	228,0	456%	not OK
400	31,6	171,9	344%	not OK
500	47,0	137,7	275%	not OK

Structure number 1.3.3

d) Beam analysis - The design load

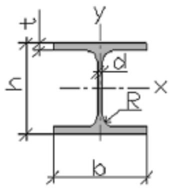
BSK 2007		
HEB	**q_d max** [kN/m]	**Limited by**
200	0,9	c) Deflection
300	4,0	c) Deflection
400	9,2	c) Deflection
500	17,1	c) Deflection

Eurocode 3: Design of steel structures - Part 1-1		
HEB	**q_d max** [kN/m]	**Limited by**
200	0,9	c) Deflection
300	4,0	c) Deflection
400	9,2	c) Deflection
500	17,1	c) Deflection

Structure number 2.1.1
Steel beam on steel beam, span length 5 m, centre distance bracings 1 m

Input data

gamma_n	1,2		partial factor with regard to safety class (Safety class 3), only BSK 2007
gamma_m	1		partial factor with regard to uncertainties in determining resistance
gamma_my	2		partial factor with regard to friction
f_yk	275	[MPa]	characteristic yield stress
f_yd	229	[MPa]	design yield stress, only BSK 2007
E_k	210	[GPa]	Young modulus
G_k	80,77	[Gpa]	shear modulus
my	0,2		friction coefficient between steel and timber
my_db	0,08		BSK 2007, design friction coefficient between steel and timber
my_de	0,1		Eurocode 3, design friction coefficient between steel and timber
L_beam	5	[m]	beam span length
s_brac	1	[m]	distance between timber wailings/bracing points



HEB **h** [mm]	**b** [mm]	**t_flange** [mm]	**I_x** [10^6x mm^4]	**Z_x** [10^3x mm^3]	**W_x** [10^3x mm^3]	**I_y** [10^6x mm^4]	**I_t** [10^6 x mm^4]	**I_w** [10^9 x mm^6]
200	200	15	56,96	643	570	20,03	0,595	171
300	300	19	251,7	1870	1680	85,63	1,86	1690
400	300	24	576,8	3230	2880	108,2	3,57	3820
500	300	28	1072	4810	4290	126,2	5,4	7020

I_x, I_y	moment of inertia
W_x, Z_x	elastic and plastic bending restistance
I_t	S:t Venants torsion constant
I_w	warping constant

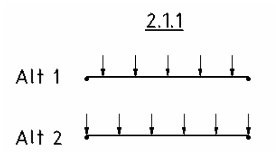
Structure number 2.1.1

a) Beam analysis - take no bracings into account - free LTB

						BSK 2007		
HEB	**z_g** [mm]	**C_1**	**C_2**	**M_cr** [kNm]	**lambda**	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]
200	100	1,127	0,454	287	0,78	0,87	128,0	41,0
300	150	1,127	0,454	1162	0,67	0,93	399,7	127,9
400	200	1,127	0,454	1863	0,69	0,92	681,5	218,1
500	250	1,127	0,454	2576	0,72	0,91	1000,2	320,1

		Eurocode 3: Design of steel structures - Part 1-1					
HEB		**lambda_0**	**beta**	**alfa_LT**	**phei_LT**	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]
200		0,4	0,75	0,34	0,80	0,83	146,0	46,7
300		0,4	0,75	0,34	0,71	0,89	456,0	145,9
400		0,4	0,75	0,34	0,73	0,87	776,7	248,5
500		0,4	0,75	0,34	0,75	0,86	1139,3	364,6

M_cr	elastic critical moment with regard to LTB
lambda	slenderness factor regarding LTB
w_b	reduction factor regarding LTB
z_g	the distance between the shear centre and the load application point
C_1, C_2	coefficients depending on the loading and support conditions
lamda_0	value of the plateau length for buckling curves of hot-rolled sections
beta	correction factor for buckling curves of hot-rolled sections
alfa_LT	imperfection factor
phei_LT	help factor
chei_LT	reduction factor regarding LTB



Load alternativ
Simplification - assume distributed load

Structure number 2.1.1

b) Beam analysis - take friction into account as bracing force - prevented LTB

Load alternativ 1 - see figure above

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	47,2	47,2	3,9	6,9	57%	not OK
300	1	428,5	137,1	137,1	11,4	13,1	87%	not OK
400	1	740,2	236,9	236,9	19,7	16,5	120%	OK
500	1	1102,3	352,7	352,7	29,4	19,3	153%	OK

May full bracing be assumed?

x_1	2,5	[m]		M_1	highest bending moment in the observed beam section
x_2	1,5	[m]		M_2	bending moment in the opposite end of the observed beam section

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	147,4	123,8	5,0	10,0	OK
300	428,5	360,0	3,3	10,0	OK
400	740,2	621,8	3,3	10,0	OK
500	1102,3	925,9	3,3	10,0	OK

Q_brac	concentrated load from one beam
F_my	friction force capacity
F_con.max	design connection force BSK for connection near mid-span
F_con.max	design connection force Eurocode 3 for connection near mid-span

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	56,6	56,6	5,7	20,6	27%	not OK
300	1	514,3	164,6	164,6	16,5	39,2	42%	not OK
400	1	888,3	284,2	284,2	28,4	49,5	57%	not OK
500	1	1322,8	423,3	423,3	42,3	57,8	73%	not OK

Full bracing can be assumed, see description in Mathcad

Structure number 2.1.1

Load alternativ 2 - see figure above

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	47,2	47,2	3,9	6,9	57%	not OK
300	1	428,5	137,1	137,1	11,4	13,1	87%	not OK
400	1	740,2	236,9	236,9	19,7	16,5	120%	OK
500	1	1102,3	352,7	352,7	29,4	19,3	153%	OK

May full bracing be assumed?

x_1	2	[m]
x_2	3	[m]

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	141,5	141,5	5,0	8,3	OK
300	411,4	411,4	3,3	8,3	OK
400	710,6	710,6	3,3	8,3	OK
500	1058,2	1058,2	3,3	8,3	OK

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	56,6	56,6	5,7	20,6	27%	not OK
300	1	514,3	164,6	164,6	16,5	39,2	42%	not OK
400	1	888,3	284,2	284,2	28,4	49,5	57%	not OK
500	1	1322,8	423,3	423,3	42,3	57,8	73%	not OK

Full bracing can be assumed, see description in Mathcad

Structure number 2.1.1

c) Beam analysis - deformation limit

d_max= min { L/300= 16,7 = 16,7 [mm]
50,0

d deflection
d_max maximum deflection

With regard to maximum deflection

HEB	**q_d** [kN/m]
200	24,5
300	108,3
400	248,1
500	461,0

- If 'not OK' the maximum load is limited by the deflection

- If 'OK' the maximum load is either the load from a) or, if the demands in b) are fullfilled, the load from b).

From a) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	41,0	27,9	167%	not OK
300	127,9	19,7	118%	not OK
400	218,1	14,7	88%	OK
500	320,1	11,6	69%	OK

From a) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	46,7	31,8	191%	not OK
300	145,9	22,5	135%	not OK
400	248,5	16,7	100%	not OK
500	364,6	13,2	79%	OK

From b) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	47,2	32,1	192%	not OK
300	137,1	21,1	127%	not OK
400	236,9	15,9	95%	OK
500	352,7	12,8	77%	OK

From b) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	56,6	38,5	231%	not OK
300	164,6	25,3	152%	not OK
400	284,2	19,1	115%	not OK
500	423,3	15,3	92%	OK

Structure number 2.1.1

d) Beam analysis - The design load

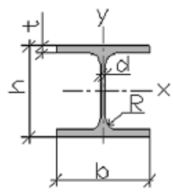
BSK 2007		
HEB	**q_d max** [kN/m]	**Limited by**
200	24,5	c) Deflection
300	108,3	c) Deflection
400	236,9	b) Prevented LTB
500	352,7	b) Prevented LTB

Eurocode 3: Design of steel structures - Part 1-1		
HEB	**q_d max** [kN/m]	**Limited by**
200	24,5	c) Deflection
300	108,3	c) Deflection
400	248,1	c) Deflection
500	364,6	a) Free LTB

Structure number 2.1.2
Steel beam on steel beam, span length 5 m, centre distance bracings 1,5 m

Input data

gamma_n	1,2		partial factor with regard to safety class (Safety class 3), only BSK 2007
gamma_m	1		partial factor with regard to uncertainties in determining resistance
gamma_my	2		partial factor with regard to friction
f_yk	275	[MPa]	characteristic yield stress
f_yd	229	[MPa]	design yield stress, only BSK 2007
E_k	210	[GPa]	Young modulus
G_k	80,77	[Gpa]	shear modulus
my	0,2		friction coefficient between steel and timber
my_db	0,08		BSK 2007, design friction coefficient between steel and timber
my_de	0,1		Eurocode 3, design friction coefficient between steel and timber
L_beam	5	[m]	beam span length
s_brac	1,5	[m]	distance between timber wailings/bracing points



HEB **h** [mm]	**b** [mm]	**t_flange** [mm]	**I_x** [10^6x mm^4]	**Z_x** [10^3x mm^3]	**W_x** [10^3x mm^3]	**I_y** [10^6x mm^4]	**I_t** [10^6 x mm^4]	**I_w** [10^9 x mm^6]
200	200	15	56,96	643	570	20,03	0,595	171
300	300	19	251,7	1870	1680	85,63	1,86	1690
400	300	24	576,8	3230	2880	108,2	3,57	3820
500	300	28	1072	4810	4290	126,2	5,4	7020

I_x, I_y	moment of inertia
W_x, Z_x	elastic and plastic bending restistance
I_t	S:t Venants torsion constant
I_w	warping constant

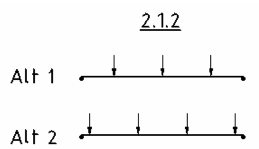
Structure number 2.1.2

a) Beam analysis - take no bracings into account - free LTB

						BSK 2007		
HEB	**z_g** [mm]	**C_1**	**C_2**	**M_cr** [kNm]	**lambda**	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]
200	100	1,127	0,454	287	0,78	0,87	128,0	41,0
300	150	1,127	0,454	1162	0,67	0,93	399,7	127,9
400	200	1,127	0,454	1863	0,69	0,92	681,5	218,1
500	250	1,127	0,454	2576	0,72	0,91	1000,2	320,1

		Eurocode 3: Design of steel structures - Part 1-1						
HEB		**lambda_0**	**beta**	**alfa_LT**	**phei_LT**	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]
200		0,4	0,75	0,34	0,80	0,83	146,0	46,7
300		0,4	0,75	0,34	0,71	0,89	456,0	145,9
400		0,4	0,75	0,34	0,73	0,87	776,7	248,5
500		0,4	0,75	0,34	0,75	0,86	1139,3	364,6

M_cr elastic critical moment with regard to LTB
lambda slenderness factor regarding LTB
w_b reduction factor regarding LTB
z_g the distance between the shear centre and the load application point
C_1, C_2 coefficients depending on the loading and support conditions
lamda_0 value of the plateau length for buckling curves of hot-rolled sections
beta correction factor for buckling curves of hot-rolled sections
alfa_LT imperfection factor
phei_LT help factor
chei_LT reduction factor regarding LTB



Load alternativ
Simplification - assume distributed load

Structure number 2.1.2

b) Beam analysis - take friction into account as bracing force - prevented LTB
<u>Load alternativ 1</u> - see figure above

			BSK 2007					
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	47,2	70,7	5,9	6,9	86%	not OK
300	1	428,5	137,1	205,7	17,1	13,1	131%	OK
400	1	740,2	236,9	355,3	29,6	16,5	179%	OK
500	1	1102,3	352,7	529,1	44,1	19,3	229%	OK

<u>May full bracing be assumed?</u>
x_1 2,5 [m] M_1 highest bending moment in the observed beam section
x_2 1 [m] M_2 bending moment in the opposite end of the observed beam section

			BSK 2007		
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	147,4	94,3	7,5	11,9	OK
300	428,5	274,3	5,0	11,9	OK
400	740,2	473,7	5,0	11,9	OK
500	1102,3	705,5	5,0	11,9	OK

Q_brac concentrated load from one beam
F_my friction force capacity
F_con.max design connection force BSK for connection near mid-span
F_con.max design connection force Eurocode 3 for connection near mid-span

			Eurocode 3: Design of steel structures - Part 1-1					
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	56,6	84,9	8,5	20,6	41%	not OK
300	1	514,3	164,6	246,8	24,7	39,2	63%	not OK
400	1	888,3	284,2	426,4	42,6	49,5	86%	not OK
500	1	1322,8	423,3	634,9	63,5	57,8	110%	OK

Full bracing can be assumed, see description in Mathcad

Structure number 2.1.2

Load alternativ 2 - see figure above

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	47,2	70,7	5,9	6,9	86%	not OK
300	1	428,5	137,1	205,7	17,1	13,1	131%	OK
400	1	740,2	236,9	355,3	29,6	16,5	179%	OK
500	1	1102,3	352,7	529,1	44,1	19,3	229%	OK

May full bracing be assumed?

x_1	1,75	[m]
x_2	3,25	[m]

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	134,1	134,1	7,5	8,3	OK
300	390,0	390,0	5,0	8,3	OK
400	673,6	673,6	5,0	8,3	OK
500	1003,1	1003,1	5,0	8,3	OK

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	56,6	84,9	8,5	20,6	41%	not OK
300	1	514,3	164,6	246,8	24,7	39,2	63%	not OK
400	1	888,3	284,2	426,4	42,6	49,5	86%	not OK
500	1	1322,8	423,3	634,9	63,5	57,8	110%	OK

Full bracing can be assumed, see description in Mathcad

Structure number 2.1.2

c) Beam analysis - deformation limit

d_max= min { L/300= 16,7 = 16,7 [mm]
50,0

d deflection
d_max maximum deflection

With regard to maximum deflection

HEB	**q_d** [kN/m]
200	24,5
300	108,3
400	248,1
500	461,0

- If 'not OK' the maximum load is limited by the deflection

- If 'OK' the maximum load is either the load from a) or, if the demands in b) are fullfilled, the load from b).

From a) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	41,0	27,9	167%	not OK
300	127,9	19,7	118%	not OK
400	218,1	14,7	88%	OK
500	320,1	11,6	69%	OK

From a) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	46,7	31,8	191%	not OK
300	145,9	22,5	135%	not OK
400	248,5	16,7	100%	not OK
500	364,6	13,2	79%	OK

From b) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	47,2	32,1	192%	not OK
300	137,1	21,1	127%	not OK
400	236,9	15,9	95%	OK
500	352,7	12,8	77%	OK

From b) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	56,6	38,5	231%	not OK
300	164,6	25,3	152%	not OK
400	284,2	19,1	115%	not OK
500	423,3	15,3	92%	OK

Structure number 2.1.2

d) Beam analysis - The design load

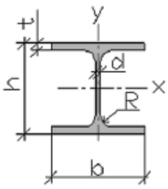
BSK 2007		
HEB	**q_d max** [kN/m]	**Limited by**
200	24,5	c) Deflection
300	108,3	c) Deflection
400	236,9	b) Prevented LTB
500	352,7	b) Prevented LTB

Eurocode 3: Design of steel structures - Part 1-1		
HEB	**q_d max** [kN/m]	**Limited by**
200	24,5	c) Deflection
300	108,3	c) Deflection
400	248,1	c) Deflection
500	423,3	a) Prevented LTB

Structure number 2.1.3
Steel beam on steel beam, span length 5 m, centre distance bracings 2 m

Input data

gamma_n	1,2		partial factor with regard to safety class (Safety class 3), only BSK 2007
gamma_m	1		partial factor with regard to uncertainties in determining resistance
gamma_my	2		partial factor with regard to friction
f_yk	275	[MPa]	characteristic yield stress
f_yd	229	[MPa]	design yield stress, only BSK 2007
E_k	210	[GPa]	Young modulus
G_k	80,77	[Gpa]	shear modulus
my	0,2		friction coefficient between steel and timber
my_db	0,08		BSK 2007, design friction coefficient between steel and timber
my_de	0,1		Eurocode 3, design friction coefficient between steel and timber
L_beam	5	[m]	beam span length
s_brac	2	[m]	distance between timber wailings/bracing points



HEB **h** [mm]	**b** [mm]	**t_flange** [mm]	**I_x** [10^6x mm^4]	**Z_x** [10^3x mm^3]	**W_x** [10^3x mm^3]	**I_y** [10^6x mm^4]	**I_t** [10^6 x mm^4]	**I_w** [10^9 x mm^6]
200	200	15	56,96	643	570	20,03	0,595	171
300	300	19	251,7	1870	1680	85,63	1,86	1690
400	300	24	576,8	3230	2880	108,2	3,57	3820
500	300	28	1072	4810	4290	126,2	5,4	7020

I_x, I_y	moment of inertia
W_x, Z_x	elastic and plastic bending restistance
I_t	S:t Venants torsion constant
I_w	warping constant

Structure number 2.1.3

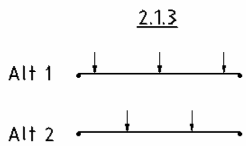
a) Beam analysis - take no bracings into account - free LTB

Load alternativ 1 - see figure below

						BSK 2007		
HEB	**z_g** [mm]	**C_1**	**C_2**	**M_cr** [kNm]	**lambda**	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]
200	100	1,127	0,454	287	0,78	0,87	128,0	41,0
300	150	1,127	0,454	1162	0,67	0,93	399,7	127,9
400	200	1,127	0,454	1863	0,69	0,92	681,5	218,1
500	250	1,127	0,454	2576	0,72	0,91	1000,2	320,1

		Eurocode 3: Design of steel structures - Part 1-1					
HEB		**lambda_0**	**beta**	**alfa_LT**	**phei_LT**	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]
200		0,4	0,75	0,34	0,80	0,83	146,0	46,7
300		0,4	0,75	0,34	0,71	0,89	456,0	145,9
400		0,4	0,75	0,34	0,73	0,87	776,7	248,5
500		0,4	0,75	0,34	0,75	0,86	1139,3	364,6

M_cr	elastic critical moment with regard to LTB
lambda	slenderness factor regarding LTB
w_b	reduction factor regarding LTB
z_g	the distance between the shear centre and the load application point
C_1, C_2	coefficients depending on the loading and support conditions
lamda_0	value of the plateau length for buckling curves of hot-rolled sections
beta	correction factor for buckling curves of hot-rolled sections
alfa_LT	imperfection factor
phei_LT	help factor
chei_LT	reduction factor regarding LTB



Load alternativ
Alt 1: Simplification - assume distributed load
Alt 2: Two point loads

Analytical calculations
2.1.3

Structure number 2.1.3

Load alternativ 2 - see figure above

						BSK 2007		
HEB	**z_g** [mm]	**C_1**	**C_2**	**M_cr** [kNm]	**lambda**	**w_b**	**M_Rd** [kNm]	**P_d** [kN]
200		use LTBeam		270	0,81	0,85	125,7	83,8
300		use LTBeam		1089	0,69	0,92	395,3	263,5
400		use LTBeam		1746	0,71	0,91	672,9	448,6
500		use LTBeam		2414	0,74	0,89	986,0	657,3

		Eurocode 3: Design of steel structures - Part 1-1						
HEB		**lambda_0**	**beta**	**alfa_LT**	**phei_LT**	**chei_LT**	**M_Rd** [kNm]	**P_d** [kN]
200		0,4	0,75	0,34	0,82	0,81	143,6	95,7
300		0,4	0,75	0,34	0,73	0,88	450,5	300,3
400		0,4	0,75	0,34	0,74	0,86	766,5	511,0
500		0,4	0,75	0,34	0,76	0,85	1123,2	748,8

Structure number 2.1.3

b) Beam analysis - take friction into account as bracing force - prevented LTB

Load alternativ 1 - see figure above

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	47,2	94,3	7,9	6,9	114%	OK
300	1	428,5	137,1	274,3	22,9	13,1	175%	OK
400	1	740,2	236,9	473,7	39,5	16,5	239%	OK
500	1	1102,3	352,7	705,5	58,8	19,3	305%	OK

May full bracing be assumed?

x_1 2,5 [m] M_1 highest bending moment in the observed beam section

x_2 0,5 [m] M_2 bending moment in the opposite end of the observed beam section

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	147,4	53,0	10,0	14,2	OK
300	428,5	154,3	6,7	14,2	OK
400	740,2	266,5	6,7	14,2	OK
500	1102,3	396,8	6,7	14,2	OK

Q_brac concentrated load from one beam

F_my friction force capacity

F_con.max design connection force BSK for connection near mid-span

F_con.max design connection force Eurocode 3 for connection near mid-span

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	56,6	113,2	11,3	20,6	55%	not OK
300	1	514,3	164,6	329,1	32,9	39,2	84%	not OK
400	1	888,3	284,2	568,5	56,8	49,5	115%	OK
500	1	1322,8	423,3	846,6	84,7	57,8	147%	OK

Full bracing can be assumed, see description in Mathcad

Structure number 2.1.3

Load alternativ 2 - see figure above

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**P_d** [kN]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	98,2	98,2	8,2	6,9	119%	OK
300	1	428,5	285,7	285,7	23,8	13,1	182%	OK
400	1	740,2	493,5	493,5	41,1	16,5	249%	OK
500	1	1102,3	734,9	734,9	61,2	19,3	318%	OK

May full bracing be assumed?

x_1 1,5 [m]

x_2 3,5 [m]

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	147,4	147,4	10,0	8,3	not OK
300	428,5	428,5	6,7	8,3	OK
400	740,2	740,2	6,7	8,3	OK
500	1102,3	1102,3	6,7	8,3	OK

Eurocode 3: Design of steel structures - Part 1-1		
M_cr [kNm]	**lambda**	**lambda < lambda_0?**
1854	0,31	OK
10836	0,22	OK
18163	0,22	OK
26371	0,22	OK

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**P_d** [kN]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	117,9	117,9	11,8	20,6	57%	not OK
300	1	514,3	342,8	342,8	34,3	39,2	87%	not OK
400	1	888,3	592,2	592,2	59,2	49,5	120%	OK
500	1	1322,8	881,8	881,8	88,2	57,8	153%	OK

Structure number 2.1.3

c) Beam analysis - deformation limit

d_max=	min	{	L/300=	16,7	=	16,7	[mm]	d	deflection
				50,0				d_max	maximum deflection

With regard to maximum deflection

HEB	q_d (Alt 1) [kN/m]	P_d (Alt 2) [kN]
200	24,5	48,3
300	108,3	213,6
400	248,1	489,4
500	461,0	909,6

- If 'not OK' the maximum load is limited by the deflection

- If 'OK' the maximum load is either the load from a) or, if the demands in b) are fullfilled, the load from b).

Load alternativ 1 - see figure above
From a) - BSK 2007

HEB	q_d [kN/m]	d [mm]	d / d_max	
200	41,0	27,9	167%	not OK
300	127,9	19,7	118%	not OK
400	218,1	14,7	88%	OK
500	320,1	11,6	69%	OK

Load alternativ 1 - see figure above
From a) - Eurocode 3

HEB	q_d [kN/m]	d [mm]	d / d_max	
200	46,7	31,8	191%	not OK
300	145,9	22,5	135%	not OK
400	248,5	16,7	100%	not OK
500	364,6	13,2	79%	OK

Load alternativ 2 - see figure above
From a) - BSK 2007

HEB	P_d [kN]	d [mm]	d / d_max	
200	83,8	28,9	173%	not OK
300	263,5	20,6	123%	not OK
400	448,6	15,3	92%	OK
500	657,3	12,0	72%	OK

Load alternativ 2 - see figure above
From a) - Eurocode 3

HEB	P_d [kN]	d [mm]	d / d_max	
200	95,7	33,0	198%	not OK
300	300,3	23,4	141%	not OK
400	511,0	17,4	104%	not OK
500	748,8	13,7	82%	OK

Structure number 2.1.3

Load alternativ 1 - see figure above
From b) - BSK 2007

HEB	q_d [kN/m]	d [mm]	d / d_max	
200	47,2	32,1	192%	not OK
300	137,1	21,1	127%	not OK
400	236,9	15,9	95%	OK
500	352,7	12,8	77%	OK

Load alternativ 1 - see figure above
From b) - Eurocode 3

HEB	q_d [kN/m]	d [mm]	d / d_max	
200	56,6	38,5	231%	not OK
300	164,6	25,3	152%	not OK
400	284,2	19,1	115%	not OK
500	423,3	15,3	92%	OK

Load alternativ 2 - see figure above
From b) - BSK 2007

HEB	P_d [kN]	d [mm]	d / d_max	
200	98,2	33,9	203%	not OK
300	285,7	22,3	134%	not OK
400	493,5	16,8	101%	not OK
500	734,9	13,5	81%	OK

Load alternativ 2 - see figure above
From b) - Eurocode 3

HEB	P_d [kN]	d [mm]	d / d_max	
200	117,9	40,7	244%	not OK
300	342,8	26,8	161%	not OK
400	592,2	20,2	121%	not OK
500	881,8	16,2	97%	OK

Structure number 2.1.3

d) Beam analysis - The design load

Load alternativ 1 - see figure above

BSK 2007		
HEB	**q_d max** [kN/m]	**Limited by**
200	24,5	c) Deflection
300	108,3	c) Deflection
400	236,9	b) Prevented LTB
500	352,7	b) Prevented LTB

Load alternativ 1 - see figure above

Eurocode 3: Design of steel structures - Part 1-1		
HEB	**q_d max** [kN/m]	**Limited by**
200	24,5	c) Deflection
300	108,3	c) Deflection
400	248,1	c) Deflection
500	423,3	a) Prevented LTB

Load alternativ 2 - see figure above

BSK 2007		
HEB	**P_d max** [kN]	**Limited by**
200	48,3	c) Deflection
300	213,6	c) Deflection
400	448,6	b) Free LTB
500	734,9	b) Prevented LTB

Load alternativ 2 - see figure above

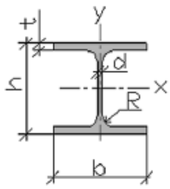
Eurocode 3: Design of steel structures - Part 1-1		
HEB	**P_d max** [kN]	**Limited by**
200	48,3	c) Deflection
300	213,6	c) Deflection
400	489,4	c) Deflection
500	881,8	a) Prevented LTB

Structure number 2.1.4

Steel beam on steel beam, span length 5 m, centre distance bracings 2,5 m

Input data

gamma_n	1,2		partial factor with regard to safety class (Safety class 3), only BSK 2007
gamma_m	1		partial factor with regard to uncertainties in determining resistance
gamma_my	2		partial factor with regard to friction
f_yk	275	[MPa]	characteristic yield stress
f_yd	229	[MPa]	design yield stress, only BSK 2007
E_k	210	[GPa]	Young modulus
G_k	80,77	[Gpa]	shear modulus
my	0,2		friction coefficient between steel and timber
my_db	0,08		BSK 2007, design friction coefficient between steel and timber
my_de	0,1		Eurocode 3, design friction coefficient between steel and timber
L_beam	5	[m]	beam span length
s_brac	2,5	[m]	distance between timber wailings/bracing points



HEB **h** [mm]	**b** [mm]	**t_flange** [mm]	**I_x** [10^6x mm^4]	**Z_x** [10^3x mm^3]	**W_x** [10^3x mm^3]	**I_y** [10^6x mm^4]	**I_t** [10^6 x mm^4]	**I_w** [10^9 x mm^6]
200	200	15	56,96	643	570	20,03	0,595	171
300	300	19	251,7	1870	1680	85,63	1,86	1690
400	300	24	576,8	3230	2880	108,2	3,57	3820
500	300	28	1072	4810	4290	126,2	5,4	7020

I_x, I_y	moment of inertia
W_x, Z_x	elastic and plastic bending restistance
I_t	S:t Venants torsion constant
I_w	warping constant

Structure number 2.1.4

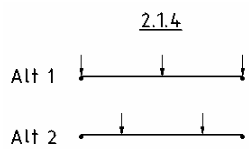
a) Beam analysis - take no bracings into account - free LTB

Load alternativ 1 - see figure below

						BSK 2007		
HEB	**z_g** [mm]	**C_1**	**C_2**	**M_cr** [kNm]	**lambda**	**w_b**	**M_Rd** [kNm]	**P_d** [kN]
200	100	1,348	0,63	315	0,75	0,89	131,0	104,8
300	150	1,348	0,63	1232	0,65	0,94	403,4	322,7
400	200	1,348	0,63	1967	0,67	0,93	688,1	550,5
500	250	1,348	0,63	2707	0,70	0,92	1010,2	808,2

		Eurocode 3: Design of steel structures - Part 1-1					
HEB		**lambda_0**	**beta**	**alfa_LT**	**phei_LT**	**chei_LT**	**M_Rd** [kNm]	**P_d** [kN]
200		0,4	0,75	0,34	0,77	0,84	149,3	119,4
300		0,4	0,75	0,34	0,70	0,90	460,7	368,5
400		0,4	0,75	0,34	0,72	0,88	784,7	627,8
500		0,4	0,75	0,34	0,73	0,87	1151,0	920,8

M_cr elastic critical moment with regard to LTB
lambda slenderness factor regarding LTB
w_b reduction factor regarding LTB
z_g the distance between the shear centre and the load application point
C_1, C_2 coefficients depending on the loading and support conditions
lamda_0 value of the plateau length for buckling curves of hot-rolled sections
beta correction factor for buckling curves of hot-rolled sections
alfa_LT imperfection factor
phei_LT help factor
chei_LT reduction factor regarding LTB



Load alternativ
Alt 1: One point load
Alt 2: Two point loads

Structure number 2.1.4

Load alternativ 2 - see figure above

						BSK 2007		
HEB	**z_g** [mm]	**C_1**	**C_2**	**M_cr** [kNm]	**lambda**	**w_b**	**M_Rd** [kNm]	**P_d** [kN]
200		use LTBeam		269	0,81	0,85	125,6	100,5
300		use LTBeam		1096	0,68	0,92	395,7	316,6
400		use LTBeam		1760	0,71	0,91	674,0	539,2
500		use LTBeam		2436	0,74	0,90	988,1	790,5

		Eurocode 3: Design of steel structures - Part 1-1					
HEB		**lambda_0**	**beta**	**alfa_LT**	**phei_LT**	**chei_LT**	**M_Rd** [kNm]	**P_d** [kN]
200		0,4	0,75	0,34	0,82	0,81	143,4	114,8
300		0,4	0,75	0,34	0,72	0,88	451,0	360,8
400		0,4	0,75	0,34	0,74	0,86	767,8	614,2
500		0,4	0,75	0,34	0,76	0,85	1125,5	900,4

Structure number 2.1.4

b) Beam analysis - take friction into account as bracing force - prevented LTB

Load alternativ 1 - see figure above

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**P_d** [kN]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	117,9	117,9	9,8	6,9	143%	OK
300	1	428,5	342,8	342,8	28,6	13,1	219%	OK
400	1	740,2	592,2	592,2	49,3	16,5	299%	OK
500	1	1102,3	881,8	881,8	73,5	19,3	382%	OK

May full bracing be assumed?

x_1 2,5 [m] M_1 highest bending moment in the observed beam section

x_2 0 [m] M_2 bending moment in the opposite end of the observed beam section

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	147,4	0,0	12,5	16,6	OK
300	428,5	0,0	8,3	16,6	OK
400	740,2	0,0	8,3	16,6	OK
500	1102,3	0,0	8,3	16,6	OK

Eurocode 3: Design of steel structures - Part 1-1		
M_cr [kNm]	**lambda**	**lambda < lambda_0?**
1541	0,34	OK
8331	0,25	OK
13864	0,25	OK
19978	0,26	OK

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**P_d** [kN]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	141,5	141,5	14,1	20,6	69%	not OK
300	1	514,3	411,4	411,4	41,1	39,2	105%	OK
400	1	888,3	710,6	710,6	71,1	49,5	144%	OK
500	1	1322,8	1058,2	1058,2	105,8	57,8	183%	OK

Full bracing can be assumed, see description in Mathcad

Structure number 2.1.4

Load alternativ 2 - see figure above

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**P_d** [kN]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	117,9	117,9	9,8	6,9	143%	OK
300	1	428,5	342,8	342,8	28,6	13,1	219%	OK
400	1	740,2	592,2	592,2	49,3	16,5	299%	OK
500	1	1102,3	881,8	881,8	73,5	19,3	382%	OK

May full bracing be assumed?

x_1 1,25 [m]

x_2 3,75 [m]

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	147,4	147,4	12,5	8,3	not OK
300	428,5	428,5	8,3	8,3	OK
400	740,2	740,2	8,3	8,3	OK
500	1102,3	1102,3	8,3	8,3	OK

Eurocode 3: Design of steel structures - Part 1-1		
M_cr [kNm]	**lambda**	**lambda < lambda_0?**
1622	0,33	OK
9410	0,23	OK
15766	0,24	OK
22879	0,24	OK

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**P_d** [kN]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	141,5	141,5	14,1	20,6	69%	not OK
300	1	514,3	411,4	411,4	41,1	39,2	105%	OK
400	1	888,3	710,6	710,6	71,1	49,5	144%	OK
500	1	1322,8	1058,2	1058,2	105,8	57,8	183%	OK

Structure number 2.1.4

c) Beam analysis - deformation limit

d_max= min { L/300= 16,7 = 16,7 [mm]
50,0

d deflection
d_max maximum deflection

With regard to maximum deflection

HEB	P_d (Alt 1) [kN]	P_d (Alt 2) [kN]
200	76,6	55,7
300	338,3	246,0
400	775,2	563,8
500	1440,8	1047,8

- If 'not OK' the maximum load is limited by the deflection

- If 'OK' the maximum load is either the load from a) or, if the demands in b) are fullfilled, the load from b).

Load alternativ 1 - see figure above
From a) - BSK 2007

HEB	P_d [kN]	d [mm]	d / d_max	
200	104,8	22,8	137%	not OK
300	322,7	15,9	95%	OK
400	550,5	11,8	71%	OK
500	808,2	9,3	56%	OK

Load alternativ 1 - see figure above
From a) - Eurocode 3

HEB	P_d [kN]	d [mm]	d / d_max	
200	119,4	26,0	156%	not OK
300	368,5	18,2	109%	not OK
400	627,8	13,5	81%	OK
500	920,8	10,7	64%	OK

Load alternativ 2 - see figure above
From a) - BSK 2007

HEB	P_d [kN]	d [mm]	d / d_max	
200	100,5	30,1	180%	not OK
300	316,6	21,4	129%	not OK
400	539,2	15,9	96%	OK
500	790,5	12,6	75%	OK

Load alternativ 2 - see figure above
From a) - Eurocode 3

HEB	P_d [kN]	d [mm]	d / d_max	
200	114,8	34,4	206%	not OK
300	360,8	24,4	147%	not OK
400	614,2	18,2	109%	not OK
500	900,4	14,3	86%	OK

Structure number 2.1.4

Load alternativ 1 - see figure above
From b) - BSK 2007

HEB	P_d [kN]	d [mm]	d / d_max	
200	117,9	25,7	154%	not OK
300	342,8	16,9	101%	not OK
400	592,2	12,7	76%	OK
500	881,8	10,2	61%	OK

Load alternativ 1 - see figure above
From b) - Eurocode 3

HEB	P_d [kN]	d [mm]	d / d_max	
200	141,5	30,8	185%	not OK
300	411,4	20,3	122%	not OK
400	710,6	15,3	92%	OK
500	1058,2	12,2	73%	OK

Load alternativ 2 - see figure above
From b) - BSK 2007

HEB	P_d [kN]	d [mm]	d / d_max	
200	117,9	35,3	212%	not OK
300	342,8	23,2	139%	not OK
400	592,2	17,5	105%	not OK
500	881,8	14,0	84%	OK

Load alternativ 2 - see figure above
From b) - Eurocode 3

HEB	P_d [kN]	d [mm]	d / d_max	
200	141,5	42,3	254%	not OK
300	411,4	27,9	167%	not OK
400	710,6	21,0	126%	not OK
500	1058,2	16,8	101%	not OK

Structure number 2.1.4

d) Beam analysis - The design load

Load alternativ 1 - see figure above

BSK 2007		
HEB	**P_d max** [kN]	**Limited by**
200	76,6	c) Deflection
300	322,7	a) Free LTB
400	592,2	b) Prevented LTB
500	881,8	b) Prevented LTB

Load alternativ 1 - see figure above

Eurocode 3: Design of steel structures - Part 1-1		
HEB	**P_d max** [kN]	**Limited by**
200	76,6	c) Deflection
300	338,3	c) Deflection
400	710,6	b) Prevented LTB
500	1058,2	b) Prevented LTB

Load alternativ 2 - see figure above

BSK 2007		
HEB	**P_d max** [kN]	**Limited by**
200	55,7	c) Deflection
300	246,0	c) Deflection
400	539,2	a) Free LTB
500	881,8	b) Prevented LTB

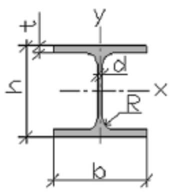
Load alternativ 2 - see figure above

Eurocode 3: Design of steel structures - Part 1-1		
HEB	**P_d max** [kN]	**Limited by**
200	55,7	c) Deflection
300	246,0	c) Deflection
400	563,8	c) Deflection
500	900,4	a) Free LTB

Structure number 2.2.1
Steel beam on steel beam, span length 10 m, centre distance bracings 1 m

Input data

gamma_n	1,2		partial factor with regard to safety class (Safety class 3), only BSK 2007
gamma_m	1		partial factor with regard to uncertainties in determining resistance
gamma_my	2		partial factor with regard to friction
f_yk	275	[MPa]	characteristic yield stress
f_yd	229	[MPa]	design yield stress, only BSK 2007
E_k	210	[GPa]	Young modulus
G_k	80,77	[Gpa]	shear modulus
my	0,2		friction coefficient between steel and timber
my_db	0,08		BSK 2007, design friction coefficient between steel and timber
my_de	0,1		Eurocode 3, design friction coefficient between steel and timber
L_beam	10	[m]	beam span length
s_brac	1	[m]	distance between timber wailings/bracing points



HEB **h** [mm]	**b** [mm]	**t_flange** [mm]	**I_x** [10^6x mm^4]	**Z_x** [10^3x mm^3]	**W_x** [10^3x mm^3]	**I_y** [10^6x mm^4]	**I_t** [10^6 x mm^4]	**I_w** [10^9 x mm^6]
200	200	15	56,96	643	570	20,03	0,595	171
300	300	19	251,7	1870	1680	85,63	1,86	1690
400	300	24	576,8	3230	2880	108,2	3,57	3820
500	300	28	1072	4810	4290	126,2	5,4	7020

I_x, I_y moment of inertia
W_x, Z_x elastic and plastic bending restistance
I_t S:t Venants torsion constant
I_w warping constant

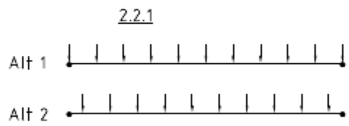
Structure number 2.2.1

a) Beam analysis - take no bracings into account - free LTB

HEB	z_g [mm]	C_1	C_2	M_cr [kNm]	lambda	BSK 2007 w_b	M_Rd [kNm]	q_d [kN/m]
200	100	1,127	0,454	145	1,10	0,65	95,3	7,6
300	150	1,127	0,454	524	0,99	0,73	312,0	25,0
400	200	1,127	0,454	819	1,04	0,69	511,8	40,9
500	250	1,127	0,454	1095	1,10	0,65	717,0	57,4

HEB		Eurocode 3: Design of steel structures - Part 1-1 lambda_0	beta	alfa_LT	phei_LT	chei_LT	M_Rd [kNm]	q_d [kN/m]
200		0,4	0,75	0,34	1,08	0,64	112,5	9,0
300		0,4	0,75	0,34	0,97	0,71	362,8	29,0
400		0,4	0,75	0,34	1,02	0,67	599,0	47,9
500		0,4	0,75	0,34	1,07	0,64	845,5	67,6

M_cr — elastic critical moment with regard to LTB
lambda — slenderness factor regarding LTB
w_b — reduction factor regarding LTB
z_g — the distance between the shear centre and the load application point
C_1, C_2 — coefficients depending on the loading and support conditions
lamda_0 — value of the plateau length for buckling curves of hot-rolled sections
beta — correction factor for buckling curves of hot-rolled sections
alfa_LT — imperfection factor
phei_LT — help factor
chei_LT — reduction factor regarding LTB



Load alternativ
Simplification - assume distributed load

Structure number 2.2.1

b) Beam analysis - take friction into account as bracing force - prevented LTB

Load alternativ 1

HEB	w_b	M_Rd [kNm]	q_d [kN/m]	BSK 2007 Q_brac [kN]	F_my [kN]	F_con.max [kN]	F_my / F_con.max	
200	1	147,4	11,8	11,8	1,0	6,9	14%	not OK
300	1	428,5	34,3	34,3	2,9	13,1	22%	not OK
400	1	740,2	59,2	59,2	4,9	16,5	30%	not OK
500	1	1102,3	88,2	88,2	7,3	19,3	38%	not OK

May full bracing be assumed?

x_1 5 [m] — M_1 highest bending moment in the observed beam section
x_2 4 [m] — M_2 bending moment in the opposite end of the observed beam section

HEB	M_1 [kNm]	M_2 [kNm]	BSK 2007 Left side	Right side	Test
200	147,4	141,5	5,0	8,7	OK
300	428,5	411,4	3,3	8,7	OK
400	740,2	710,6	3,3	8,7	OK
500	1102,3	1058,2	3,3	8,7	OK

Q_brac — concentrated load from one beam
F_my — friction force capacity
F_con.max — design connection force BSK for connection near mid-span
F_con.max — design connection force Eurocode 3 for connection near mid-span

HEB	chei_LT	M_Rd [kNm]	q_d [kN/m]	Eurocode 3: Design of steel structures - Part 1-1 Q_brac [kN]	F_my [kN]	F_con.max [kN]	F_my / F_con.max	
200	1	176,8	14,1	14,1	1,4	20,6	7%	not OK
300	1	514,3	41,1	41,1	4,1	39,2	10%	not OK
400	1	888,3	71,1	71,1	7,1	49,5	14%	not OK
500	1	1322,8	105,8	105,8	10,6	57,8	18%	not OK

Full bracing can be assumed, see description in Mathcad

Structure number 2.2.1

Load alternativ 2

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	11,8	11,8	1,0	6,9	14%	not OK
300	1	428,5	34,3	34,3	2,9	13,1	22%	not OK
400	1	740,2	59,2	59,2	4,9	16,5	30%	not OK
500	1	1102,3	88,2	88,2	7,3	19,3	38%	not OK

May full bracing be assumed?

x_1	4,5	[m]
x_2	5,5	[m]

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	145,9	145,9	5,0	8,3	OK
300	424,3	424,3	3,3	8,3	OK
400	732,8	732,8	3,3	8,3	OK
500	1091,3	1091,3	3,3	8,3	OK

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	14,1	14,1	1,4	20,6	7%	not OK
300	1	514,3	41,1	41,1	4,1	39,2	10%	not OK
400	1	888,3	71,1	71,1	7,1	49,5	14%	not OK
500	1	1322,8	105,8	105,8	10,6	57,8	18%	not OK

Full bracing can be assumed, see description in Mathcad

Structure number 2.2.1

c) Beam analysis - deformation limit

d_max= min { L/300= 33,3 = 33,3 [mm]
50,0

d deflection
d_max maximum deflection

With regard to maximum deflection

HEB	**q_d** [kN/m]
200	3,1
300	13,5
400	31,0
500	57,6

- If 'not OK' the maximum load is limited by the deflection

- If 'OK' the maximum load is either the load from a) or, if the demands in b) are fullfilled, the load from b).

From a) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	7,6	83,0	249%	not OK
300	25,0	61,5	184%	not OK
400	40,9	44,0	132%	not OK
500	57,4	33,2	100%	OK

From a) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	9,0	98,0	294%	not OK
300	29,0	71,5	214%	not OK
400	47,9	51,5	155%	not OK
500	67,6	39,1	117%	not OK

From b) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	11,8	128,3	385%	not OK
300	34,3	84,5	253%	not OK
400	59,2	63,7	191%	not OK
500	88,2	51,0	153%	not OK

From b) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	14,1	154,0	462%	not OK
300	41,1	101,3	304%	not OK
400	71,1	76,4	229%	not OK
500	105,8	61,2	184%	not OK

Structure number 2.2.1

d) Beam analysis - The design load

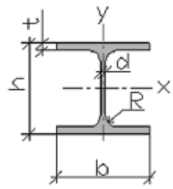
BSK 2007		
HEB	**q_d max** [kN/m]	**Limited by**
200	3,1	c) Deflection
300	13,5	c) Deflection
400	31,0	c) Deflection
500	57,4	b) Free LTB

Eurocode 3: Design of steel structures - Part 1-1		
HEB	**q_d max** [kN/m]	**Limited by**
200	3,1	c) Deflection
300	13,5	c) Deflection
400	31,0	c) Deflection
500	57,6	c) Deflection

Structure number 2.2.2
Steel beam on steel beam, span length 10 m, centre distance bracings 1,5 m

Input data

gamma_n	1,2		partial factor with regard to safety class (Safety class 3), only BSK 2007
gamma_m	1		partial factor with regard to uncertainties in determining resistance
gamma_my	2		partial factor with regard to friction
f_yk	275	[MPa]	characteristic yield stress
f_yd	229	[MPa]	design yield stress, only BSK 2007
E_k	210	[GPa]	Young modulus
G_k	80,77	[Gpa]	shear modulus
my	0,2		friction coefficient between steel and timber
my_db	0,08		BSK 2007, design friction coefficient between steel and timber
my_de	0,1		Eurocode 3, design friction coefficient between steel and timber
L_beam	10	[m]	beam span length
s_brac	1,5	[m]	distance between timber wailings/bracing points



HEB **h** [mm]	**b** [mm]	**t_flange** [mm]	**I_x** [10^6x mm^4]	**Z_x** [10^3x mm^3]	**W_x** [10^3x mm^3]	**I_y** [10^6x mm^4]	**I_t** [10^6 x mm^4]	**I_w** [10^9 x mm^6]
200	200	15	56,96	643	570	20,03	0,595	171
300	300	19	251,7	1870	1680	85,63	1,86	1690
400	300	24	576,8	3230	2880	108,2	3,57	3820
500	300	28	1072	4810	4290	126,2	5,4	7020

I_x, I_y	moment of inertia
W_x, Z_x	elastic and plastic bending restistance
I_t	S:t Venants torsion constant
I_w	warping constant

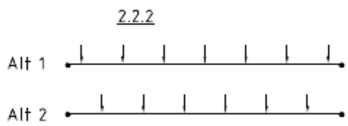
Structure number 2.2.2

a) Beam analysis - take no bracings into account - free LTB

						BSK 2007		
HEB	**z_g** [mm]	**C_1**	**C_2**	**M_cr** [kNm]	**lambda**	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]
200	100	1,127	0,454	145	1,10	0,65	95,3	7,6
300	150	1,127	0,454	524	0,99	0,73	312,0	25,0
400	200	1,127	0,454	819	1,04	0,69	511,8	40,9
500	250	1,127	0,454	1095	1,10	0,65	717,0	57,4

		Eurocode 3: Design of steel structures - Part 1-1						
HEB		**lambda_0**	**beta**	**alfa_LT**	**phei_LT**	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]
200		0,4	0,75	0,34	1,08	0,64	112,5	9,0
300		0,4	0,75	0,34	0,97	0,71	362,8	29,0
400		0,4	0,75	0,34	1,02	0,67	599,0	47,9
500		0,4	0,75	0,34	1,07	0,64	845,5	67,6

M_cr elastic critical moment with regard to LTB
lambda slenderness factor regarding LTB
w_b reduction factor regarding LTB
z_g the distance between the shear centre and the load application point
C_1, C_2 coefficients depending on the loading and support conditions
lamda_0 value of the plateau length for buckling curves of hot-rolled sections
beta correction factor for buckling curves of hot-rolled sections
alfa_LT imperfection factor
phei_LT help factor
chei_LT reduction factor regarding LTB



Load alternativ
Simplification - assume distributed load

Structure number 2.2.2

b) Beam analysis - take friction into account as bracing force - prevented LTB

Load alternativ 1

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	11,8	17,7	1,5	6,9	21%	not OK
300	1	428,5	34,3	51,4	4,3	13,1	33%	not OK
400	1	740,2	59,2	88,8	7,4	16,5	45%	not OK
500	1	1102,3	88,2	132,3	11,0	19,3	57%	not OK

May full bracing be assumed?

x_1 5 [m] M_1 highest bending moment in the observed beam section
x_2 3,5 [m] M_2 bending moment in the opposite end of the observed beam section

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	147,4	134,1	7,5	9,3	OK
300	428,5	390,0	5,0	9,3	OK
400	740,2	673,6	5,0	9,3	OK
500	1102,3	1003,1	5,0	9,3	OK

Q_brac concentrated load from one beam
F_my friction force capacity
F_con.max design connection force BSK for connection near mid-span
F_con.max design connection force Eurocode 3 for connection near mid-span

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	14,1	21,2	2,1	20,6	10%	not OK
300	1	514,3	41,1	61,7	6,2	39,2	16%	not OK
400	1	888,3	71,1	106,6	10,7	49,5	22%	not OK
500	1	1322,8	105,8	158,7	15,9	57,8	27%	not OK

Full bracing can be assumed, see description in Mathcad

Structure number 2.2.2

Load alternativ 2

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	11,8	17,7	1,5	6,9	21%	not OK
300	1	428,5	34,3	51,4	4,3	13,1	33%	not OK
400	1	740,2	59,2	88,8	7,4	16,5	45%	not OK
500	1	1102,3	88,2	132,3	11,0	19,3	57%	not OK

May full bracing be assumed?

x_1	4,25	[m]
x_2	5,75	[m]

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	144,0	144,0	7,5	8,3	OK
300	418,9	418,9	5,0	8,3	OK
400	723,6	723,6	5,0	8,3	OK
500	1077,5	1077,5	5,0	8,3	OK

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	14,1	21,2	2,1	20,6	10%	not OK
300	1	514,3	41,1	61,7	6,2	39,2	16%	not OK
400	1	888,3	71,1	106,6	10,7	49,5	22%	not OK
500	1	1322,8	105,8	158,7	15,9	57,8	27%	not OK

Full bracing can be assumed, see description in Mathcad

Structure number 2.2.2

c) Beam analysis - deformation limit

d_max= min { L/300= 33,3 = 33,3 [mm]
50,0

d deflection
d_max maximum deflection

With regard to maximum deflection

HEB	**q_d** [kN/m]
200	3,1
300	13,5
400	31,0
500	57,6

- If 'not OK' the maximum load is limited by the deflection

- If 'OK' the maximum load is either the load from a) or, if the demands in b) are fullfilled, the load from b).

From a) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	7,6	83,0	249%	not OK
300	25,0	61,5	184%	not OK
400	40,9	44,0	132%	not OK
500	57,4	33,2	100%	OK

From a) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	9,0	98,0	294%	not OK
300	29,0	71,5	214%	not OK
400	47,9	51,5	155%	not OK
500	67,6	39,1	117%	not OK

From b) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	11,8	128,3	385%	not OK
300	34,3	84,5	253%	not OK
400	59,2	63,7	191%	not OK
500	88,2	51,0	153%	not OK

From b) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	14,1	154,0	462%	not OK
300	41,1	101,3	304%	not OK
400	71,1	76,4	229%	not OK
500	105,8	61,2	184%	not OK

Structure number 2.2.2

d) Beam analysis - The design load

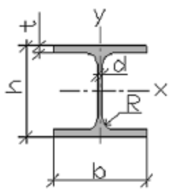
BSK 2007		
HEB	**q_d max** [kN/m]	**Limited by**
200	3,1	c) Deflection
300	13,5	c) Deflection
400	31,0	c) Deflection
500	57,4	b) Free LTB

Eurocode 3: Design of steel structures - Part 1-1		
HEB	**q_d max** [kN/m]	**Limited by**
200	3,1	c) Deflection
300	13,5	c) Deflection
400	31,0	c) Deflection
500	57,6	c) Deflection

Structure number 2.2.3
Steel beam on steel beam, span length 10 m, centre distance bracings 2 m

Input data

gamma_n	1,2		partial factor with regard to safety class (Safety class 3), only BSK 2007
gamma_m	1		partial factor with regard to uncertainties in determining resistance
gamma_my	2		partial factor with regard to friction
f_yk	275	[MPa]	characteristic yield stress
f_yd	229	[MPa]	design yield stress, only BSK 2007
E_k	210	[GPa]	Young modulus
G_k	80,77	[Gpa]	shear modulus
my	0,2		friction coefficient between steel and timber
my_db	0,08		BSK 2007, design friction coefficient between steel and timber
my_de	0,1		Eurocode 3, design friction coefficient between steel and timber
L_beam	10	[m]	beam span length
s_brac	2	[m]	distance between timber wailings/bracing points



HEB **h** [mm]	**b** [mm]	**t_flange** [mm]	**I_x** [10^6x mm^4]	**Z_x** [10^3x mm^3]	**W_x** [10^3x mm^3]	**I_y** [10^6x mm^4]	**I_t** [10^6 x mm^4]	**I_w** [10^9 x mm^6]
200	200	15	56,96	643	570	20,03	0,595	171
300	300	19	251,7	1870	1680	85,63	1,86	1690
400	300	24	576,8	3230	2880	108,2	3,57	3820
500	300	28	1072	4810	4290	126,2	5,4	7020

I_x, I_y	moment of inertia
W_x, Z_x	elastic and plastic bending restistance
I_t	S:t Venants torsion constant
I_w	warping constant

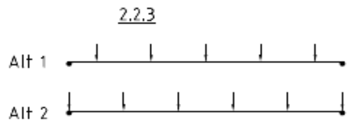
Structure number 2.2.3

a) Beam analysis - take no bracings into account - free LTB

						BSK 2007		
HEB	**z_g** [mm]	**C_1**	**C_2**	**M_cr** [kNm]	**lambda**	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]
200	100	1,127	0,454	145	1,10	0,65	95,3	7,6
300	150	1,127	0,454	524	0,99	0,73	312,0	25,0
400	200	1,127	0,454	819	1,04	0,69	511,8	40,9
500	250	1,127	0,454	1095	1,10	0,65	717,0	57,4

		Eurocode 3: Design of steel structures - Part 1-1						
HEB		**lambda_0**	**beta**	**alfa_LT**	**phei_LT**	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]
200		0,4	0,75	0,34	1,08	0,64	112,5	9,0
300		0,4	0,75	0,34	0,97	0,71	362,8	29,0
400		0,4	0,75	0,34	1,02	0,67	599,0	47,9
500		0,4	0,75	0,34	1,07	0,64	845,5	67,6

M_cr elastic critical moment with regard to LTB
lambda slenderness factor regarding LTB
w_b reduction factor regarding LTB
z_g the distance between the shear centre and the load application point
C_1, C_2 coefficients depending on the loading and support conditions
lamda_0 value of the plateau length for buckling curves of hot-rolled sections
beta correction factor for buckling curves of hot-rolled sections
alfa_LT imperfection factor
phei_LT help factor
chei_LT reduction factor regarding LTB



Load alternativ
Simplification - assume distributed load

Structure number 2.2.3

b) Beam analysis - take friction into account as bracing force - prevented LTB

Load alternativ 1

				BSK 2007				
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	11,8	23,6	2,0	6,9	29%	not OK
300	1	428,5	34,3	68,6	5,7	13,1	44%	not OK
400	1	740,2	59,2	118,4	9,9	16,5	60%	not OK
500	1	1102,3	88,2	176,4	14,7	19,3	76%	not OK

May full bracing be assumed?

x_1 5 [m] M_1 highest bending moment in the observed beam section
x_2 3 [m] M_2 bending moment in the opposite end of the observed beam section

			BSK 2007		
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	147,4	123,8	10,0	10,0	OK
300	428,5	360,0	6,7	10,0	OK
400	740,2	621,8	6,7	10,0	OK
500	1102,3	925,9	6,7	10,0	OK

Q_brac concentrated load from one beam
F_my friction force capacity
F_con.max design connection force BSK for connection near mid-span
F_con.max design connection force Eurocode 3 for connection near mid-span

				Eurocode 3: Design of steel structures - Part 1-1				
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	14,1	28,3	2,8	20,6	14%	not OK
300	1	514,3	41,1	82,3	8,2	39,2	21%	not OK
400	1	888,3	71,1	142,1	14,2	49,5	29%	not OK
500	1	1322,8	105,8	211,6	21,2	57,8	37%	not OK

Structure number 2.2.3

Load alternativ 2

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	11,8	23,6	2,0	6,9	29%	not OK
300	1	428,5	34,3	68,6	5,7	13,1	44%	not OK
400	1	740,2	59,2	118,4	9,9	16,5	60%	not OK
500	1	1102,3	88,2	176,4	14,7	19,3	76%	not OK

May full bracing be assumed?

x_1	4	[m]
x_2	6	[m]

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	141,5	141,5	10,0	8,3	not OK
300	411,4	411,4	6,7	8,3	OK
400	710,6	710,6	6,7	8,3	OK
500	1058,2	1058,2	6,7	8,3	OK

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	14,1	28,3	2,8	20,6	14%	not OK
300	1	514,3	41,1	82,3	8,2	39,2	21%	not OK
400	1	888,3	71,1	142,1	14,2	49,5	29%	not OK
500	1	1322,8	105,8	211,6	21,2	57,8	37%	not OK

Structure number 2.2.3

c) Beam analysis - deformation limit

d_max= min { L/300= 33,3 = 33,3 [mm]
50,0

d deflection
d_max maximum deflection

With regard to maximum deflection

HEB	**q_d** [kN/m]
200	3,1
300	13,5
400	31,0
500	57,6

- If 'not OK' the maximum load is limited by the deflection

- If 'OK' the maximum load is either the load from a) or, if the demands in b) are fullfilled, the load from b).

From a) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	7,6	83,0	249%	not OK
300	25,0	61,5	184%	not OK
400	40,9	44,0	132%	not OK
500	57,4	33,2	100%	OK

From a) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	9,0	98,0	294%	not OK
300	29,0	71,5	214%	not OK
400	47,9	51,5	155%	not OK
500	67,6	39,1	117%	not OK

From b) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	11,8	128,3	385%	not OK
300	34,3	84,5	253%	not OK
400	59,2	63,7	191%	not OK
500	88,2	51,0	153%	not OK

From b) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	14,1	154,0	462%	not OK
300	41,1	101,3	304%	not OK
400	71,1	76,4	229%	not OK
500	105,8	61,2	184%	not OK

Structure number 2.2.3

d) Beam analysis - The design load

BSK 2007		
HEB	**q_d max** [kN/m]	**Limited by**
200	3,1	c) Deflection
300	13,5	c) Deflection
400	31,0	c) Deflection
500	57,4	b) Free LTB

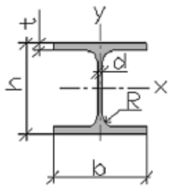
Eurocode 3: Design of steel structures - Part 1-1		
HEB	**q_d max** [kN/m]	**Limited by**
200	3,1	c) Deflection
300	13,5	c) Deflection
400	31,0	c) Deflection
500	57,6	c) Deflection

Structure number 2.2.4

Steel beam on steel beam, span length 10 m, centre distance bracings 2,5 m

Input data

gamma_n	1,2		partial factor with regard to safety class (Safety class 3), only BSK 2007
gamma_m	1		partial factor with regard to uncertainties in determining resistance
gamma_my	2		partial factor with regard to friction
f_yk	275	[MPa]	characteristic yield stress
f_yd	229	[MPa]	design yield stress, only BSK 2007
E_k	210	[GPa]	Young modulus
G_k	80,77	[Gpa]	shear modulus
my	0,2		friction coefficient between steel and timber
my_db	0,08		BSK 2007, design friction coefficient between steel and timber
my_de	0,1		Eurocode 3, design friction coefficient between steel and timber
L_beam	10	[m]	beam span length
s_brac	2,5	[m]	distance between timber wailings/bracing points



HEB **h** [mm]	**b** [mm]	**t_flange** [mm]	**I_x** [10^6x mm^4]	**Z_x** [10^3x mm^3]	**W_x** [10^3x mm^3]	**I_y** [10^6x mm^4]	**I_t** [10^6 x mm^4]	**I_w** [10^9 x mm^6]
200	200	15	56,96	643	570	20,03	0,595	171
300	300	19	251,7	1870	1680	85,63	1,86	1690
400	300	24	576,8	3230	2880	108,2	3,57	3820
500	300	28	1072	4810	4290	126,2	5,4	7020

I_x, I_y	moment of inertia
W_x, Z_x	elastic and plastic bending restistance
I_t	S:t Venants torsion constant
I_w	warping constant

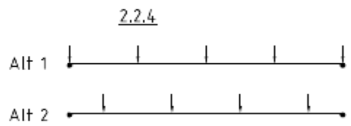
Structure number 2.2.4

a) Beam analysis - take no bracings into account - free LTB

						BSK 2007		
HEB	**z_g** [mm]	**C_1**	**C_2**	**M_cr** [kNm]	**lambda**	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]
200	100	1,127	0,454	145	1,10	0,65	95,3	7,6
300	150	1,127	0,454	524	0,99	0,73	312,0	25,0
400	200	1,127	0,454	819	1,04	0,69	511,8	40,9
500	250	1,127	0,454	1095	1,10	0,65	717,0	57,4

		Eurocode 3: Design of steel structures - Part 1-1						
HEB		**lambda_0**	**beta**	**alfa_LT**	**phei_LT**	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]
200		0,4	0,75	0,34	1,08	0,64	112,5	9,0
300		0,4	0,75	0,34	0,97	0,71	362,8	29,0
400		0,4	0,75	0,34	1,02	0,67	599,0	47,9
500		0,4	0,75	0,34	1,07	0,64	845,5	67,6

M_cr	elastic critical moment with regard to LTB
lambda	slenderness factor regarding LTB
w_b	reduction factor regarding LTB
z_g	the distance between the shear centre and the load application point
C_1, C_2	coefficients depending on the loading and support conditions
lamda_0	value of the plateau length for buckling curves of hot-rolled sections
beta	correction factor for buckling curves of hot-rolled sections
alfa_LT	imperfection factor
phei_LT	help factor
chei_LT	reduction factor regarding LTB



Load alternativ
Simplification - assume distributed load

Structure number 2.2.4

b) Beam analysis - take friction into account as bracing force - prevented LTB

Load alternativ 1

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	11,8	29,5	2,5	6,9	36%	not OK
300	1	428,5	34,3	85,7	7,1	13,1	55%	not OK
400	1	740,2	59,2	148,0	12,3	16,5	75%	not OK
500	1	1102,3	88,2	220,5	18,4	19,3	95%	not OK

May full bracing be assumed?

x_1	5	[m]	M_1	highest bending moment in the observed beam section
x_2	2,5	[m]	M_2	bending moment in the opposite end of the observed beam section

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	147,4	110,5	12,5	10,9	not OK
300	428,5	321,4	8,3	10,9	OK
400	740,2	555,2	8,3	10,9	OK
500	1102,3	826,7	8,3	10,9	OK

Q_brac	concentrated load from one beam
F_my	friction force capacity
F_con.max	design connection force BSK for connection near mid-span
F_con.max	design connection force Eurocode 3 for connection near mid-span

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	14,1	35,4	3,5	20,6	17%	not OK
300	1	514,3	41,1	102,9	10,3	39,2	26%	not OK
400	1	888,3	71,1	177,7	17,8	49,5	36%	not OK
500	1	1322,8	105,8	264,6	26,5	57,8	46%	not OK

Structure number 2.2.4

Load alternativ 2

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	11,8	29,5	2,5	6,9	36%	not OK
300	1	428,5	34,3	85,7	7,1	13,1	55%	not OK
400	1	740,2	59,2	148,0	12,3	16,5	75%	not OK
500	1	1102,3	88,2	220,5	18,4	19,3	95%	not OK

May full bracing be assumed?

x_1 3,75 [m]
x_2 6,25 [m]

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	138,1	138,1	12,5	8,3	not OK
300	401,8	401,8	8,3	8,3	OK
400	693,9	693,9	8,3	8,3	OK
500	1033,4	1033,4	8,3	8,3	OK

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	14,1	35,4	3,5	20,6	17%	not OK
300	1	514,3	41,1	102,9	10,3	39,2	26%	not OK
400	1	888,3	71,1	177,7	17,8	49,5	36%	not OK
500	1	1322,8	105,8	264,6	26,5	57,8	46%	not OK

Structure number 2.2.4

c) Beam analysis - deformation limit

d_max= min { L/300= 33,3 = 33,3 [mm]
50,0

d deflection
d_max maximum deflection

With regard to maximum deflection

HEB	**q_d** [kN/m]
200	3,1
300	13,5
400	31,0
500	57,6

- If 'not OK' the maximum load is limited by the deflection

- If 'OK' the maximum load is either the load from a) or, if the demands in b) are fullfilled, the load from b).

From a) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	7,6	83,0	249%	not OK
300	25,0	61,5	184%	not OK
400	40,9	44,0	132%	not OK
500	57,4	33,2	100%	OK

From a) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	9,0	98,0	294%	not OK
300	29,0	71,5	214%	not OK
400	47,9	51,5	155%	not OK
500	67,6	39,1	117%	not OK

From b) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	11,8	128,3	385%	not OK
300	34,3	84,5	253%	not OK
400	59,2	63,7	191%	not OK
500	88,2	51,0	153%	not OK

From b) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	14,1	154,0	462%	not OK
300	41,1	101,3	304%	not OK
400	71,1	76,4	229%	not OK
500	105,8	61,2	184%	not OK

Structure number 2.2.4

d) Beam analysis - The design load

BSK 2007		
HEB	**q_d max** [kN/m]	**Limited by**
200	3,1	c) Deflection
300	13,5	c) Deflection
400	31,0	c) Deflection
500	57,4	b) Free LTB

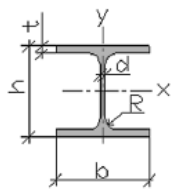
Eurocode 3: Design of steel structures - Part 1-1		
HEB	**q_d max** [kN/m]	**Limited by**
200	3,1	c) Deflection
300	13,5	c) Deflection
400	31,0	c) Deflection
500	57,6	c) Deflection

Structure number 2.3.1

Steel beam on steel beam, span length 15 m, centre distance bracings 1 m

Input data

gamma_n	1,2		partial factor with regard to safety class (Safety class 3), only BSK 2007
gamma_m	1		partial factor with regard to uncertainties in determining resistance
gamma_my	2		partial factor with regard to friction
f_yk	275	[MPa]	characteristic yield stress
f_yd	229	[MPa]	design yield stress, only BSK 2007
E_k	210	[GPa]	Young modulus
G_k	80,77	[Gpa]	shear modulus
my	0,2		friction coefficient between steel and timber
my_db	0,08		BSK 2007, design friction coefficient between steel and timber
my_de	0,1		Eurocode 3, design friction coefficient between steel and timber
L_beam	15	[m]	beam span length
s_brac	1	[m]	distance between timber wailings/bracing points



HEB **h** [mm]	**b** [mm]	**t_flange** [mm]	**I_x** [10^6x mm^4]	**Z_x** [10^3x mm^3]	**W_x** [10^3x mm^3]	**I_y** [10^6x mm^4]	**I_t** [10^6 x mm^4]	**I_w** [10^9 x mm^6]
200	200	15	56,96	643	570	20,03	0,595	171
300	300	19	251,7	1870	1680	85,63	1,86	1690
400	300	24	576,8	3230	2880	108,2	3,57	3820
500	300	28	1072	4810	4290	126,2	5,4	7020

I_x, I_y	moment of inertia
W_x, Z_x	elastic and plastic bending restistance
I_t	S:t Venants torsion constant
I_w	warping constant

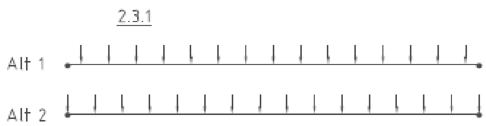
Structure number 2.3.1

a) Beam analysis - take no bracings into account - free LTB

						BSK 2007		
HEB	**z_g** [mm]	**C_1**	**C_2**	**M_cr** [kNm]	**lambda**	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]
200	100	1,127	0,454	99	1,34	0,50	73,3	2,6
300	150	1,127	0,454	351	1,21	0,58	246,7	8,8
400	200	1,127	0,454	546	1,28	0,53	395,4	14,1
500	250	1,127	0,454	724	1,35	0,49	539,8	19,2

		Eurocode 3: Design of steel structures - Part 1-1					
HEB	**lambda_0**	**beta**	**alfa_LT**	**phei_LT**	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]
200	0,4	0,75	0,34	1,33	0,50	89,1	3,2
300	0,4	0,75	0,34	1,19	0,57	295,0	10,5
400	0,4	0,75	0,34	1,26	0,54	476,9	17,0
500	0,4	0,75	0,34	1,35	0,50	657,0	23,4

M_cr	elastic critical moment with regard to LTB
lambda	slenderness factor regarding LTB
w_b	reduction factor regarding LTB
z_g	the distance between the shear centre and the load application point
C_1, C_2	coefficients depending on the loading and support conditions
lamda_0	value of the plateau length for buckling curves of hot-rolled sections
beta	correction factor for buckling curves of hot-rolled sections
alfa_LT	imperfection factor
phei_LT	help factor
chei_LT	reduction factor regarding LTB



Load alternativ
Simplification - assume distributed load

Structure number 2.3.1

b) Beam analysis - take friction into account as bracing force - prevented LTB

Load alternativ 1

			BSK 2007					
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	5,2	5,2	0,4	6,9	6%	not OK
300	1	428,5	15,2	15,2	1,3	13,1	10%	not OK
400	1	740,2	26,3	26,3	2,2	16,5	13%	not OK
500	1	1102,3	39,2	39,2	3,3	19,3	17%	not OK

May full bracing be assumed?

x_1	7,5	[m]		M_1	highest bending moment in the observed beam section
x_2	6,5	[m]		M_2	bending moment in the opposite end of the observed beam section

		BSK 2007			
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	147,4	144,7	5,0	8,5	OK
300	428,5	420,9	3,3	8,5	OK
400	740,2	727,0	3,3	8,5	OK
500	1102,3	1082,7	3,3	8,5	OK

Q_brac	concentrated load from one beam
F_my	friction force capacity
F_con.max	design connection force BSK for connection near mid-span
F_con.max	design connection force Eurocode 3 for connection near mid-span

			Eurocode 3: Design of steel structures - Part 1-1					
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	6,3	6,3	0,6	20,6	3%	not OK
300	1	514,3	18,3	18,3	1,8	39,2	5%	not OK
400	1	888,3	31,6	31,6	3,2	49,5	6%	not OK
500	1	1322,8	47,0	47,0	4,7	57,8	8%	not OK

Full bracing can be assumed, see description in Mathcad

Structure number 2.3.1

Load alternativ 2

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	5,2	5,2	0,4	6,9	6%	not OK
300	1	428,5	15,2	15,2	1,3	13,1	10%	not OK
400	1	740,2	26,3	26,3	2,2	16,5	13%	not OK
500	1	1102,3	39,2	39,2	3,3	19,3	17%	not OK

May full bracing be assumed?
x_1 7 [m]
x_2 8 [m]

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	146,7	146,7	5,0	8,3	OK
300	426,6	426,6	3,3	8,3	OK
400	736,9	736,9	3,3	8,3	OK
500	1097,4	1097,4	3,3	8,3	OK

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	6,3	6,3	0,6	20,6	3%	not OK
300	1	514,3	18,3	18,3	1,8	39,2	5%	not OK
400	1	888,3	31,6	31,6	3,2	49,5	6%	not OK
500	1	1322,8	47,0	47,0	4,7	57,8	8%	not OK

Full bracing can be assumed, see description in Mathcad

Structure number 2.3.1

c) Beam analysis - deformation limit

d_max= min { L/300= 50,0 = 50,0 [mm]
50,0

d deflection
d_max maximum deflection

With regard to maximum deflection

HEB	**q_d** [kN/m]
200	0,9
300	4,0
400	9,2
500	17,1

- If 'not OK' the maximum load is limited by the deflection

- If 'OK' the maximum load is either the load from a) or, if the demands in b) are fullfilled, the load from b).

From a) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	2,6	143,7	287%	not OK
300	8,8	109,4	219%	not OK
400	14,1	76,5	153%	not OK
500	19,2	56,2	112%	not OK

From a) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	3,2	174,6	349%	not OK
300	10,5	130,8	262%	not OK
400	17,0	92,3	185%	not OK
500	23,4	68,4	137%	not OK

From b) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	5,2	288,7	577%	not OK
300	15,2	190,0	380%	not OK
400	26,3	143,2	286%	not OK
500	39,2	114,8	230%	not OK

From b) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	6,3	346,5	693%	not OK
300	18,3	228,0	456%	not OK
400	31,6	171,9	344%	not OK
500	47,0	137,7	275%	not OK

Structure number 2.3.1

d) Beam analysis - The design load

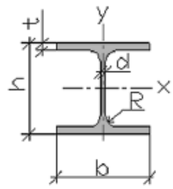
BSK 2007		
HEB	**q_d max** [kN/m]	**Limited by**
200	0,9	c) Deflection
300	4,0	c) Deflection
400	9,2	c) Deflection
500	17,1	c) Deflection

Eurocode 3: Design of steel structures - Part 1-1		
HEB	**q_d max** [kN/m]	**Limited by**
200	0,9	c) Deflection
300	4,0	c) Deflection
400	9,2	c) Deflection
500	17,1	c) Deflection

Structure number 2.3.2
Steel beam on steel beam, span length 15 m, centre distance bracings 1,5 m

Input data

gamma_n	1,2		partial factor with regard to safety class (Safety class 3), only BSK 2007
gamma_m	1		partial factor with regard to uncertainties in determining resistance
gamma_my	2		partial factor with regard to friction
f_yk	275	[MPa]	characteristic yield stress
f_yd	229	[MPa]	design yield stress, only BSK 2007
E_k	210	[GPa]	Young modulus
G_k	80,77	[Gpa]	shear modulus
my	0,2		friction coefficient between steel and timber
my_db	0,08		BSK 2007, design friction coefficient between steel and timber
my_de	0,1		Eurocode 3, design friction coefficient between steel and timber
L_beam	15	[m]	beam span length
s_brac	1,5	[m]	distance between timber wailings/bracing points



HEB **h** [mm]	**b** [mm]	**t_flange** [mm]	**I_x** $[10^6 x\ mm^4]$	**Z_x** $[10^3 x\ mm^3]$	**W_x** $[10^3 x\ mm^3]$	**I_y** $[10^6 x\ mm^4]$	**I_t** $[10^6\ x\ mm^4]$	**I_w** $[10^9\ x\ mm^6]$
200	200	15	56,96	643	570	20,03	0,595	171
300	300	19	251,7	1870	1680	85,63	1,86	1690
400	300	24	576,8	3230	2880	108,2	3,57	3820
500	300	28	1072	4810	4290	126,2	5,4	7020

I_x, I_y moment of inertia
W_x, Z_x elastic and plastic bending restistance
I_t S:t Venants torsion constant
I_w warping constant

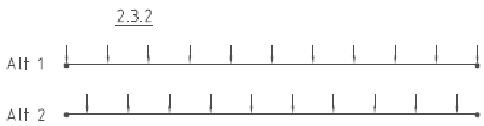
Structure number 2.3.2

a) Beam analysis - take no bracings into account - free LTB

						BSK 2007		
HEB	**z_g** [mm]	**C_1**	**C_2**	**M_cr** [kNm]	**lambda**	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]
200	100	1,127	0,454	99	1,34	0,50	73,3	2,6
300	150	1,127	0,454	351	1,21	0,58	246,7	8,8
400	200	1,127	0,454	546	1,28	0,53	395,4	14,1
500	250	1,127	0,454	724	1,35	0,49	539,8	19,2

	Eurocode 3: Design of steel structures - Part 1-1					
HEB	**lambda_0**	**beta**	**alfa_LT**	**phei_LT**	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]
200	0,4	0,75	0,34	1,33	0,50	89,1	3,2
300	0,4	0,75	0,34	1,19	0,57	295,0	10,5
400	0,4	0,75	0,34	1,26	0,54	476,9	17,0
500	0,4	0,75	0,34	1,35	0,50	657,0	23,4

M_cr	elastic critical moment with regard to LTB
lambda	slenderness factor regarding LTB
w_b	reduction factor regarding LTB
z_g	the distance between the shear centre and the load application point
C_1, C_2	coefficients depending on the loading and support conditions
lamda_0	value of the plateau length for buckling curves of hot-rolled sections
beta	correction factor for buckling curves of hot-rolled sections
alfa_LT	imperfection factor
phei_LT	help factor
chei_LT	reduction factor regarding LTB



Load alternativ
Simplification - assume distributed load

Structure number 2.3.2

b) Beam analysis - take friction into account as bracing force - prevented LTB

Load alternativ 1

			BSK 2007					
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	5,2	7,9	0,7	6,9	10%	not OK
300	1	428,5	15,2	22,9	1,9	13,1	15%	not OK
400	1	740,2	26,3	39,5	3,3	16,5	20%	not OK
500	1	1102,3	39,2	58,8	4,9	19,3	25%	not OK

<u>May full bracing be assumed?</u>

x_1	7,5	[m]	M_1	highest bending moment in the observed beam section
x_2	6	[m]	M_2	bending moment in the opposite end of the observed beam section

			BSK 2007		
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	147,4	141,5	7,5	8,7	OK
300	428,5	411,4	5,0	8,7	OK
400	740,2	710,6	5,0	8,7	OK
500	1102,3	1058,2	5,0	8,7	OK

Q_brac	concentrated load from one beam
F_my	friction force capacity
F_con.max	design connection force BSK for connection near mid-span
F_con.max	design connection force Eurocode 3 for connection near mid-span

			Eurocode 3: Design of steel structures - Part 1-1					
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	6,3	9,4	0,9	20,6	5%	not OK
300	1	514,3	18,3	27,4	2,7	39,2	7%	not OK
400	1	888,3	31,6	47,4	4,7	49,5	10%	not OK
500	1	1322,8	47,0	70,5	7,1	57,8	12%	not OK

Full bracing can be assumed, see description in Mathcad

Structure number 2.3.2

Load alternativ 2

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	5,2	7,9	0,7	6,9	10%	not OK
300	1	428,5	15,2	22,9	1,9	13,1	15%	not OK
400	1	740,2	26,3	39,5	3,3	16,5	20%	not OK
500	1	1102,3	39,2	58,8	4,9	19,3	25%	not OK

May full bracing be assumed?

x_1	6,75	[m]
x_2	8,25	[m]

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	145,9	145,9	7,5	8,3	OK
300	424,3	424,3	5,0	8,3	OK
400	732,8	732,8	5,0	8,3	OK
500	1091,3	1091,3	5,0	8,3	OK

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	6,3	9,4	0,9	20,6	5%	not OK
300	1	514,3	18,3	27,4	2,7	39,2	7%	not OK
400	1	888,3	31,6	47,4	4,7	49,5	10%	not OK
500	1	1322,8	47,0	70,5	7,1	57,8	12%	not OK

Full bracing can be assumed, see description in Mathcad

Structure number 2.3.2

c) Beam analysis - deformation limit

d_max= min { L/300= 50,0 = 50,0 [mm]
50,0

d deflection
d_max maximum deflection

With regard to maximum deflection

HEB	**q_d** [kN/m]
200	0,9
300	4,0
400	9,2
500	17,1

- If 'not OK' the maximum load is limited by the deflection

- If 'OK' the maximum load is either the load from a) or, if the demands in b) are fullfilled, the load from b).

From a) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	2,6	143,7	287%	not OK
300	8,8	109,4	219%	not OK
400	14,1	76,5	153%	not OK
500	19,2	56,2	112%	not OK

From a) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	3,2	174,6	349%	not OK
300	10,5	130,8	262%	not OK
400	17,0	92,3	185%	not OK
500	23,4	68,4	137%	not OK

From b) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	5,2	288,7	577%	not OK
300	15,2	190,0	380%	not OK
400	26,3	143,2	286%	not OK
500	39,2	114,8	230%	not OK

From b) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	6,3	346,5	693%	not OK
300	18,3	228,0	456%	not OK
400	31,6	171,9	344%	not OK
500	47,0	137,7	275%	not OK

Structure number 2.3.2

d) Beam analysis - The design load

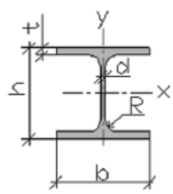
BSK 2007		
HEB	**q_d max** [kN/m]	**Limited by**
200	0,9	c) Deflection
300	4,0	c) Deflection
400	9,2	c) Deflection
500	17,1	c) Deflection

Eurocode 3: Design of steel structures - Part 1-1		
HEB	**q_d max** [kN/m]	**Limited by**
200	0,9	c) Deflection
300	4,0	c) Deflection
400	9,2	c) Deflection
500	17,1	c) Deflection

Structure number 2.3.3
Steel beam on steel beam, span length 15 m, centre distance bracings 2 m

Input data

gamma_n	1,2		partial factor with regard to safety class (Safety class 3), only BSK 2007
gamma_m	1		partial factor with regard to uncertainties in determining resistance
gamma_my	2		partial factor with regard to friction
f_yk	275	[MPa]	characteristic yield stress
f_yd	229	[MPa]	design yield stress, only BSK 2007
E_k	210	[GPa]	Young modulus
G_k	80,77	[Gpa]	shear modulus
my	0,2		friction coefficient between steel and timber
my_db	0,08		BSK 2007, design friction coefficient between steel and timber
my_de	0,1		Eurocode 3, design friction coefficient between steel and timber
L_beam	15	[m]	beam span length
s_brac	2	[m]	distance between timber wailings/bracing points



HEB **h** [mm]	**b** [mm]	**t_flange** [mm]	**I_x** [10^6x mm^4]	**Z_x** [10^3x mm^3]	**W_x** [10^3x mm^3]	**I_y** [10^6x mm^4]	**I_t** [10^6 x mm^4]	**I_w** [10^9 x mm^6]
200	200	15	56,96	643	570	20,03	0,595	171
300	300	19	251,7	1870	1680	85,63	1,86	1690
400	300	24	576,8	3230	2880	108,2	3,57	3820
500	300	28	1072	4810	4290	126,2	5,4	7020

I_x, I_y	moment of inertia
W_x, Z_x	elastic and plastic bending restistance
I_t	S:t Venants torsion constant
I_w	warping constant

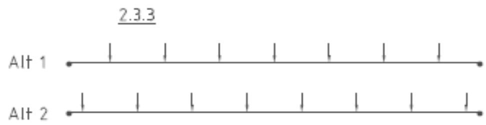
Structure number 2.3.3

a) Beam analysis - take no bracings into account - free LTB

						BSK 2007		
HEB	**z_g** [mm]	**C_1**	**C_2**	**M_cr** [kNm]	**lambda**	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]
200	100	1,127	0,454	99	1,34	0,50	73,3	2,6
300	150	1,127	0,454	351	1,21	0,58	246,7	8,8
400	200	1,127	0,454	546	1,28	0,53	395,4	14,1
500	250	1,127	0,454	724	1,35	0,49	539,8	19,2

		Eurocode 3: Design of steel structures - Part 1-1						
HEB		**lambda_0**	**beta**	**alfa_LT**	**phei_LT**	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]
200		0,4	0,75	0,34	1,33	0,50	89,1	3,2
300		0,4	0,75	0,34	1,19	0,57	295,0	10,5
400		0,4	0,75	0,34	1,26	0,54	476,9	17,0
500		0,4	0,75	0,34	1,35	0,50	657,0	23,4

M_cr	elastic critical moment with regard to LTB
lambda	slenderness factor regarding LTB
w_b	reduction factor regarding LTB
z_g	the distance between the shear centre and the load application point
C_1, C_2	coefficients depending on the loading and support conditions
lamda_0	value of the plateau length for buckling curves of hot-rolled sections
beta	correction factor for buckling curves of hot-rolled sections
alfa_LT	imperfection factor
phei_LT	help factor
chei_LT	reduction factor regarding LTB



Load alternativ
Simplification - assume distributed load

Structure number 2.3.3

b) Beam analysis - take friction into account as bracing force - prevented LTB

<u>Load alternativ 1</u>

				BSK 2007				
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	5,2	10,5	0,9	6,9	13%	not OK
300	1	428,5	15,2	30,5	2,5	13,1	19%	not OK
400	1	740,2	26,3	52,6	4,4	16,5	27%	not OK
500	1	1102,3	39,2	78,4	6,5	19,3	34%	not OK

<u>May full bracing be assumed?</u>

x_1	7,5	[m]	M_1	highest bending moment in the observed beam section
x_2	5,5	[m]	M_2	bending moment in the opposite end of the observed beam section

			BSK 2007		
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	147,4	136,9	10,0	9,1	not OK
300	428,5	398,1	6,7	9,1	OK
400	740,2	687,6	6,7	9,1	OK
500	1102,3	1023,9	6,7	9,1	OK

Q_brac	concentrated load from one beam
F_my	friction force capacity
F_con.max	design connection force BSK for connection near mid-span
F_con.max	design connection force Eurocode 3 for connection near mid-span

				Eurocode 3: Design of steel structures - Part 1-1				
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	6,3	12,6	1,3	20,6	6%	not OK
300	1	514,3	18,3	36,6	3,7	39,2	9%	not OK
400	1	888,3	31,6	63,2	6,3	49,5	13%	not OK
500	1	1322,8	47,0	94,1	9,4	57,8	16%	not OK

Structure number 2.3.3

Load alternativ 2

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	5,2	10,5	0,9	6,9	13%	not OK
300	1	428,5	15,2	30,5	2,5	13,1	19%	not OK
400	1	740,2	26,3	52,6	4,4	16,5	27%	not OK
500	1	1102,3	39,2	78,4	6,5	19,3	34%	not OK

May full bracing be assumed?

x_1 6,5 [m]
x_2 8,5 [m]

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	144,7	144,7	10,0	8,3	not OK
300	420,9	420,9	6,7	8,3	OK
400	727,0	727,0	6,7	8,3	OK
500	1082,7	1082,7	6,7	8,3	OK

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	6,3	12,6	1,3	20,6	6%	not OK
300	1	514,3	18,3	36,6	3,7	39,2	9%	not OK
400	1	888,3	31,6	63,2	6,3	49,5	13%	not OK
500	1	1322,8	47,0	94,1	9,4	57,8	16%	not OK

Structure number 2.3.3

c) Beam analysis - deformation limit

d_max= min { L/300= 50,0 = 50,0 [mm]
50,0

d deflection
d_max maximum deflection

With regard to maximum deflection

HEB	**q_d** [kN/m]
200	0,9
300	4,0
400	9,2
500	17,1

- If 'not OK' the maximum load is limited by the deflection

- If 'OK' the maximum load is either the load from a) or, if the demands in b) are fullfilled, the load from b).

From a) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	2,6	143,7	287%	not OK
300	8,8	109,4	219%	not OK
400	14,1	76,5	153%	not OK
500	19,2	56,2	112%	not OK

From a) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	3,2	174,6	349%	not OK
300	10,5	130,8	262%	not OK
400	17,0	92,3	185%	not OK
500	23,4	68,4	137%	not OK

From b) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	5,2	288,7	577%	not OK
300	15,2	190,0	380%	not OK
400	26,3	143,2	286%	not OK
500	39,2	114,8	230%	not OK

From b) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	6,3	346,5	693%	not OK
300	18,3	228,0	456%	not OK
400	31,6	171,9	344%	not OK
500	47,0	137,7	275%	not OK

Structure number 2.3.3

d) Beam analysis - The design load

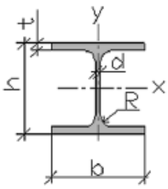
BSK 2007		
HEB	**q_d max** [kN/m]	**Limited by**
200	0,9	c) Deflection
300	4,0	c) Deflection
400	9,2	c) Deflection
500	17,1	c) Deflection

Eurocode 3: Design of steel structures - Part 1-1		
HEB	**q_d max** [kN/m]	**Limited by**
200	0,9	c) Deflection
300	4,0	c) Deflection
400	9,2	c) Deflection
500	17,1	c) Deflection

Structure number 2.3.4
Steel beam on steel beam, span length 15 m, centre distance bracings 2,5 m

Input data

gamma_n	1,2		partial factor with regard to safety class (Safety class 3), only BSK 2007
gamma_m	1		partial factor with regard to uncertainties in determining resistance
gamma_my	2		partial factor with regard to friction
f_yk	275	[MPa]	characteristic yield stress
f_yd	229	[MPa]	design yield stress, only BSK 2007
E_k	210	[GPa]	Young modulus
G_k	80,77	[Gpa]	shear modulus
my	0,2		friction coefficient between steel and timber
my_db	0,08		BSK 2007, design friction coefficient between steel and timber
my_de	0,1		Eurocode 3, design friction coefficient between steel and timber
L_beam	15	[m]	beam span length
s_brac	2,5	[m]	distance between timber wailings/bracing points



HEB **h** [mm]	**b** [mm]	**t_flange** [mm]	**I_x** [10^6x mm^4]	**Z_x** [10^3x mm^3]	**W_x** [10^3x mm^3]	**I_y** [10^6x mm^4]	**I_t** [10^6 x mm^4]	**I_w** [10^9 x mm^6]
200	200	15	56,96	643	570	20,03	0,595	171
300	300	19	251,7	1870	1680	85,63	1,86	1690
400	300	24	576,8	3230	2880	108,2	3,57	3820
500	300	28	1072	4810	4290	126,2	5,4	7020

I_x, I_y	moment of inertia
W_x, Z_x	elastic and plastic bending restistance
I_t	S:t Venants torsion constant
I_w	warping constant

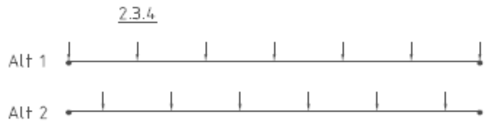
Structure number 2.3.4

a) Beam analysis - take no bracings into account - free LTB

						BSK 2007		
HEB	**z_g** [mm]	**C_1**	**C_2**	**M_cr** [kNm]	**lambda**	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]
200	100	1,127	0,454	99	1,34	0,50	73,3	2,6
300	150	1,127	0,454	351	1,21	0,58	246,7	8,8
400	200	1,127	0,454	546	1,28	0,53	395,4	14,1
500	250	1,127	0,454	724	1,35	0,49	539,8	19,2

		Eurocode 3: Design of steel structures - Part 1-1						
HEB		**lambda_0**	**beta**	**alfa_LT**	**phei_LT**	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]
200		0,4	0,75	0,34	1,33	0,50	89,1	3,2
300		0,4	0,75	0,34	1,19	0,57	295,0	10,5
400		0,4	0,75	0,34	1,26	0,54	476,9	17,0
500		0,4	0,75	0,34	1,35	0,50	657,0	23,4

M_cr elastic critical moment with regard to LTB
lambda slenderness factor regarding LTB
w_b reduction factor regarding LTB
z_g the distance between the shear centre and the load application point
C_1, C_2 coefficients depending on the loading and support conditions
lamda_0 value of the plateau length for buckling curves of hot-rolled sections
beta correction factor for buckling curves of hot-rolled sections
alfa_LT imperfection factor
phei_LT help factor
chei_LT reduction factor regarding LTB



Load alternativ
Simplification - assume distributed load

Analytical calculations
2.3.4

Structure number 2.3.4

b) Beam analysis - take friction into account as bracing force - prevented LTB

<u>Load alternativ 1</u>

			BSK 2007					
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	5,2	13,1	1,1	6,9	16%	not OK
300	1	428,5	15,2	38,1	3,2	13,1	24%	not OK
400	1	740,2	26,3	65,8	5,5	16,5	33%	not OK
500	1	1102,3	39,2	98,0	8,2	19,3	42%	not OK

<u>May full bracing be assumed?</u>

x_1 7,5 [m] M_1 highest bending moment in the observed beam section
x_2 5 [m] M_2 bending moment in the opposite end of the observed beam section

			BSK 2007		
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	147,4	131,0	12,5	9,5	not OK
300	428,5	380,9	8,3	9,5	OK
400	740,2	658,0	8,3	9,5	OK
500	1102,3	979,8	8,3	9,5	OK

Q_brac concentrated load from one beam
F_my friction force capacity
F_con.max design connection force BSK for connection near mid-span
F_con.max design connection force Eurocode 3 for connection near mid-span

			Eurocode 3: Design of steel structures - Part 1-1					
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	6,3	15,7	1,6	20,6	8%	not OK
300	1	514,3	18,3	45,7	4,6	39,2	12%	not OK
400	1	888,3	31,6	79,0	7,9	49,5	16%	not OK
500	1	1322,8	47,0	117,6	11,8	57,8	20%	not OK

Structure number 2.3.4

Load alternativ 2

BSK 2007								
HEB	**w_b**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	147,4	5,2	13,1	1,1	6,9	16%	not OK
300	1	428,5	15,2	38,1	3,2	13,1	24%	not OK
400	1	740,2	26,3	65,8	5,5	16,5	33%	not OK
500	1	1102,3	39,2	98,0	8,2	19,3	42%	not OK

May full bracing be assumed?

x_1	6,25	[m]
x_2	8,75	[m]

BSK 2007					
HEB	**M_1** [kNm]	**M_2** [kNm]	**Left side**	**Right side**	**Test**
200	143,3	143,3	12,5	8,3	not OK
300	416,6	416,6	8,3	8,3	OK
400	719,6	719,6	8,3	8,3	OK
500	1071,7	1071,7	8,3	8,3	OK

Eurocode 3: Design of steel structures - Part 1-1								
HEB	**chei_LT**	**M_Rd** [kNm]	**q_d** [kN/m]	**Q_brac** [kN]	**F_my** [kN]	**F_con.max** [kN]	**F_my / F_con.max**	
200	1	176,8	6,3	15,7	1,6	20,6	8%	not OK
300	1	514,3	18,3	45,7	4,6	39,2	12%	not OK
400	1	888,3	31,6	79,0	7,9	49,5	16%	not OK
500	1	1322,8	47,0	117,6	11,8	57,8	20%	not OK

Structure number 2.3.4

c) Beam analysis - deformation limit

$$d\_max = \min \begin{cases} L/300 = 50{,}0 \\ 50{,}0 \end{cases} = 50{,}0 \text{ [mm]}$$

d deflection
d_max maximum deflection

With regard to maximum deflection

HEB	**q_d** [kN/m]
200	0,9
300	4,0
400	9,2
500	17,1

- If 'not OK' the maximum load is limited by the deflection

- If 'OK' the maximum load is either the load from a) or, if the demands in b) are fullfilled, the load from b).

From a) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	2,6	143,7	287%	not OK
300	8,8	109,4	219%	not OK
400	14,1	76,5	153%	not OK
500	19,2	56,2	112%	not OK

From a) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	3,2	174,6	349%	not OK
300	10,5	130,8	262%	not OK
400	17,0	92,3	185%	not OK
500	23,4	68,4	137%	not OK

From b) - BSK 2007

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	5,2	288,7	577%	not OK
300	15,2	190,0	380%	not OK
400	26,3	143,2	286%	not OK
500	39,2	114,8	230%	not OK

From b) - Eurocode 3

HEB	**q_d** [kN/m]	**d** [mm]	**d / d_max**	
200	6,3	346,5	693%	not OK
300	18,3	228,0	456%	not OK
400	31,6	171,9	344%	not OK
500	47,0	137,7	275%	not OK

Structure number 2.3.4

d) Beam analysis - The design load

BSK 2007		
HEB	**q_d max** [kN/m]	**Limited by**
200	0,9	c) Deflection
300	4,0	c) Deflection
400	9,2	c) Deflection
500	17,1	c) Deflection

Eurocode 3: Design of steel structures - Part 1-1		
HEB	**q_d max** [kN/m]	**Limited by**
200	0,9	c) Deflection
300	4,0	c) Deflection
400	9,2	c) Deflection
500	17,1	c) Deflection

Appendix B Reasonable Loads for Bridge Formwork

This Appendix includes a MathCAD document that contains the calculations of reasonable load on a bridge formwork beam. The calculation outcome is a load interval that is used when deciding which structure configurations and beam sizes that will be modelled with finite element software.

Reasonable loads for bridge formwork

The purpose of this calculation is to find some approximate limits of the reasonable load distributions for bridge formwork. The limits will be used when deciding which structure configurations and beam sizes to further investigate by FEM software.
The calculations are made with help from Christer Carlsson, supervisor of this Master's Thesis and experienced formwork designer.

Input

Concrete weight for different plate thickness $\rho_c := 25\frac{kN}{m^3}$

Example structure, 1

$h_1 := 0.5m$ concrete thickness

Use steel beams with timber wailings on top.

$s_1 := 1m$ centre distance steel

Thus the line load on one steel beam is:

$$q_1 := h_1 \cdot \rho_c \cdot s_1 = 12.5 \cdot \frac{kN}{m}$$

Example structure, 2

$h_2 := 2m$ concrete thickness (beam)

Use steel beams with other steel beams on top.

$s_2 := 2.5m$ centre distance steel

Thus the line load on one steel beam is:

$$q_2 := h_2 \cdot \rho_c \cdot s_2 = 125 \cdot \frac{kN}{m}$$

Example structure, 3

$h_3 := 0.8m$ concrete thickness

Use steel beams with timber wailings on top.

$s_3 := 1.5m$ centre distance steel

Thus the line load on one steel beam is:

$$q_3 := h_3 \cdot \rho_c \cdot s_3 = 30 \cdot \frac{kN}{m}$$

Ending comments

Only structures with load capabilities similar to the structures in this document will be treated further

$$q_{min} := q_1 = 12.5 \cdot \frac{kN}{m}$$

$$q_{max} := q_2 = 125 \cdot \frac{kN}{m}$$

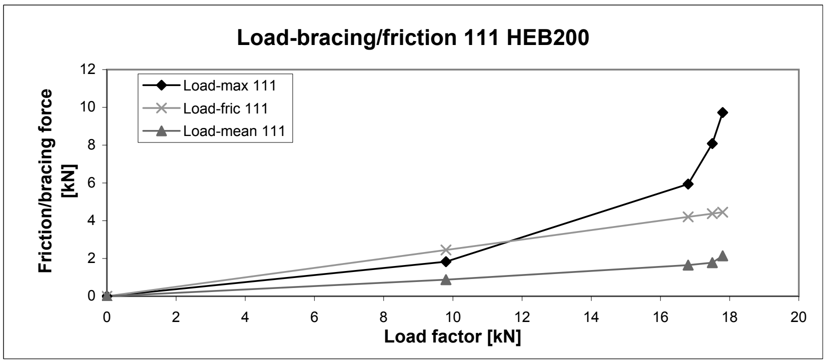
Appendix C Results from Finite Element Analysis - Timber Beams on Steel Beams

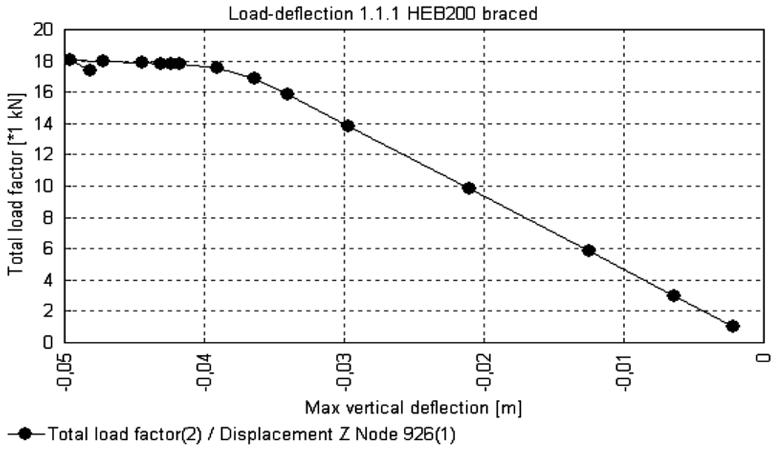
This Appendix includes a excel document with different graphs visualising results from the finite element analyses for each structure configuration and beam size that starts with number 1, i.e. timber beams on steel beams.

Structure 1.1.1 HEB 200

Load factor (=applied load [kN])	Friction Fmy [kN]	Max Fy[kN]	Mean Fy[kN]
0,0	0,00	0,00	0,00
9,8	2,45	1,83	0,88
16,8	4,20	5,94	1,65
17,5	4,38	8,08	1,78
17,8	4,45	9,73	2,14

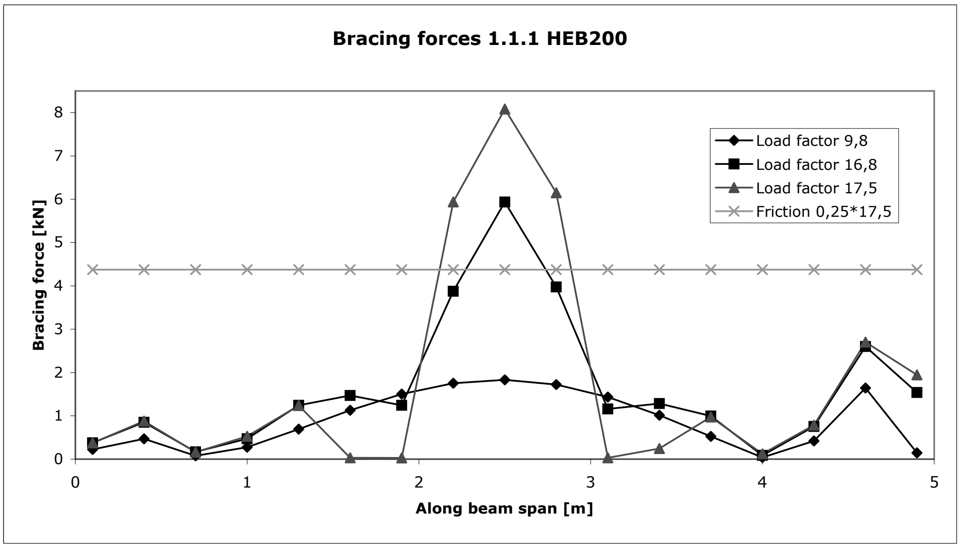
Friction my_d = 0,25





Results Finite Element Analysis
Timber on steel beams

Structure 1.1.1 HEB 200



From analytical calculations

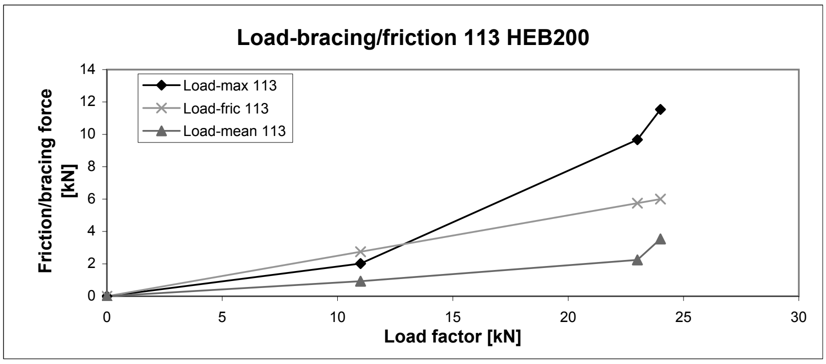
Max load (Eurocode) q_d = 56,6 kN/m which gives P_d = 17,0 kN

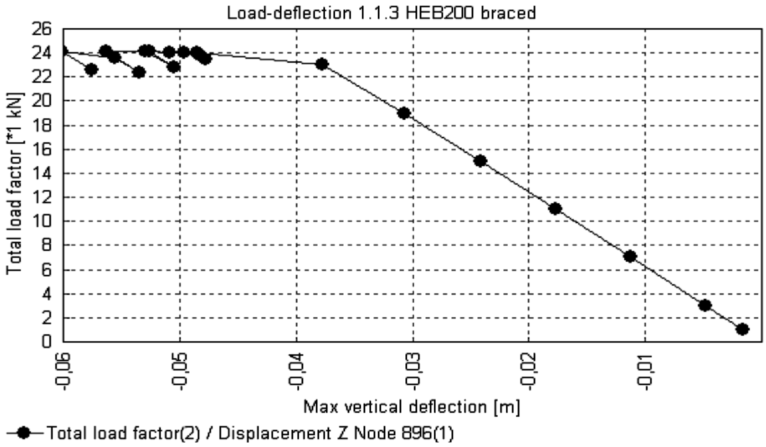
Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	6,9 kN	not OK
Eurocode	F_con.max =	20,6 kN	not OK

Structure 1.1.3 HEB 200

Load factor (=applied load [kN])	Friction Fmy [kN]	Max Fy[kN]	Mean Fy[kN]
0,0	0,00	0	0
11,0	2,75	2,02	0,93
23,0	5,75	9,67	2,25
24,0	6,00	11,54	3,54

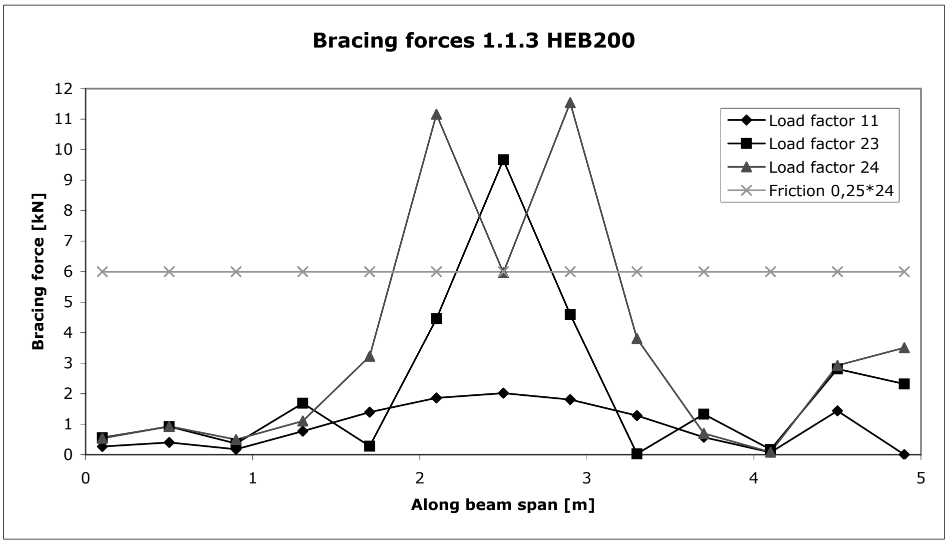
Friction my_d = 0,25





Results Finite Element Analysis
Timber on steel beams

Structure 1.1.3 HEB 200



From analytical calculations

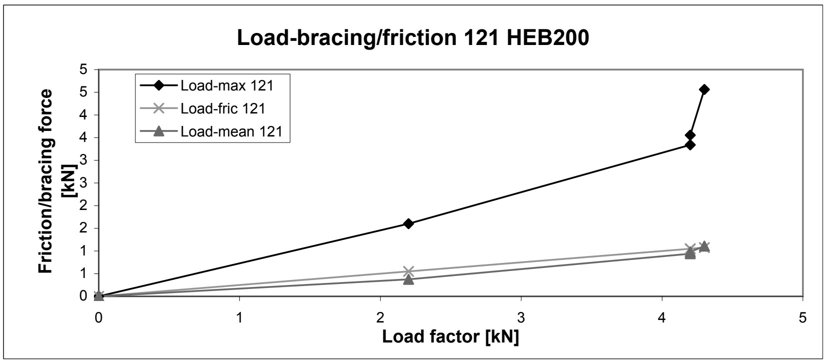
Max load (Eurocode) q_d = 56,6 kN/m which gives P_d = 22,6 kN

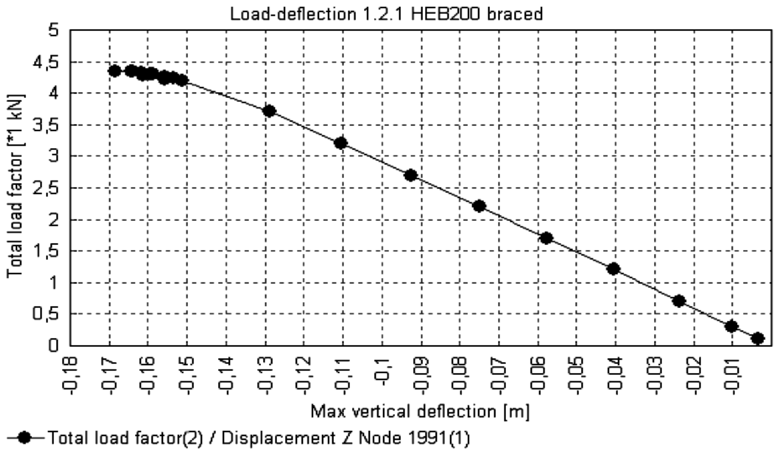
Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	6,9 kN	not OK
Eurocode	F_con.max =	20,6 kN	not OK

Structure 1.2.1 HEB 200

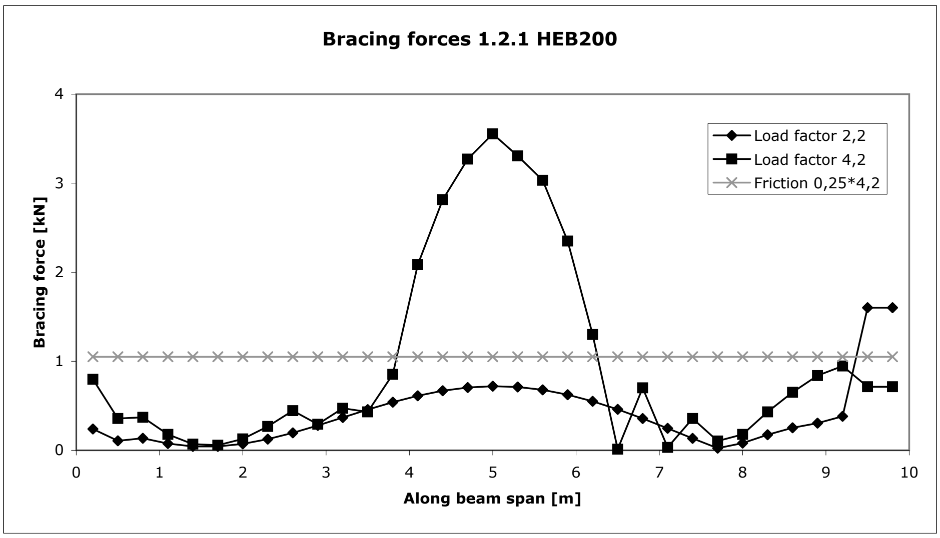
Load factor (=applied load [kN])	Friction Fmy [kN]	Max Fy[kN]	Mean Fy[kN]
0,0	0,00	0,00	0,00
2,2	0,55	1,60	0,37
4,2	1,05	3,34	0,94
4,2	1,05	3,55	0,98
4,3	1,08	4,56	1,11

Friction my_d = 0,25





Structure 1.2.1 HEB 200



From analytical calculations

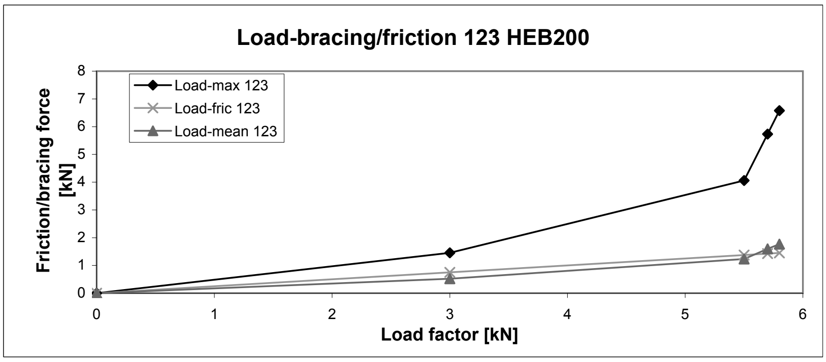
Max load (Eurocode) q_d = 14,1 kN/m which gives P_d = 4,2 kN

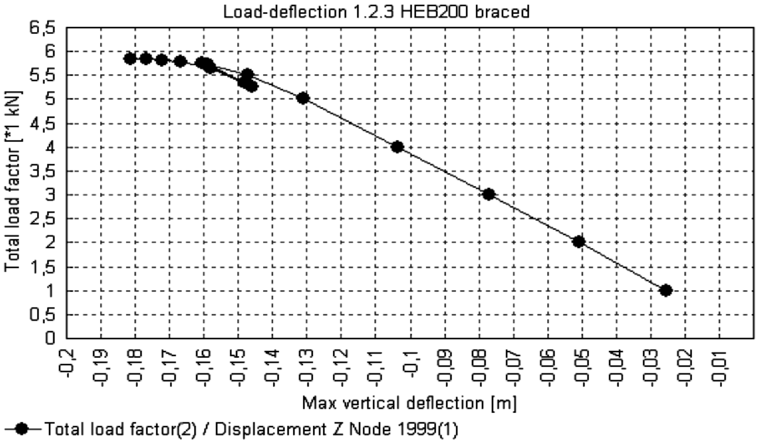
			Friction enough according to calculations?
Needed bracing			
BSK	F_con.max =	6,9 kN	not OK
Eurocode	F_con.max =	20,6 kN	not OK

Structure 1.2.3 HEB 200

Load factor (=applied load [kN])	Friction Fmy [kN]	Max Fy[kN]	Mean Fy[kN]
0,0	0,00	0,00	0,00
3,0	0,75	1,45	0,52
5,5	1,38	4,06	1,23
5,7	1,43	5,73	1,60
5,8	1,45	6,58	1,77

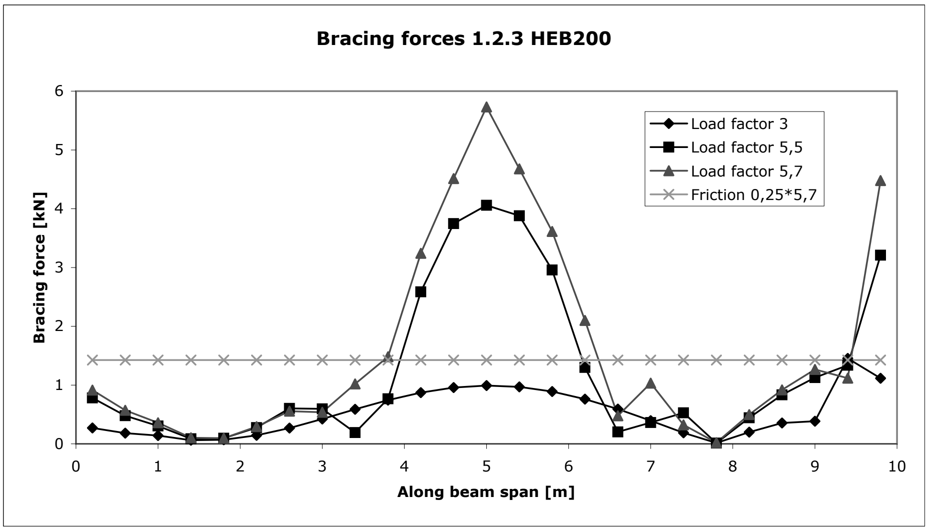
Friction my_d = 0,25





Results Finite Element Analysis
Timber on steel beams

Structure 1.2.3 HEB 200



From analytical calculations

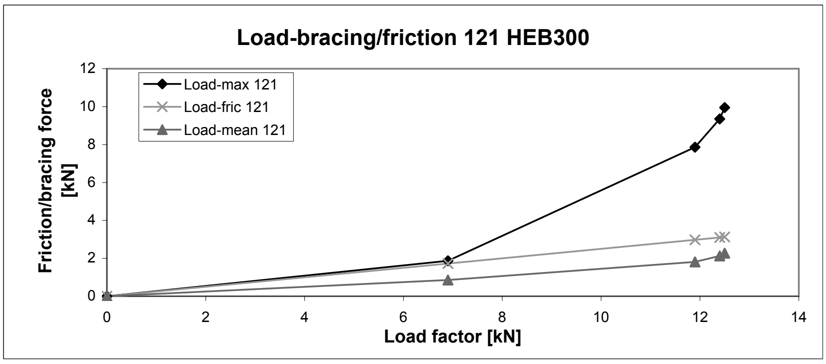
Max load (Eurocode) q_d = 14,1 kN/m which gives P_d = 5,7 kN

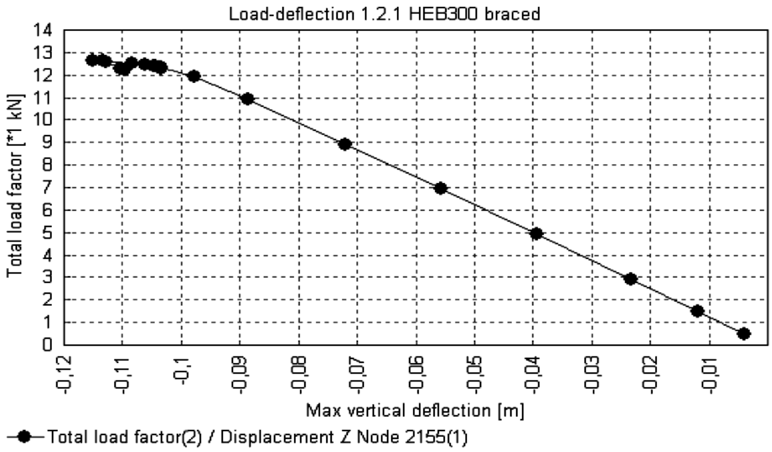
Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	6,9 kN	not OK
Eurocode	F_con.max =	20,6 kN	not OK

Structure 1.2.1 HEB 300

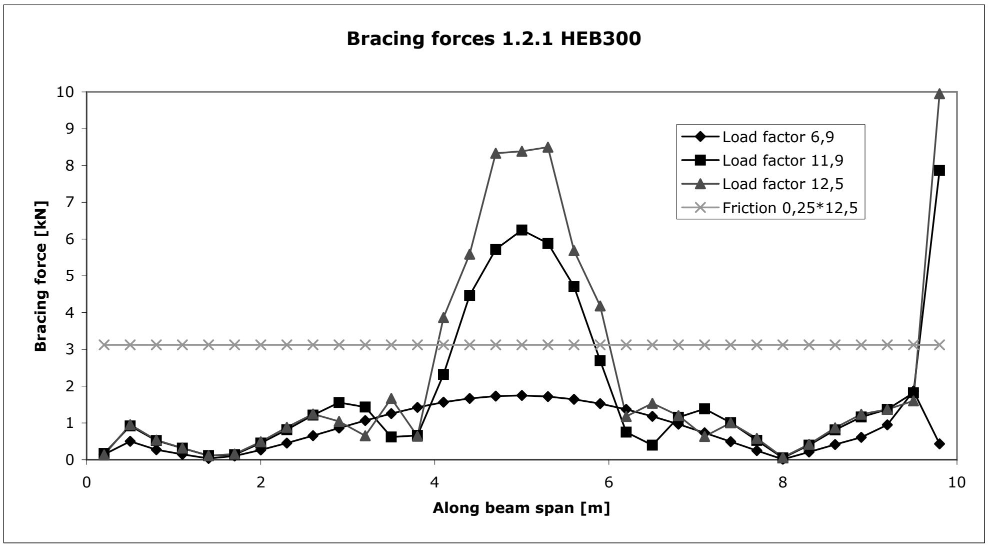
Load factor (=applied load [kN])	Friction Fmy [kN]	Max Fy[kN]	Mean Fy[kN]
0,0	0,00	0,00	0,00
6,9	1,73	1,87	0,86
11,9	2,98	7,86	1,81
12,4	3,10	9,35	2,13
12,5	3,13	9,95	2,27

Friction my_d = 0,25





Structure 1.2.1 HEB 300



From analytical calculations

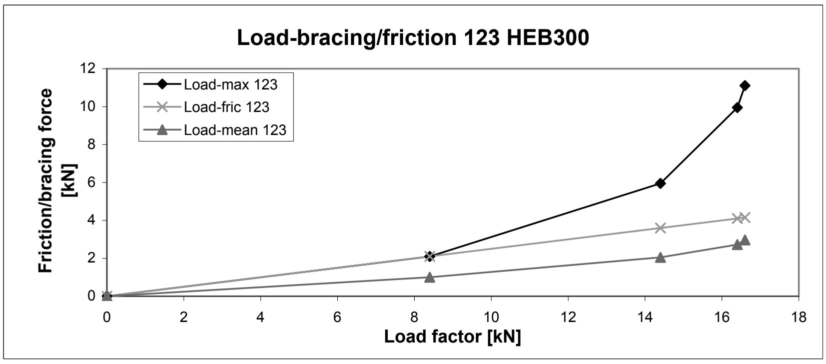
Max load (Eurocode) q_d = 41,1 kN/m which gives P_d = 12,3 kN

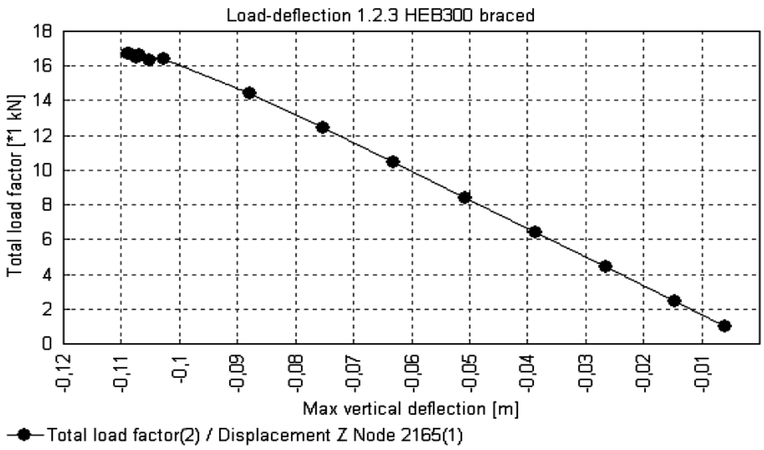
Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	13,1 kN	not OK
Eurocode	F_con.max =	39,2 kN	not OK

Structure 1.2.3 HEB 300

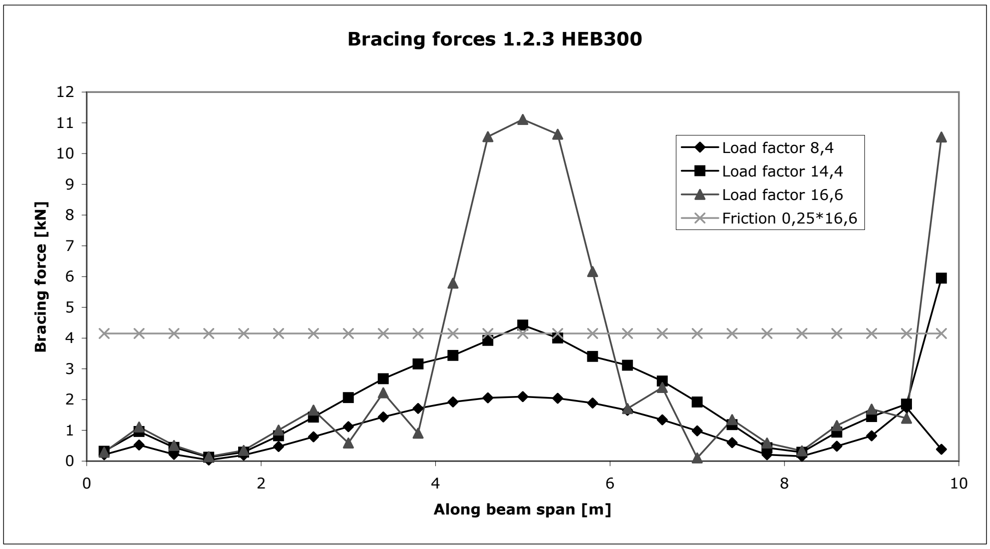
Load factor (=applied load [kN])	Friction Fmy [kN]	Max Fy[kN]	Mean Fy[kN]
0,0	0,00	0	0
8,4	2,10	2,10	1,00
14,4	3,60	5,95	2,05
16,4	4,10	9,95	2,72
16,6	4,15	11,11	2,97

Friction my_d = 0,25





Structure 1.2.3 HEB 300



From analytical calculations

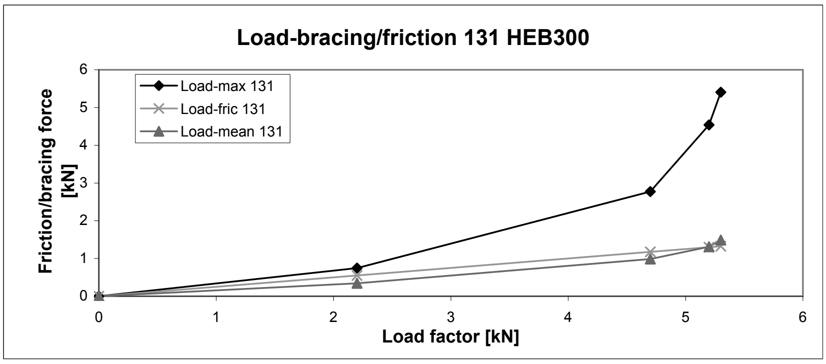
Max load (Eurocode) q_d = 41,1 kN/m which gives P_d = 16,4 kN

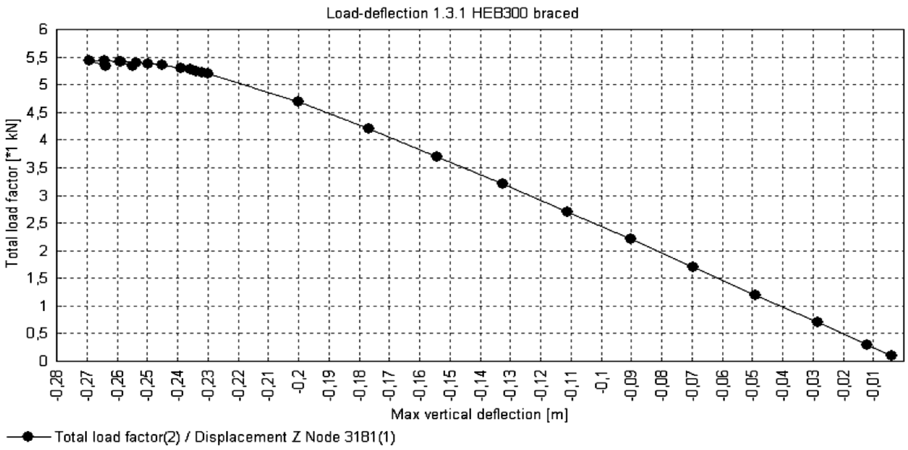
			Friction enough according to calculations?
Needed bracing			
BSK	F_con.max =	13,1 kN	not OK
Eurocode	F_con.max =	39,2 kN	not OK

Structure 1.3.1 HEB 300

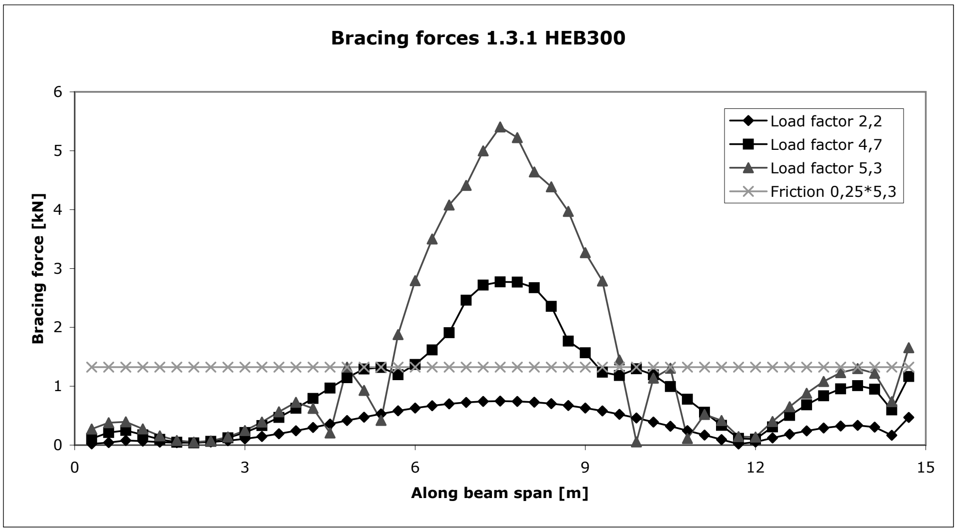
Load factor (=applied load [kN])	Friction Fmy [kN]	Max Fy[kN]	Mean Fy[kN]
0,0	0,00	0,00	0,00
2,2	0,55	0,75	0,34
4,7	1,18	2,77	0,98
5,2	1,30	4,54	1,31
5,3	1,33	5,41	1,49

Friction my_d = 0,25





Structure 1.3.1 HEB 300



From analytical calculations

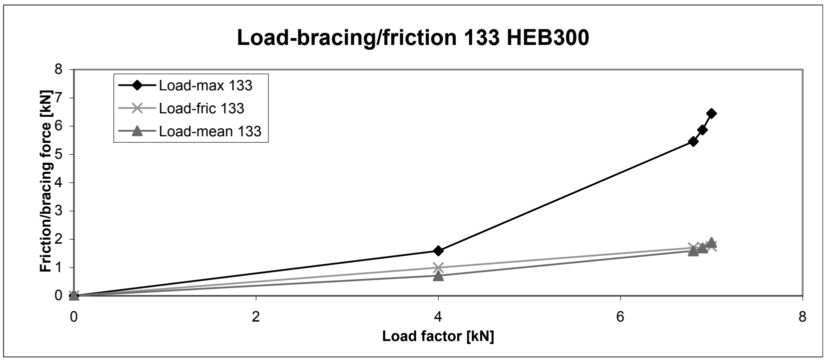
Max load (Eurocode) q_d = 18,3 kN/m which gives P_d = 5,5 kN

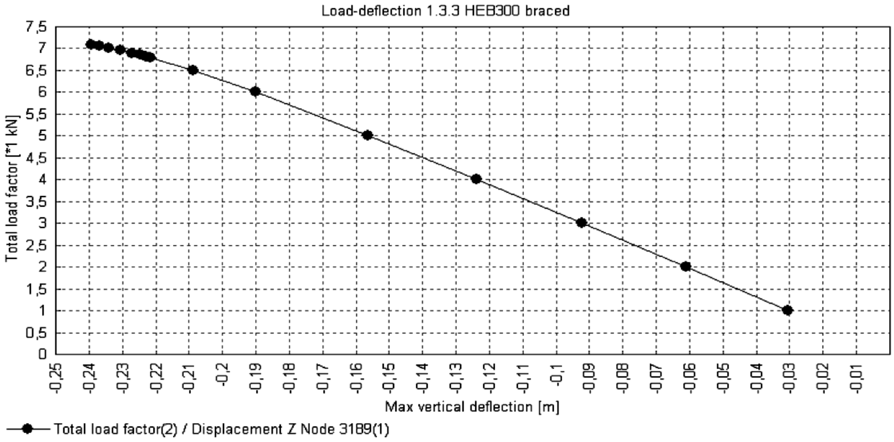
Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	13,1 kN	not OK
Eurocode	F_con.max =	39,2 kN	not OK

Structure 1.3.3 HEB 300

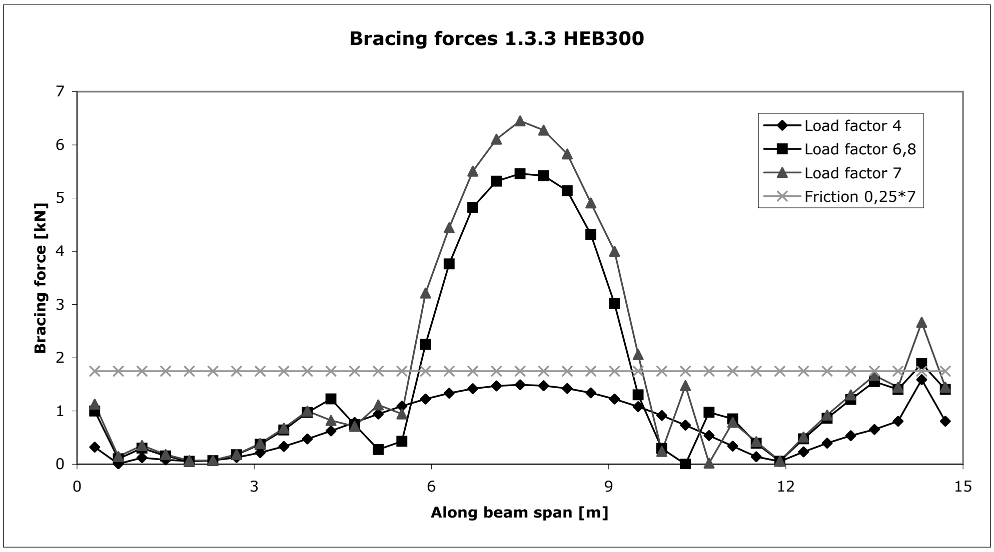
Load factor (=applied load [kN])	Friction Fmy [kN]	Max Fy[kN]	Mean Fy[kN]
0,0	0,00	0,00	0,00
4,0	1,00	1,59	0,71
6,8	1,70	5,46	1,59
6,9	1,73	5,87	1,70
7,0	1,75	6,45	1,89

Friction my_d = 0,25





Structure 1.3.3 HEB 300



From analytical calculations

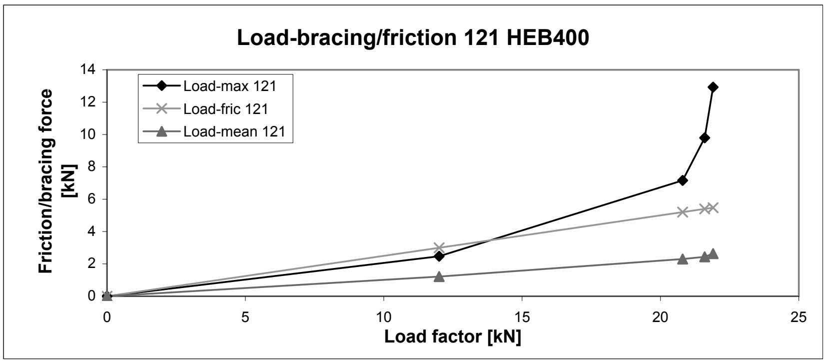
Max load (Eurocode) q_d = 18,3 kN/m which gives P_d = 7,3 kN

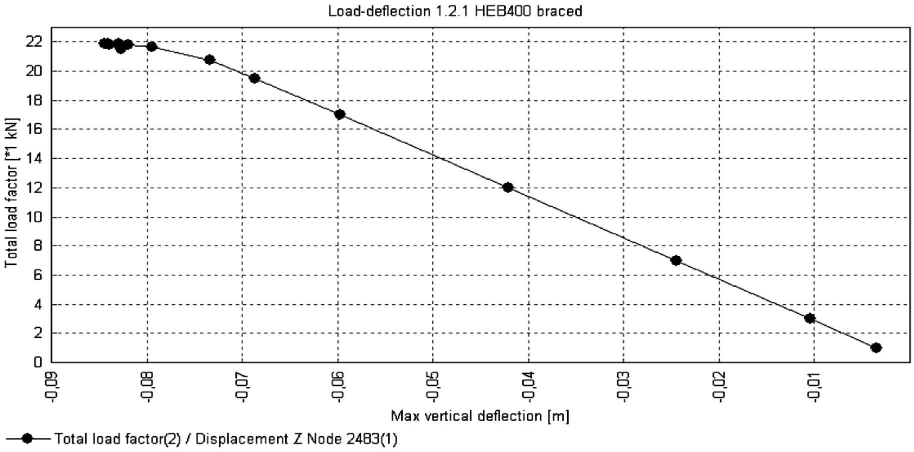
Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	13,1 kN	not OK
Eurocode	F_con.max =	39,2 kN	not OK

Structure 1.2.1 HEB 400

Load factor (=applied load [kN])	Friction Fmy [kN]	Max Fy[kN]	Mean Fy[kN]
0,0	0,00	0,00	0,00
12,0	3,00	2,47	1,22
20,8	5,20	7,16	2,30
21,6	5,40	9,79	2,43
21,9	5,48	12,93	2,64

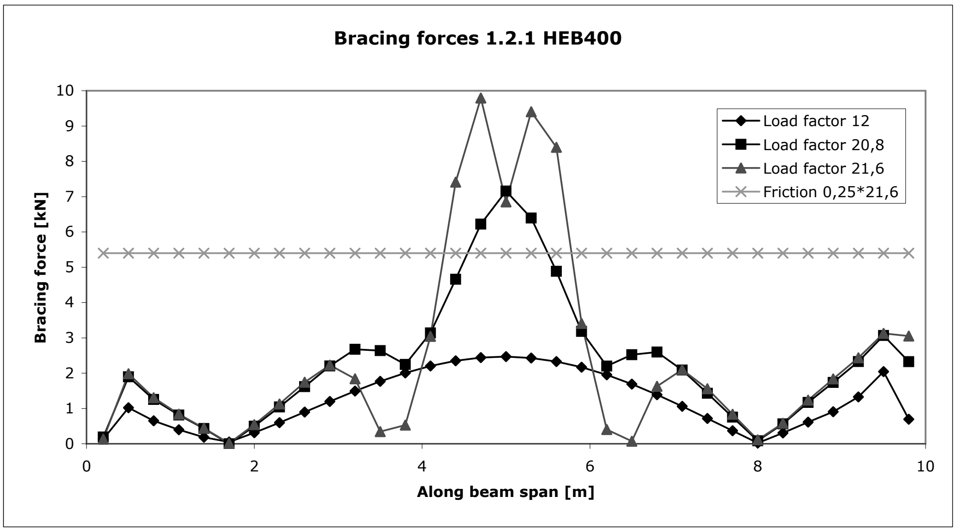
Friction   my_d =   0,25





Results Finite Element Analysis
Timber on steel beams

Structure 1.2.1 HEB 400



From analytical calculations

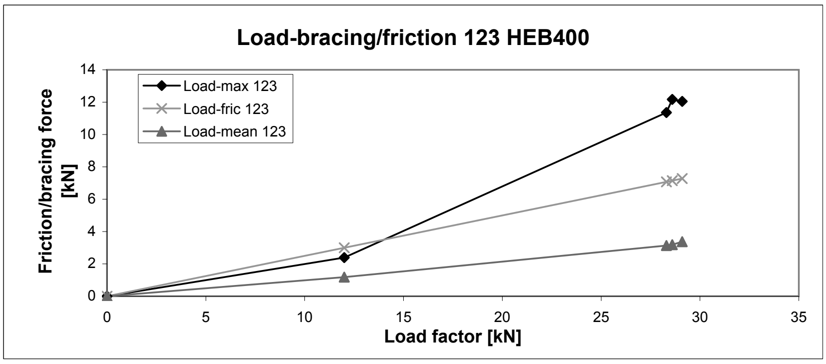
Max load (Eurocode) q_d = 71,1 kN/m which gives P_d = 21,3 kN

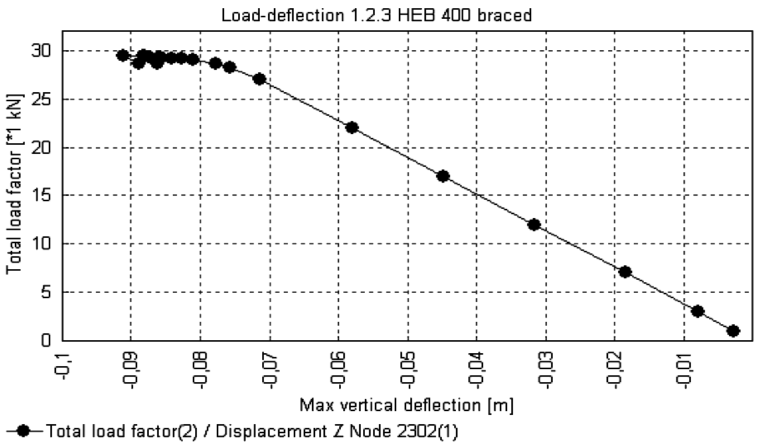
Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	16,5 kN	not OK
Eurocode	F_con.max =	49,5 kN	not OK

Structure 1.2.3 HEB 400

Load factor (=applied load [kN])	Friction Fmy [kN]	Max Fy[kN]	Mean Fy[kN]
0,0	0,00	0	0
12,0	3,00	2,39	1,18
28,3	7,08	11,36	3,13
28,6	7,15	12,17	3,19
29,1	7,28	12,05	3,37

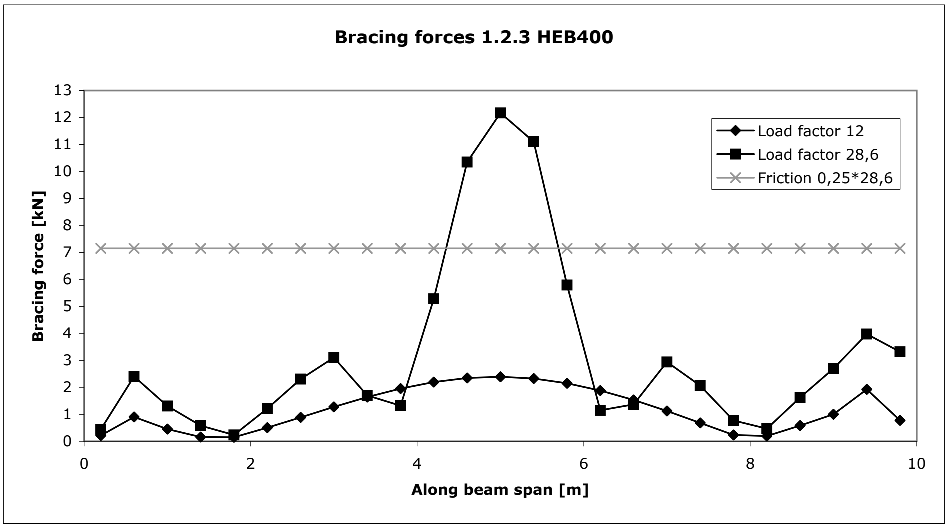
Friction my_d = 0,25





Results Finite Element Analysis
Timber on steel beams

Structure 1.2.3 HEB 400



From analytical calculations

Max load (Eurocode) q_d = 71,1 kN/m which gives P_d = 28,4 kN

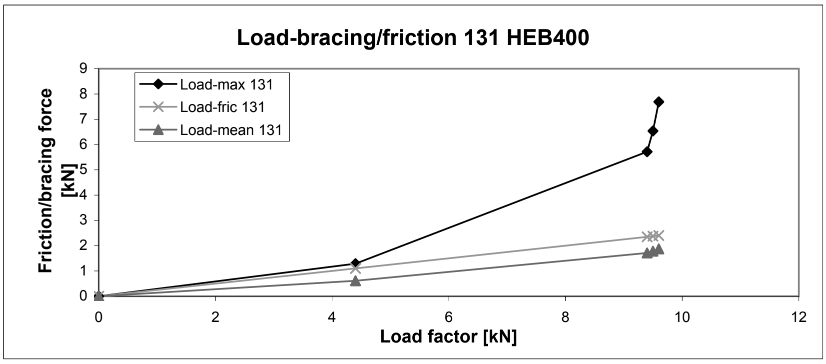
Needed bracing
BSK F_con.max = 16,5 kN
Eurocode F_con.max = 49,5 kN

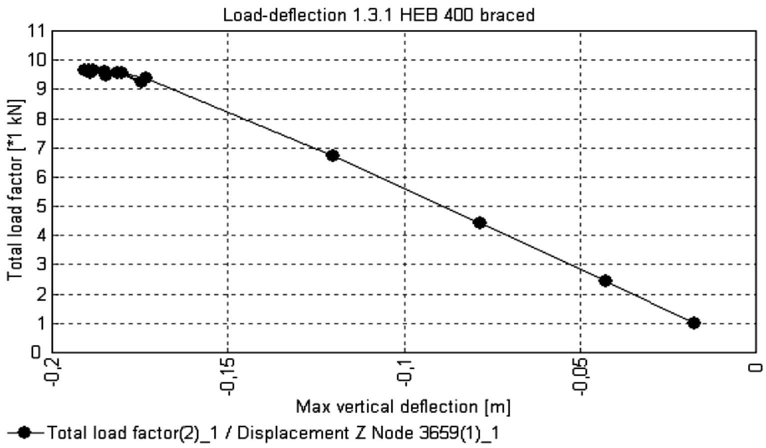
Friction enough according to calculations?
not OK
not OK

Structure 1.3.1 HEB 400

Load factor (=applied load [kN])	Friction Fmy [kN]	Max Fy[kN]	Mean Fy[kN]
0,0	0,00	0,00	0,00
4,4	1,10	1,29	0,61
9,4	2,35	5,72	1,71
9,5	2,38	6,54	1,78
9,6	2,40	7,69	1,88

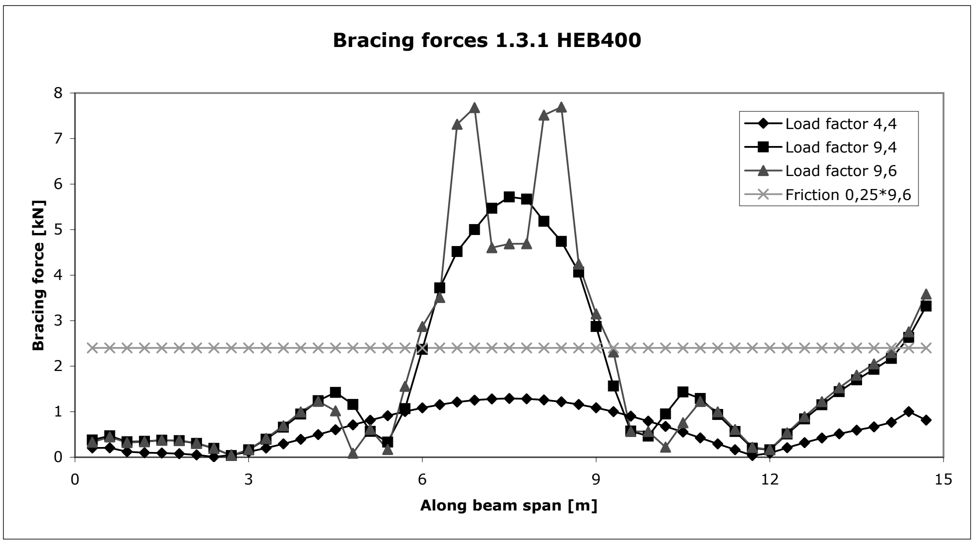
Friction my_d = 0,25





Results Finite Element Analysis
Timber on steel beams

Structure 1.3.1 HEB 400



From analytical calculations

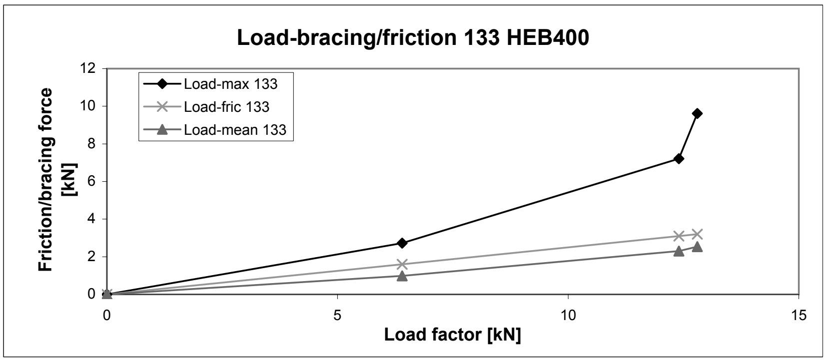
Max load (Eurocode) q_d = 31,6 kN/m which gives P_d = 9,5 kN

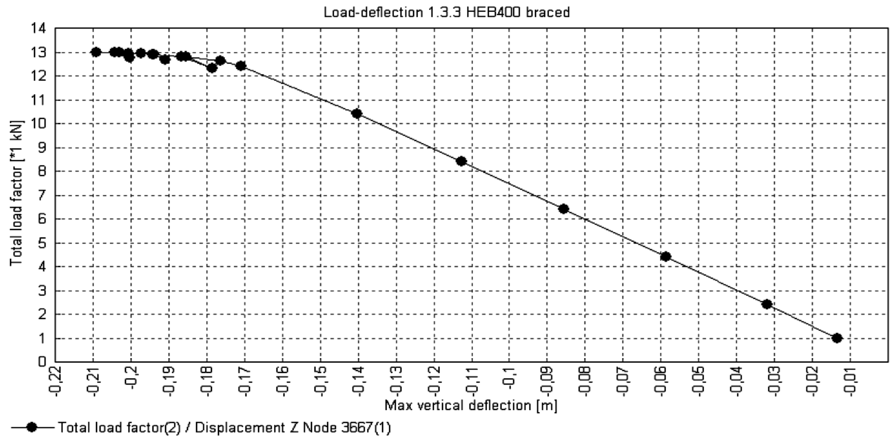
Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	16,5 kN	not OK
Eurocode	F_con.max =	49,5 kN	not OK

Structure 1.3.3 HEB 400

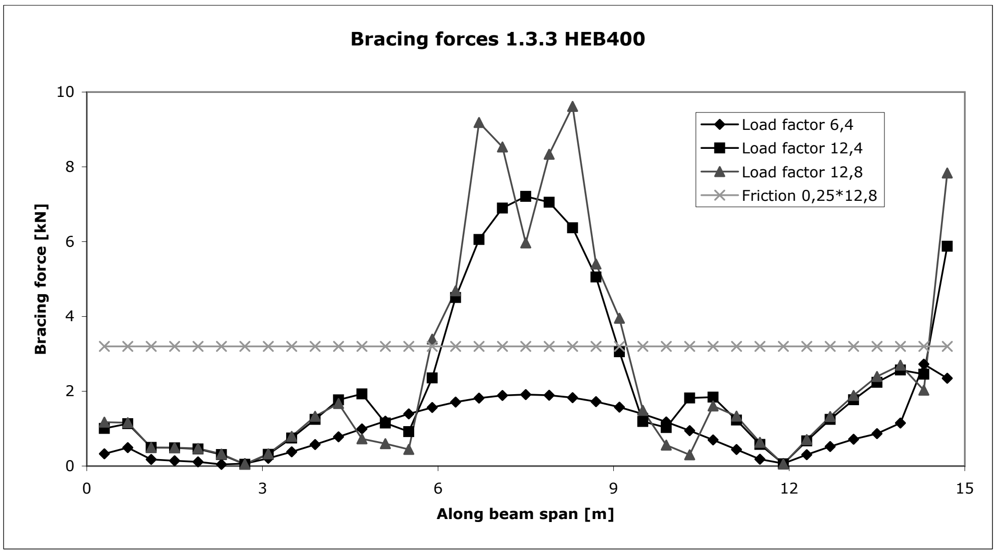
Load factor (=applied load [kN])	Friction Fmy [kN]	Max Fy[kN]	Mean Fy[kN]
0,0	0,00	0,00	0,00
6,4	1,60	2,73	0,98
12,4	3,10	7,21	2,30
12,8	3,20	9,62	2,54

Friction my_d = 0,25





Structure 1.3.3 HEB 400



From analytical calculations

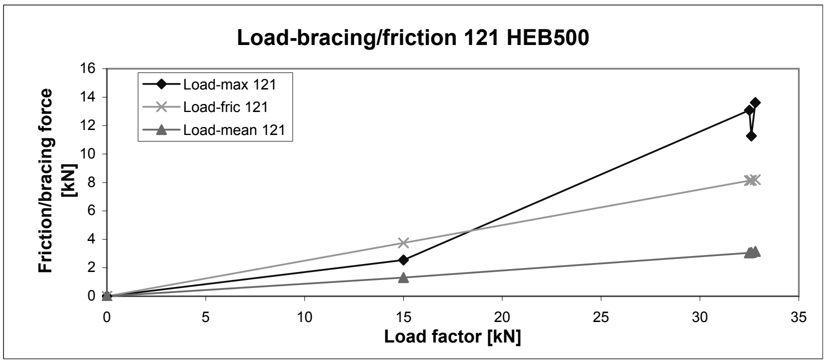
Max load (Eurocode) q_d = 31,6 kN/m which gives P_d = 12,6 kN

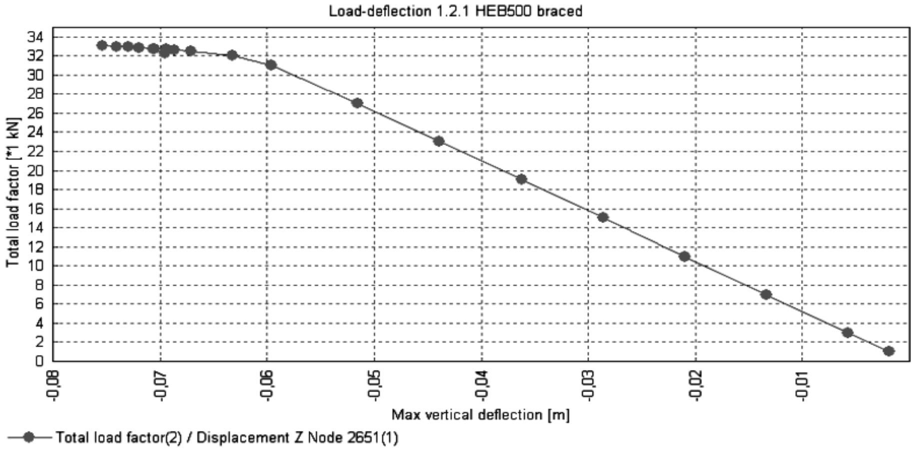
Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	16,5 kN	not OK
Eurocode	F_con.max =	49,5 kN	not OK

Structure 1.2.1 HEB 500

Load factor (=applied load [kN])	Friction Fmy [kN]	Max Fy[kN]	Mean Fy[kN]
0,0	0,00	0,00	0,00
15,0	3,75	2,55	1,31
32,5	8,13	13,08	3,05
32,6	8,15	11,27	3,08
32,8	8,20	13,62	3,15

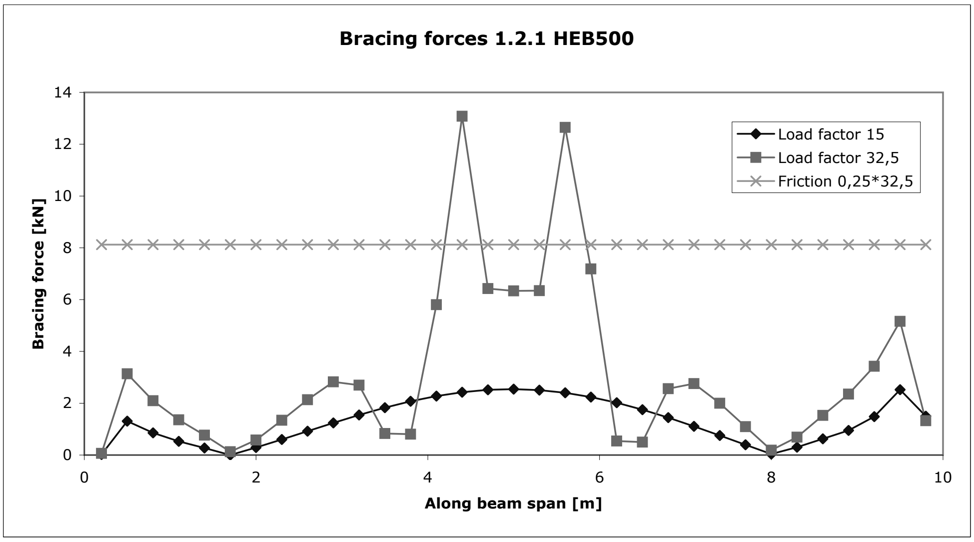
Friction my_d = 0,25





Results Finite Element Analysis
Timber on steel beams

Structure 1.2.1 HEB 500



From analytical calculations

Max load (Eurocode) q_d = 105,8 kN/m which gives P_d = 31,7 kN

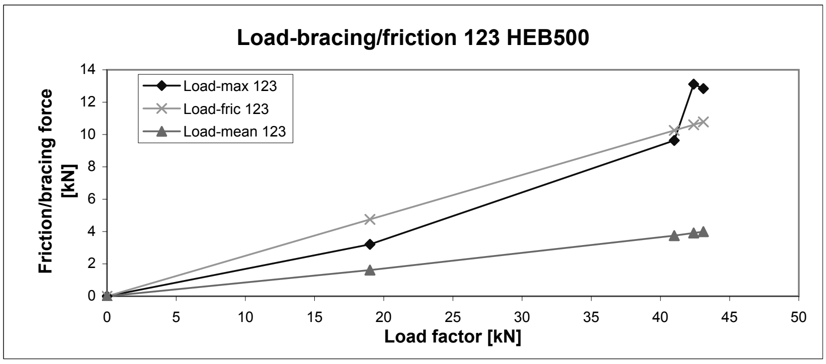
Needed bracing
BSK F_con.max = 19,3 kN
Eurocode F_con.max = 57,8 kN

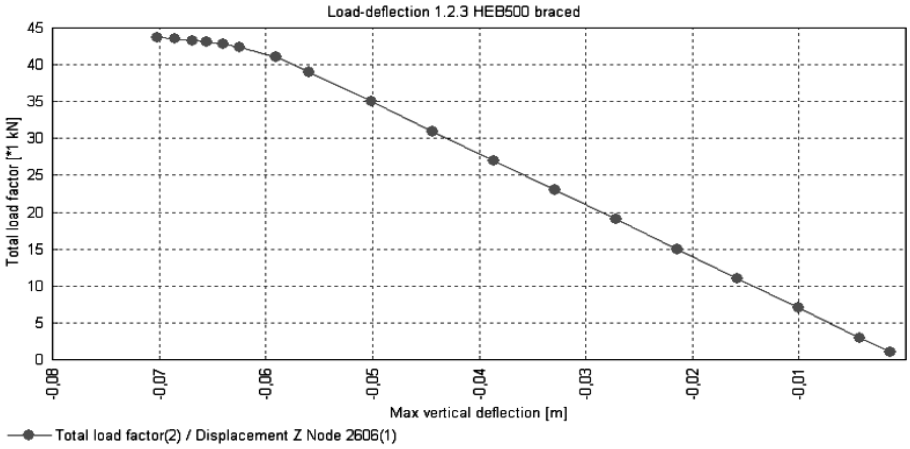
Friction enough according to calculations?
not OK
not OK

Structure 1.2.3 HEB 500

Load factor (=applied load [kN])	Friction Fmy [kN]	Max Fy[kN]	Mean Fy[kN]
0,0	0,00	0	0
19,0	4,75	3,21	1,62
41,0	10,25	9,63	3,75
42,4	10,60	13,11	3,91
43,1	10,78	12,84	3,99

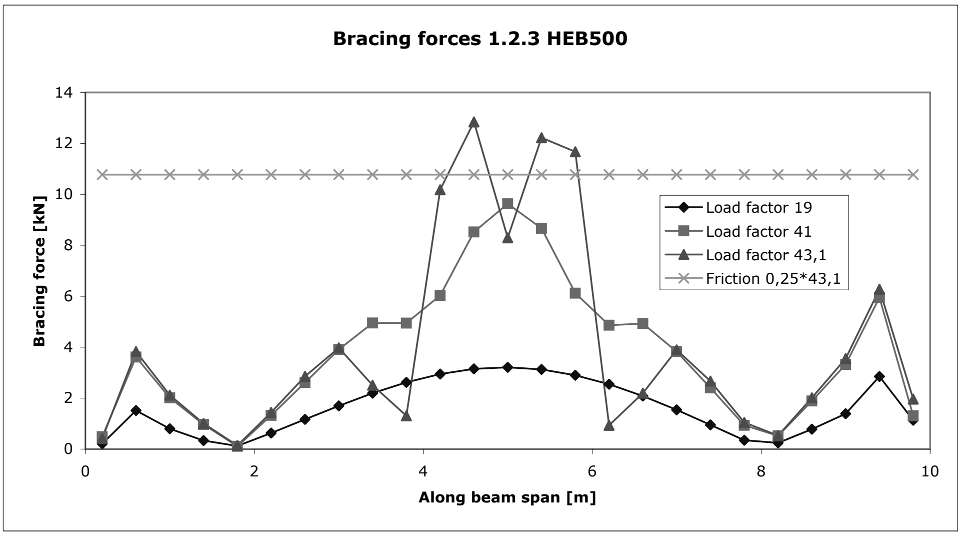
Friction my_d = 0,25





Results Finite Element Analysis
Timber on steel beams

Structure 1.2.3 HEB 500



From analytical calculations

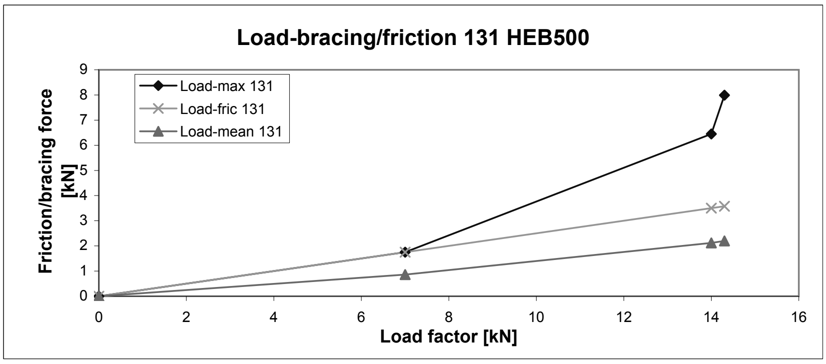
Max load (Eurocode) q_d = 105,8 kN/m which gives P_d = 42,3 kN

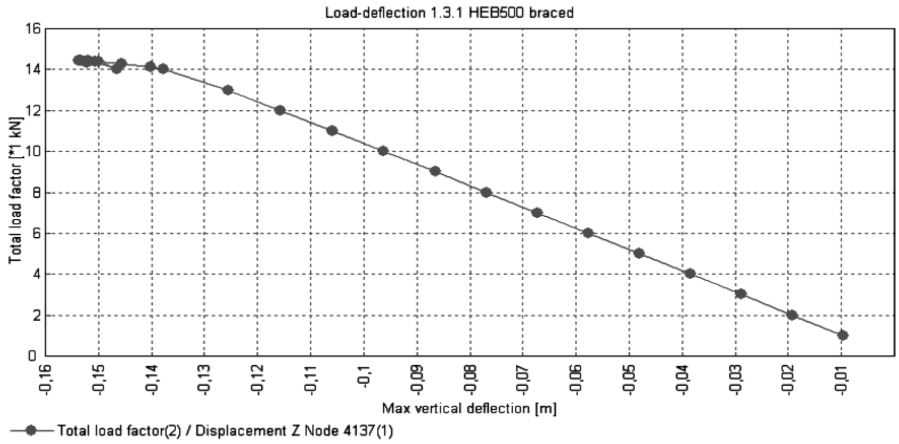
			Friction enough according to calculations?
Needed bracing			
BSK	F_con.max =	19,3 kN	not OK
Eurocode	F_con.max =	57,8 kN	not OK

Structure 1.3.1 HEB 500

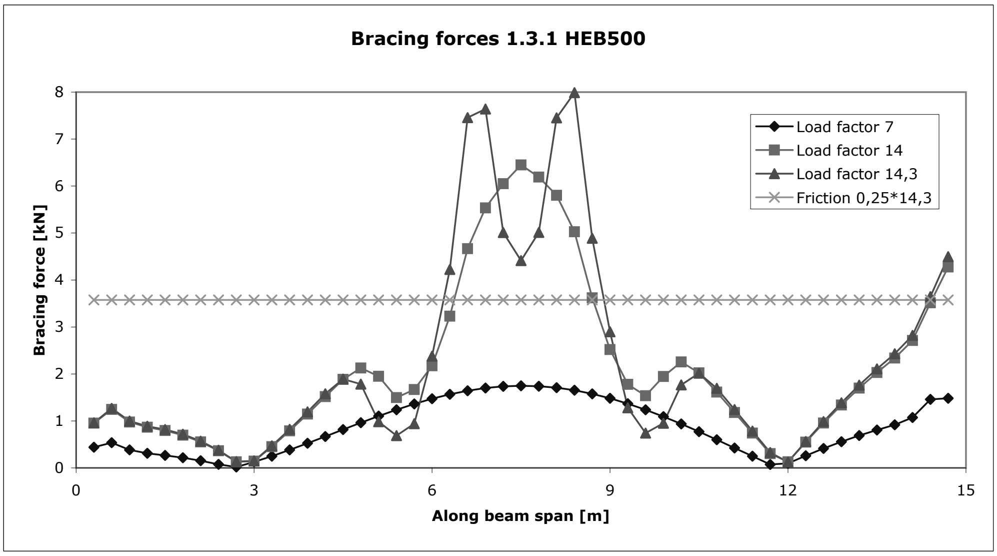
Load factor (=applied load [kN])	Friction Fmy [kN]	Max Fy[kN]	Mean Fy[kN]
0,0	0,00	0,00	0,00
7,0	1,75	1,75	0,86
14,0	3,50	6,45	2,12
14,3	3,58	7,99	2,20

Friction my_d = 0,25





Structure 1.3.1 HEB 500



From analytical calculations

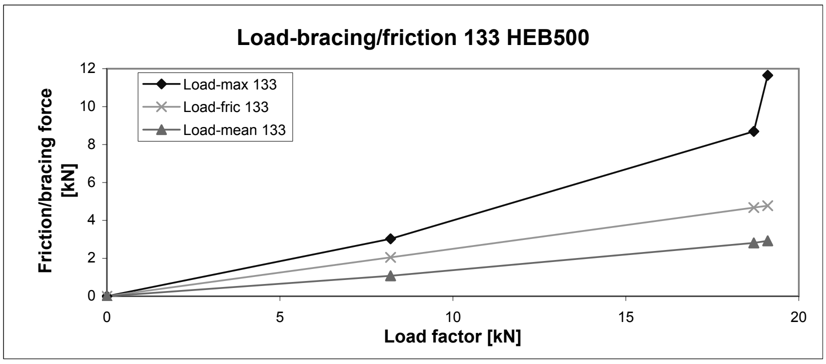
Max load (Eurocode) q_d = 47 kN/m which gives P_d = 14,1 kN

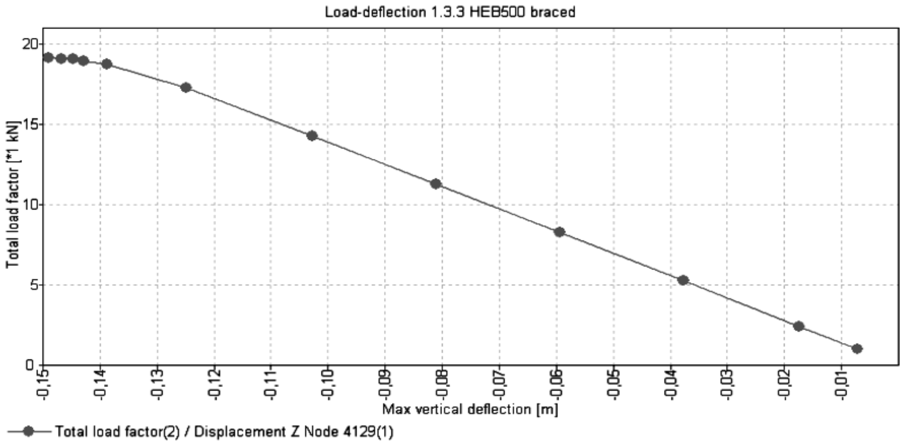
Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	19,3 kN	not OK
Eurocode	F_con.max =	57,8 kN	not OK

Structure 1.3.3 HEB 500

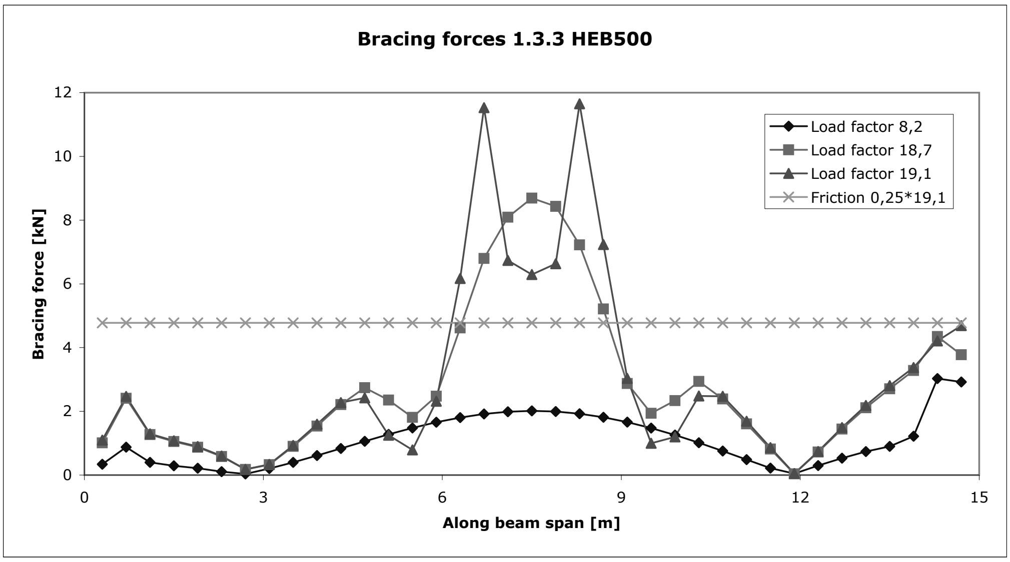
Load factor (=applied load [kN])	Friction Fmy [kN]	Max Fy[kN]	Mean Fy[kN]
0,0	0,00	0,00	0,00
8,2	2,05	3,03	1,07
18,7	4,68	8,69	2,81
19,1	4,78	11,65	2,92

Friction my_d = 0,25





Structure 1.3.3 HEB 500



From analytical calculations

Max load (Eurocode) q_d = 47 kN/m which gives P_d = 18,8 kN

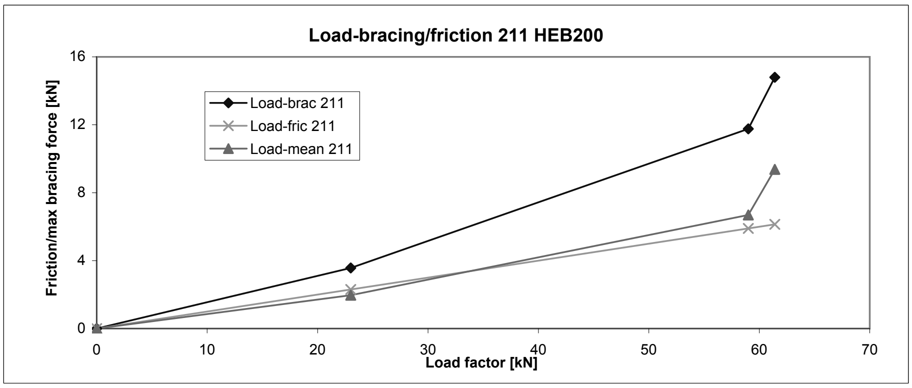
Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	19,3 kN	not OK
Eurocode	F_con.max =	57,8 kN	not OK

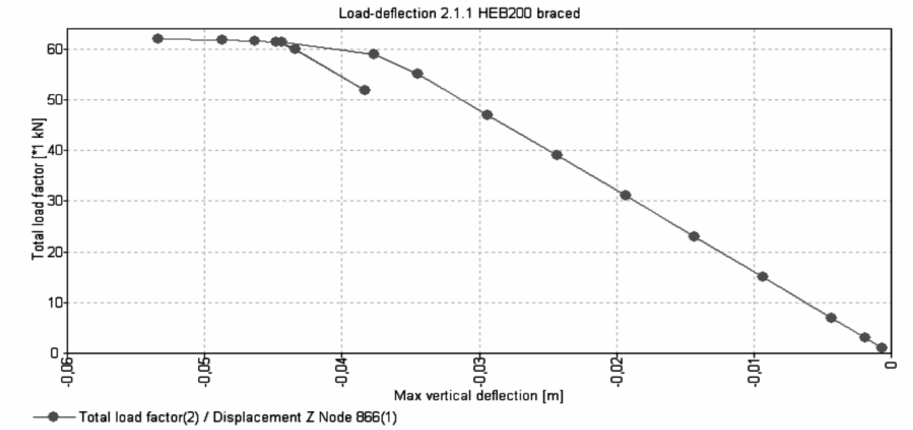
Appendix D Results from Finite Element Analysis - Steel Beams on Steel Beams

This Appendix includes a excel document with different graphs visualising results from the finite element analyses for each structure configuration and beam size that starts with number 2, i.e. steel beams on steel beams.

Structure 2.1.1 HEB 200

	Load factor (=applied load [kN])			
	0	23	59	61,4
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
256	0	0,53	0,61	3,10
636	0	3,57	11,66	14,80
1016	0	3,48	11,76	14,20
1396	0	0,26	2,74	5,41
Mean	0,00	1,96	6,69	9,38
Max	0,00	3,57	11,76	14,80



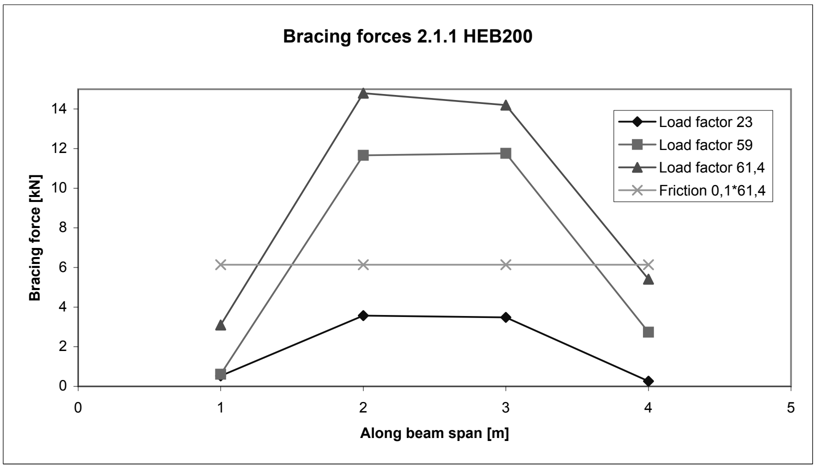


Sum up

Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
23	3,57	1,96	2,3
59	11,76	6,69	5,9
61,4	14,80	9,38	6,14

Friction my_d = 0,1
Fy bracing force
F_my friction force

Structure 2.1.1 HEB 200



From analytical calculations

Max load (Eurocode) q_d = 56,6 kN/m which gives P_d = 56,6 kN

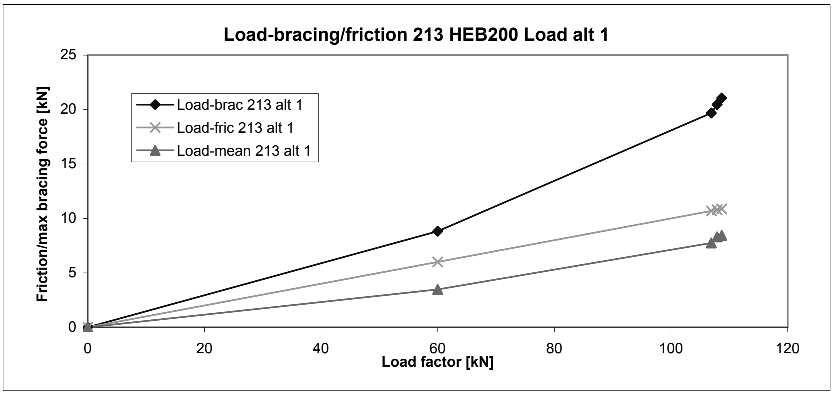
Needed bracing
BSK F_con.max = 6,9 kN
Eurocode F_con.max = 20,6 kN

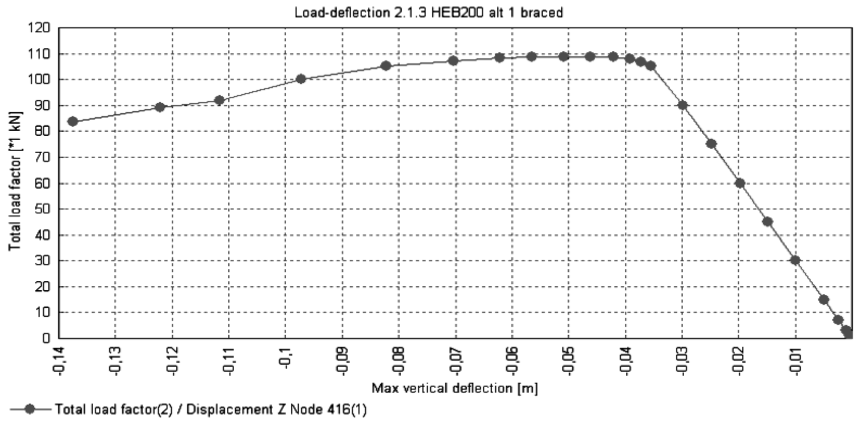
Friction enough according to calculations?
not OK
not OK

Structure 2.1.3 HEB 200 Load alt 1

Load factor (=applied load [kN])

	0	60	106,9	107,9	108,7
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
66	0	1,40	0,26	0,65	0,69
256	0	8,83	19,69	20,47	21,06
1016	0	0,20	3,30	3,80	3,57
Mean	0,00	3,48	7,75	8,31	8,44
Max	0,00	8,83	19,69	20,47	21,06





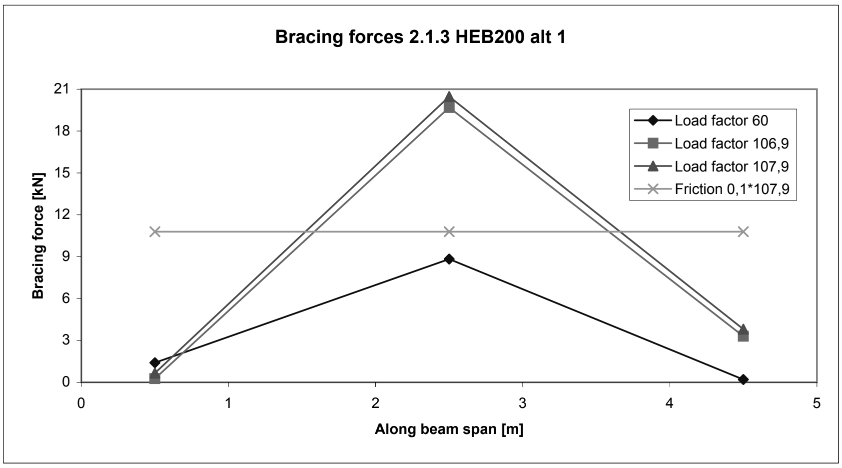
Sum up

Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
60	8,83	3,48	6
106,9	19,69	7,75	10,69
107,9	20,47	8,31	10,79
108,7	21,06	8,44	10,87

Friction my_d = 0,1
Fy bracing force
F_my friction force

Results Finite Element Analysis
Steel on steel beams

Structure 2.1.3 HEB 200 Load alt 1



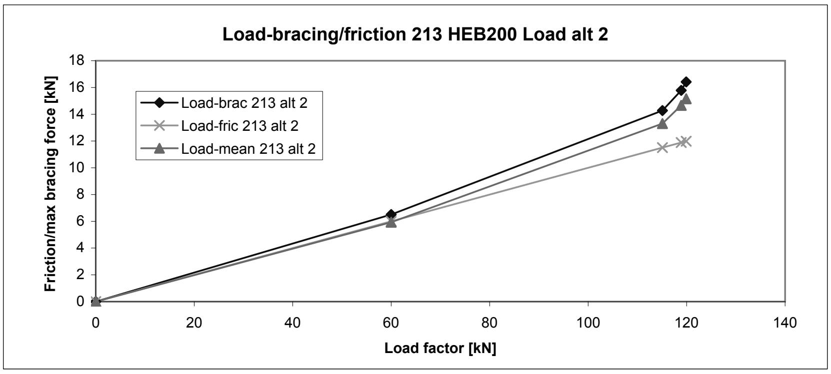
From analytical calculations

Max load (Eurocode) q_d = 56,6 kN/m which gives P_d = 113,2 kN

Needed bracing				Friction enough according to calculations?
BSK	F_con.max =	6,9	kN	OK
Eurocode	F_con.max =	20,6	kN	not OK

Structure 2.1.3 HEB 200 Load alt 2

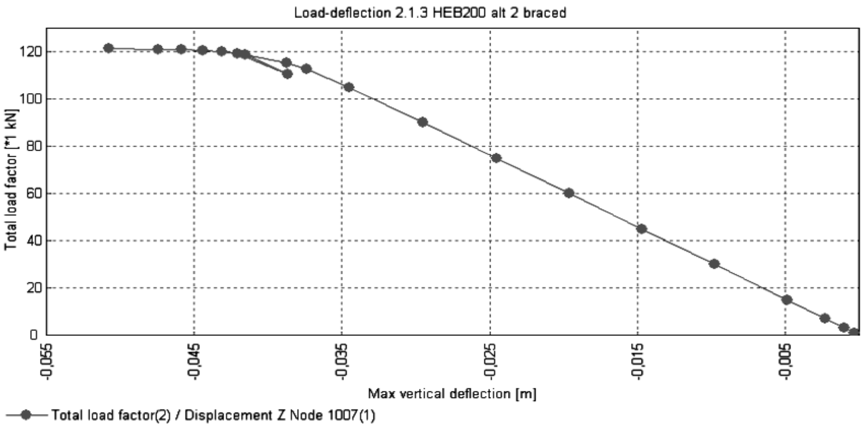
	Load factor (=applied load [kN])				
	0	60	115,1	118,9	119,9
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
66	0	6,51	14,28	15,78	16,42
826	0	5,354	12,33	13,54	13,89
Mean	0,00	5,93	13,31	14,66	15,16
Max	0,00	6,51	14,28	15,78	16,42



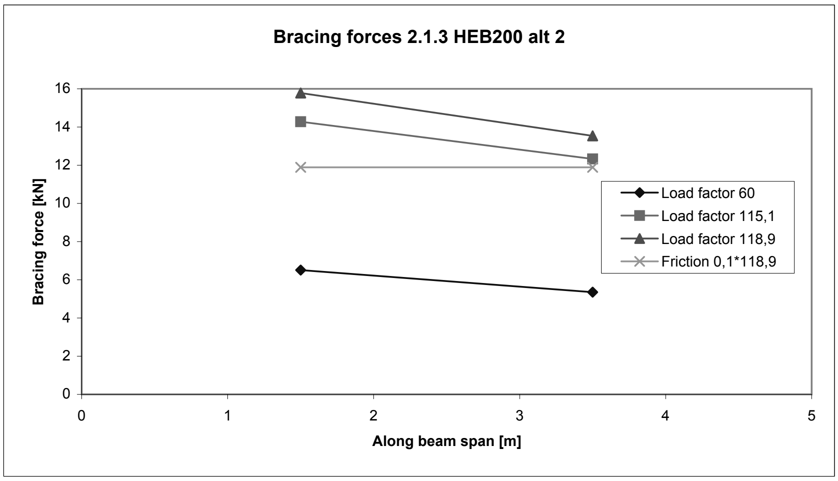
Sum up

Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
60	6,51	5,93	6
115,1	14,28	13,31	11,51
118,9	15,78	14,66	11,89
119,9	16,42	15,16	11,99

Friction my_d = 0,1
Fy bracing force
F_my friction force



Structure 2.1.3 HEB 200 Load alt 2



From analytical calculations

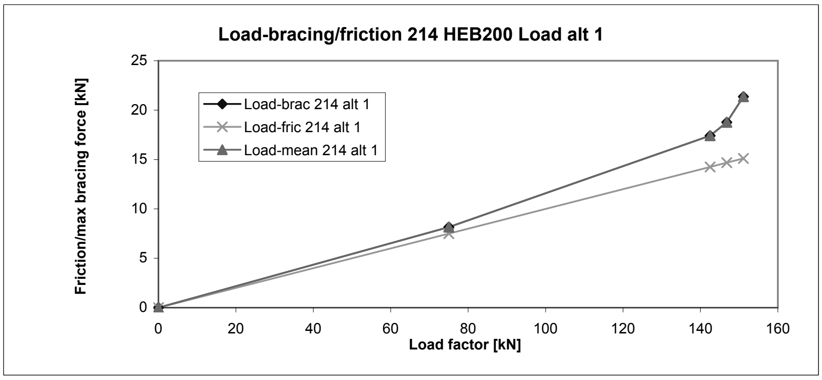
Max load (Eurocode) P_d = 117,9 kN

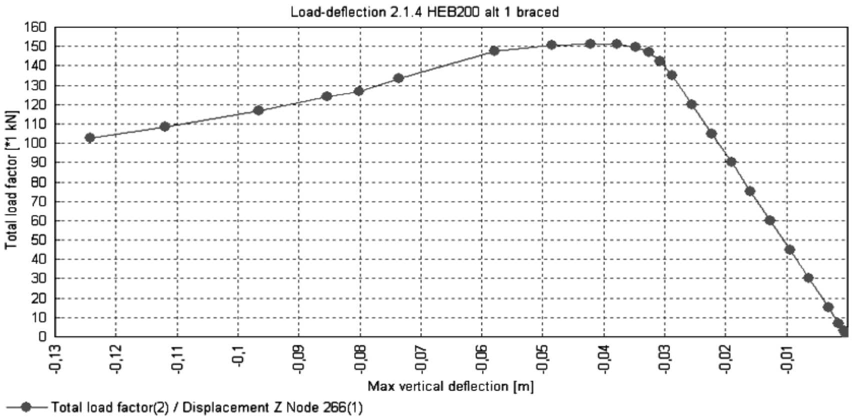
Needed bracing				Friction enough according to calculations?
BSK	F_con.max =	6,9	kN	not OK
Eurocode	F_con.max =	20,6	kN	not OK

Structure 2.1.4 HEB 200 Load alt 1

Load factor (=applied load [kN])

	0	75	142,5	146,8	151,1
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
66	0	8,16	17,41	18,77	21,36
Mean	0,00	8,16	17,41	18,77	21,36
Max	0,00	8,16	17,41	18,77	21,36



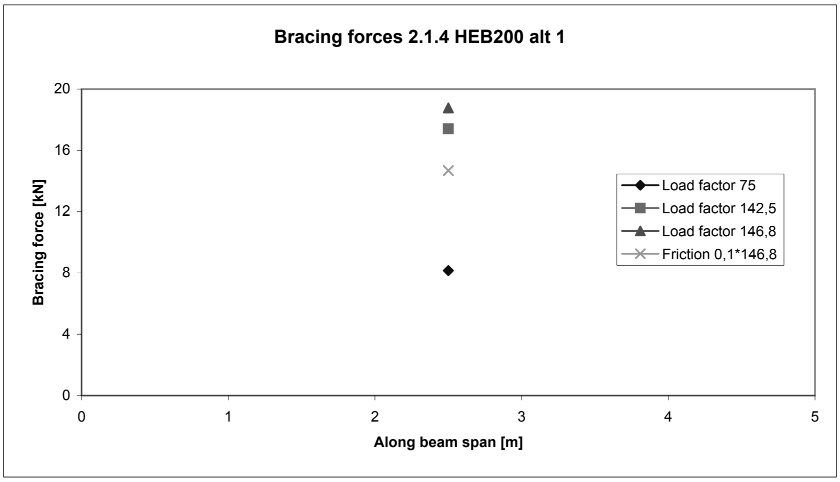


Sum up

Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
75	8,16	8,16	7,5
142,5	17,41	17,41	14,25
146,8	18,77	18,77	14,68
151,1	21,36	21,36	15,11

Friction my_d = 0,1
Fy bracing force
F_my friction force

Structure 2.1.4 HEB 200 Load alt 1



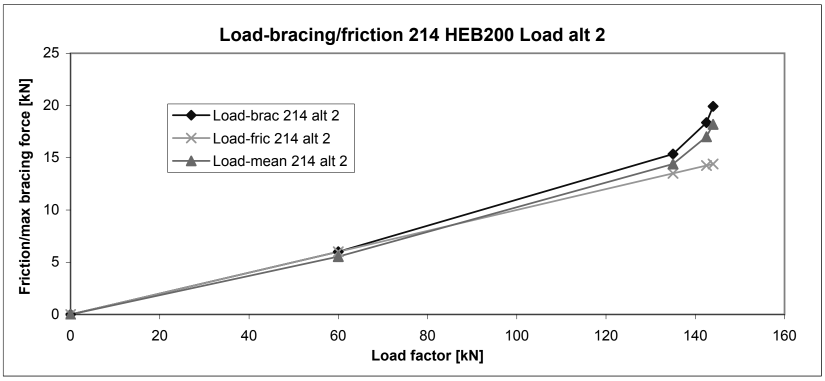
From analytical calculations

Max load (Eurocode) P_d = 141,5 kN

Needed bracing
BSK F_con.max = 6,9 kN
Eurocode F_con.max = 20,6 kN

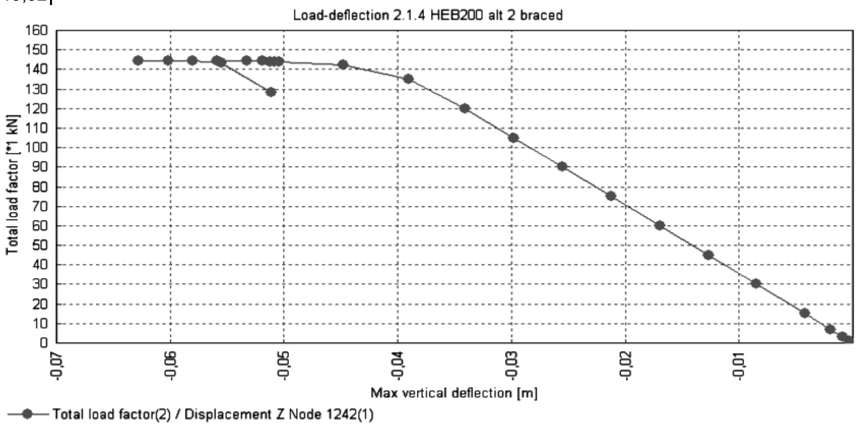
Friction enough according to calculations?
OK
not OK

Structure 2.1.4 HEB 200 Load alt 2



Load factor (=applied load [kN])

	0	60	135	142,5	144
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
66	0	6,00	15,35	18,36	19,92
1016	0	5,06	13,46	15,67	16,47
Mean	0,00	5,53	14,41	17,02	18,20
Max	0,00	6,00	15,35	18,36	19,92

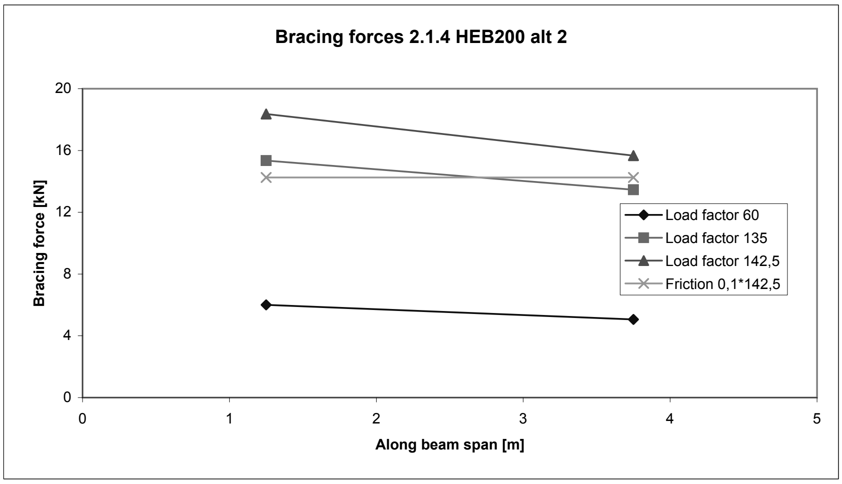


Sum up

Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
60	6,00	5,53	6
135	15,35	14,41	13,5
142,5	18,36	17,02	14,25
144	19,92	18,20	14,4

Friction my_d = 0,1
Fy bracing force
F_my friction force

Structure 2.1.4 HEB 200 Load alt 2



From analytical calculations

Max load (Eurocode) P_d = 141,5 kN

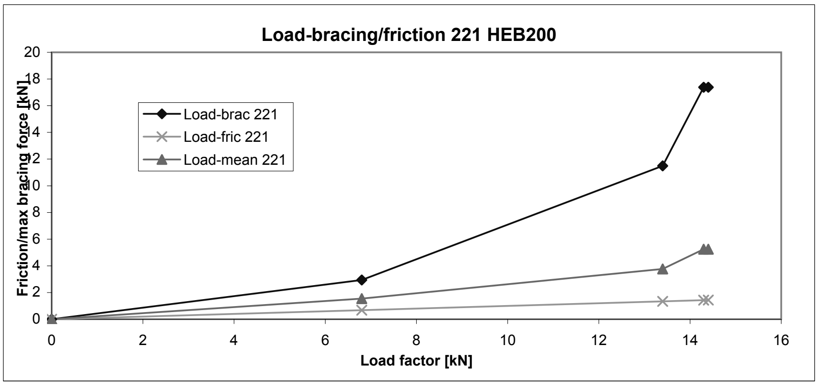
Needed bracing
BSK F_con.max = 6,9 kN
Eurocode F_con.max = 20,6 kN

Friction enough according to calculations?
not OK
not OK

Structure 2.2.1 HEB 200

Load factor (=applied load [kN])

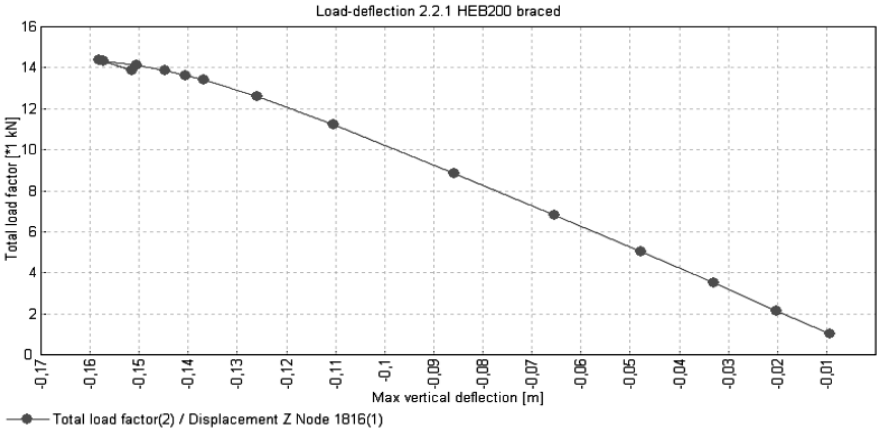
	0	6,8	13,4	14,3	14,4
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
256	0	0,25	0,06	0,31	0,31
636	0	0,40	1,24	1,11	1,11
1016	0	1,61	1,60	1,46	1,46
1396	0	2,59	6,13	8,71	8,71
1776	0	2,94	11,49	17,38	17,38
2156	0	2,53	6,68	9,81	9,81
2536	0	1,37	0,92	1,85	1,85
2916	0	0,01	0,38	0,32	0,32
3296	0	2,19	5,43	6,25	6,25
Mean	0,00	1,54	3,77	5,24	5,24
Max	0,00	2,94	11,49	17,38	17,38



Sum up

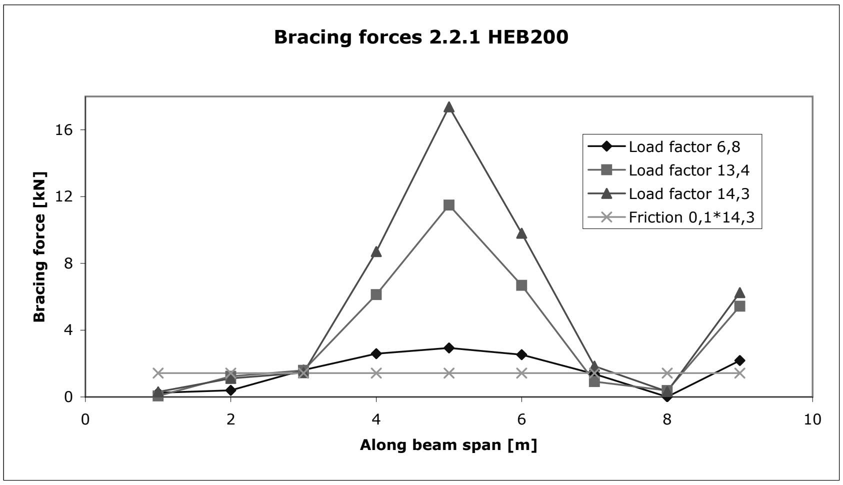
Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
6,8	2,94	1,54	0,68
13,4	11,49	3,77	1,34
14,3	17,38	5,24	1,43
14,4	17,38	5,24	1,44

Friction my_d = 0,1
Fy bracing force
F_my friction force



Results Finite Element Analysis
Steel on steel beams

Structure 2.2.1 HEB 200



From analytical calculations

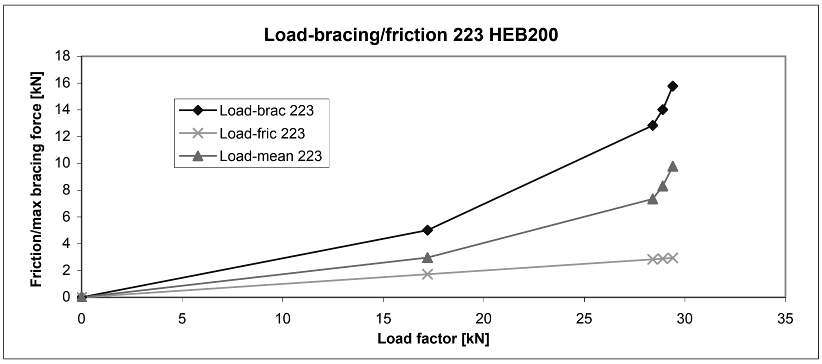
Max load (Eurocode) q_d = 14,1 kN/m which gives P_d = 14,1 kN

Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	6,9 kN	not OK
Eurocode	F_con.max =	20,6 kN	not OK

Structure 2.2.3 HEB 200

Load factor (=applied load [kN])

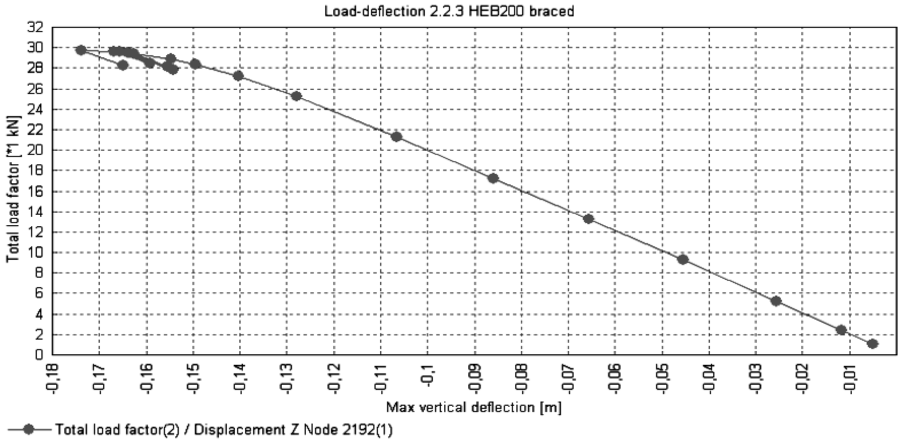
	0	17,2	28,4	28,9	29,4
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
66	0	0,97	0,32	1,01	2,11
1016	0	4,58	11,39	12,47	14,11
1966	0	5,01	12,84	14,02	15,77
2916	0	1,30	4,85	5,75	7,16
Mean	0,00	2,97	7,35	8,31	9,79
Max	0,00	5,01	12,84	14,02	15,77



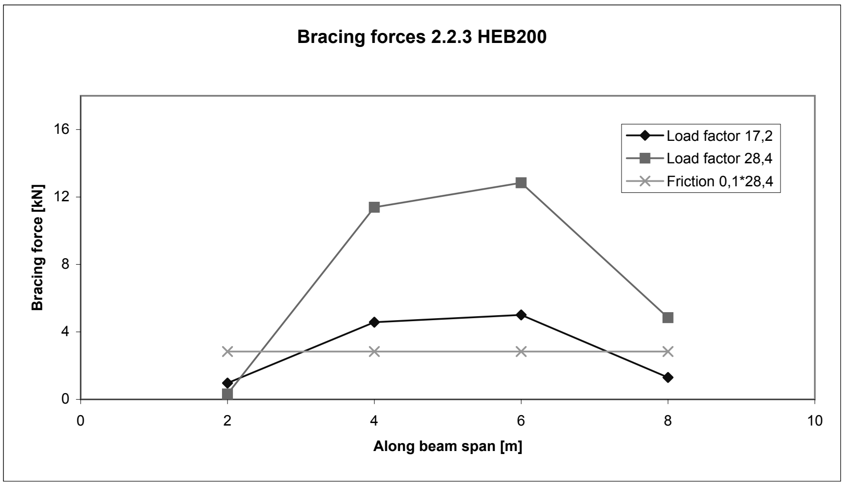
Sum up

Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
17,2	5,01	2,97	1,72
28,4	12,84	7,35	2,84
28,9	14,02	8,31	2,89
29,4	15,77	9,79	2,94

Friction my_d = 0,1
Fy bracing force
F_my friction force



Structure 2.2.3 HEB 200



From analytical calculations

Max load (Eurocode) q_d = 14,1 kN/m which gives P_d = 28,2 kN

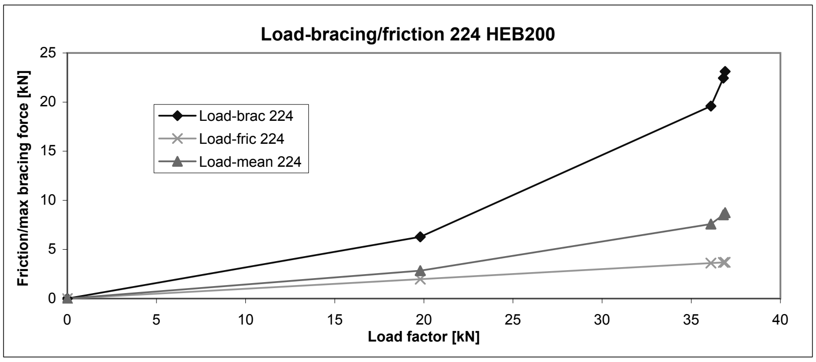
Needed bracing
BSK F_con.max = 6,9 kN
Eurocode F_con.max = 20,6 kN

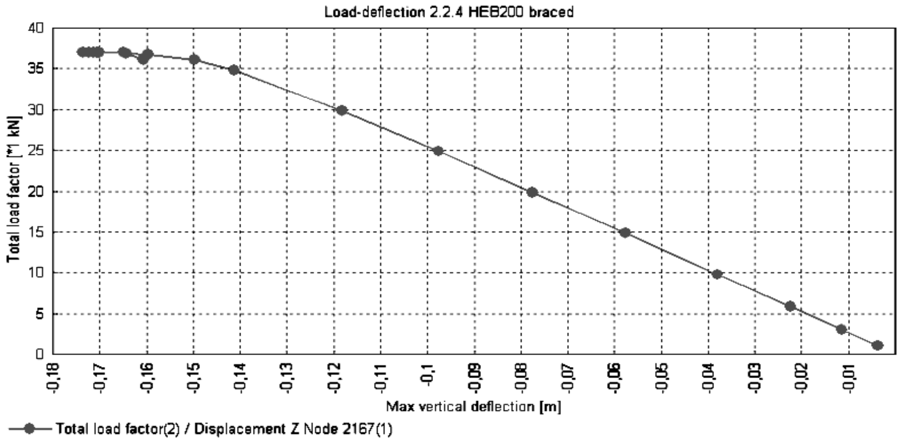
Friction enough according to calculations?
not OK
not OK

Structure 2.2.4 HEB 200

Load factor (=applied load [kN])

	0	19,8	36,1	36,8	36,9
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
66	0	1,97	1,92	1,06	0,98
1016	0	6,28	19,59	22,44	23,11
1966	0	0,28	1,24	2,09	2,13
Mean	0,00	2,84	7,58	8,53	8,74
Max	0,00	6,28	19,59	22,44	23,11



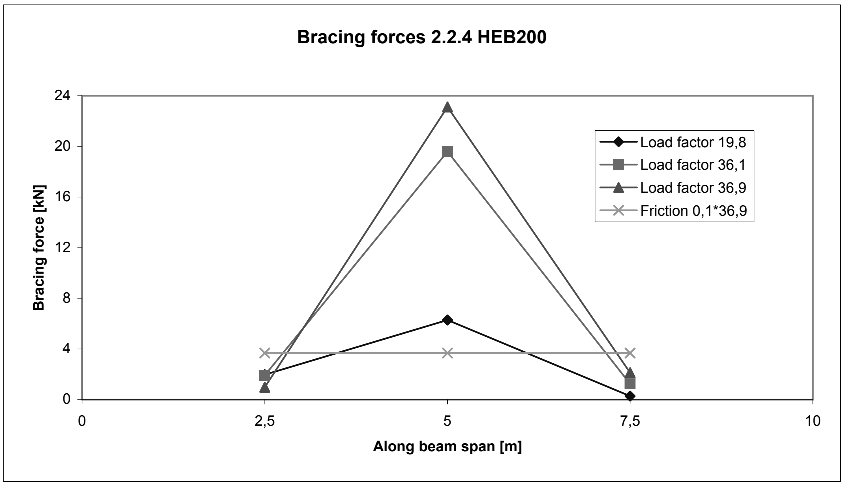


Sum up

Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
19,8	6,28	2,84	1,98
36,1	19,59	7,58	3,61
36,8	22,44	8,53	3,68
36,9	23,11	8,74	3,69

Friction my_d = 0,1
Fy bracing force
F_my friction force

Structure 2.2.4 HEB 200



From analytical calculations

Max load (Eurocode) q_d = 14,1 kN/m which gives P_d = 35,3 kN

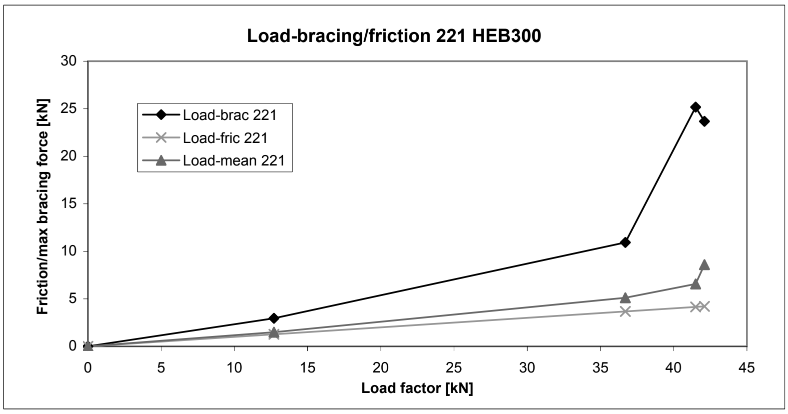
Needed bracing
BSK F_con.max = 6,9 kN
Eurocode F_con.max = 20,6 kN

Friction enough according to calculations?
not OK
not OK

Structure 2.2.1 HEB 300

Load factor (=applied load [kN])

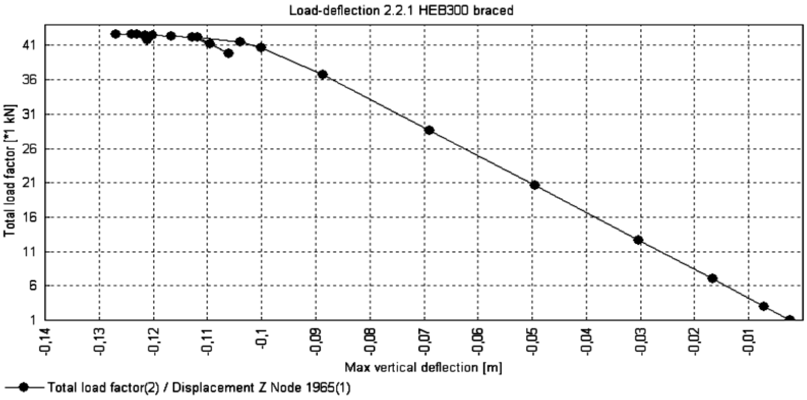
	0	12,7	36,7	41,5	42,1
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
285	0	0,41	1,44	1,81	1,92
695	0	0,56	1,55	2,87	3,63
1105	0	1,63	5,28	0,42	4,41
1515	0	2,60	8,34	9,24	14,26
1925	0	2,95	10,93	25,17	23,67
2335	0	2,49	8,30	10,37	15,27
2745	0	1,35	4,81	1,48	5,45
3155	0	0,07	0,40	1,64	2,33
3565	0	1,37	4,93	6,10	6,45
Mean	0,00	1,49	5,11	6,57	8,60
Max	0,00	2,95	10,93	25,17	23,67



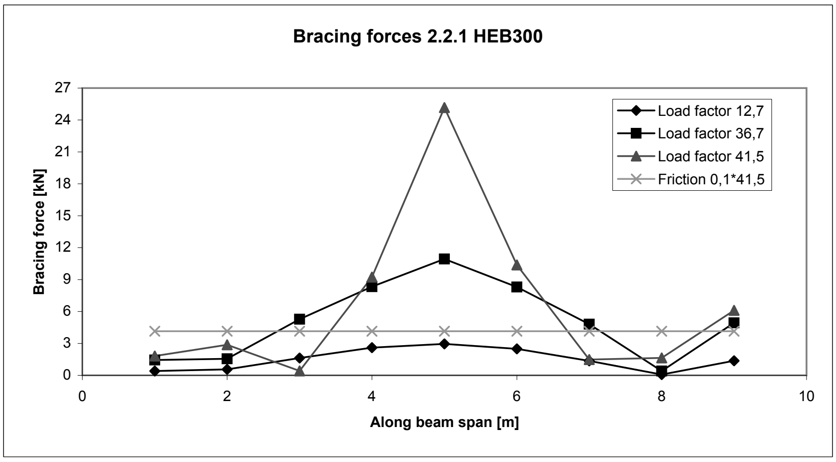
Sum up

Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
12,7	2,95	1,49	1,27
36,7	10,93	5,11	3,67
41,5	25,17	6,57	4,15
42,1	23,67	8,60	4,21

Friction my_d = 0,1
Fy bracing force
F_my friction force



Structure 2.2.1 HEB 300



From analytical calculations

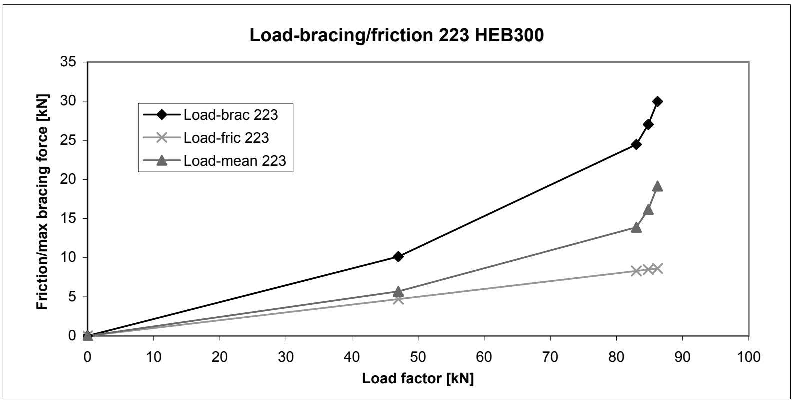
Max load (Eurocode) q_d = 41,1 kN/m which gives P_d = 41,1 kN

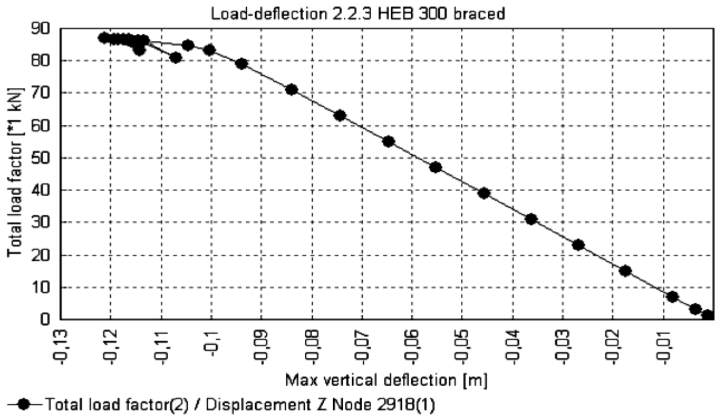
Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	13,1 kN	not OK
Eurocode	F_con.max =	39,2 kN	not OK

Structure 2.2.3 HEB 300

Load factor (=applied load [kN])

	0	47	83	84,8	86,2
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
122	0	1,59	1,28	3,17	5,82
370	0	10,14	23,59	26,02	29,54
618	0	10,05	24,47	27,03	29,96
866	0	0,97	6,19	8,39	11,27
Mean	0,00	5,69	13,88	16,15	19,15
Max	0,00	10,14	24,47	27,03	29,96



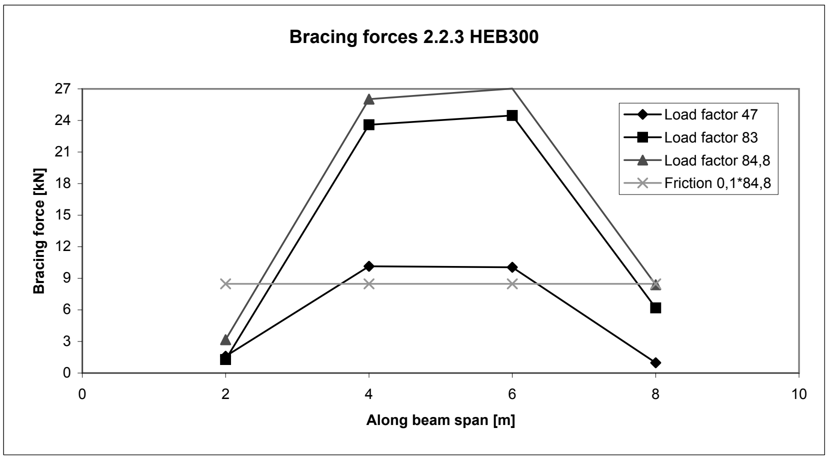


Sum up

Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
47	10,14	5,69	4,7
83	24,47	13,88	8,3
84,8	27,03	16,15	8,48
86,2	29,96	19,15	8,62

Friction my_d = 0,1
Fy bracing force
F_my friction force

Structure 2.2.3 HEB 300



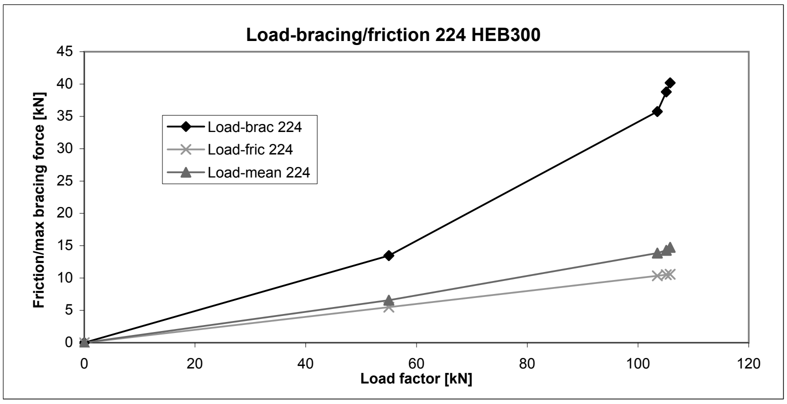
From analytical calculations

Max load (Eurocode) q_d = 41,1 kN/m which gives P_d = 82,2 kN

Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	13,1 kN	not OK
Eurocode	F_con.max =	39,2 kN	not OK

Structure 2.2.4 HEB 300

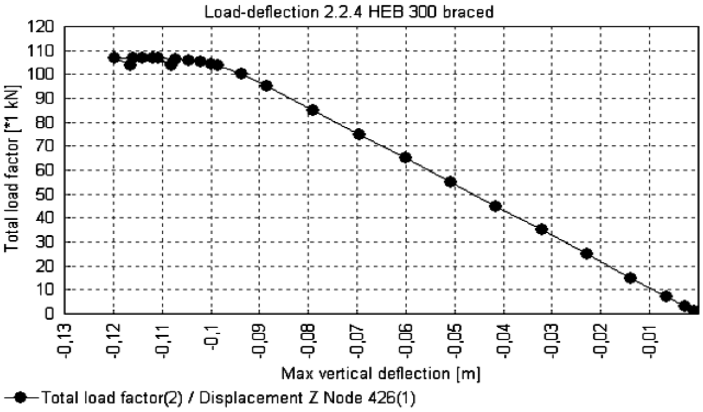
	Load factor (=applied load [kN])				
	0	55	103,5	105,1	105,8
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
122	0	4,26	4,92	3,75	3,28
370	0	13,47	35,74	38,79	40,18
618	0	1,97	0,92	0,31	0,81
Mean	0,00	6,57	13,86	14,28	14,75
Max	0,00	13,47	35,74	38,79	40,18



Sum up

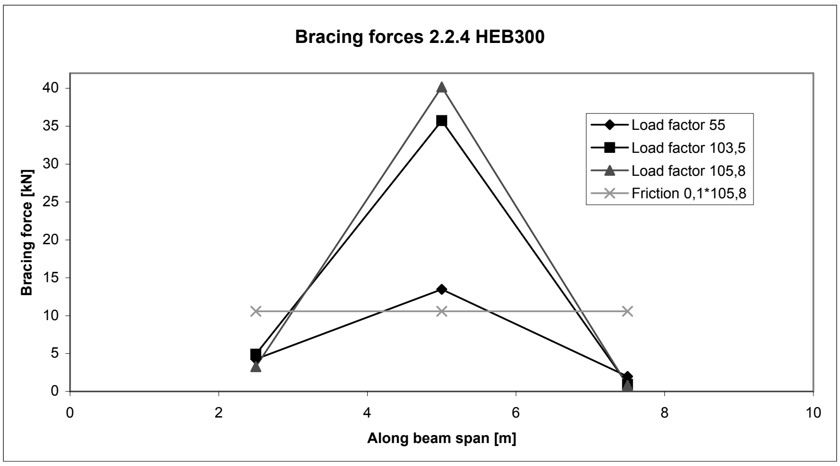
Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
55	13,47	6,57	5,5
103,5	35,74	13,86	10,35
105,1	38,79	14,28	10,51
105,8	40,18	14,75	10,58

Friction my_d = 0,1
Fy bracing force
F_my friction force



Results Finite Element Analysis
Steel on steel beams

Structure 2.2.4 HEB 300



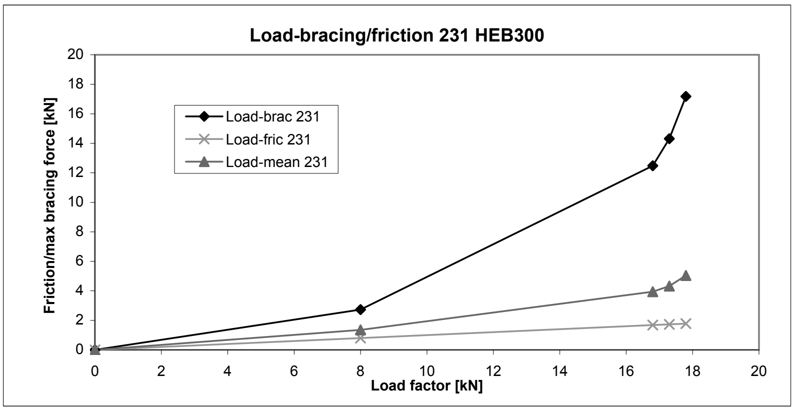
From analytical calculations

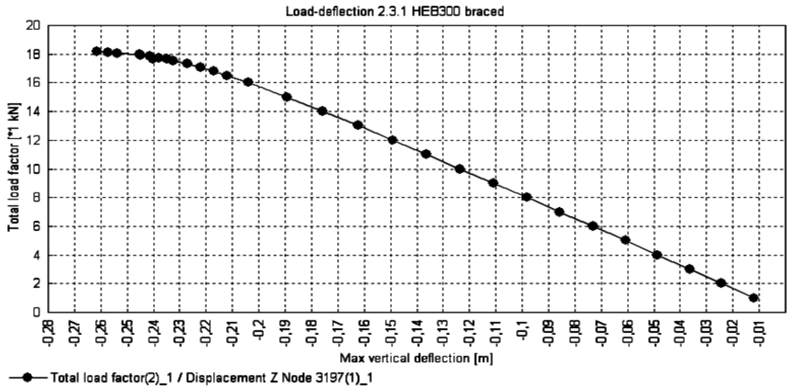
Max load (Eurocode) q_d = 41,1 kN/m which gives P_d = 102,8 kN

Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	13,1 kN	not OK
Eurocode	F_con.max =	39,2 kN	not OK

Structure 2.3.1 HEB 300

	Load factor (=applied load [kN])				
	0	8	16,8	17,3	17,8
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
285	0	0,20	0,78	0,91	1,13
695	0	0,15	0,14	0,14	0,12
1105	0	0,38	0,73	0,83	1,12
1515	0	0,98	2,79	2,54	1,06
1925	0	1,71	1,51	0,57	2,03
2335	0	2,35	5,41	7,13	8,86
2745	0	2,73	11,94	13,86	16,70
3155	0	2,73	12,48	14,31	17,18
3565	0	2,33	6,95	9,01	10,84
3975	0	1,61	1,13	0,32	0,54
4385	0	0,71	2,32	1,47	0,94
4795	0	0,22	0,46	0,33	0,02
5205	0	0,85	2,35	2,53	2,80
5615	0	2,03	6,21	6,65	7,23
Mean	0,00	1,36	3,94	4,33	5,04
Max	0,00	2,73	12,48	14,31	17,18



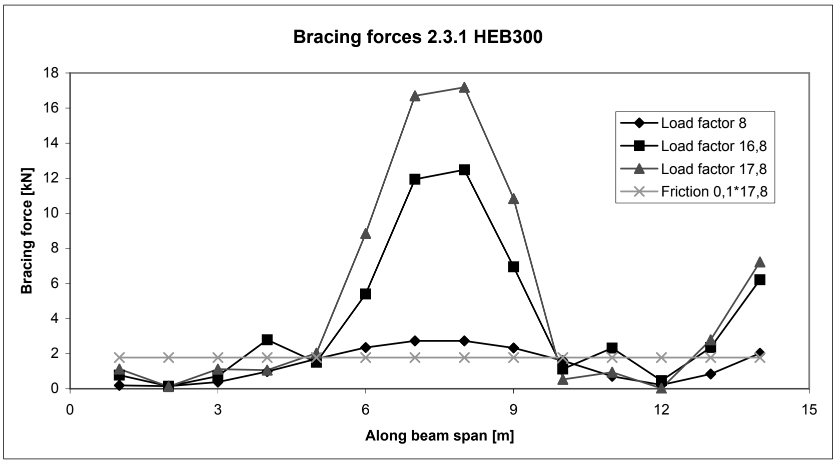


Sum up

Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
8	2,73	1,36	0,8
16,8	12,48	3,94	1,68
17,3	14,31	4,33	1,73
17,8	17,18	5,04	1,78

Friction my_d = 0,1
Fy bracing force
F_my friction force

Structure 2.3.1 HEB 300



From analytical calculations

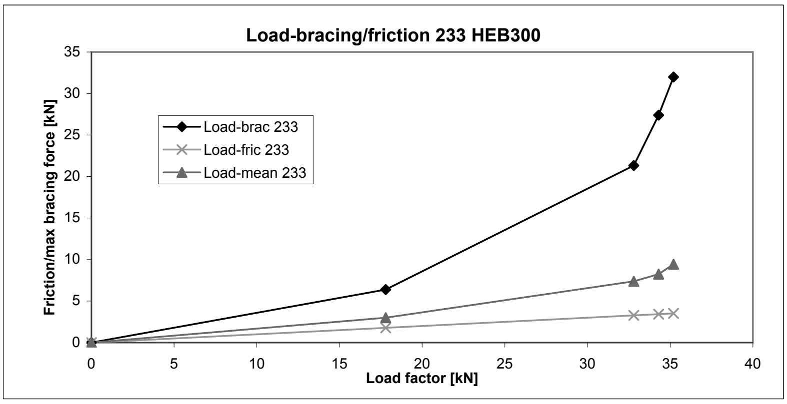
Max load (Eurocode) q_d = 18,3 kN/m which gives P_d = 18,3 kN

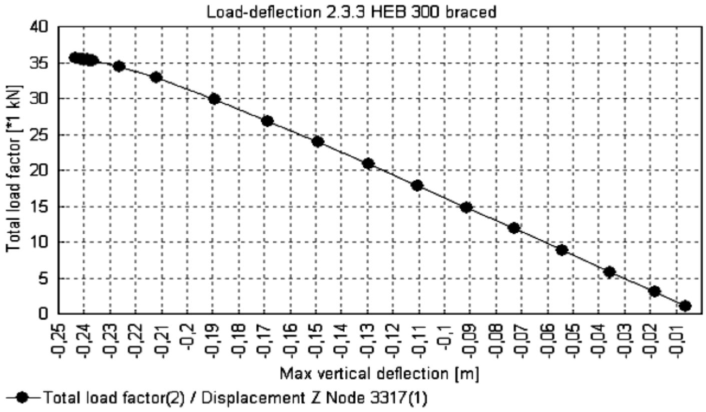
Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	13,1 kN	not OK
Eurocode	F_con.max =	39,2 kN	not OK

Structure 2.3.3 HEB 300

Load factor (=applied load [kN])

	0	17,8	32,8	34,3	35,2
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
80	0	0,32	0,72	1,28	1,87
695	0	1,48	2,74	1,32	0,37
1515	0	4,70	8,49	8,52	9,08
2335	0	6,39	21,32	27,39	31,99
3155	0	4,62	9,66	10,67	11,96
3975	0	0,57	1,21	0,75	2,82
4795	0	2,94	7,52	7,84	7,97
Mean	0,00	3,00	7,38	8,25	9,44
Max	0,00	6,39	21,32	27,39	31,99



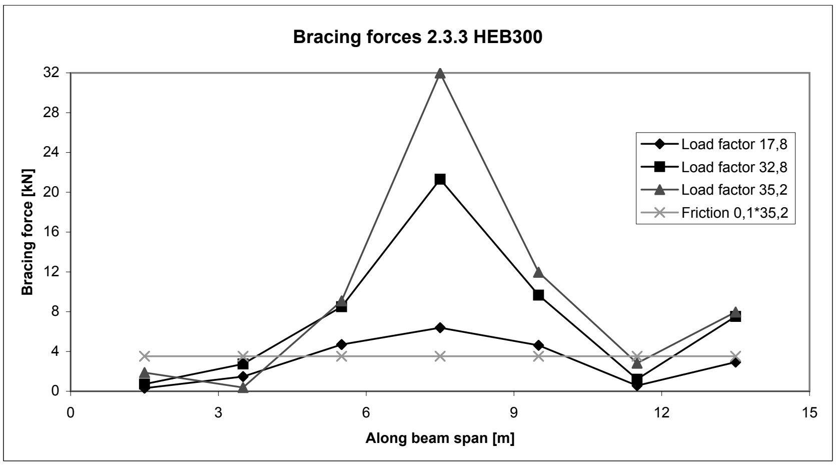


Sum up

Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
17,8	6,39	3,00	1,78
32,8	21,32	7,38	3,28
34,3	27,39	8,25	3,43
35,2	31,99	9,44	3,52

Friction my_d = 0,1
Fy bracing force
F_my friction force

Structure 2.3.3 HEB 300



From analytical calculations

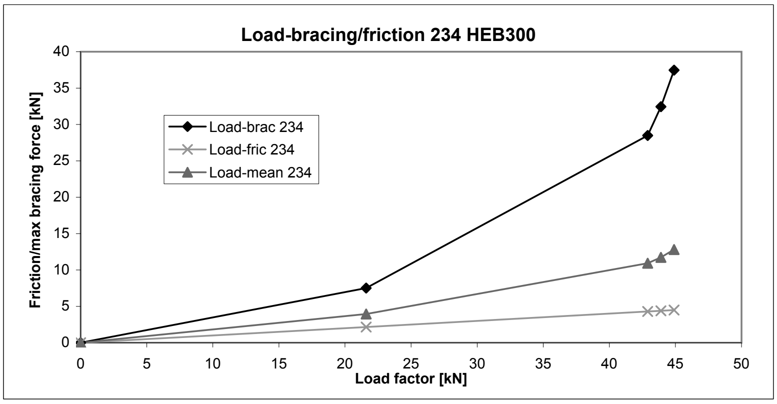
Max load (Eurocode) q_d = 18,3 kN/m which gives P_d = 36,6 kN

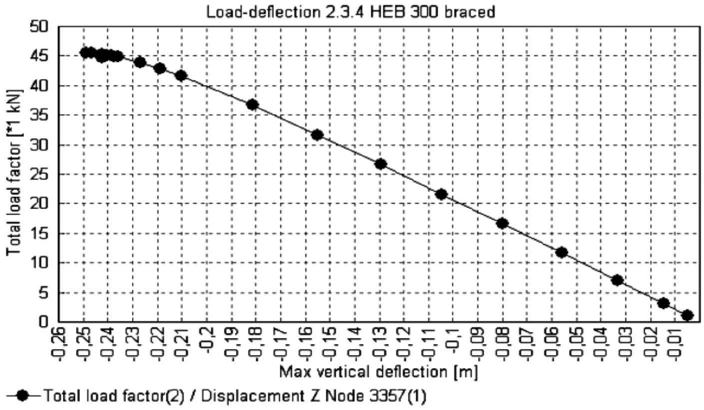
Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	13,1 kN	not OK
Eurocode	F_con.max =	39,2 kN	not OK

Structure 2.3.4 HEB 300

Load factor (=applied load [kN])

	0	21,6	42,9	43,9	44,9
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
80	0	0,73	1,61	1,35	0,86
1105	0	4,55	7,83	7,24	6,60
2130	0	7,51	28,48	32,45	37,47
3155	0	4,54	9,82	9,80	9,88
4180	0	2,43	6,87	7,84	9,23
Mean	0,00	3,95	10,92	11,74	12,81
Max	0,00	7,51	28,48	32,45	37,47



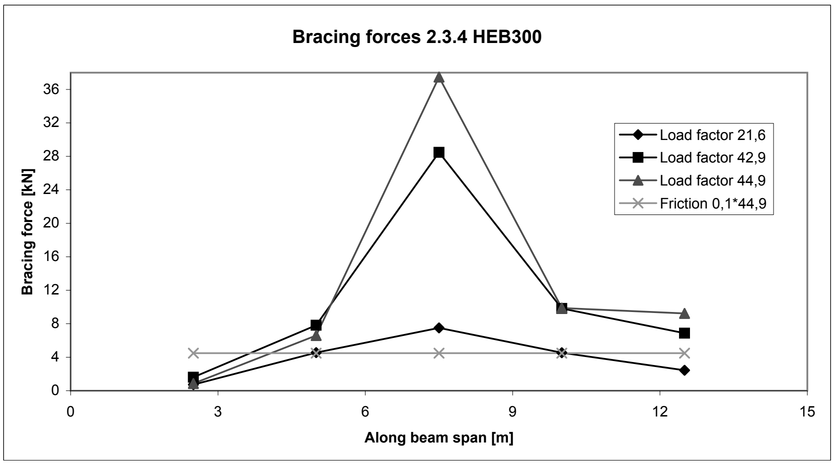


Sum up

Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
21,6	7,51	3,95	2,16
42,9	28,48	10,92	4,29
43,9	32,45	11,74	4,39
44,9	37,47	12,81	4,49

Friction my_d = 0,1
Fy bracing force
F_my friction force

Structure 2.3.4 HEB 300



From analytical calculations

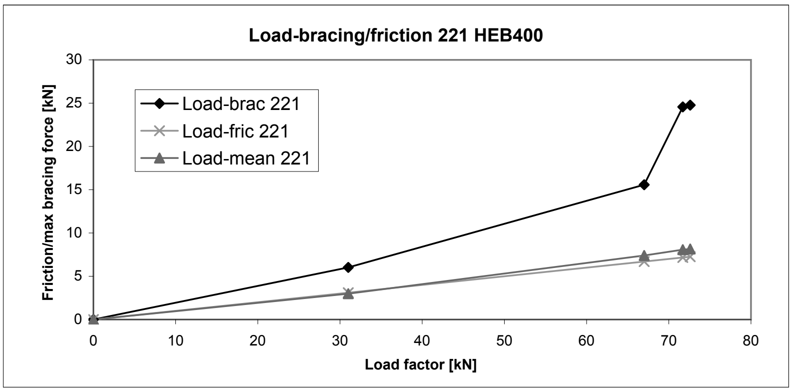
Max load (Eurocode) q_d = 18,3 kN/m which gives P_d = 45,8 kN

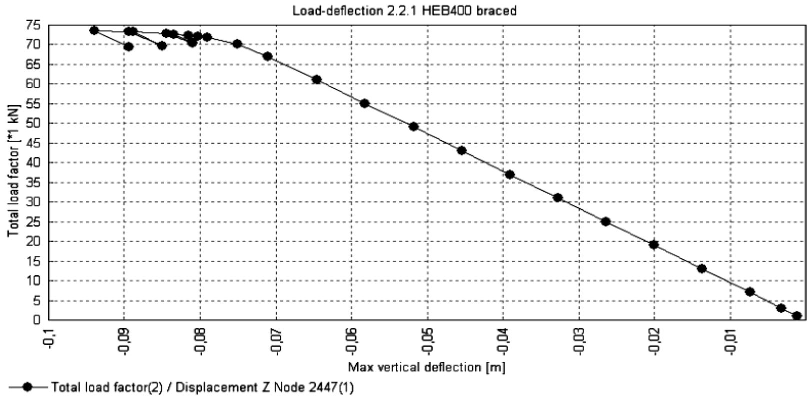
Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	13,1 kN	not OK
Eurocode	F_con.max =	39,2 kN	not OK

Structure 2.2.1 HEB 400

Load factor (=applied load [kN])

	0	31	67	71,7	72,6
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
248	0	1,42	3,38	3,56	3,62
718	0	0,37	1,30	1,44	1,27
1188	0	2,09	4,86	5,79	4,89
1658	0	4,47	9,39	2,54	3,10
2128	0	6,02	15,45	23,71	24,73
2598	0	5,95	15,58	24,56	24,77
3068	0	4,21	9,22	2,29	3,34
3538	0	1,59	4,13	4,91	3,79
4008	0	1,80	3,61	3,81	3,58
4478	0	1,99	7,02	8,09	8,48
Mean	0,00	2,99	7,39	8,07	8,16
Max	0,00	6,02	15,58	24,56	24,77





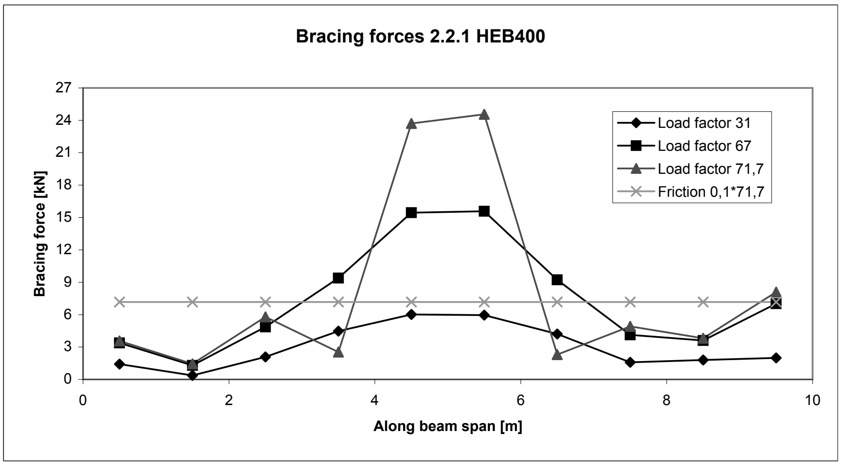
Sum up

Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
31	6,02	2,99	3,1
67	15,58	7,39	6,7
71,7	24,56	8,07	7,17
72,6	24,77	8,16	7,26

Friction my_d = 0,1
Fy bracing force
F_my friction force

Results Finite Element Analysis
Steel on steel beams

Structure 2.2.1 HEB 400



From analytical calculations

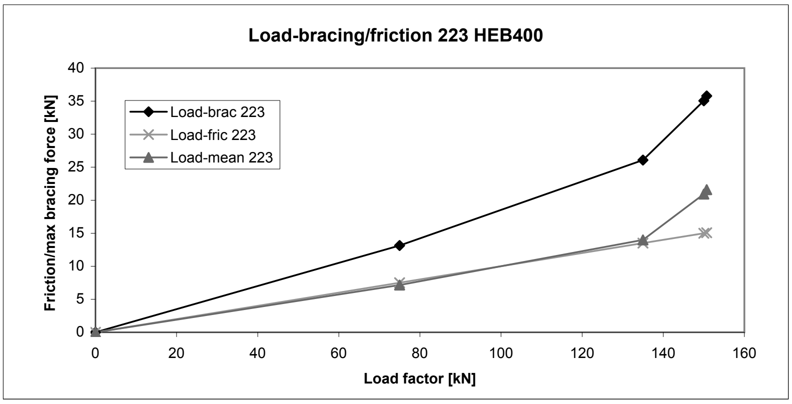
Max load (Eurocode) q_d = 71,1 kN/m which gives P_d = 71,1 kN

Needed bracing
BSK F_con.max = 16,5 kN
Eurocode F_con.max = 49,5 kN

Friction enough according to calculations?
not OK
not OK

Structure 2.2.3 HEB 400

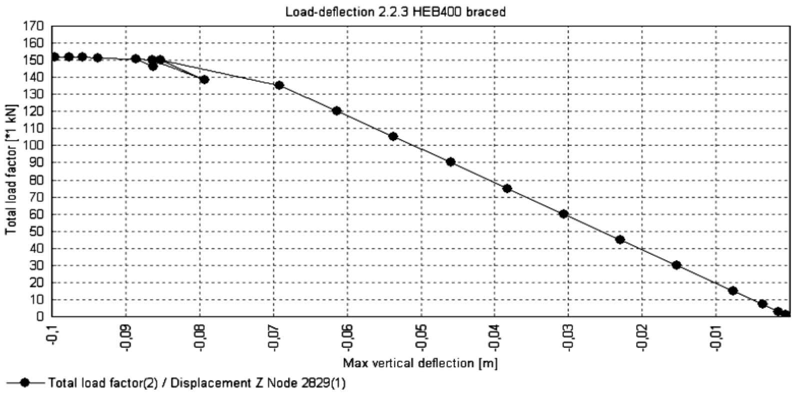
	Load factor (=applied load [kN])				
	0	75	135	150	150,7
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
388	0	1,19	1,65	4,37	4,93
1328	0	13,13	25,65	34,97	35,79
2268	0	13,01	26,07	35,06	35,78
3208	0	1,29	2,62	9,29	9,88
Mean	0,00	7,15	14,00	20,92	21,59
Max	0,00	13,13	26,07	35,06	35,79



Sum up

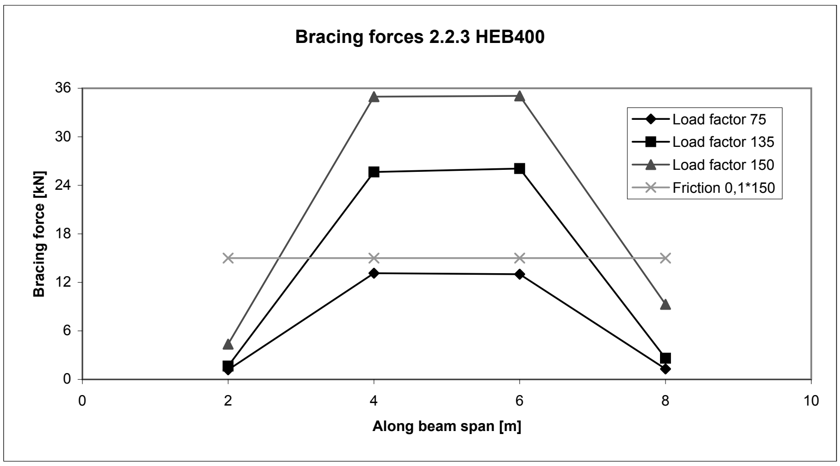
Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
75	13,13	7,15	7,5
135	26,07	14,00	13,5
150	35,06	20,92	15
150,7	35,79	21,59	15,07

Friction my_d = 0,1
Fy bracing force
F_my friction force



Results Finite Element Analysis
Steel on steel beams

Structure 2.2.3 HEB 400



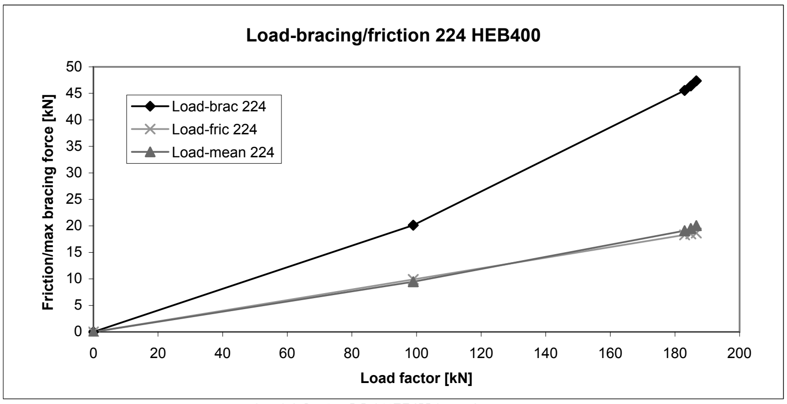
From analytical calculations

Max load (Eurocode) q_d = 71,1 kN/m which gives P_d = 142,2 kN

Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	16,5 kN	not OK
Eurocode	F_con.max =	49,5 kN	not OK

Structure 2.2.4 HEB 400

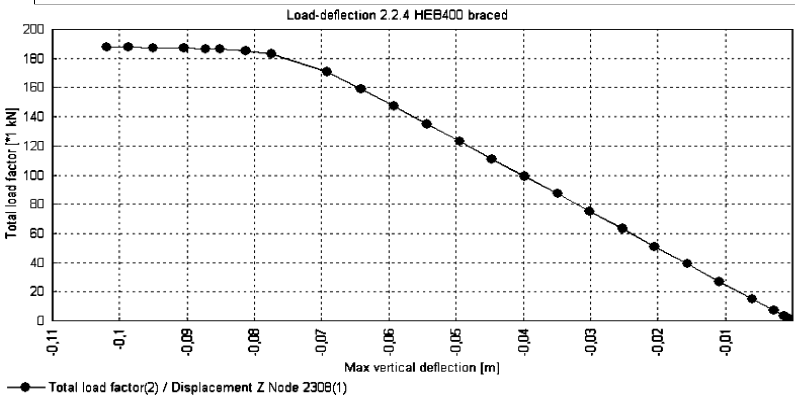
	Load factor (=applied load [kN])				
	0	99	183	184,9	186,6
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
458	0	5,39	7,77	7,96	8,22
1633	0	20,13	45,55	46,41	47,36
2808	0	2,90	3,94	4,15	4,57
Mean	0,00	9,47	19,09	19,50	20,05
Max	0,00	20,13	45,55	46,41	47,36



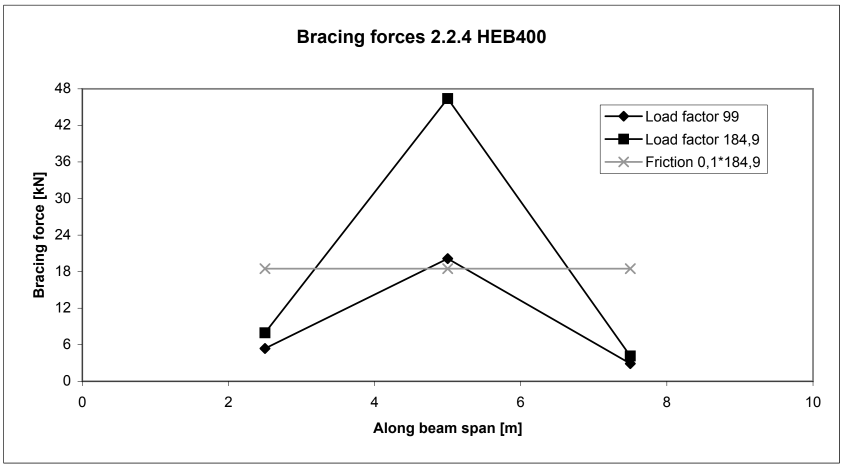
Sum up

Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
99	20,13	9,47	9,9
183	45,55	19,09	18,3
184,9	46,41	19,50	18,49
186,6	47,36	20,05	18,66

Friction my_d = 0,1
Fy bracing force
F_my friction force



Structure 2.2.4 HEB 400



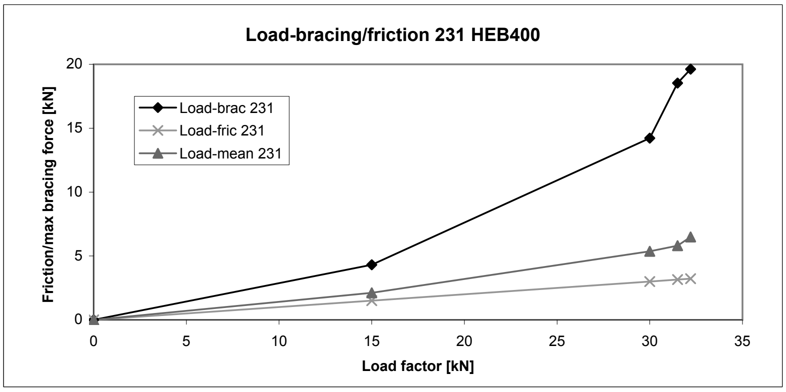
From analytical calculations

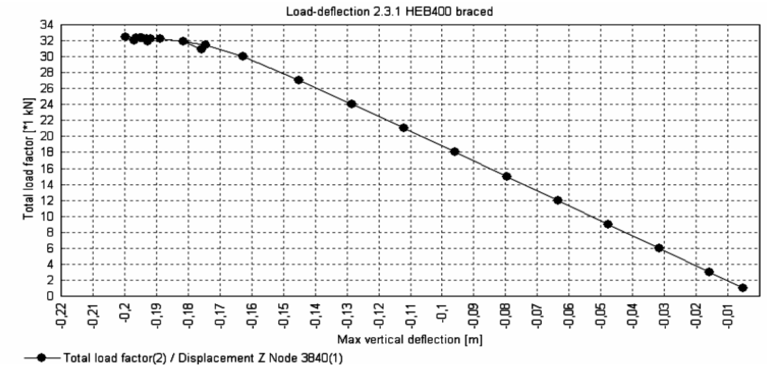
Max load (Eurocode) q_d = 71,1 kN/m which gives P_d = 177,8 kN

Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	16,5 kN	not OK
Eurocode	F_con.max =	49,5 kN	not OK

Structure 2.3.1 HEB 400

	Load factor (=applied load [kN])				
	0	15	30	31,5	32,2
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
413	0	0,54	1,38	1,42	1,36
883	0	0,18	0,94	1,02	1,05
1353	0	0,39	0,48	0,46	0,50
1823	0	1,45	3,40	3,88	3,89
2293	0	2,65	5,34	1,73	1,53
2763	0	3,69	6,98	8,13	11,49
3233	0	4,30	13,64	17,88	19,40
3703	0	4,31	14,22	18,53	19,62
4173	0	3,70	7,75	9,61	13,53
4643	0	2,57	5,42	1,77	1,17
5113	0	1,15	3,43	3,77	3,47
5583	0	0,32	0,63	0,64	0,58
6053	0	1,46	3,61	3,91	4,13
6523	0	2,95	7,86	8,57	9,06
Mean	0,00	2,12	5,36	5,81	6,48
Max	0,00	4,31	14,22	18,53	19,62





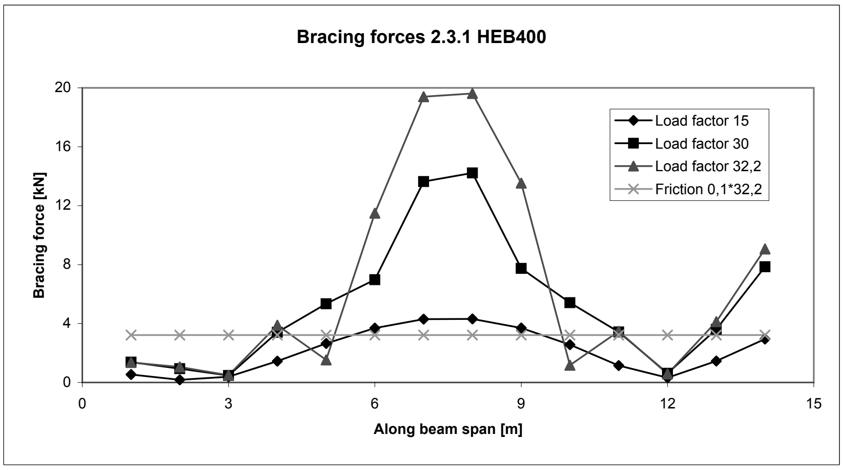
Sum up

Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
15	4,31	2,12	1,5
30	14,22	5,36	3
31,5	18,53	5,81	3,15
32,2	19,62	6,48	3,22

Friction my_d = 0,1
Fy bracing force
F_my friction force

Results Finite Element Analysis
Steel on steel beams

Structure 2.3.1 HEB 400



From analytical calculations

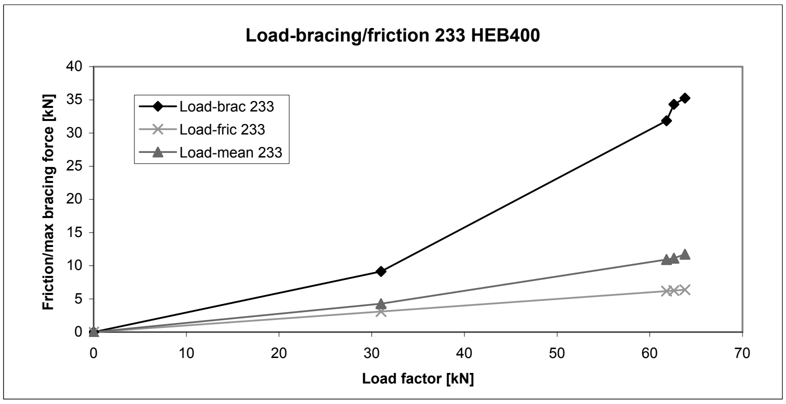
Max load (Eurocode) q_d = 31,6 kN/m which gives P_d = 31,6 kN

Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	16,5 kN	not OK
Eurocode	F_con.max =	49,5 kN	not OK

Structure 2.3.3 HEB 400

Load factor (=applied load [kN])

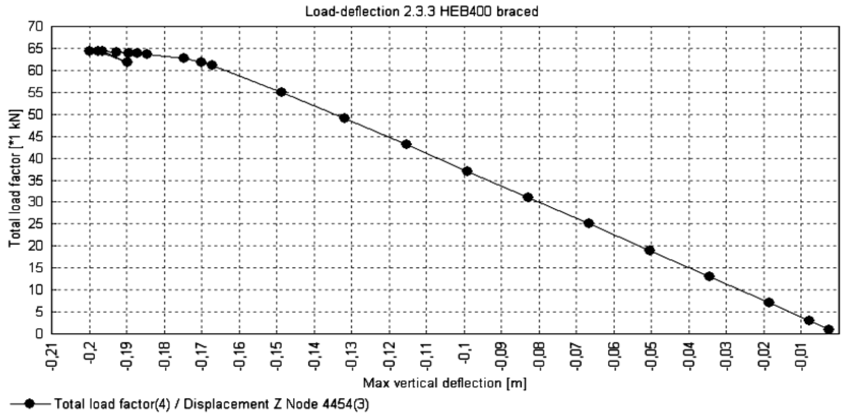
	0	31	61,8	62,6	63,8
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
318	0	0,70	2,11	1,97	1,35
1093	0	1,84	2,93	2,37	0,13
2033	0	6,69	12,68	12,58	15,23
2973	0	9,14	31,85	34,32	35,25
3913	0	6,69	14,41	14,57	17,82
4853	0	0,77	1,70	1,06	1,41
5793	0	4,05	10,89	11,02	10,97
Mean	0,00	4,27	10,94	11,13	11,74
Max	0,00	9,14	31,85	34,32	35,25



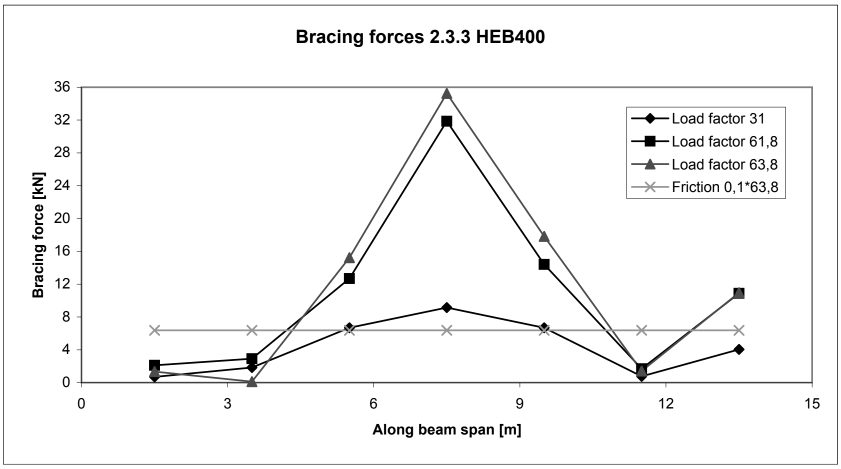
Sum up

Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
31	9,14	4,27	3,1
61,8	31,85	10,94	6,18
62,6	34,32	11,13	6,26
63,8	35,25	11,74	6,38

Friction my_d = 0,1
Fy bracing force
F_my friction force



Structure 2.3.3 HEB 400



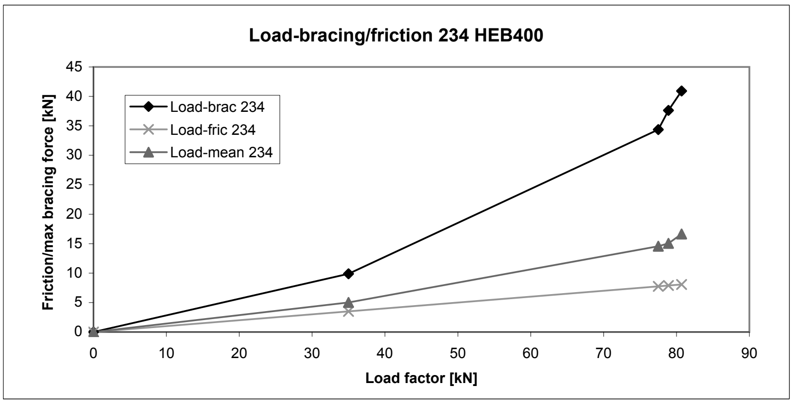
From analytical calculations

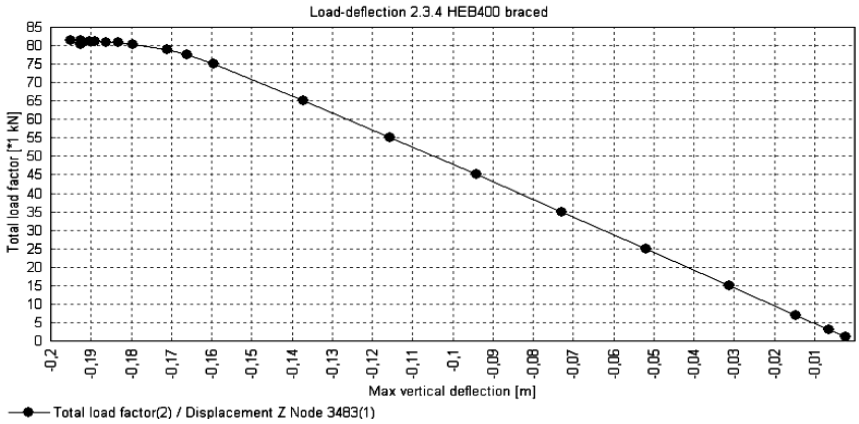
Max load (Eurocode) q_d = 31,6 kN/m which gives P_d = 63,2 kN

Needed bracing | Friction enough according to calculations?
BSK F_con.max = 16,5 kN not OK
Eurocode F_con.max = 49,5 kN not OK

Structure 2.3.4 HEB 400

	Load factor (=applied load [kN])				
	0	35	77,5	78,9	80,7
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
458	0	0,01	0,90	0,95	1,89
1633	0	6,04	13,27	12,45	13,09
2808	0	9,88	34,36	37,63	40,92
3983	0	6,01	15,40	14,90	16,32
5158	0	3,17	8,88	9,29	11,01
Mean	0,00	5,02	14,56	15,04	16,65
Max	0,00	9,88	34,36	37,63	40,92



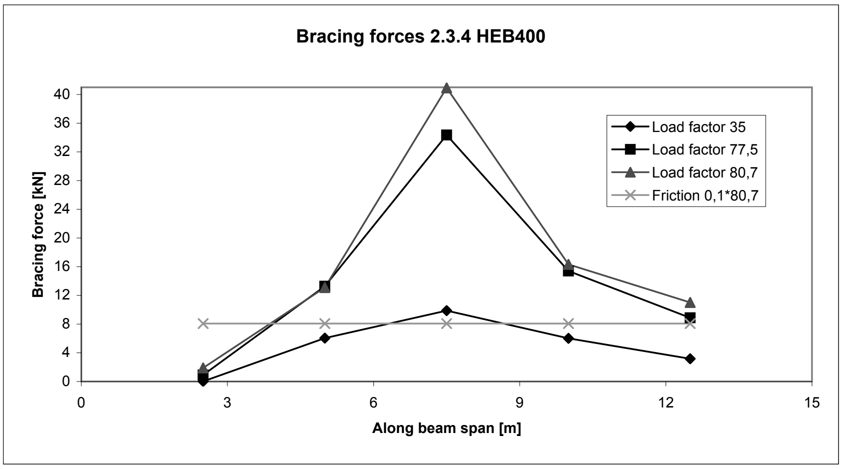


Sum up

Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
35	9,88	5,02	3,5
77,5	34,36	14,56	7,75
78,9	37,63	15,04	7,89
80,7	40,92	16,65	8,07

Friction my_d = 0,1
Fy bracing force
F_my friction force

Structure 2.3.4 HEB 400



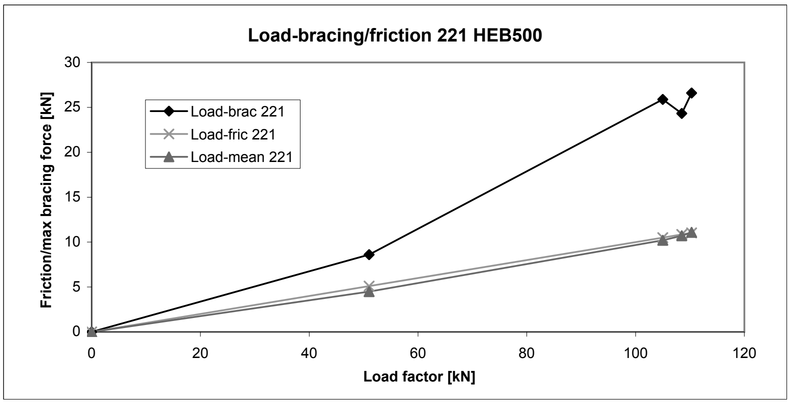
From analytical calculations

Max load (Eurocode) q_d = 31,6 kN/m which gives P_d = 79,0 kN

Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	16,5 kN	not OK
Eurocode	F_con.max =	49,5 kN	not OK

Structure 2.2.1 HEB 500

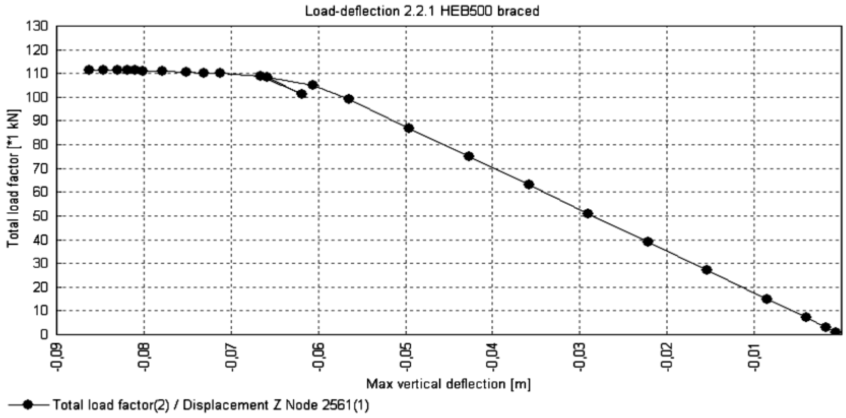
	Load factor (=applied load [kN])				
	0	51	105	108,5	110,3
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
401	0	2,60	6,16	6,55	6,79
931	0	1,12	2,31	3,48	4,22
1461	0	4,54	8,91	4,03	0,50
1991	0	7,50	14,24	20,25	25,86
2521	0	8,60	25,88	24,32	21,18
3051	0	7,35	14,53	21,19	26,60
3581	0	4,13	8,52	3,23	0,17
4111	0	0,29	1,18	2,42	3,15
4641	0	4,22	10,12	10,85	11,34
Mean	0,00	4,48	10,21	10,70	11,09
Max	0,00	8,60	25,88	24,32	26,60



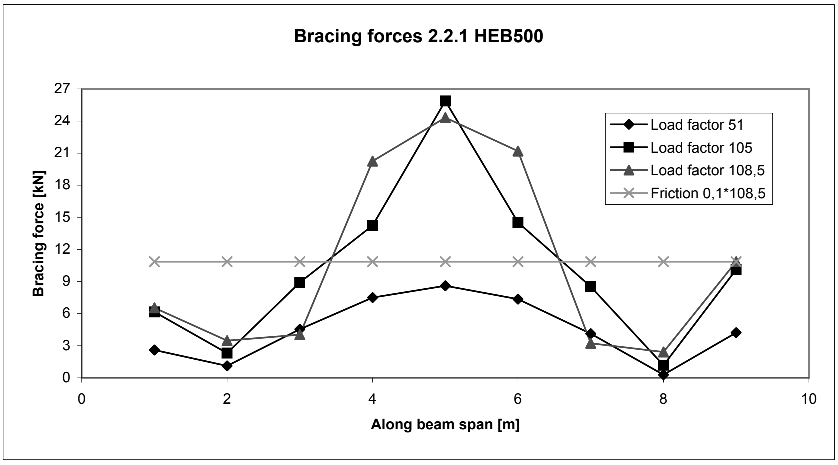
Sum up

Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
51	8,60	4,48	5,1
105	25,88	10,21	10,5
108,5	24,32	10,70	10,85
110,3	26,60	11,09	11,03

Friction my_d = 0,1
Fy bracing force
F_my friction force



Structure 2.2.1 HEB 500



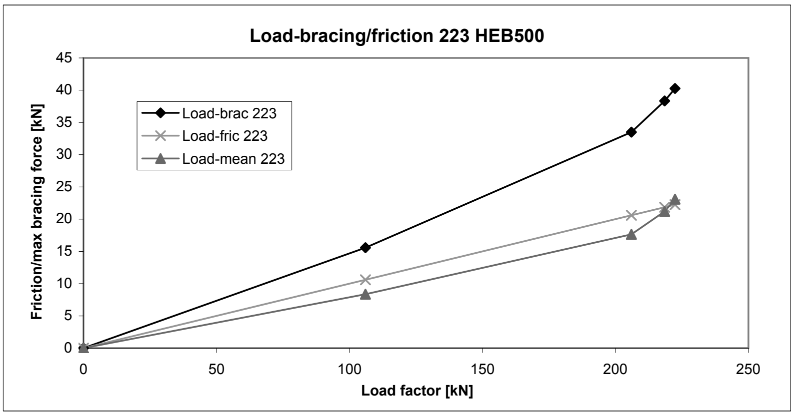
From analytical calculations

Max load (Eurocode) q_d = 105,8 kN/m which gives P_d = 105,8 kN

Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	19,3 kN	not OK
Eurocode	F_con.max =	57,8 kN	not OK

Structure 2.2.3 HEB 500

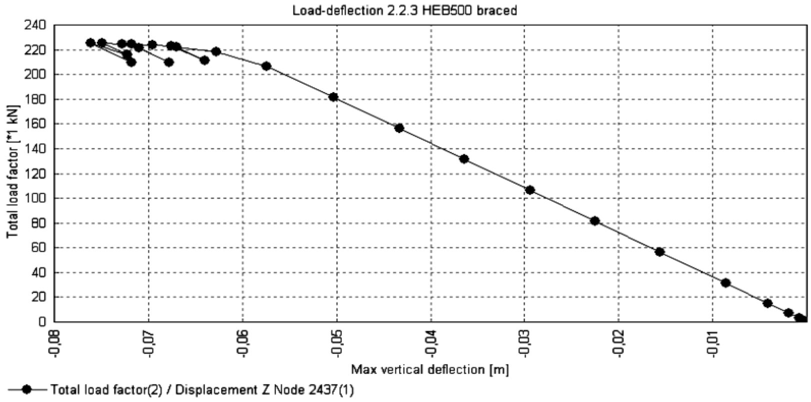
	Load factor (=applied load [kN])				
	0	106	206	218,5	222,4
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
136	0	0,857	0,7986	2,06	3,717
1 196	0	15,57	32,84	37,63	40,01
2 256	0	15,48	33,49	38,34	40,26
3 316	0	1,542	3,448	6,74	8,378
Mean	0,00	8,36	17,64	21,19	23,09
Max	0,00	15,57	33,49	38,34	40,26



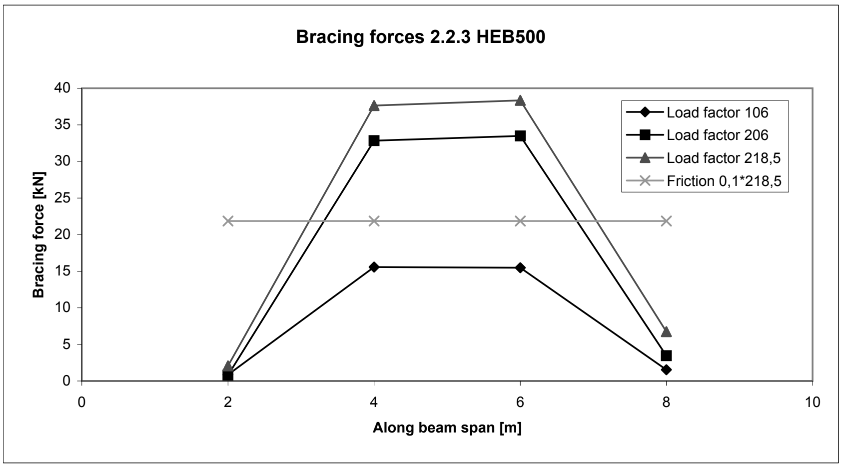
Sum up

Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
106	15,57	8,36	10,6
206	33,49	17,64	20,6
218,5	38,34	21,19	21,85
222,4	40,26	23,09	22,24

Friction my_d = 0,1
Fy bracing force
F_my friction force



Structure 2.2.3 HEB 500



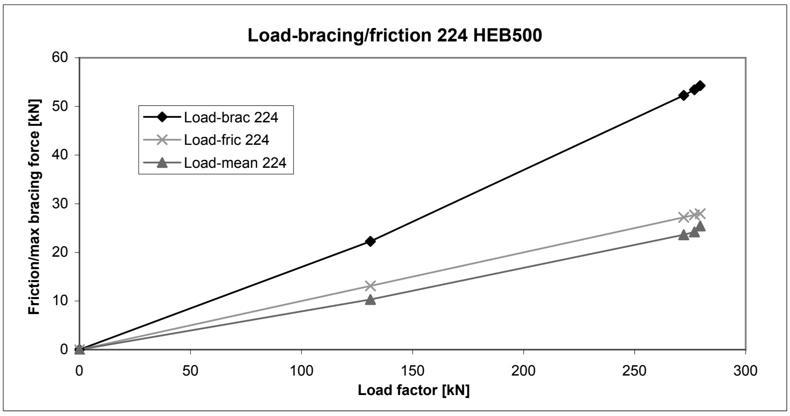
From analytical calculations

Max load (Eurocode) q_d = 105,8 kN/m which gives P_d = 211,6 kN

Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	19,3 kN	not OK
Eurocode	F_con.max =	57,8 kN	not OK

Structure 2.2.4 HEB 500

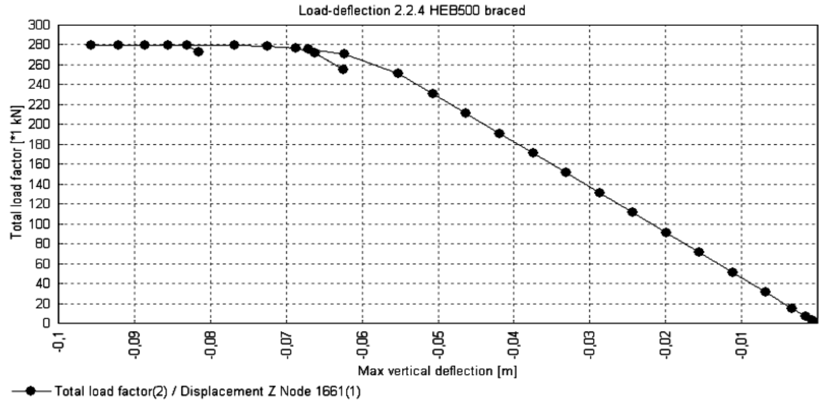
	Load factor (=applied load [kN])				
	0	131	272,1	276,9	279,5
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
136	0	5,47	10,96	11,27	11,68
1461	0	22,27	52,27	53,42	54,27
2786	0	3,20	7,65	7,97	10,33
Mean	0,00	10,31	23,63	24,22	25,43
Max	0,00	22,27	52,27	53,42	54,27



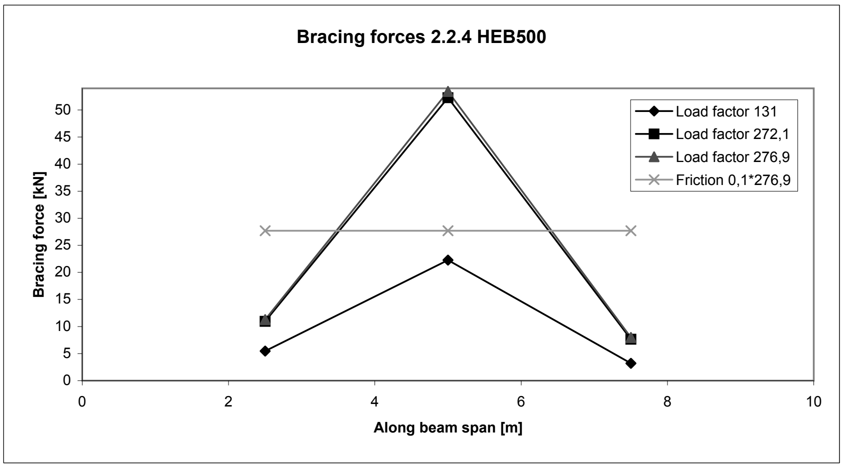
Sum up

Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
131	22,27	10,31	13,1
272,1	52,27	23,63	27,21
276,9	53,42	24,22	27,69
279,5	54,27	25,43	27,95

Friction my_d = 0,1
Fy bracing force
F_my friction force



Structure 2.2.4 HEB 500



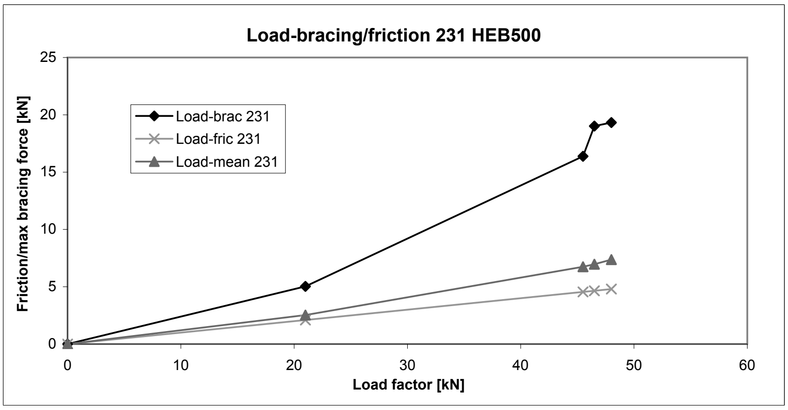
From analytical calculations

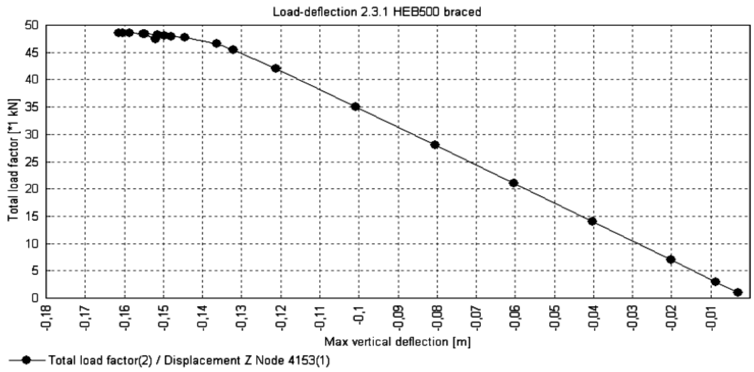
Max load (Eurocode) q_d = 105,8 kN/m which gives P_d = 264,5 kN

Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	19,3 kN	not OK
Eurocode	F_con.max =	57,8 kN	not OK

Structure 2.3.1 HEB 500

	Load factor (=applied load [kN])				
	0	21	45,5	46,5	48
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
401	0	1,26	3,51	3,60	3,71
931	0	0,41	1,77	1,83	1,90
1461	0	0,42	0,47	0,45	0,34
1991	0	1,72	4,19	4,52	5,49
2521	0	3,13	7,32	6,34	0,92
3051	0	4,33	8,93	8,19	13,87
3581	0	5,02	15,85	18,26	19,21
4111	0	5,04	16,38	19,02	19,32
4641	0	4,33	9,54	9,04	15,87
5171	0	3,04	7,66	6,54	0,82
5701	0	1,41	4,34	4,72	5,75
6231	0	0,30	0,51	0,53	0,65
6761	0	1,68	4,41	4,54	4,78
7291	0	3,35	9,55	9,89	10,54
Mean	0,00	2,53	6,74	6,96	7,37
Max	0,00	5,04	16,38	19,02	19,32



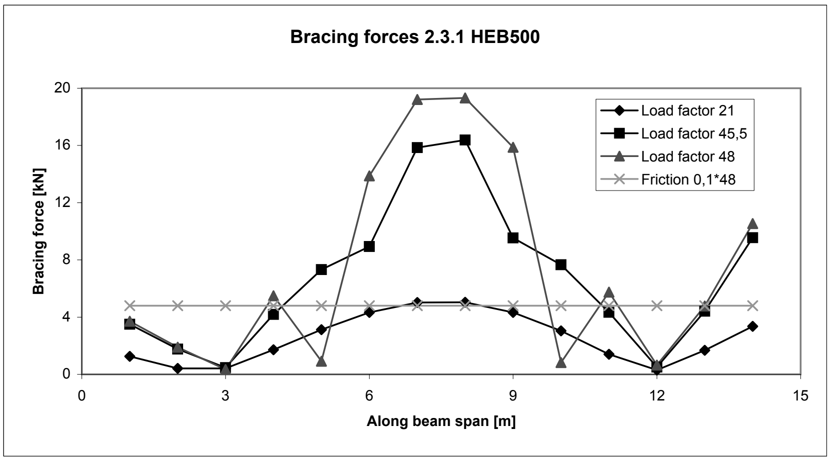


Sum up

Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
21	5,04	2,53	2,1
45,5	16,38	6,74	4,55
46,5	19,02	6,96	4,65
48	19,32	7,37	4,8

Friction my_d = 0,1
Fy bracing force
F_my friction force

Structure 2.3.1 HEB 500



From analytical calculations

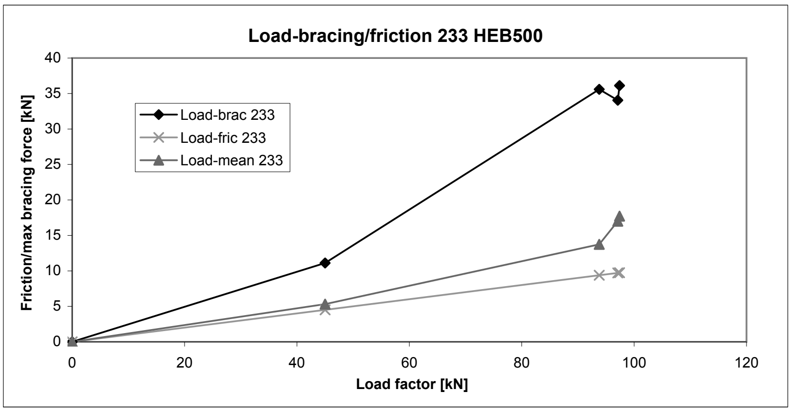
Max load (Eurocode) q_d = 47 kN/m which gives P_d = 47,0 kN

Needed bracing
BSK F_con.max = 19,3 kN
Eurocode F_con.max = 57,8 kN

Friction enough according to calculations?
not OK
not OK

Structure 2.3.3 HEB 500

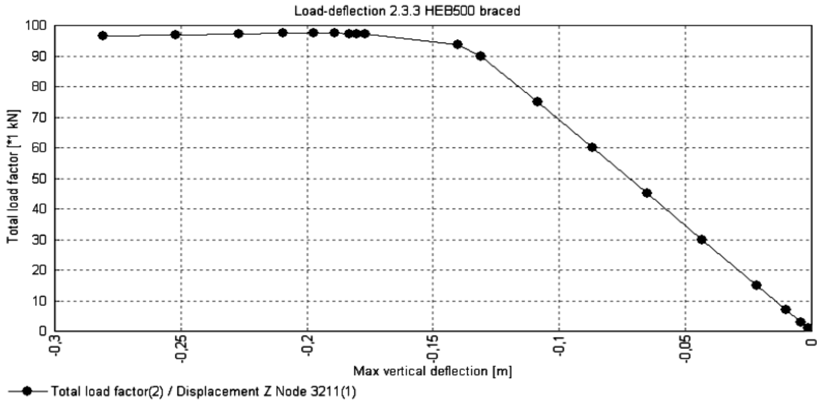
	Load factor (=applied load [kN])				
	0	45	93,8	97,1	97,4
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
136	0	1,66	4,80	2,99	2,79
931	0	2,23	3,63	3,69	4,26
1991	0	8,19	17,25	27,95	28,52
3051	0	11,11	35,59	31,29	32,00
4111	0	8,21	19,14	34,05	36,12
5171	0	1,04	2,65	6,80	8,11
6231	0	4,76	13,08	12,21	12,25
Mean	0,00	5,31	13,73	17,00	17,72
Max	0,00	11,11	35,59	34,05	36,12



Sum up

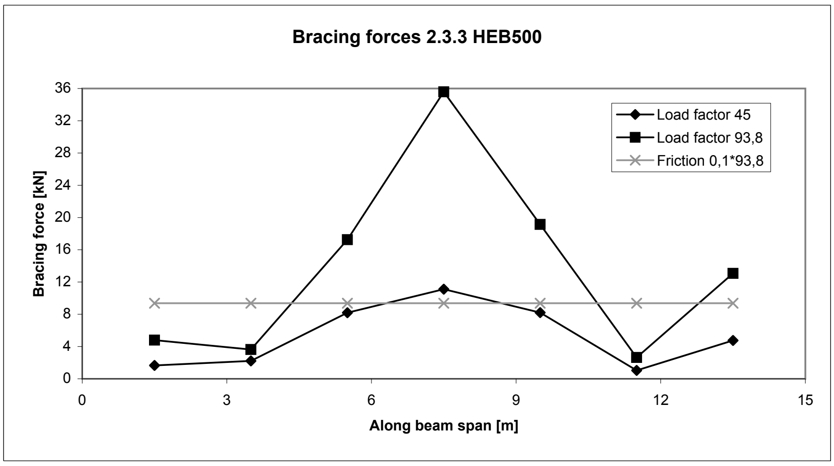
Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
45	11,11	5,31	4,5
93,8	35,59	13,73	9,38
97,1	34,05	17,00	9,71
97,4	36,12	17,72	9,74

Friction my_d = 0,1
Fy bracing force
F_my friction force



Results Finite Element Analysis
Steel on steel beams

Structure 2.3.3 HEB 500



From analytical calculations

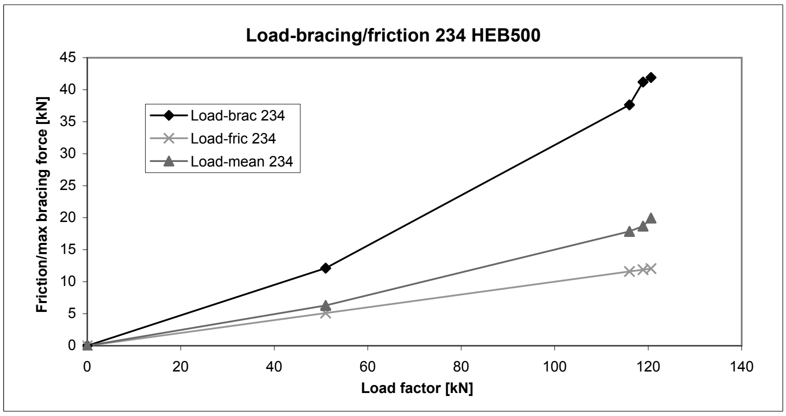
Max load (Eurocode) q_d = 47 kN/m which gives P_d = 94,0 kN

Needed bracing			Friction enough according to calculations?
BSK	F_con.max =	19,3 kN	not OK
Eurocode	F_con.max =	57,8 kN	not OK

Structure 2.3.4 HEB 500

Load factor (=applied load [kN])

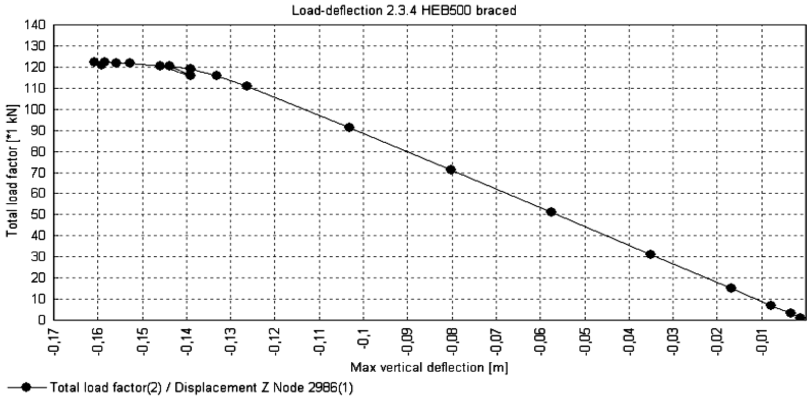
	0	51	116	118,9	120,6
Node	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]	Fy [kN]
136	0	0,58	2,93	3,18	4,17
1461	0	7,58	18,24	17,83	19,16
2786	0	12,12	37,63	41,21	41,92
4111	0	7,50	20,37	20,42	22,25
5436	0	3,74	10,21	10,89	12,30
Mean	0,00	6,30	17,88	18,71	19,96
Max	0,00	12,12	37,63	41,21	41,92



Sum up

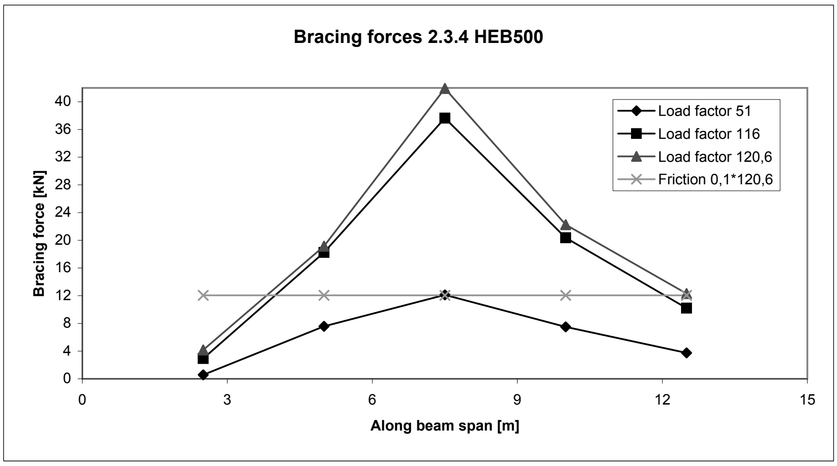
Load	Max Fy	Mean Fy	Fmy
0	0,00	0,00	0
51	12,12	6,30	5,1
116	37,63	17,88	11,6
118,9	41,21	18,71	11,89
120,6	41,92	19,96	12,06

Friction my_d = 0,1
Fy bracing force
F_my friction force



Results Finite Element Analysis
Steel on steel beams

Structure 2.3.4 HEB 500



From analytical calculations

Max load (Eurocode) q_d = 47 kN/m which gives P_d = 117,5 kN

Needed bracing
BSK F_con.max = 19,3 kN
Eurocode F_con.max = 57,8 kN

Friction enough according to calculations?
not OK
not OK

Appendix E Comparison of Different Sources for Calculation of the Critical Moment

This Appendix includes the explaining MathCAD document and the excel document that contain the comparison of different sources for calculation of the elastic critical moment with regard to lateral-torsional buckling. Three different methods have been compared, at first in their most simple formulation and secondly in the formulation representing an example of the static system and load distribution, like the beams in this Master's Thesis.

First read through the MathCAD document to understand the formulations used in excel. In excel the formulations are hidden and only the input data and the answers appear.

Comparison of different sources for calculation of the critical moment

Test with the simpliest case

For description of the notations, see Excel

<u>StBK-K2 , Chapter 4:3</u>

$$M_{cr} = \pi \cdot \frac{\sqrt{B_y \cdot C}}{L} \cdot \sqrt{1 + \frac{\pi^2}{(kL)^2}}$$

$$B_y = E \cdot I_y$$

$$kL = L \cdot \sqrt{\frac{C}{C_w}}$$

<u>NCCI, SN003a-EN-EU</u>

$$M_{cr} = \frac{\pi^2 \cdot E \cdot I_y}{L^2} \cdot \sqrt{\frac{I_w}{I_y} + \frac{L^2 \cdot G \cdot I_t}{\pi^2 \cdot E \cdot I_y}}$$

<u>LTBeam</u>

FEM-program from CTICM (Centre Technique Industriel de la Construction Métallique) used for comparison to the analytical calculations

Test with the case of distributed load and simply supported beam

<u>StBK-K2 , Chapter 4:3</u>

$$q_{cr} = m \cdot \frac{\sqrt{B_y \cdot C}}{L^3} \cdot \sqrt{1 + \frac{\pi^2}{(kL)^2}} \qquad M_{cr} = \frac{q_{cr} \cdot L^2}{8}$$

m - taken graphically from diagram, depends on (kL) and where the load point of action

<u>NCCI, SN003a-EN-EU</u>

$$M_{cr} = C_1 \cdot \frac{\pi^2 \cdot E \cdot I_y}{L^2} \left[\sqrt{\frac{I_w}{I_y} + \frac{L^2 \cdot G \cdot I_t}{\pi^2 \cdot E \cdot I_y} + \left(C_2 \cdot z_g\right)^2} - C_2 \cdot z_g \right]$$

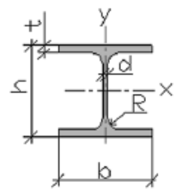
C_1 and C_2 are coefficients depending on the loading and support conditions

z_g is the distance between the shear centre and the load application point

Comparison of different sources for calculation of the critical moment

Input data

E_k	210	[GPa]	Young modulus
G_k	80,77	[Gpa]	shear modulus
L_beam	10	[m]	beam span length



HEB	**b**	**t_flange**	**I_x**	**Z_x**	**W_x**	**I_y**	**C**	**C_w**	**I_t**	**I_w**
h [mm]	[mm]	[mm]	[10^6x mm^4]	[10^3x mm^3]	[10^3x mm^3]	[10^6x mm^4]	[10^9xNmm^2]	[10^{15}xNmm^4]	[10^6 x mm^4]	[10^9 x mm^6]
200	200	15	56,96	643	570	20,03	48,2	35,9	0,595	171
300	300	19	251,7	1870	1680	85,63	151	354	1,86	1690
400	300	24	576,8	3230	2880	108,2	289	802	3,57	3820
500	300	28	1072	4810	4290	126,2	437	1470	5,4	7020

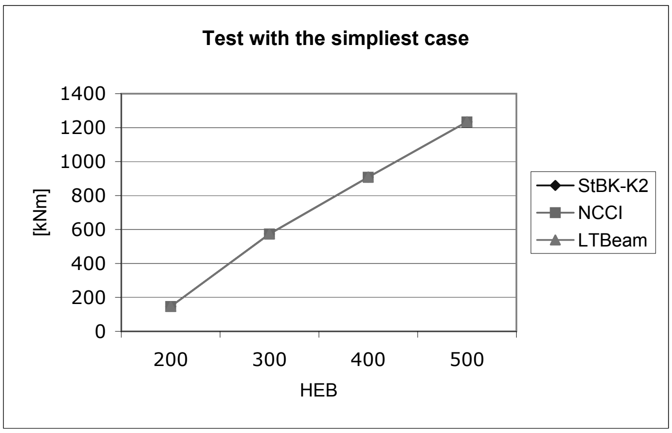
I_x, I_y	moment of inertia
W_x, Z_x	elastic and plastic bending restistance
I_t	S:t Venants torsion constant
C	torsion resistance
I_w	warping constant
C_w	warping resistance

Test with the simpliest case - simply supported beam with equal end moments

	StBK-K2, Chapter 4:3		*NCCI*	*LTBeam*
HEB	**kL**	**M_cr** [kNm]	**M_cr** [kNm]	**M_cr** [kNm]
200	11,6	147	146	146
300	6,5	574	573	573
400	6,0	909	908	908
500	5,5	1234	1233	1234

M_cr elastic critical moment with regard to LTB

All the methods seem to be accurate, as they all returns the same Mcr.



Test with the case of distributed load and simply supported beam

	StBK-K2, Chapter 4:3		
HEB	**m** fr diagram	**q_cr** [kN/m]	**M_cr** [kNm]
200	24,5	11,8	148
300	23,2	47,1	588
400	22,9	74,8	934
500	22,5	102,0	1275

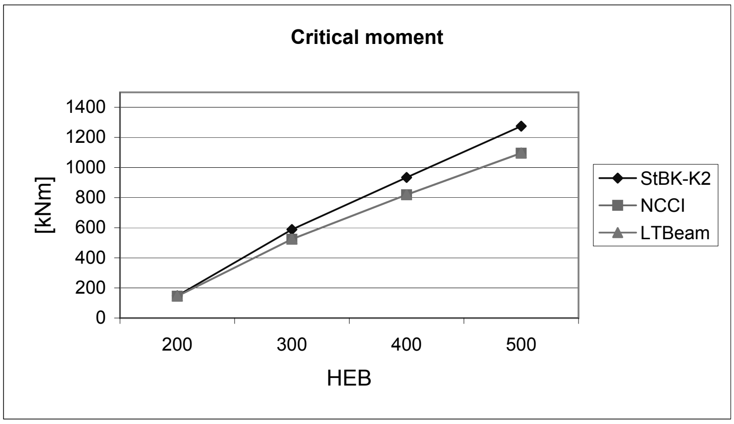
NCCI, SN003a-EN-EU			
z_g [mm]	**C_1**	**C_2**	**M_cr** [kNm]
100	1,127	0,454	145
150	1,127	0,454	524
200	1,127	0,454	819
250	1,127	0,454	1095

LTBeam
M_cr [kNm]
145
525
820
1097

As seen in the diagram the StBK-K2 method differs from the other two. This might have to do with the graphically read value m, that is a risk for error.

The NCCI method will be used in the calculations, both with BSK 07 and Eurocode 3.

LTBeam will be used if there is need for comparison

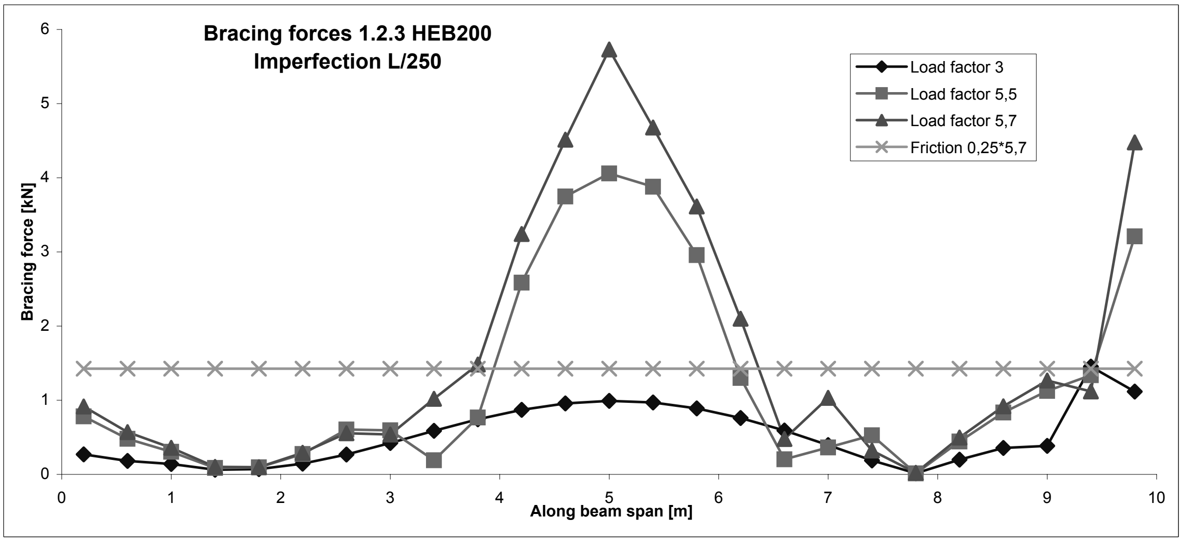


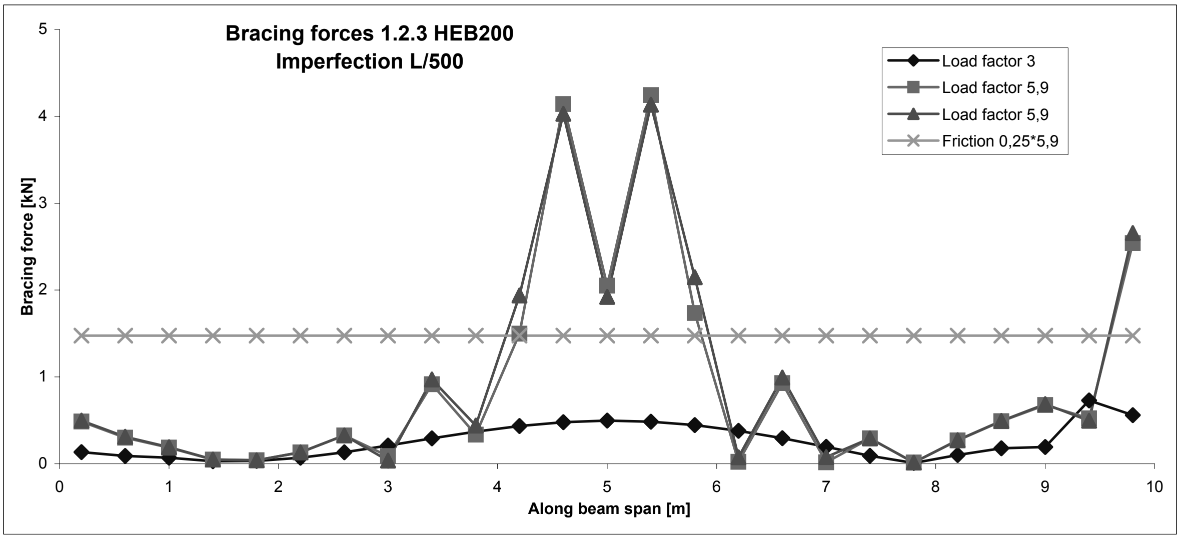
Appendix F Variation of the Initial Imperfection Used in the Finite Element Analyses

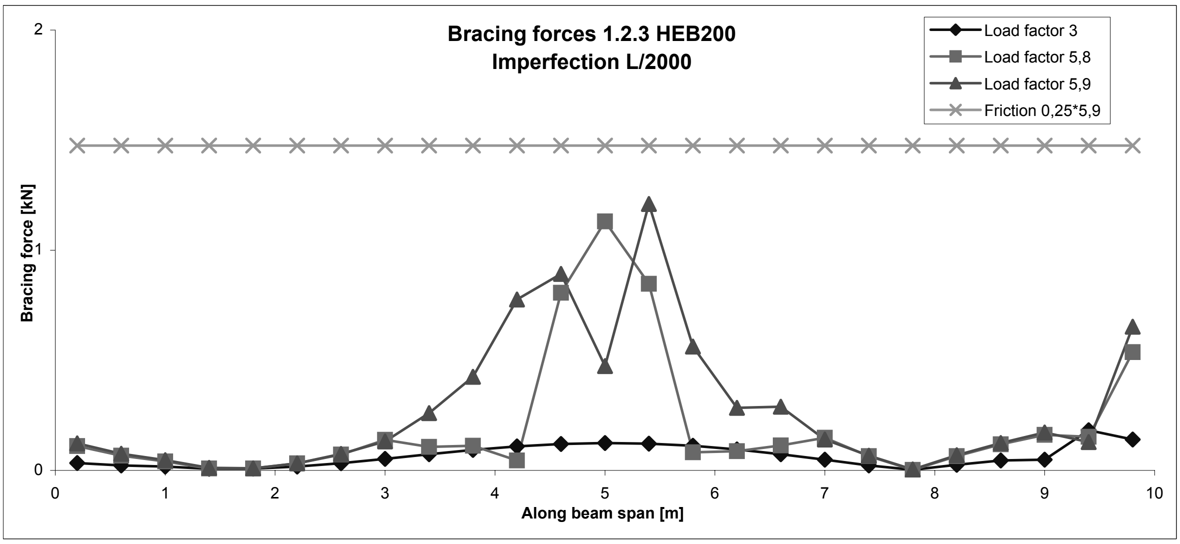
This Appendix includes the results from the test of variation of the initial imperfection, according a discussion point in Section 5. The variation test has only been performed for structure configuration 1.2.3 and HEB 200, 300, 400 and 500. The initial imperfection was set to L/250, L/500 and L/2000, and for each of the different initial imperfections a finite element analysis was performed. In LUSAS the initial imperfection is set by the deformed mesh factor.

Variation of the imperfection

Structure 1.2.3 HEB 200

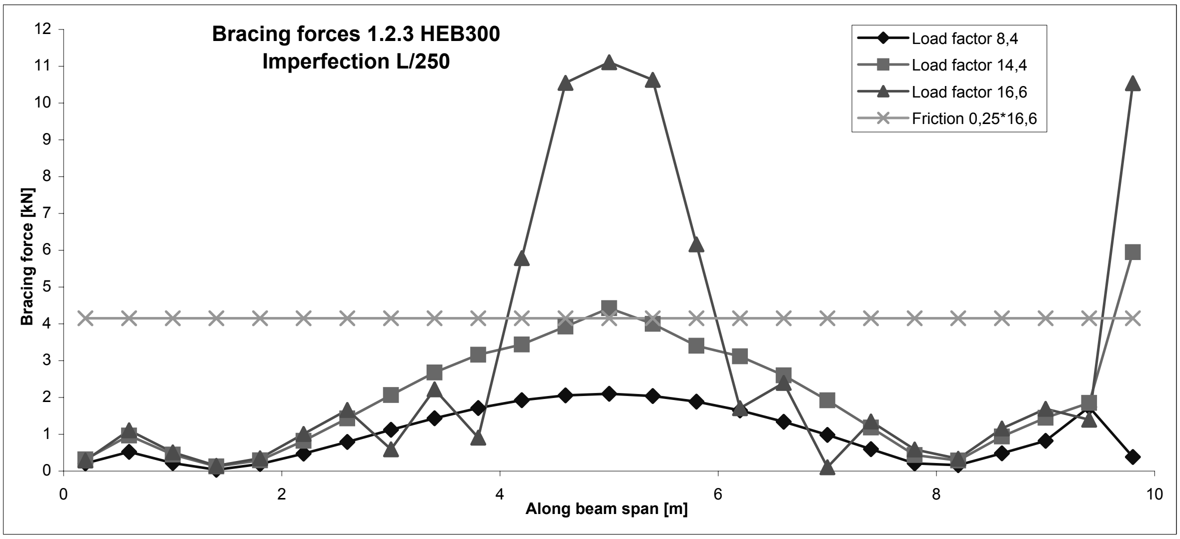


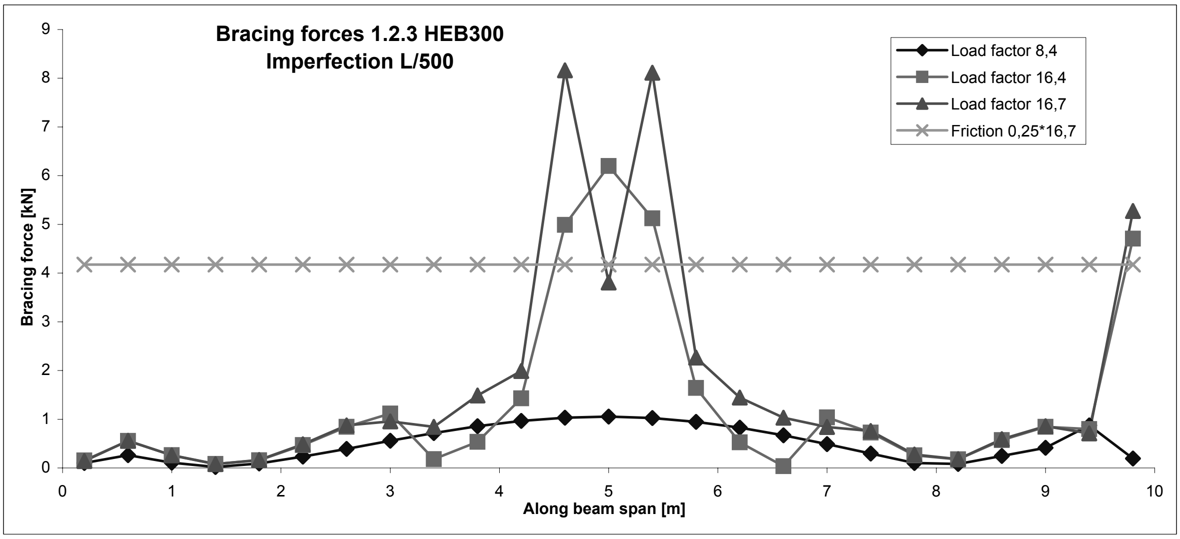


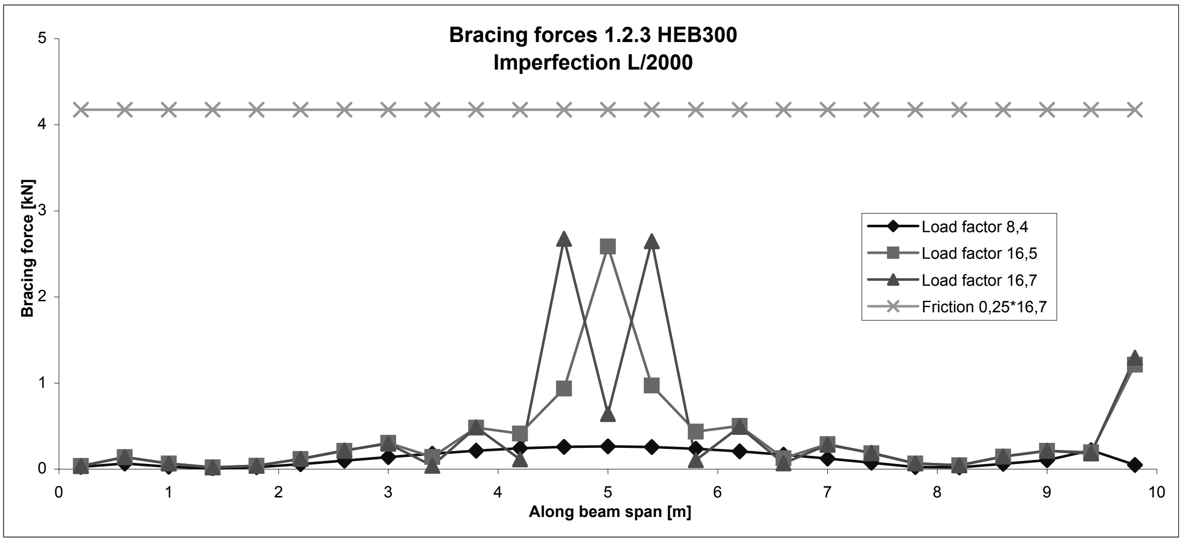


Variation of the imperfection

Structure 1.2.3 HEB 300

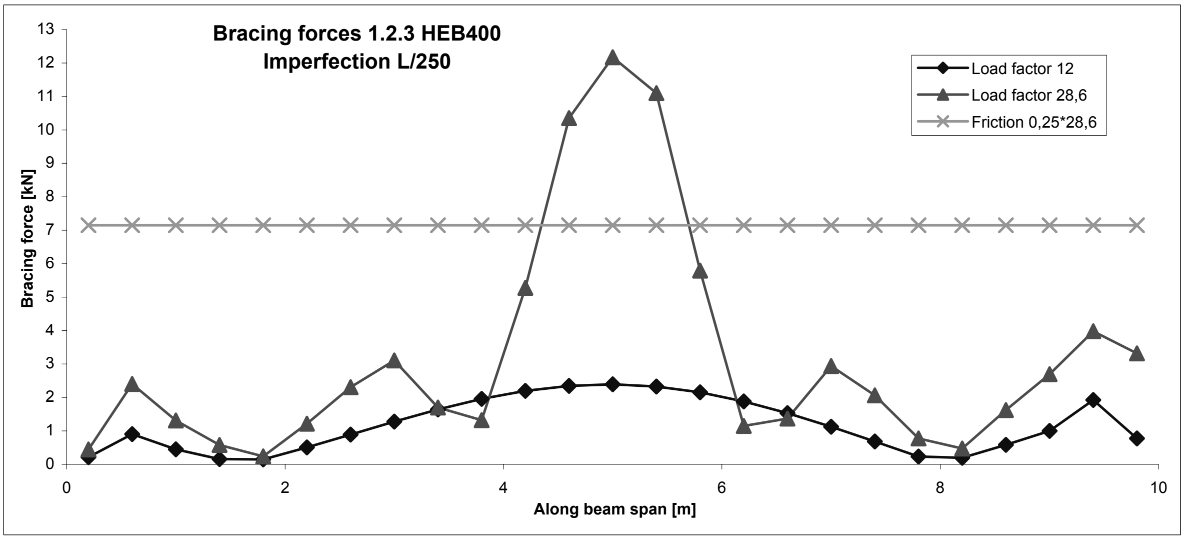


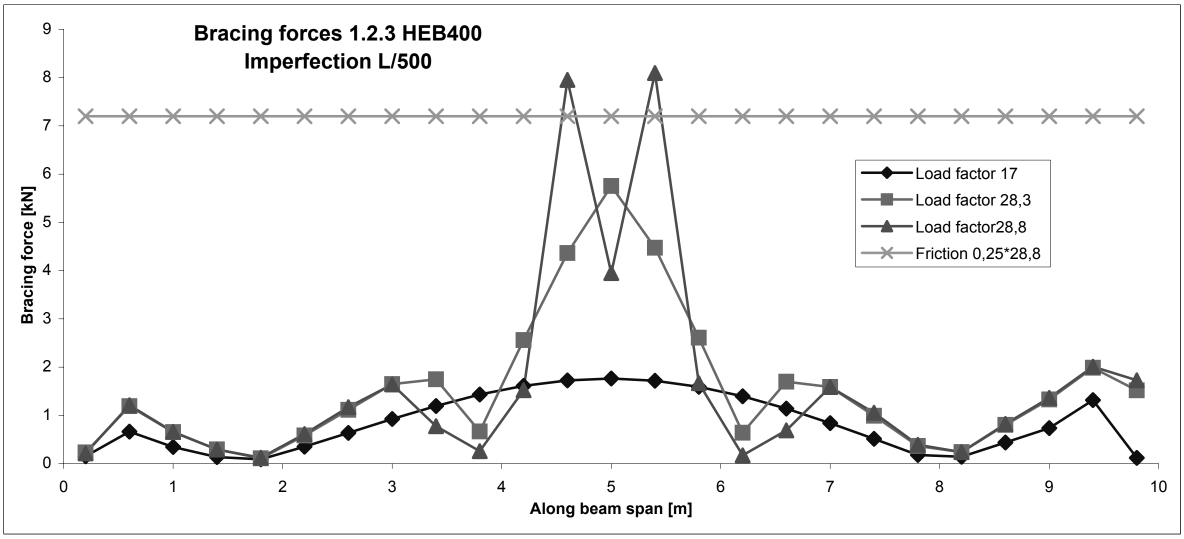


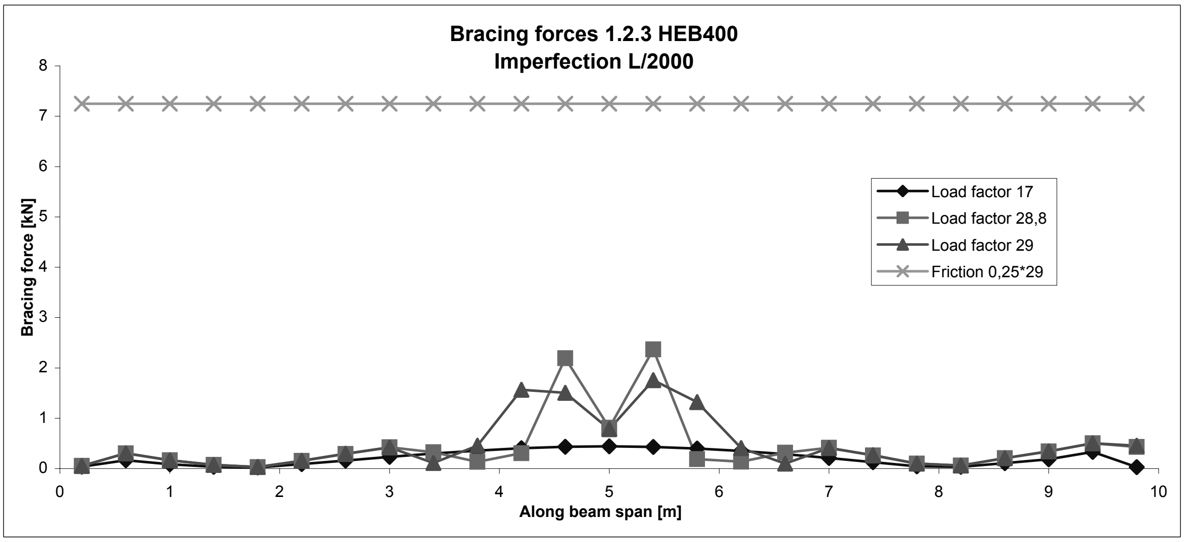


Variation of the imperfection

Structure 1.2.3 HEB 400







Variation of the imperfection

Structure 1.2.3 HEB 500