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Cost and Environmental Benefits of Fatigue Enhancement of Bridges

A Case Study of a Highway Bridge

Master's Thesis in the Master's Programme Structural Engineering and Building Technology

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Department of Civil and Environmental Engineering
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Road bridge over E4 in Skulnäs

Department of Civil and Environmental Engineering
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ABSTRACT

Fatigue is a well-known problem in steel structures and has caused serious accidents over the years in the form of a sudden failure. Fatigue is often the governing factor of steel bridge design and limits the use of high strength steel. The application of Post Weld Treatment has shown improvement in fatigue life of steel structures. With the improved fatigue design, the fatigue limit state is no longer the limiting state of the design, allowing less material usage. This also gives the possibility of using higher steel strength allowing further material saving.

The aim of the thesis is to measure the benefits of Post Weld Treatment application on a bridge in terms of material savings that are quantified based on Life Cycle Assessment and Life Cycle Cost Analysis. A highway bridge in Sweden is studied with the application of High Frequency Mechanical Impact Treatment. Proposed guidelines for the treatment give recommendations on how much improvement in fatigue strength can be expected. Given the improvement, the bridge is recalculated with a new cross section that is verified so all design criteria are fulfilled. The environmental and economic benefits of the material that is saved is than obtained with LCA and LCC.

The results show that increased fatigue strength obtained with the application of HFMI and the use of high strength steel results in a reduction of material up to 20%. The environmental benefits are consistent to the material savings but the benefits of cost are limited due to higher cost of high strength steel.

Key words: Fatigue, Structural Steel, Highway Bridges, Post Weld Treatment, High Frequency Mechanical Impact Treatment, Life Cycle Assessment, Life Cycle Cost.

Contents

Preface

The thesis was carried out at the department of Civil and Environmental Engineering, division of Structural Engineering at Chalmers University of Technology during the spring of 2016. I would like to thank my supervisor Poja Shams Hakimi for guidance and support throughout the work of the thesis.

Gothenburg, August 2016

Guðrún María Guðjónsdóttir

Notations

Abbreviations

CO_{2e}	Carbon Dioxide Equivalent
$FLM3$	Fatigue Load Model 3
FLS	Fatigue Limit State
GWP	Global Warming Potential
$HFMI$	High Frequency Mechanical Impact Treatment
$HSLA$	Hot Rolled High Strength Low Alloy Steel
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCI	Life Cycle Inventory
$LCIA$	Life Cycle Impact Assessment
$LM1$	Load Model 1
PWT	Post Weld Treatment
NPV	Net Present Value
SEK	Swedish Crown
SLS	Serviceability Limit State
UIT	Ultrasonic Impact Treatment
ULS	Ultimate Limit State

Roman Symbols

B	Axle load of load model ANM.2
E_{cm}	Secant modulus of elasticity of concrete
E_a	Modulus of elasticity of structural steel
N	Number of load cycles
N_i	Crack initiation life
N_{obs}	Number of heavy vehicles expected per year and per slow lane
N_p	Crack propagation life
R	Stress ration of a load cycle
σ_a	Stress amplitude of a load cycle
σ_m	Mean stress of a load cycle
$\sigma_{\max}$	Maximum stress of a load cycle
$\sigma_{\min}$	Minimum stress of a load cycle
Q_{ik}	Characteristic axle load on notional lane number i
f_y	Yield strength

m	Slope of fatigue strength curve
n_0	Modular ratio for short term loading
n_L	Modular ratio depending on type of loading
q	Distributed load of load model ANM.2
q_{ik}	Characteristic vertical uniformly distributed load on notional lane number *i*
w	Carriageway width for road bridge

Greek Symbols

$\Delta\sigma$	Stress range of a load cycle
$\Delta\sigma_C, \Delta\tau_C$	Reference value of fatigue strength at 2 million cycles
$\Delta\sigma_D$	Fatigue limit for constant amplitude stress range
$\Delta\sigma_{E2}$	Equivalent constant amplitude stress range
$\Delta\sigma_L$	Cut-off limit for stress range
$\Delta\sigma_p$	Nominal stress range
α_Q	Adjustment factor for axle loads of load model 1
α_q	Adjustment factor for distributed loads of load model 1
γ_{Ff}	Partial factor for equivalent constant amplitude stress range
γ_{Mf}	Partial factor for fatigue strength
$\delta_{\max}$	Maximum deflection in SLS
λ_i	Damage equivalent factors
ϕ_2	Dynamic equivalent impact factor
φ_t	Creep coefficient
ψ_{axel}	Load factor axle loads
ψ_{dist}	Load factor uniformly distributed loads
ψ_L	Creep multiplier

1 Introduction

Fatigue is a well-known problem in metal structures and especially in welded details. Fatigue failures have caused some serious accidents over the years in the form of a sudden failure of structures. The failure can occur after several years of service, without problems, because of micro-damage at welded joints. Fatigue design is therefore important in order to prevent such failure during the design life of the structure (Schijve 2009).

Fatigue limit state is often the governing factor of steel bridge design. With the implementation of Eurocode and its strict fatigue requirements, the fatigue design has become even more prominent in bridges. This limits the use of high strength steel in bridge design since fatigue strength of welded structures is not expected to change depending on material properties (Kuhlmann et al. 2006).

Fatigue enhancement technologies, which exist today, can achieve great improvement of the fatigue life of steel structures. These technologies have been used widely in different industries such as wind power, offshore structures and automotive industries with good results.

In many steel bridges, a failure of only limited number of fatigue-sensitive details is a decisive factor. Due to this, the material usage proves to be more excessive than required in the ultimate and serviceability limit states. Fatigue improvement methods could be applied in order to make the ultimate limit state dominating instead of the fatigue limit state and consequently save material. This also enables the use of higher strength steel, allowing further material saving (Shams Hakimi & Al-Emrani 2014).

1.1 Purpose and aim

The purpose of this master's thesis is to determine how much benefit can be gained by fatigue enhancement with the application of High Frequency Mechanical Impact Treatment (HFMI) on bridges. Recalculations of an existing bridge design will be carried out at first and the benefits measured by means of material saving. The economic and environmental benefits will then be quantified based on Life Cycle Cost (LCC) and Life Cycle Assessment (LCA) considering carbon dioxide emissions.

1.2 Method

The first step of the work is a literature study and a search for different recommendations on how much improvement can be utilized in bridges by HFMI. Based on the investigations, the degree of fatigue improvement is taken into account and used for recalculations of a bridge which is governed by fatigue and designed according to Eurocode. The bridge studied is a highway bridge in Sweden and the recalculations of the new bridge design are performed with the same methods and assumptions as in the original design, fulfilling all design criteria.

The final step is to perform a LCC and LCA analysis based on the material savings. The LCC analysis will be carried out to investigate the economic feasibility of the improvement including initial cost saving and potential long-term savings. This will be followed by LCA analysis for the environmental aspect of the benefits, based on the same factors as for the LCC analysis.

1.3 Limitations

The study will only focus on a case study of one bridge. The environmental impacts will only be considered for a part of the life cycle of the steel and the impacts will only be represented in terms of carbon dioxide equivalents, CO_{2e}. Other environmental impacts will not be included. The cost only considers the cost of the raw material of the steel and the application of HFMI.

2 Introduction to fatigue

Fatigue is a permanent and progressive structural damage that occurs in metallic materials which are subjected to cyclic loading over a period of time. The damage accumulates in the material and after a certain amount of time and number of cycles it leads to failure. This happens even though the stresses applied are well below the elastic limit of the material (Boardman 1990). Fatigue usually occurs at relatively low stress levels and the limit of cyclic loading where fatigue failure does not occur is called fatigue limit.

The fatigue life is normally divided into two phases; crack initiation phase and crack propagation phase. The process starts with the initiation phase when local plastic deformations occur during cycling loading. These deformations initiate growth of micro cracks invisible to the naked eye. During the propagation phase the cracks grow to a macroscopic size which will finally lead to failure.

For non-welded plain steel details, the initiation phase covers a large proportion of the fatigue life. Nucleation of micro cracks starts early, almost immediately after a load over the fatigue limit is applied, and the growth is slow. Researches have shown that as soon as they become visible, the remaining fatigue life is not long (Schijve 2009). It can be hard to detect the fatigue damage, especially in the initial stages, due to lack of visible deformation. This enables cracks to form undetected throughout the member and therefore failure can happen suddenly and without a notice (Gurney 1968).

Fatigue is a localized failure which starts in small areas that are either under high local stresses or where local defects can be found in the material. A detail that contains notches or any change in geometry, suffers a certain change in the stress distribution which becomes inhomogeneous and causes stress concentration. Increased stress concentration causes problems with decreased fatigue strength and the design should therefore always attempt to reduce the stress concentration as much as possible (Schijve 2009).

Fatigue is the main failure type of welded structures and therefore it is important for all welded structures that undergo cyclic loading to consider fatigue design. Welds give rise to both stress concentrations (due to geometry change) and weld defects, which act as local stress raisers. In addition, tensile residual stresses are present due to the cooling process of the weld. This makes welds a critical location for fatigue failures and causes the fatigue strength of the structure to be decided primarily by welds (Wang et al. 2009).

2.1 Fatigue properties

Fatigue properties of a material can be obtained by testing of specimens under constant amplitude loading. In a laboratory the stress is kept within a certain stress range or between a maximum stress (σ_{max}) and a minimum stress (σ_{min}) of the cycle. The maximum value represents the maximum tensile stress and the minimum value can represent either the minimum tensile stress or a certain amount of compressive stress that can be considered as a negative tensile stress (Boardman 1990). The stress range for one cycle can therefore be expressed as:

$$\Delta\sigma = \sigma_{max} - \sigma_{min} \tag{2.1}$$

Stress ratio of the cycle is defined as the ratio of the minimum stress and the maximum stress and can be expressed as:

$$R = \frac{\sigma_{min}}{\sigma_{max}} \tag{2.2}$$

The load cycle can also be expressed in terms of mean stress (σ_m) and stress amplitude (σ_a). The characteristic stress levels of a load cycle can be seen in Figure 2-1 (Schijve 2009).

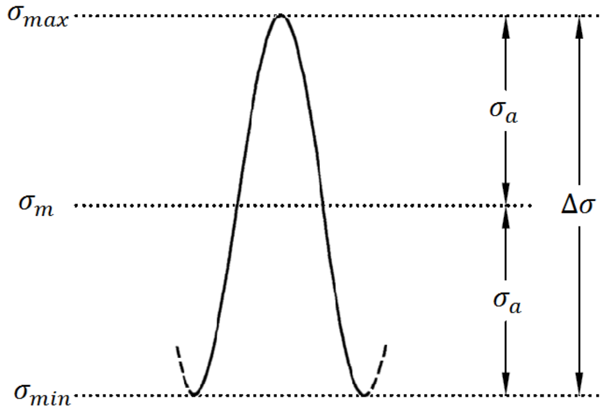

Figure 2-1 Stress levels of one load cycle (Schijve 2009).

2.1.1 S-N curves

A common way to represents the results of fatigue tests is with S-N (stress-number of cycles) curves or Wöhler-diagrams. The tests are carried out on several similar specimens until failure occurs or until the test is stopped after a certain number of cycles. The curves are obtained by linear regression and show the fatigue life in terms of number of cycles to failure versus the stress range. The results are usually plotted in log-log scale which gives a linear relation between the number of cycles on the x-axis and stress range on the y-axis. A typical example of S-N curve can be seen in Figure 2-2.

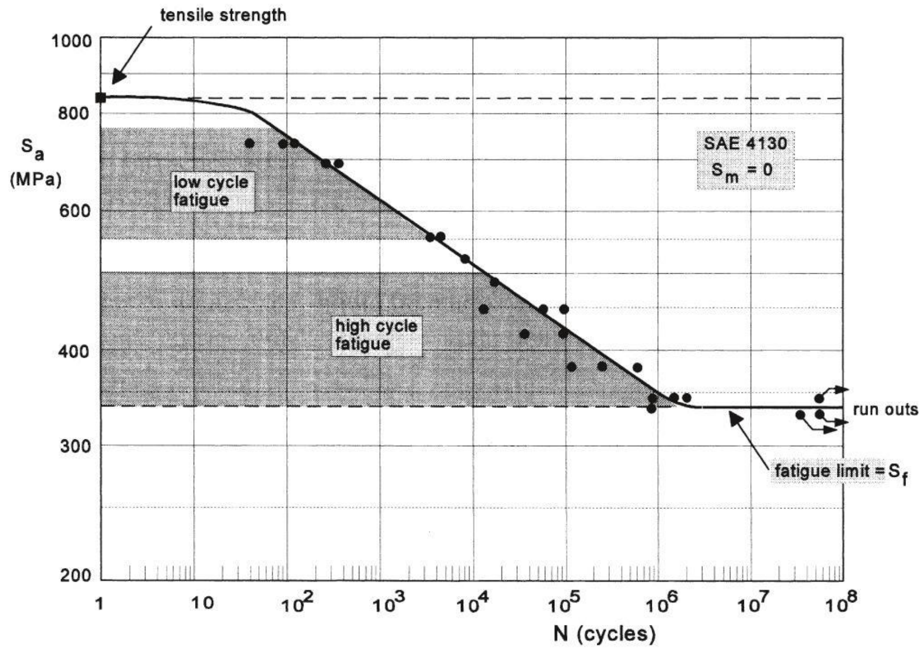

Figure 2-2 S-N curve showing the test results of a specimen (Schijve 2009).

The left part of the graph shows a region that is often called low cycle fatigue. The stress range applied is high and plastic deformations happen instantly and cause quick failure. The number of cycles to failure is therefore low. The right part of the graph shows high cycle fatigue, where the stress range applied is low. Below the fatigue limit or the fatigue threshold, fatigue damage does not occur for any number of load cycles (Schijve 2009).

2.2 Welded details

Welding of metals is a common and convenient way of connecting members in large structures such as bridges, ships and offshore structures. Welding is a sensitive process that requires accuracy, good training and skills of the welding operator in order to assure good quality. Good detail design and welding practice is necessary in structures where fatigue is a decisive factor (Schijve 2009). Defects around the weld and residual stress caused by welding are the main contributors to stress concentration of the detail and thereby the decrease of fatigue strength.

2.2.1 Weld defects

Welding can result in discontinuities and cracks in both the weld and the base material. The quality of the weld is usually determined by these defects and their severity depends on size, shape and orientation, and by the magnitude and direction of the design and fabrications stresses. Defects are mainly caused by improper design, incorrect selection of a welding process and improper care of the electrode or the flux.

Weld defects may be divided into three main categories; cracks and crack-like discontinuities, geometric discontinuities and volumetric discontinuities. Some of them can be seen in Figure 2-3 (Barsom & Rolfe 1999).

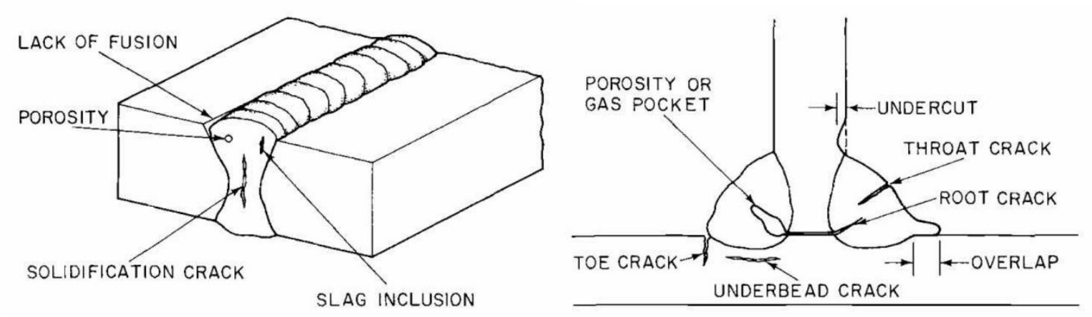

Figure 2-3 Defects in welded joints (Barsom & Rolfe 1999).

Defects around the weld toe are frequently the source of fatigue cracking due to the sharp transition between the weld and the base material (Jármai et al. 2014).

2.2.2 Residual stress

Residual stress is defined as a stress distribution present in a structural component that is independent of external loading. This type of stress is sometimes referred to as internal stress and consists of tensile and compressive components that are balanced within the material and satisfy equilibrium conditions if no external load is applied Tensile residual stress can have harmful effect on fatigue resistance while compressive residual stress can improve the fatigue resistance.

Residual stress forms during the cooling of welds. The metal is heated during welding and when it cools down to ambient temperature it shrinks. Since the weld and the base material are fixed together the shrinkage causes stress to form in both longitudinal and transverse direction as can be seen in Figure 2-4 (Maddox 1991).

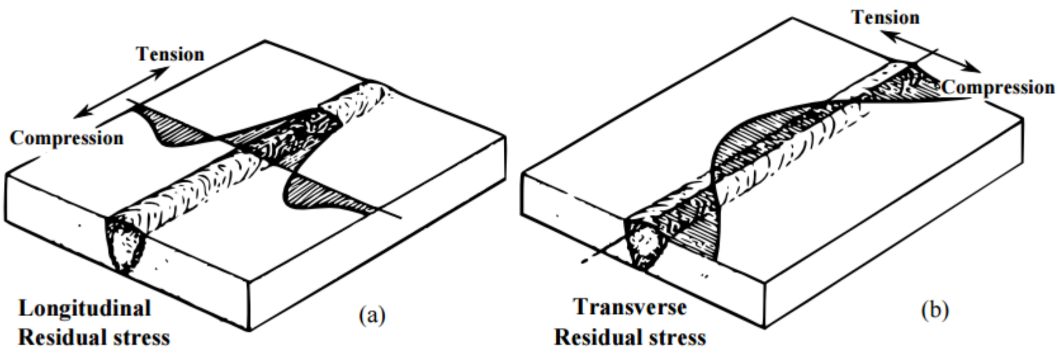

Figure 2-4 Residual stress distribution in a welded joint (Maddox 1991).

2.3 Fatigue design according to Eurocode

The European standard (EN 1993-1-9 2005) deals with fatigue in steel structure design. The standard gives methods and requirements for fatigue assessment of members, connections and joints subjected to fatigue loading. The code uses S-N curves to represent fatigue strength of details. The curves are obtained from results of fatigue tests performed at different stress ranges.

Each detail is assigned a detail category or a fatigue class (FAT class) that describes the fatigue strength. The categories are specified with a number that represents the stress range in MPa corresponding to a fatigue life of $N = 2$ million cycles and is referred to as the reference fatigue strength $\Delta\sigma_c$ and $\Delta\tau_c$.

2.3.1 Details subjected to normal stress

The fatigue strength of details subjected to normal stress are represented by S-N curves with the slope of $m = 3$ that gives the best fit of a number of different details tested in fatigue. The constant amplitude fatigue limit is defined at $N = 5$ million cycles and the stress range corresponding to that can be obtained by the following equation

$$\Delta\sigma_D = 0{,}737 \cdot \Delta\sigma_C \tag{2.3}$$

The S-N curves continue after 5 million cycles with the slope of $m = 5$. The cut-off limit is defined at $N = 100$ million cycles and the stress range corresponding to that is obtained by the following equation

$$\Delta\sigma_L = 0{,}549 \cdot \Delta\sigma_D \tag{2.4}$$

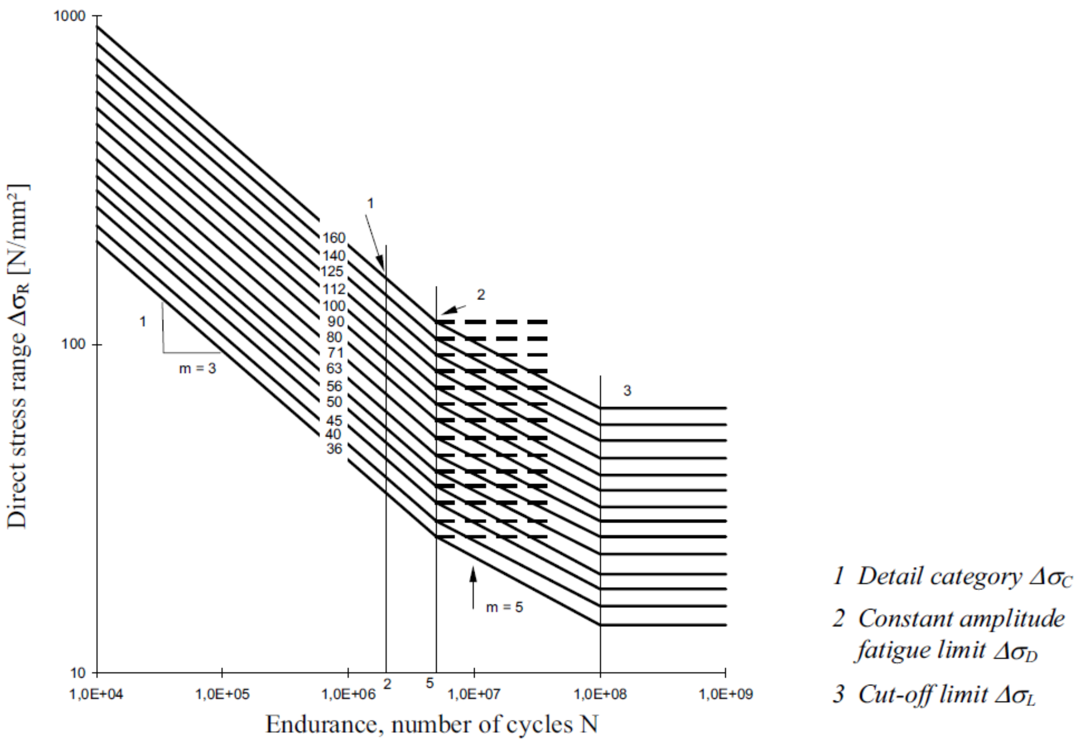

Figure 2-5 S-N curves for details subjected to normal stress (EN 1993-1-9 2005).

2.3.2 Details subjected to shear stress

For details subjected to shear stress, Eurocode defines two S-N curves with the slope of $m = 5$. No constant amplitude fatigue limit is defined but the cut-off limit is defined at $N = 100$ million cycles.

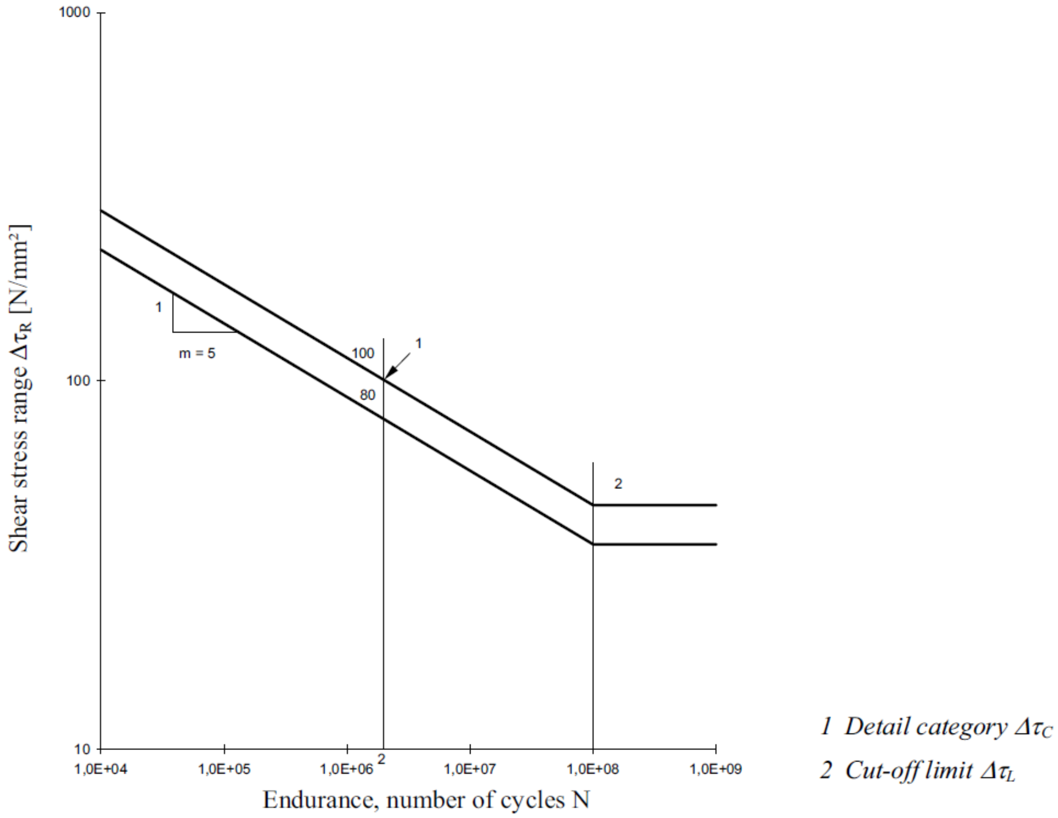

Figure 2-6 S-N curves for details subjected to shear stress (EN 1993-1-9 2005).

3 Post Weld Treatment

Fatigue performance of welded details can be improved by applying good detail design and with good craftsmanship. However, in some cases where critical details cannot be avoided, the fatigue resistance can be improved by applying post weld treatments. Post weld treatments aim to improve the fatigue life of details by treating the weld toe area (Kirkhope et al. 1999).

Welding causes a significant decrease in the initiation phase so the crack propagation phase becomes the main part of the fatigue life. By applying post weld treatment, the initiation phase becomes significantly longer. Longer initiation phase leads to improved fatigue strength and increased number of load cycles needed to reach failure. A representation of the restored crack initiation phase can be seen in Figure 3-1.

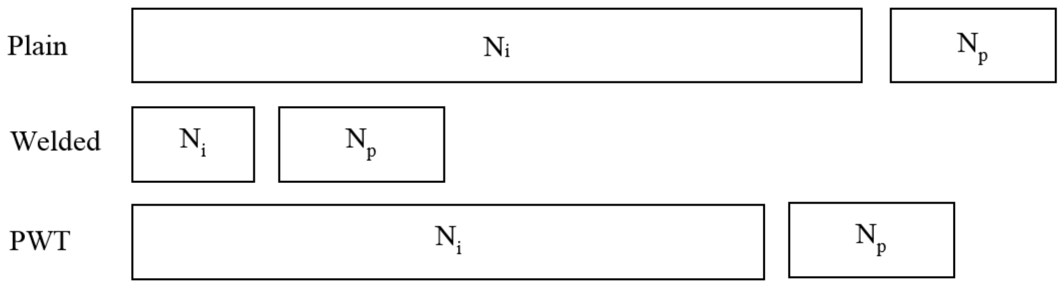

Figure 3-1 Restored crack initiation phase of a welded specimen (Mosiello & Kostakakis 2013).

The initiation phase is highly dependent on material properties and increases with increased yield strength. The propagation phase, however, is almost independent of steel strength. The benefits of higher steel strength for welded details is therefore limited but with the extended initiation phase of post weld treatment, increased steel strength becomes relevant for improved fatigue strength of the detail (Kuhlmann et al. 2006).

3.1 Classification of PWT methods

Post weld treatments are usually divided into two groups; geometry improvement methods and residual stress methods. The weld geometry improvement methods aim to reduce or remove defects around the weld toe introduced during welding and reduce the stress concentration, by smoothening the transition between the weld and the base material. Residual stress method mainly alters the residual stress state around the weld toe by introducing compressive stresses that counteracts the tensile stresses formed during welding (Kirkhope et al. 1999).

Post weld treatments have in common to improve the fatigue resistance of the weld toe region. Therefore, failure at other locations must be considered. Various methods have been researched and they have shown increase in fatigue strength. Figure 3-2 shows the most common methods (Kuhlmann et al. 2006).

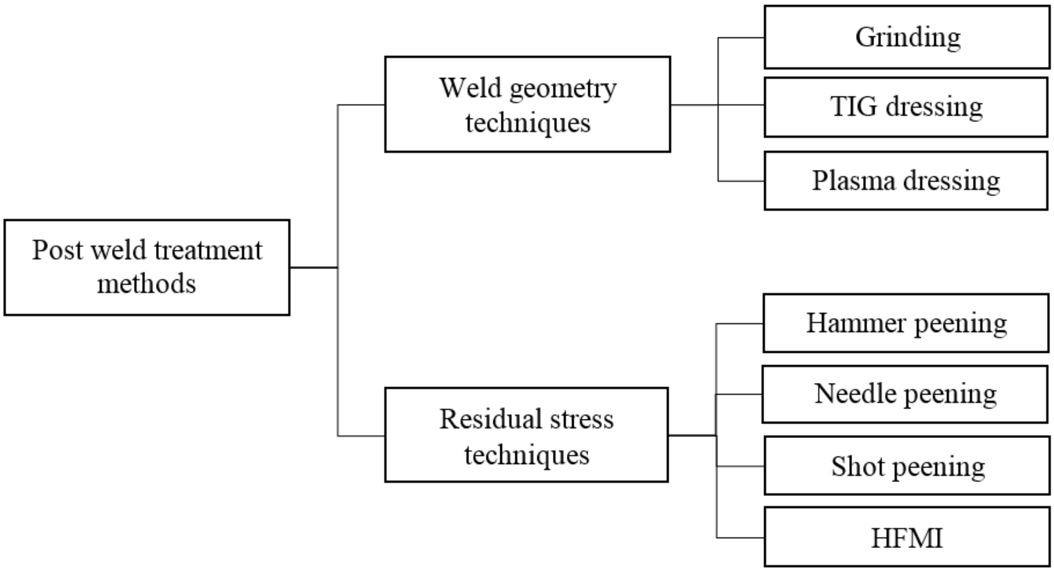

Figure 3-2 Classification of post weld treatment methods (Kuhlmann et al. 2006).

The grinding methods and the dressing methods aim to remove defects and smoothen the transition between the weld and the base. The grinding methods use a high speed pneumatic or electric grinder to remove material around the weld toe and blend the weld metal to the base plate, while the dressing methods use a specific welding equipment (Tungsten Inert Gas or Plasma welding equipment) to re-melt the material at the weld toe, achieving an improved weld shape.

The peening methods use different tools or small metal balls to impact the surface of the weld toe region with high frequency. This introduces compressive residual stresses at the weld toe due to mechanical plastic deformation of the surface. Additional benefit of the peening methods is an improved weld profile resulting in reduced stress concentration and a hardened surface of the material (Kirkhope et al. 1999).

The term high frequency mechanical impact (HFMI) treatment covers a few technologies of high frequency peening. These methods have it in common to be performed by applying hardened steel indenters with high frequency to impact the material. A number of HFMI equipment exist today for different techniques such as Ultrasonic impact treatment (UIT), ultrasonic peening treatment (UPI) and high frequency impact treatment (HiFIT) to name a few (Marquis & Yildirim 2015). The benefits of HFMI are the same as for the other peening methods but the difference is that HFMI is applied with higher frequency, resulting in more uniform plastic deformation and better surface finish (Ummenhofer et al. 2013).

Researches have shown a significant improvement of post weld treatments, especially for the residual stress methods, but the amount of improvement depends on which method is used and also on the operation (Wang et al. 2009).

3.2 Recommendations

The variation of the amount of improvement promoted the need for standardized methods in order to produce guidelines for the expected improvement. The

International Institute of Welding (IIW) published in 2007 recommendations for post weld treatment methods for steel and aluminium structures (Haagensen & Maddox 2010) The recommendations give instructions about equipment and procedure of burr grinding, TIG dressing, hammer peening and needle peening, along with instructions about training of operators and inspectors, safety aspects and quality control.

3.2.1 High frequency mechanical impact treatment

In 2011 IIW started to develop guidelines for HFMI. (Marquis & Barsoum 2014b) present guidelines for equipment and procedure including training of operators and inspectors, safety aspects and quality control of HFMI. Because of different types of HFMI equipment some of the instructions are presented generally.

Proposal of guidelines for fatigue assessment of HFMI are presented in (Marquis & Barsoum 2014a). The guidelines describe the fatigue strength in terms of S-N curves based on laboratory experiments. In the former IIW guidelines, the fatigue strength was described with S-N curves with a slope of $m = 3$ as for as-welded joints. For the HFMI methods it was discovered that a slope of $m = 5$ was more appropriate for the test data so the guidelines use S-N curves with the slope of $m = 5$ to describe the improved fatigue strength. Due to the increase in slope from $m = 3$, the curve for as-welded details crosses the curve of the HFMI improved details for a low number of cycles and therefore no improvement can be expected for low cycle fatigue.

The guidelines are limited to plate thickness of 5 to 50 mm and for plate thickness exceeding 25 mm, a thickness correction factor is introduced. Due to lack of experimental data, the same reduction factor is used as in the IIW guidelines:

$$f(t) = \left(\frac{25}{t_{eff}}\right)^{0,2} \tag{3.1}$$

$t_{eff} = L/2$ or t, whichever is larger, for $L/t < 2$ and $t_{eff} = t$ for $L/t \geq 2$ where L and t are given in Figure 3-3.

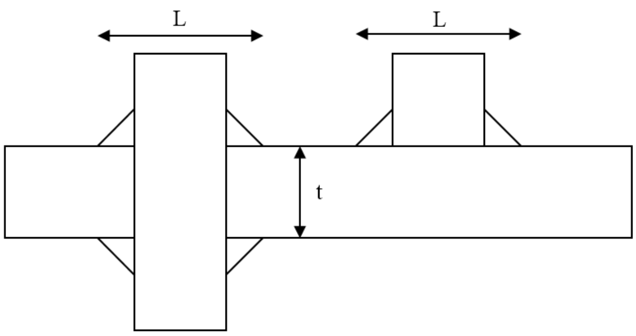

Figure 3-3 Definition of dimensions used to determine the thickness correction factor (Marquis & Barsoum 2014a).

In the IIW guidelines the benefits are only considered for details with FAT class 90 or lower. The limitations are due to the fact that details with higher FAT classes are either non-welded, not governed by failure of weld toe or have already been improved. The

HFMI guidelines are also not applicable for details with FAT class 50 or lower, since they have not been studied for HFMI.

The guidelines take into account the benefits of increased steel strength, by additional increase of fatigue classes depending on the yield strength of the material. For every 200 MPa increase in yield strength, an increase of one fatigue class is recommended as can be seen in Figure 3-4.

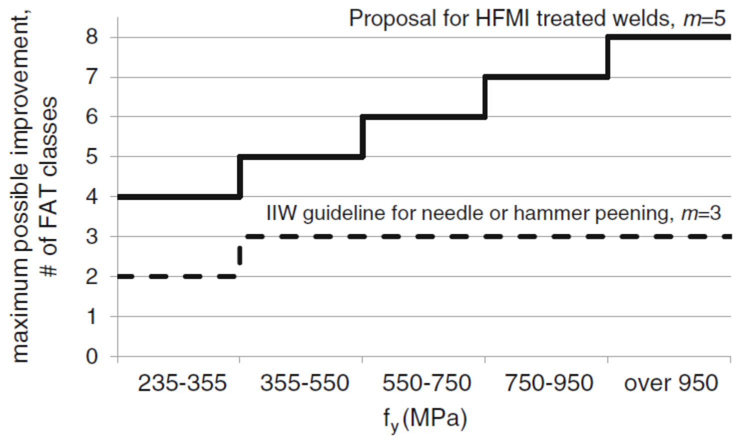

Figure 3-4 Maximum increase in the number of FAT classes (Marquis & Barsoum 2014a).

Loading effects are considered for stress ratio higher than 0,15. In the HFMI guidelines the reduction in FAT classes is given for stress ratios up to 0,52. The table was updated in (Mikkola et al. 2015) for stress ratio range up to 0,7.

Table 3-1 Minimum reduction in the number of FAT classes based on R-ratio.

R ratio	Minimum FAT class reduction
R ≤ 0,15	No reduction
0,15 < R ≤ 0,28	Reduction by one FAT class
0,28 < R ≤ 0,4	Reduction by two FAT classes
0,4 < R ≤ 0,52	Reduction by three FAT classes
0,52 < R ≤ 0,7	Reduction by four FAT classes
0,7 < R	No data available

4 Life Cycle Analysis

Life cycle based methods aim to evaluate products over the entire life cycle in order to compare different alternatives and to find the best solution. Environmental and economic aspects can be assessed with Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) (Klöpffer 2003).

4.1 Life Cycle Assessment

In recent years an increased environmental awareness has promoted the need for clear and transparent information about environmental impacts. This has led to development of methods for evaluation of these impacts and one of the methods is Life Cycle Assessment (LCA). LCA is an analytical tool used in order to assess both local and global environmental impacts of a product or a service over the entire lifetime. All phases of the product's life are taken into account, often referred to as the cradle to grave approach. This covers phases from extraction of raw materials and production to construction and usage and finally end of life treatment. The assessments include evaluation of inputs (energy, material) and outputs (emission and waste) from all phases and all transportation within the life cycle. Including the whole lifetime offers an accurate description of the environmental impacts and enables LCA to be used for sustainable decisions making.

LCA can be used to show where in the life cycle the environmental impacts are the most and how the design and manufacturing of the product can be arranged in order to minimize the impacts. The results of the assessment give numerical information about impact categories, for instance climate change, ozone depletion, acidification and human toxicity. The assessment of climate change is measured by the emissions of carbon dioxide and other greenhouse gases and their effect on global warming potential (GWP). The results are often referred to as the carbon footprint and are expressed in CO_2 equivalent (Baumann & Tillman 2004).

The International Organization for Standardization (IOS) has published a series of standards for LCA referred to as the 14040 series and are part of the 140000 series that set the framework for environmental guidelines and management. The standards model the life cycle of the product as a product system. The product system is subdivided into unit processes that are linked to one another and to the environment by flows of products, materials and/or energy. The standards divide LCA into four phases:

- Goal and scope definition
- Life Cycle Inventory Analysis (LCI)
- Life Cycle Impact Assessment (LCIA)
- Life Cycle Interpretation

The framework of LCA can be seen in Figure 4-1.

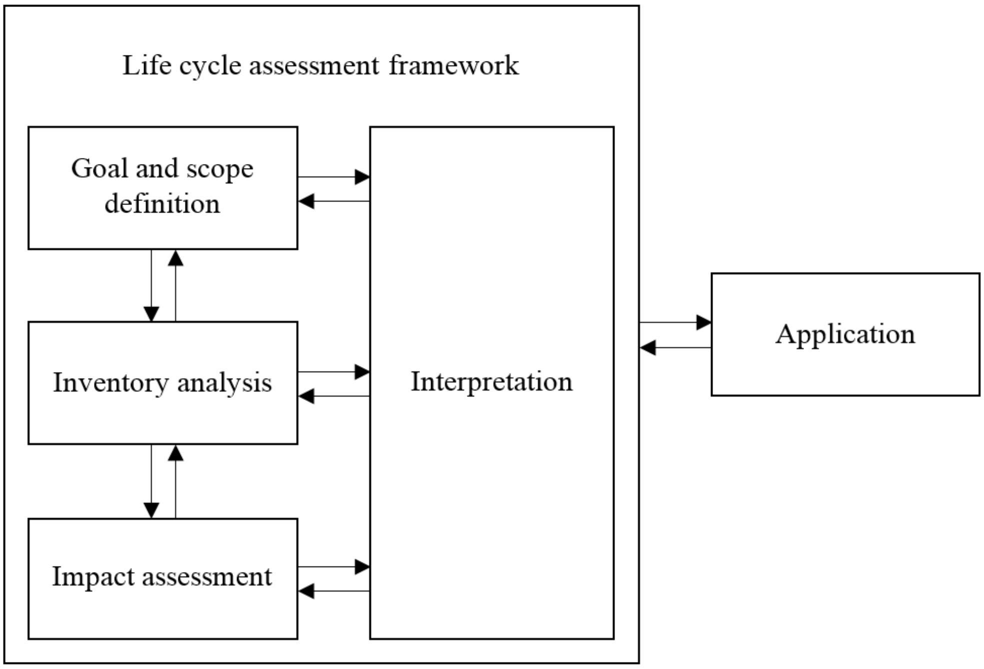

Figure 4-1 Stages of LCA (ISO 14040 2006).

The goal and scope definition aims to plan the study and define purpose and boundaries, including data requirements, assumptions and limitations. An important part of this phase is to define the functional unit which the data is referred to. The functional unit defines what is being examined and quantifies the functions of the product. All inputs and outputs are related to the functional unit and makes the results of the analysis comparable to other studies.

For each phase of the life cycle, inputs, outputs and potential environmental impacts of the product, have to be considered and evaluated. The life cycle inventory (LCI) phase includes data collection and calculations to quantify the inputs and the outputs of the product. The life cycle impact assessment (LCIA) is based on the LCI results which are analysed and converted into damage indicators or potential environmental impacts.

The results from both LCI and LCIA are summarized in the interpretation phase and evaluated for final results. It is possible to draw conclusions from the results which can help in the decision making process for the product.

The standard (ISO 14040 2006) sets the principles and framework of LCA analysis and (ISO 14044 2006) gives requirements for each phase when performing a LCA. The standards state that there is no single method for conducting LCA but LCA usually starts by defining the goal and scope and ends with interpretation. However, a LCA is an iterative process and as information are collected, modifications of the scope could be required in order to meet the original goal of the study.

4.1.1 LCA of steel structures

It has been showed that the environmental impact value per kg of high strength steel is slightly higher than for conventional steel grades. The reason is that more energy is required for the production and in some cases more alloying elements. The use of high strength steel, however, gives the benefits of less material usage that eventually results in less environmental impacts due to reduced use of energy and reduced use of raw materials. The environmental research program "The Steel Eco-Cycle" covers all life stages of steel. The program defines the life cycle of steel structures in four main phases as can be seen in Figure 4-2.

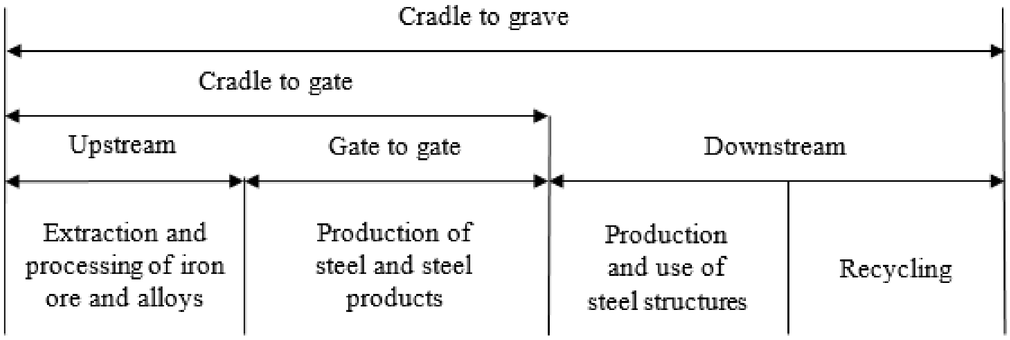

Figure 4-2 Phases of the life cycle of steel (Jernkontoret 2013).

The environmental impacts are primarily related to extraction of raw materials and the production phase for passive steel structures like buildings and bridges. For the production stage the combination of raw materials (different alloys) and production methods used has high effect on the environmental impacts. Different thicknesses also require different alloy content in order to reach a specific strength.

For steel, the life cycle is usually referred to as cradle to cradle since steel, in most cases, goes under recirculation or closed loop recycling. Steel can be recycled about infinite number of times with low energy input. The impact of steel scrap can be evaluated in different ways. The Steel Eco-Cycle program considers external steel scrap to be free from environmental impacts but is considered in the recycling process of the life cycle. Internal scrap is included in the cradle to gate analysis.

Steel production impact is usually represented by the effects on climate change (CO_{2e}), acidification, eutrophication and photo oxidant creation (Jernkontoret 2013).

4.2 Life Cycle Cost

LCC is a method to estimate the total cost for the whole life cycle in order to find the most cost efficient option. In order to minimize the total lice cycle cost, cost optimization is important when finding the most economical solution. The standard (ISO 15686-5 2008) gives guidelines for performing LCC of buildings and constructed assets and their parts. For structures the life cycle covers the whole lifetime of the structure including initial costs (design and construction), operation, maintenance and finally end of life treatment. These parts are considered agency cost and are included in the analysis along with user and society cost. Different costs over the life cycle are discounted and total to a present day value known as net present value (NPV).

Life cycle costing is based on quantifying LCC in decision making processes and are usually combined with results from other assessments, like environmental, safety and functionality assessments.

4.2.1 LCC of steel structures

Life cycle cost of steel structures can include the following agency cost components (Sarma & Adeli 2002).

Initial cost
- Planning and design
- Material and fabrication cost of structural and connection members
- Transportation, handling and storage of structural members
- Erection cost
- Operation of tools and machinery on construction site
- Preparation of project site including foundation

Maintenance
Inspection cost
Repair cost
Operating cost
Probable failure cost
Dismantling or demolishing costs

5 Case Study of a Highway Bridge

The bridge which is studied is a road bridge over E4 in Skulnäs, Sweden. The bridge has a single span of 32 meters and a life length of 80 years. The superstructure is a composite steel-concrete structure and consists of two identical steel girders with c/c = 3 m and a concrete deck. The composite action between the steel and the concrete is through two rows of shear studs which are welded to the upper flange of each girder. Ten shear studs are placed per meter. The girders consist of three segments (9,8 m + 14 m + 9,8 m) which are welded together on site. Cross-beams are attached to the girders by bolts and placed every 8 meters. The longitudinal section of the bridge can be seen in Figure 5-1.

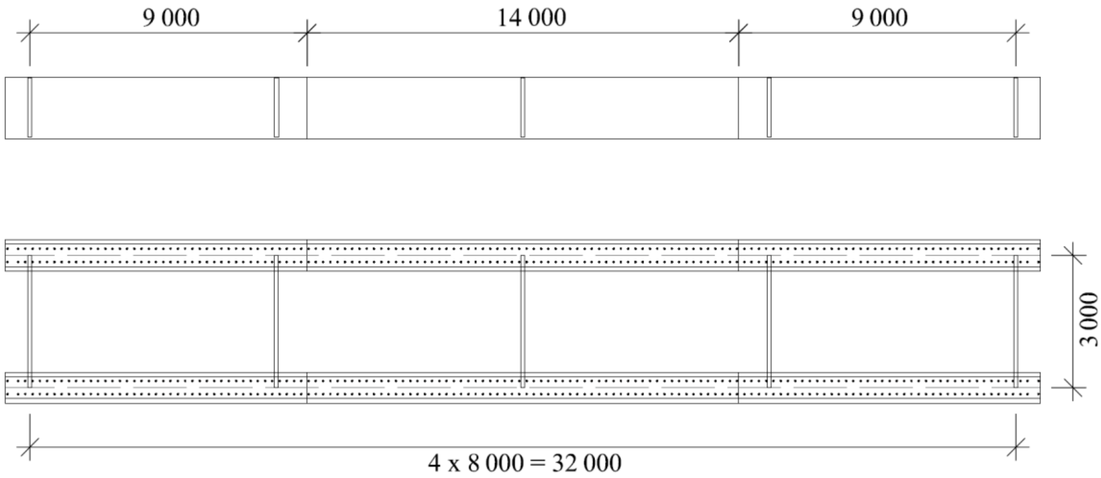

Figure 5-1 Longitudinal section of the bridge.

The deck is made of concrete of class C35/45. The deck has a free width of 5 meters between barriers and the average depth is 270 mm. Other dimensions of the cross section of the deck can be seen in Figure 5-2.

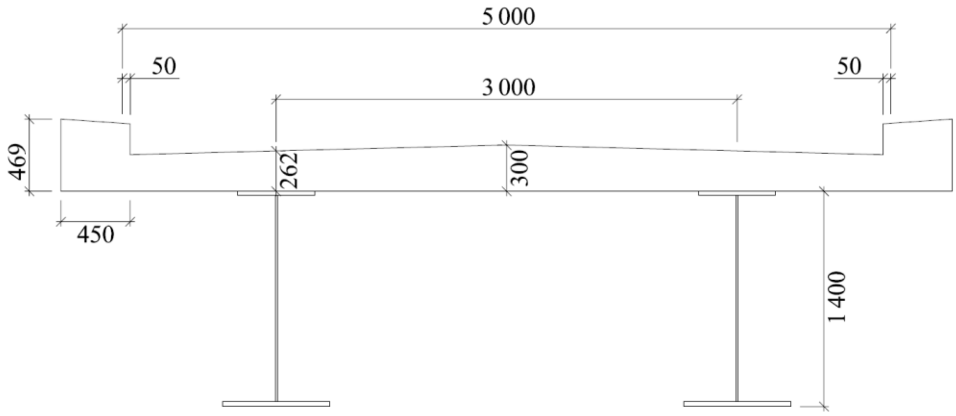

Figure 5-2 Cross section of the bridge.

The top flanges and webs of the girders have the steel grade S355 and the bottom flanges have the steel grade S420. The cross section of the girders varies along the length but the height is constant or 1400 mm. Figure 5-3 shows the cross section of the girders, lower values for the outer segments and higher values for the mid segment.

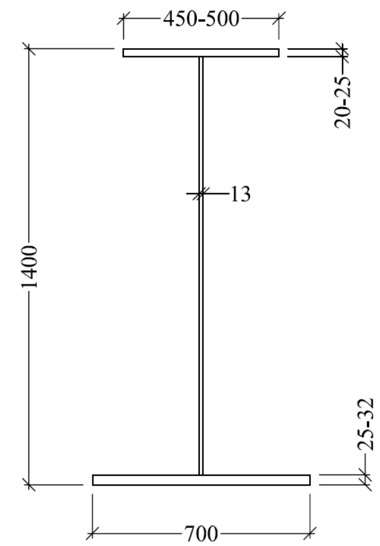

Figure 5-3 Original cross section of the girders.

5.1 Loading

According to (EN 1991-2 2003) a carriageway with a total width of 5 meters consists of one notional lane with the width of 3 meters. That gives a remaining area of 2 meters as can be seen in Figure 5-4.

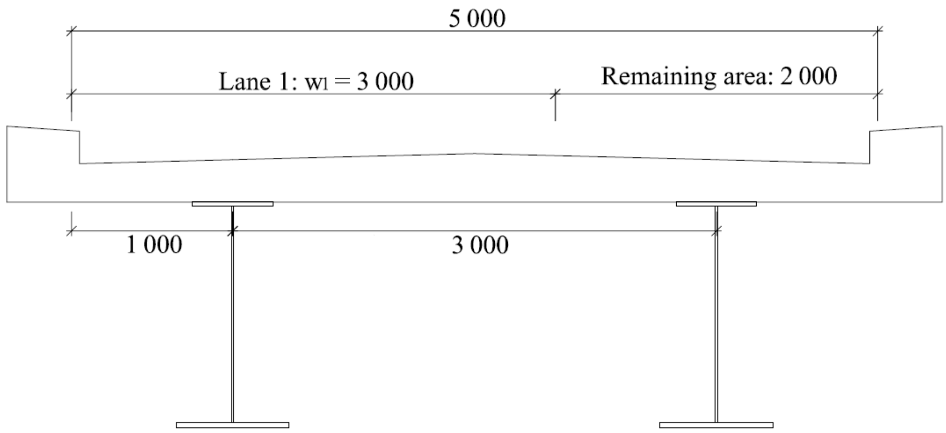

Figure 5-4 Division of the carriageway.

(EN 1991-2 2003) defines four load models for road bridges. For the road bridge studied the traffic loads are calculated from Load Model l (LM1) and additionally according to load model ANM.2 in TK bro which is nation specific for Sweden.

LM1 is used for general and local certifications and consists of two partial systems; double-axle concentrated loads and uniformly distributed loads as shown in Figure 5-5.

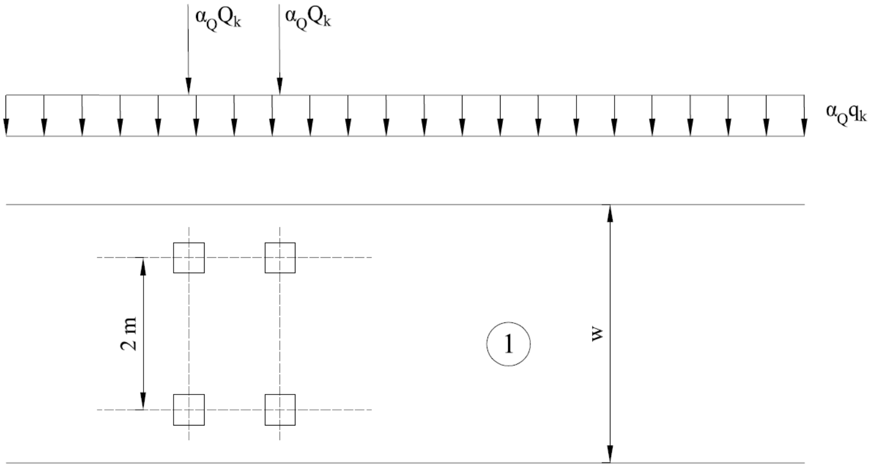

Figure 5-5 Load model 1.

The distance between the wheels is 2 meters in the width direction of the bridge and 1,2 meters in the length direction. The characteristic values of the loads are taken from Eurocode and can be seen in Table 5-1. For each axle load and uniformly distributed load, the characteristic load value is multiplied with an adjustment factor from a national annex, shown in Table 5-2. The uniformly distributed load is applied on each notional lane and on the remaining area of the carriageway.

Table 5-1 Characteristic load values.

Location	Axle loads Q_{ik} [kN]	Distributed loads q_{ik} [kN/m^2]
Lane Number 1	300	9
Lane Number 2	200	2,5
Lane Number 3	100	2,5
Other lanes	0	2,5
Remaining area (q_{rk})	0	2,5

Table 5-2 Adjustment factors in Sweden.

Lanes	
α_{Q1}	0,9
α_{Q2}	0,9
α_{Q3}	0
$\alpha_{Q\infty}$	0
α_{q1}	0,7
$\alpha_{qi}(i>1)$	1,0
α_{qr}	1,0

The application of load model ANM.2h can be seen in Figure 5-6 where $B = 300\,\text{kN}$ and $q = 5\,\text{kN/m}$. Other cases of load model ANM.2 can be seen in Appendix A.

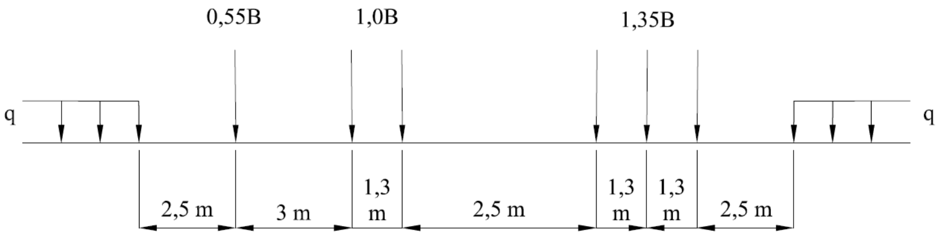

Figure 5-6 Load model ANM.2h.

5.1.1 Loads in ultimate limit state

In the ultimate limit state, the following loads are considered. The self-weight of the structure consists of the steel and the concrete. For the steel, the cross beams are taken into account by adding 18% to the total weight of the girders. Additional self-weight includes surfacing and barriers. Effects due to creep, shrinkage and earth pressure on the supports are also taken into account. Traffic loads are taken into account according to LM1 and load models in ANM.2 cases j)-l). The corresponding breaking load is considered as a longitudinal force working on top of the surfacing. The calculated moment, shear and normal forces acting on each steel girder due to loads that are applied is represented in a table in Appendix A.

5.1.2 Loads in serviceability limit state

In the serviceability limit state load models LM1 and ANM.2 case h) are considered.

5.1.3 Fatigue load

Traffic flow on bridges can cause stress spectrum to cause fatigue. (EN 1991-2 2003) defines 5 fatigue load models for highway bridges. For this study, fatigue load model 3 (FLM3) is used. The model is composed of a single vehicle with four axles with identical wheels and equal weight of 120 kN. The load model can be seen in Figure 5-7. The resulting moment and shear forces are represented in Appendix A.

FML3 is used to calculate the maximum and minimum stresses resulting from the load arrangement. The model can be used for direct verifications by the simplified lambda method covered in chapter 5.2.1.

EN 1991-2 also defines traffic categories depending on number of slow lanes and number of heavy vehicles observed per year and per slow lane (N_{obs}). In this study traffic category 4 is used.

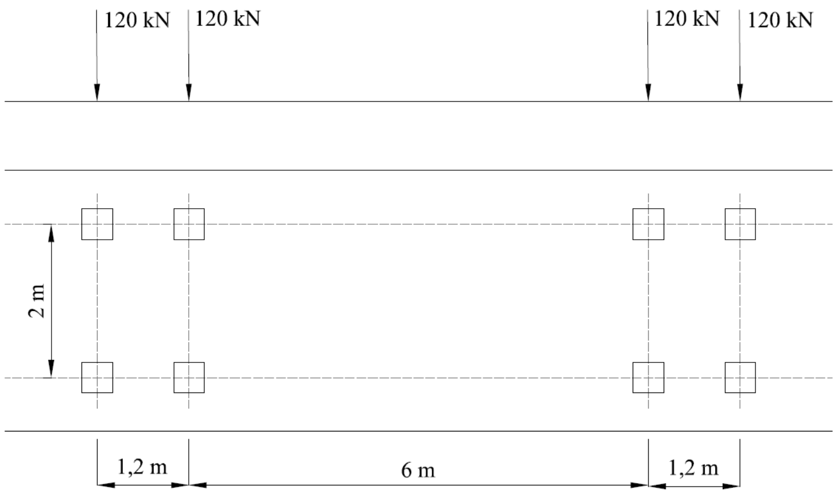

Figure 5-7 Fatigue load model 3.

Table 5-3 Number of heavy vehicles expected per year and per slow lane.

Traffic categories		N_{obs} per year and per slow lane
1	Roads and motorways with 2 or more lanes per direction with high flow rates and lorries	$2{,}0 \times 10^6$
2	Roads and motorways with medium flow rates of lorries	$0{,}5 \times 10^6$
3	Main roads with low flow rates of lorries	$0{,}125 \times 10^6$
4	Local roads with low flow rates of lorries	$0{,}05 \times 10^6$

5.2 Cross section verification

In the calculations for the cross-section constants of the composite section, only half of the bridge is considered due to symmetry and the edge beams of the concrete deck are disregarded. The remaining area of the concrete deck is converted into an equivalent steel area with the effective width, obtained with modular ratios between the steel and the concrete. The modular ratio for short term loading is given by:

$$n_0 = \frac{E_a}{E_{cm}} \tag{5.1}$$

The effects of creep are taken into account by calculating the modular ratios depending on the type of loading according to (EN 1994-2 2005):

$$n_L = n_0 \cdot (1 + \psi_L \varphi_t) \tag{5.2}$$

φ_t is the creep coefficient depending on the age of the concrete at the moment considered and the age at loading.

ψ_L is the creep multiplier depending on type of loading; 1,1 for permanent loads, 0,55 for primary and secondary effects of shrinkage and 1,5 for prestressing by imposed deformations.

Table 5-4 Modular ratios for different type of loading.

Type of loading	φ_t	ψ_L	n_0 / n_L
Short term	-	-	6,2
Self-weight concrete	2,83	1,1	25,4
Shrinkage	2,83	0,55	15,8
Additional self-weight	1,49	1,1	16,3

5.2.1 Fatigue limit state

Fillet welds of 5 mm are used to connect the flanges to the web and to the web stiffeners and butt welds are used to connect the segments of the girders. The following details are considered for the fatigue design.

Detail 1: Connection between the top flange and the shear studs at the supports for the weld, i.e. at x = 0 m.
Detail 2: Connection between the top flange and the shear studs at the mid-span for the base material, i.e. at x = 16 m.
Detail 3: Connection between flanges and the web stiffener in the span, i.e. at x = 8 m and x = 16 m.
Detail 4: Connection of the flanges between the segments at x = 9 m.
Detail 5: Connection between the web and the flanges with the highest moment in the mid span and at the connection of the segments i.e. at x = 16 m and at x = 9 m.
Detail 6: Connection between the web and the flanges with the highest shear force at the connection of the segments and at the supports, i.e. at x = 9 m and at x = 0 m.

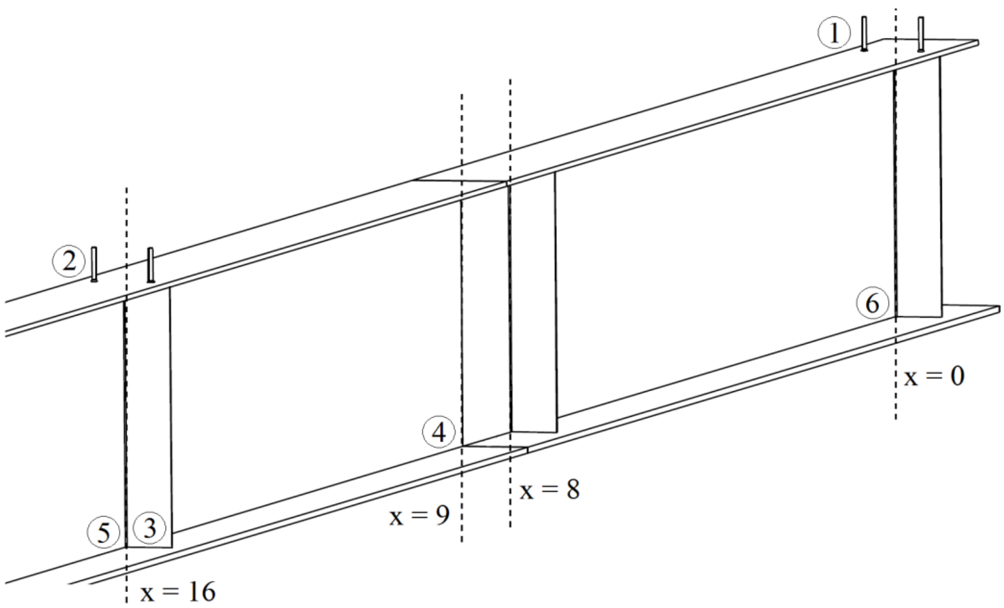

Figure 5-8 Details considered for the fatigue design.

Table 5-5 Description of details.

Detail	Table (in EN 1993-1-9)	$\Delta\sigma_c$
1	8.5 (10)	90
2	8.4 (9)	80
3	8.4 (7)	80
4	8.3 (9)	80
5	8.2 (3)	112
6	8.5 (8)	80

The most critical details are the connection of the bottom flange and the web stiffener (Detail 3) and the connection between the bottom flanges at the intersection of the segments (Detail 4). For the fatigue verification the lambda methods is used according to (EN 1993-2 2006). The lambda method uses lambda coefficients to convert the stress range due to the fatigue loading to an equivalent stress range that is compared to the fatigue strength of the studied detail. The equivalent stress range at $N = 2$ million cycles can be calculated as follows:

$$\Delta\sigma_{E2} = \lambda \cdot \phi_2 \cdot \Delta\sigma_p \tag{5.3}$$

ϕ_2 is the dynamic equivalent impact factor that can be taken as 1 for road bridges since it is included in the fatigue load model.

$\Delta\sigma_p$ is the nominal stress range at the influence area due to the fatigue loading.

The lambda coefficient or the damage equivalence factor for road bridges is obtained as follows:

$$\lambda = \lambda_1 \cdot \lambda_2 \cdot \lambda_3 \cdot \lambda_4 \qquad \lambda \leq \lambda_{max} \tag{5.4}$$

λ_1 is a factor that takes into account the span length of the bridge.

λ_2 is a factor that takes into account the traffic volume.

λ_3 is a factor that takes into account the design life of the bridge.

λ_4 is a factor that takes into account traffic on other lanes.

$\lambda_{\max}$ is the recommended maximum value of the coefficient.

The fatigue is verified with the following expression:

$$\gamma_{Ff} \cdot \Delta\sigma_{E2} \leq \frac{\Delta\sigma_c}{\gamma_{Mf}} \tag{5.5}$$

and

$$\gamma_{Ff} \cdot \Delta\tau_{E2} \leq \frac{\Delta\tau_c}{\gamma_{Mf}} \tag{5.6}$$

$\Delta\sigma_c$ is the reference fatigue strength.

γ_{Ff} is a partial factor for equivalent constant amplitude stress ranges, taken as 1.

γ_{Mf} is a partial factor for fatigue strength, taken as 1,35 and 1 for shear studs.

5.2.2 Ultimate limit state

For the ultimate limit state the bridge is checked for bending and shear according to (EN 1993-1-1 2005). The shear studs are also checked according to (EN 1994-2 2005). The partial factors for ULS are taken according to 6.10b in (EN 1990 2002).

Table 5-6 Partial factors for ULS

Permanent load		Variable load	
Self-weight	1,2	Traffic load	1,5
Surfacing	1,32		
Earth pressure	1		
Shrinkage	1,2		

During the construction phase the top flange has to be checked for buckling during casting and the girders must be able to withstand the weight of the concrete. Partial factor of 1,35 is applied on the self-weight of the steel and the concrete.

5.2.3 Serviceability limit state

TK Bro 2.4.1.2 states that the deflection due to traffic load in SLS should not exceed the span length divided by 400:

$$\delta_{max} = \frac{L}{400} = 80\ mm \tag{5.7}$$

The highest deflection due to traffic loads is when the axle loads are located on either side of the middle of the span. The load factors can be seen in Table 5-7.

Table 5-7 Load factors for traffic loads.

	ψ_{axel}	ψ_{dist}
LM1	0,75	0,40
ANM.2.h	0,75	0,75

The slenderness of the web is limited to avoid excessive breathing that might result in fatigue at the web to flange connections. Web breathing is checked according to (EN 1993-2 2006).

5.3 Fatigue improvement

Possible applications of HFMI are considered for the most critical details; the connection of the web stiffeners to the bottom flanges in the span (Detail 3) and the connection of the bottom flanges at the intersection of the segments (Detail 4). The top flanges are not affected by fatigue and therefore not treated. A reduction of the top flanges is therefore not considered and the steel strength is kept the same. The reduction is therefore only considered for the thickness of the bottom flanges and the total height is considered to be unchanged.

All the critical details have the reference fatigue strength of 80 MPa. The connection between the web and the flanges has the reference fatigue strength of 112 MPa so it is assumed to be the limiting fatigue strength since those welds are not treated. The stress ratio applied on the bridge is within the range of 0,52 to 0,7, which requires a minimum reduction of 4 FAT classes according to the HFMI guidelines. In order to get an improvement of 3 FAT classes or from category 80 to 112, a total improvement of 7 FAT classes is needed and a minimum strength of 750 MPa.

Treatment is considered for two cases:

1. Treatment of only the web stiffener in the mid span
2. Treatment of all critical details

For Case 1, steel strength of 750 MPa is used for the bottom flange of the inner element but the steel grade of the bottom flanges of the outer elements is kept as 420. The treatment of the butt-welds between the sections in Case 2 requires the use of steel with a strength of 750 MPa for the bottom flanges of the outer elements as well. The two different alternatives are investigated to see whether it would pay off to use so much high strength steel.

5.4 Results

FAT class of 112 allows reduction of the bottom flange of the inner element down to 18 mm for Case 1 and additionally down to 13 mm of the outer element for Case 2 as can be seen in Figure 5-9. The cross section was verified for the new design the same way as for the original design and the verification results can be seen in Table 5-8. The number of shear studs was not expected to be changed and therefore the number of required studs was limited to 10 studs per meter.

The amount of steel for each steel grade was calculated for the new cross sections and compared with the amount of material of the original design. The results can be found in Table 5-9 along with the toe length that is treated with HFMI.

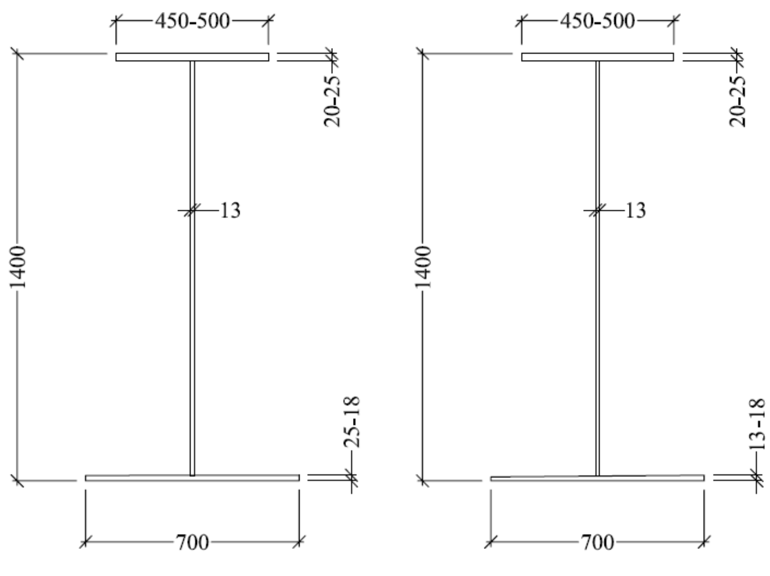

Figure 5-9 New cross section – Case 1 (left) and Case 2 (right).

Table 5-8 Design verification for the original and the new bridge designs.

	FLS	ULS Bending	ULS Shear	Studs /m	SLS
Original bridge design	0,89	0,89	0,85	8	0,54
Post weld treatment – Case 1	0,96	0,88	0,85	8	0,76
Post weld treatment – Case 2	0,99	0,91	0,85	9	0,81

Table 5-9 Amount of steel and length of toe treated with HFMI.

	Steel grade	Steel amount (kg)	HFMI (m)
Original bridge design	S355	14.493	
	S420	10.112	
	Total	**24.604**	
Post weld treatment – Case 1	S355	14.535	2
	S420	5.282	
	S750	2.717	
	Total	**22.531**	
Post weld treatment – Case 2	S355	14.581	16,2
	S750	5.463	
	Total	**20.045**	

The reduction gives 8% material savings for Case 1 and 19% for Case 2. Detailed calculations and results can be found in Appendix B.

5.4.1 Parametric study

In a study for Ultrasonic Impact Treatment (UIT) conducted by (Mori et al. 2012) it was discovered that when UIT was given under maximum load, the fatigue strength could be expected to be twice the strength of as-welded joints even for stress ratio of 0,5. Since the amount of research on the topic of HFMI-treatment under self-weight is limited and no assessment methods exist regarding degree of improvement for such conditions, a parametric study is performed for the material savings depending on FAT class increase, regardless of the stress ratio.

HFMI gives a minimum increase of 4 FAT classes regardless to yield strength. The welds which connect the flanges to the web can have a strength of 125 if no start/stop position is permitted, except when the repair is performed by a specialist and inspection is carried out to verify the proper execution of the repair. The highest FAT class considered is therefore 125.

The parametric study considers the effect of increase in FAT classes on the amount of steel assuming 1-4 FAT class improvement. For each FAT class, the permitted reduction of the bottom flanges is considered for the maximum utilization in FLS. The yield strength of the bottom flange is increased gradually in order to account for the bending requirements in ULS.

For each FAT class increase the reduction of steel in kilograms is plotted along with the utilization of FLS, ULS and SLS and the results for each case can be seen in Figure 5-10 and Figure 5-11. The required steel strength for the inner element/outer element is specified above in MPa.

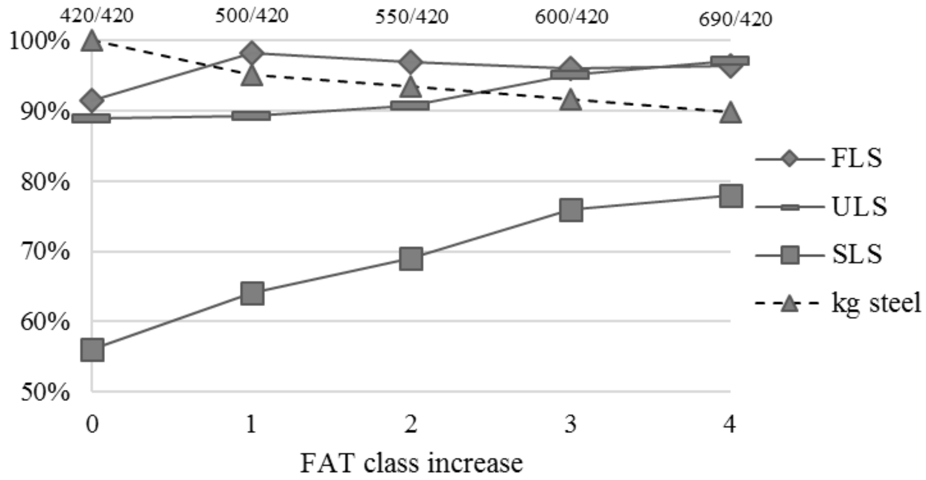

Figure 5-10 Permitted material reduction considering increase in FAT classes – Case 1.

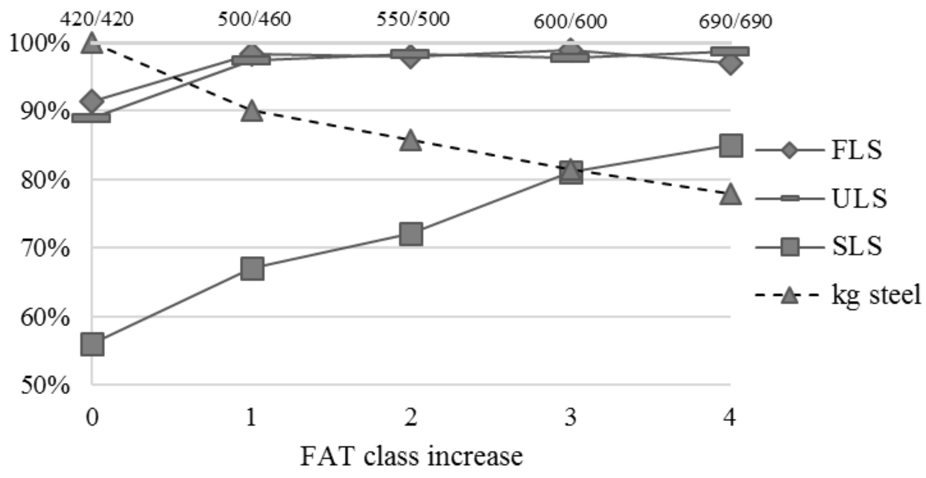

Figure 5-11 Permitted material reduction considering increase in FAT classes – Case 2.

The calculations for each cross section are carried out as in Appendix B and the results can be found in Appendix C.

6 LCA & LCC

For the LCA and LCC only the steel plates of the girders are considered since other parts of the bridge remain the same. The deck design is unaffected and so is the substructure. The bending moment, due to the self-weight of the girders, is very small compared to the weight of the concrete and other loads and therefore no significant load reduction occurs for the substructure. The number of cross beams and web stiffeners does not need to be changed for the new design.

The construction process and the amount of welding is considered to be the same and since the amount of material concerned is of a small scale, the transportation is neglected. The impacts are therefore only considered for cradle to gate analysis and the downstream phase is considered to be insignificant in comparison, assuming recycling will be the same.

The environmental impact values are considered for greenhouse effects on global warming potential (GWP) and represented in terms of CO_2 equivalents. The impact in terms of kg CO_{2e} for different steel grades are obtained from (Jernkontoret 2013) for wide strip rolled steel plates of hot rolled high strength low alloy (HSLA) steel and can be seen in Figure 6-1.

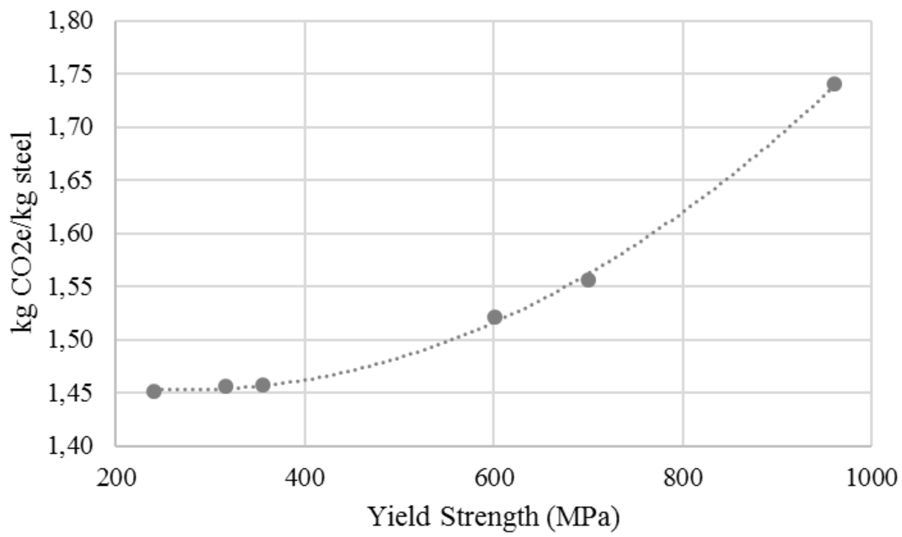

Figure 6-1 Environmental impact values (cradle to gate) for hot rolled HSLA steel plate in terms of kg CO_{2e} (Jernkontoret 2013).

The cost study only considers the raw material of the steel plates of the girders and additionally the cost of HFMI. The raw material cost for different steel grades are obtained for a few steel grades and a linear relationship is assumed as can be seen in Appendix E. The cost of HFMI is calculated assuming a cycle time of 20 min/meter of weld toe and the cost for the work of one operator as 2000 EUR per 8-hour work day.

6.1 Results

The results for the LCA and the LCC are obtained in Appendix F. The carbon dioxide equivalents for the two cases are compared with the original design in Figure 6-2 and the cost in Figure 6-3.

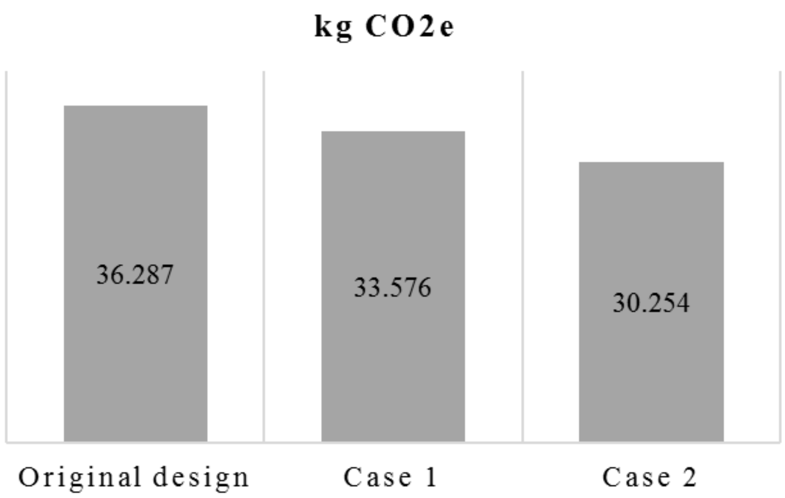

Figure 6-2 kg CO_{2e} for the original design compared to Case 1 and Case 2.

The amount of CO_{2e} is reduced by 7% for Case 1 and 17% for Case 2.

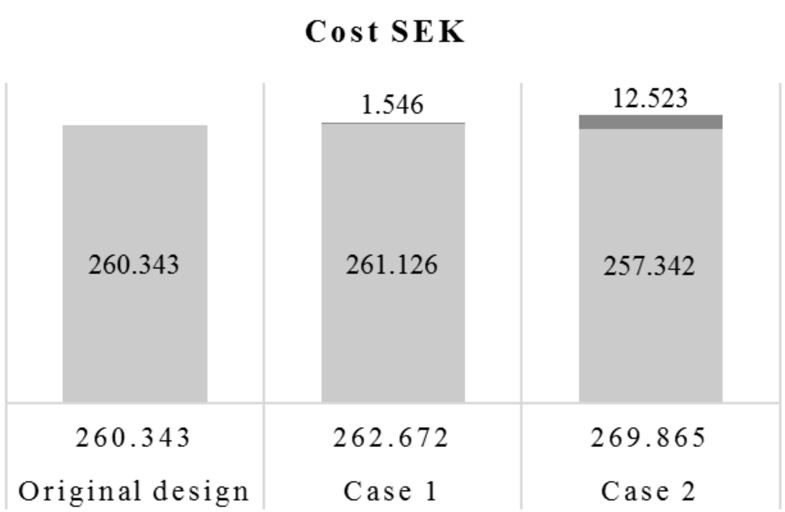

Figure 6-3 The cost of raw material (light) for the original design compared to Case 1 and Case 2 with the added cost of HFMI (dark).

6.1.1 Parametric study

The parametric study considers the effect of increase in FAT classes on the cost and kg CO_{2e} for the material reduction from the previous parametric study. The results for each case can be seen in Figure 6-4 and Figure 6-5. The required steel strength for the inner element/outer element is specified above in MPa. Calculations for different cross sections can be found in Appendix G.

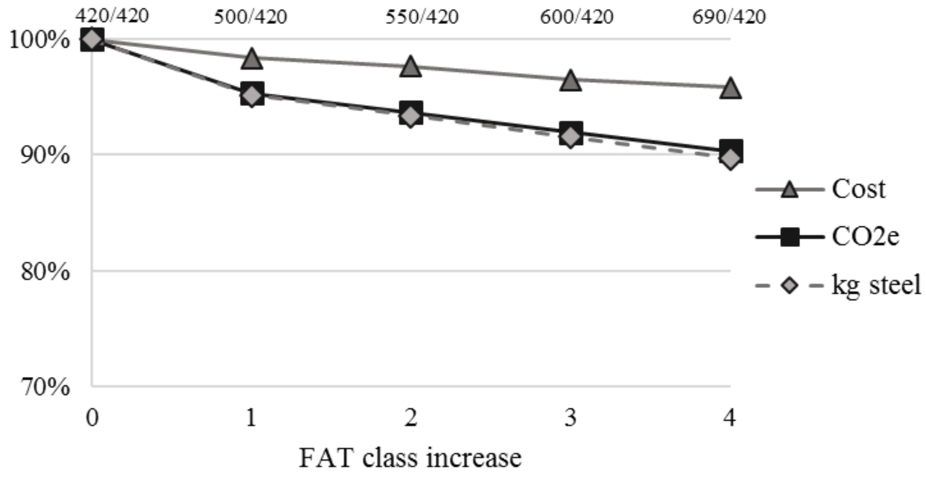

Figure 6-4 Change in cost and kg CO_{2e} considering increase in FAT classes – Case 1.

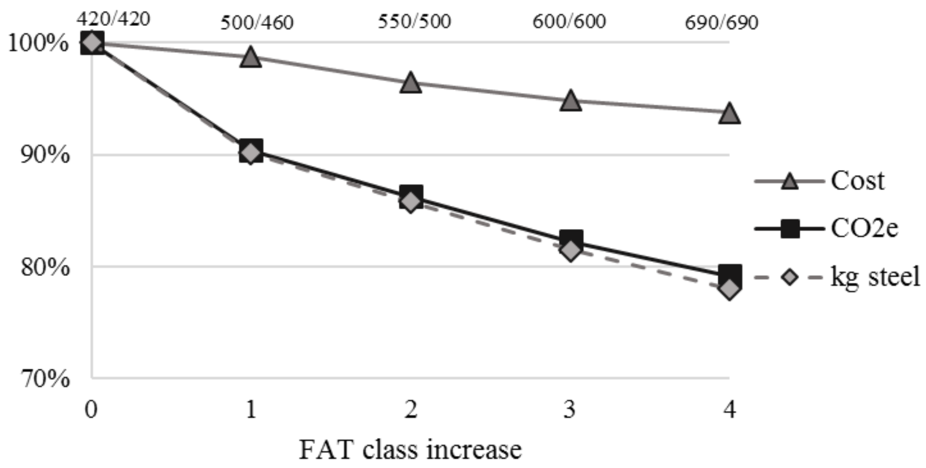

Figure 6-5 Change in cost and kg CO_{2e} considering increase in FAT classes – Case 2.

7 Discussion

In the study only the benefits of HFMI are considered for the bottom flanges since the top flanges are not affected by fatigue and therefore there is no need for treatment of the upper welds. The results show that by increasing the fatigue strength of the most critical details (Case 2) by three FAT classes and reducing the thickness of the bottom flanges, the material savings is almost 20%.

In order to achieve the increased fatigue strength, a steel grade of S750 is required according to current proposed guidelines. The results show that, for this high steel strength, the ultimate limit state is not going to be decisive and fatigue is still the limiting state. The results also show that the design is not going to be governed by deflection. The parametric study shows that lower strength is needed in order to fulfil the requirements of ULS.

The need for a steel grade of S750 has a great effect on the cost benefits of HFMI for the studied bridge. The application is not cost beneficial since the materiel used is more expensive for such a high steel grade. The comparison of the two cases shows that the cost of the steel itself is lower when all critical details are treated and high strength steel is used for the outer flanges as well (Case 2), but the additional cost of HFMI makes it less beneficial. The parametric study shows that when the stress ratio is not considered, the benefits of the treatment pay off with reduced cost and specially for Case 2.

The benefits considering the environmental perspective, on the other hand, is considerable. The environmental impacts are reduced by 17% when all critical details are treated. The reduction reflects the reduced usage of material and the fact that less material results in less environmental impacts despite the increased impacts of higher steel strength.

In this study the cost information is limited since only the raw material cost was considered for the steel girders. The reduced material amount could show more benefits of the new design in a more extensive study that would cover the whole life cycle. Impacts of external steel scrap is not included in the LCA but should be considered in the recycling part of the life cycle.

8 Conclusion

The purpose of this thesis was to determine the benefits of fatigue enhancement of bridges with the application of HFMI based on environmental and financial perspectives. A case study of a composite highway bridge was conducted and the material savings resulting from a reduced cross section were calculated and quantified based on LCA and LCC.

The results show that increased fatigue strength obtained with the application of HFMI in addition with the use of high strength steel results in reduced material usage. The environmental benefits are consistent to the material savings but the benefits of cost are limited due to higher cost of high strength steel.

Further studies could include more detailed LCA and LCC. LCA could include all phases including the recycling process and could consider other types of environmental impacts. LCC could include maintenance along with the recycling process and the use of external steel scrap. The analysis could also be applied on more bridges including different types.

9 References

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Appendices

Appendix A: Loads

Appendix B: Verification of a cross section - Case 2

Appendix C: Calculations of different cross sections – Parametric study

Appendix D: Verification of different cross sections – Parametric study

Appendix E: Impact and cost

Appendix F: LCA & LCC – Case 1 and Case 2

Appendix G: LCA & LCC – Parametric study

Appendix A

Loads

FLS

	x = 0	x=9	x=16	
	V [MN]	M [MNm]	M [MNm]	V [MN]
FLM3	2,950 E-01	2,130 E+00	2,550 E+00	3,490 E-01

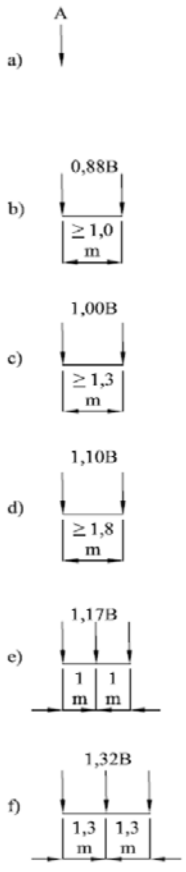
ULS

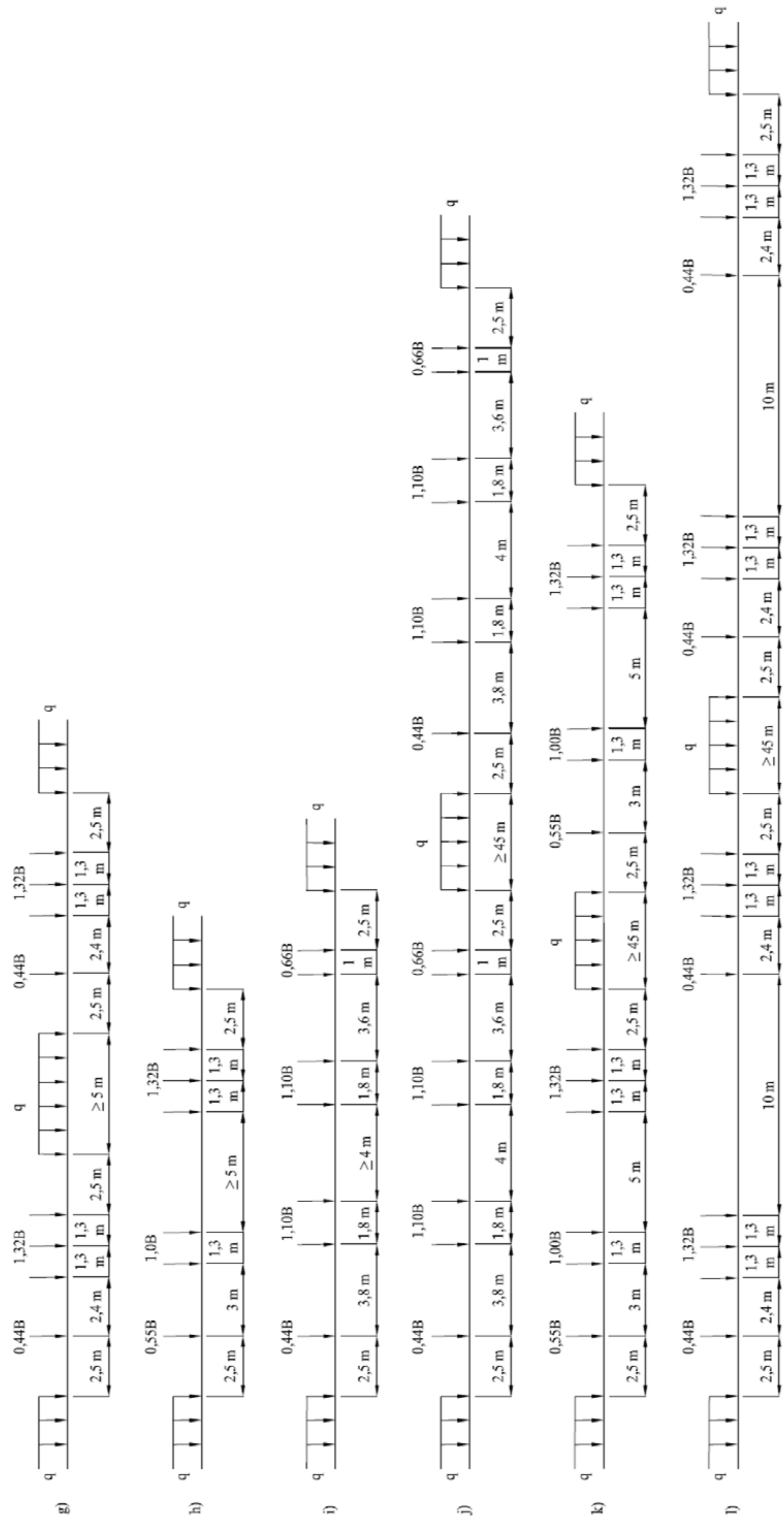
	x = 0	x=9			x=16	
	V [MN]	M [MNm]	N [MN]	V [MN]	M [MNm]	N [MN]
Steel (Original)	6,939 E-02	4,609 E-01	0,000 E+00	3,333 E-02	5,776 E-01	0,000 E+00
Concrete	3,712 E-01	2,124 E+00	0,000 E+00	1,624 E-01	2,693 E+00	0,000 E+00
Barriers	-1,440 E-02	-9,286 E-02	0,000 E+00	-6,300 E-03	-1,149 E-01	0,000 E+00
Surfacing	9,840 E-02	6,346 E-01	0,000 E+00	4,305 E-02	7,852 E-01	0,000 E+00
Earth pressure	-5,924 E-09	-5,270 E-02	-4,990 E-02	-2,558 E-09	-5,270 E-02	-4,990 E-02
Shrinkage	-1,354 E-08	1,101 E+00	-2,289 E+00	-1,354 E-08	1,188 E+00	-2,289 E+00
Axle load	6,485 E-01	4,083 E+00	0,000 E+00	4,144 E-01	5,006 E+00	0,000 E+00
Distributed load	8,005 E-02	5,175 E-01	0,000 E+00	4,138 E-02	6,400 E-01	0,000 E+00
Breaking load	1,186E-02	3,955E-03	-1,852E-01	1,180E-02	1,596E-06	-3,175E-01

	x = 0	x=9			x=16	
	V [MN]	M [MNm]	N [MN]	V [MN]	M [MNm]	N [MN]
1,2	8,327 E-02	5,531 E-01	0,000 E+00	4,000 E-02	6,931 E-01	0,000 E+00
1,2	4,454 E-01	2,549 E+00	0,000 E+00	1,949 E-01	3,232 E+00	0,000 E+00
1,2	-1,728 E-02	-1,114 E-01	0,000 E+00	-7,560 E-03	-1,379 E-01	0,000 E+00
1,32	1,299 E-01	8,377 E-01	0,000 E+00	5,683 E-02	1,036 E+00	0,000 E+00
1	-5,924 E-09	-5,270 E-02	-4,990 E-02	-2,558 E-09	-5,270 E-02	-4,990 E-02
1,2	-1,625 E-08	1,321 E+00	-2,747 E+00	-1,625 E-08	1,426 E+00	-2,747 E+00
1,5	9,728 E-01	6,125 E+00	0,000 E+00	6,216 E-01	7,509 E+00	0,000 E+00
1,5	1,201 E-01	7,763 E-01	0,000 E+00	6,207 E-02	9,600 E-01	0,000 E+00
0,75	8,895 E-03	2,966 E-03	-1,389 E-01	8,850 E-03	1,197 E-06	-2,381 E-01
	1,7430	**12,000**	**-2,936**	**0,977**	**14,665**	**-3,035**

Load model ANM2

A = 180 kN
B = 300 kN
q = 5 kN/m





Appendix B

Verificaiton of cross section - Case 2

1. Geometry and Material

$h_s := 1400mm$

Girder dimensions, inner and outer element

Inner element:

$t_{tfl.i} := 25mm$

$w_{tfl.i} := 500mm$

$t_{bfl.i} := 18mm$

$w_{bfl.i} := 700mm$

$t_{web.i} := 13mm$

$h_{web.i} := h_s - t_{tfl.i} - t_{bfl.i} = 1.357m$

Outer element:

$t_{tfl.o} := 20mm$

$w_{tfl.o} := 450mm$

$t_{bfl.o} := 13mm$

$w_{bfl.o} := 700mm$

$t_{web.o} := 13mm$

$h_{web.o} := h_s - t_{tfl.o} - t_{bfl.o} = 1.367m$

$$f_{y.web.i} := \begin{cases} 355MPa & \text{if } t_{web.i} < 16mm \\ 345MPa & \text{if } 16mm \le t_{web.i} < 40mm \\ 335MPa & \text{otherwise} \end{cases}$$

$$f_{y.web.o} := \begin{cases} 355MPa & \text{if } t_{web.o} < 16mm \\ 345MPa & \text{if } 16mm \le t_{web.o} < 40mm \\ 335MPa & \text{otherwise} \end{cases}$$

$$f_{y.tfl.i} := \begin{cases} 355MPa & \text{if } t_{tfl.i} < 16mm \\ 345MPa & \text{if } 16mm \le t_{tfl.i} < 40mm \\ 335MPa & \text{otherwise} \end{cases}$$

$$f_{y.tfl.o} := \begin{cases} 355MPa & \text{if } t_{tfl.o} < 16mm \\ 345MPa & \text{if } 16mm \le t_{tfl.o} < 40mm \\ 335MPa & \text{otherwise} \end{cases}$$

$$f_{y.bfl.i} := \begin{cases} 750MPa & \text{if } t_{bfl.i} < 16mm \\ 750MPa & \text{if } 16mm \le t_{bfl.i} < 40mm \\ 750MPa & \text{otherwise} \end{cases}$$

$$f_{y.bfl.o} := \begin{cases} 750MPa & \text{if } t_{bfl.o} < 16mm \\ 750MPa & \text{if } 16mm \le t_{bfl.o} < 40mm \\ 750MPa & \text{otherwise} \end{cases}$$

Concrete dimensions, half the deck without edge beams

$h_c := 270mm$

$w_c := 2450mm$

$h_{tot} := h_c + h_s = 1670 \cdot mm$

$L_b := 33.6m$ Length of girders

$cc := 3000mm$ Distance between girders

$a_{stiff} := 8000mm$ Spacing between stiffeners

1.1 Cross section calculations

The cross section is calculated for half the bridge due to symmetry and the edge beams of the concrete deck are disregarded. The remaining are of the deck is converted into equivalent steel area with effective width obtained with modular ratios for different types of loading.

Cross section area of the girder elements and the concrete of half the bridge

$$A_{s.i} := t_{tfl.i} \cdot w_{tfl.i} + h_{web.i} \cdot t_{web.i} + t_{bfl.i} \cdot w_{bfl.i} = 0.043\ m^2$$

$$A_{s.o} := t_{tfl.o} \cdot w_{tfl.o} + h_{web.o} \cdot t_{web.o} + t_{bfl.o} \cdot w_{bfl.o} = 0.036\ m^2$$

$$A_c := h_c \cdot w_c = 0.662\ m^2$$

No interaction between steel and concrete

Inner:

$$y_{cg.i} := \frac{\left[t_{tfl.i} \cdot w_{tfl.i} \cdot \frac{t_{tfl.i}}{2} + h_{web.i} \cdot t_{web.i} \cdot \left(t_{tfl.i} + \frac{h_{web.i}}{2} \right) \dots \atop + t_{bfl.i} \cdot w_{bfl.i} \cdot \left(t_{tfl.i} + h_{web.i} + \frac{t_{bfl.i}}{2} \right) \right]}{A_{s.i}} = 0.704\ m$$

$$I_i := \frac{\left(w_{tfl.i} \cdot t_{tfl.i}^3 \right)}{12} + w_{tfl.i} \cdot t_{tfl.i} \cdot \left(y_{cg.i} - \frac{t_{tfl.i}}{2} \right)^2 \dots \\ + \frac{t_{web.i} \cdot h_{web.i}^3}{12} + t_{web.i} \cdot h_{web.i} \cdot \left(y_{cg.i} - t_{tfl.i} - \frac{h_{web.i}}{2} \right)^2 \dots \\ + \frac{w_{bfl.i} \cdot t_{bfl.i}^3}{12} + w_{bfl.i} \cdot t_{bfl.i} \cdot \left(y_{cg.i} - t_{tfl.i} - h_{web.i} - \frac{t_{bfl.i}}{2} \right)^2 = 0.015\ m^4$$

Outer:

$$y_{cg.o} := \frac{\left[t_{tfl.o} \cdot w_{tfl.o} \cdot \frac{t_{tfl.o}}{2} + h_{web.o} \cdot t_{web.o} \cdot \left(t_{tfl.o} + \frac{h_{web.o}}{2}\right) \ldots \atop + t_{bfl.o} \cdot w_{bfl.o} \cdot \left(t_{tfl.o} + h_{web.o} + \frac{t_{bfl.o}}{2}\right)\right]}{A_{s.o}} = 0.705\ m$$

$$I_o := \frac{\left(w_{tfl.o} \cdot t_{tfl.o}^{\ 3}\right)}{12} + w_{tfl.o} \cdot t_{tfl.o} \cdot \left(y_{cg.o} - \frac{t_{tfl.o}}{2}\right)^2 \ldots = 0.011\ m^4$$
$$+ \frac{t_{web.o} \cdot h_{web.o}^{\ 3}}{12} + t_{web.o} \cdot h_{web.o} \cdot \left(y_{cg.o} - t_{tfl.o} - \frac{h_{web.o}}{2}\right)^2 \ldots$$
$$+ \frac{w_{bfl.o} \cdot t_{bfl.o}^{\ 3}}{12} + w_{bfl.o} \cdot t_{bfl.o} \cdot \left(y_{cg.o} - t_{tfl.o} - h_{web.o} - \frac{t_{bfl.o}}{2}\right)^2$$

Interaction between steel and concrete

$E_{cm} := 34GPa$

$E_a := 210GPa$

Short term

$$n_0 := \frac{E_a}{E_{cm}} = 6.176$$

Inner:

$$y_{cg.0.i} := \frac{\left[\frac{A_c}{n_0} \cdot (h_c - 107mm) + t_{tfl.i} \cdot w_{tfl.i} \cdot \left(h_c + \frac{t_{tfl.i}}{2}\right) \ldots \atop {+ h_{web.i} \cdot t_{web.i} \cdot \left(h_c + t_{tfl.i} + \frac{h_{web.i}}{2}\right) \ldots \atop + t_{bfl.i} \cdot w_{bfl.i} \cdot \left(h_c + t_{tfl.i} + h_{web.i} + \frac{t_{bfl.i}}{2}\right)}\right]}{\frac{A_c}{n_0} + A_{s.i}} = 0.394\ m$$

Center of gravity from the top of the concrete

$y_{s.0.i} := y_{cg.0.i} - h_c = 0.124\ m$

Center of gravity from the interseciton of the concrete and the steel

$$I_{0.i} := \frac{\left(\frac{w_c}{n_0} \cdot h_c^{\ 3}\right)}{12} + \frac{A_c}{n_0} \cdot \left[y_{cg.0.i} - \left(h_c - 107mm\right)\right]^2 \ldots + \frac{w_{tfl.i} \cdot t_{tfl.i}^{\ 3}}{12} + w_{tfl.i} \cdot t_{tfl.i} \cdot \left(y_{s.0.i} - \frac{t_{tfl.i}}{2}\right)^2 \ldots + \frac{t_{web.i} \cdot h_{web.i}^{\ 3}}{12} + t_{web.i} \cdot h_{web.i} \cdot \left(y_{s.0.i} - t_{tfl.i} - \frac{h_{web.i}}{2}\right)^2 \ldots + \frac{w_{bfl.i} \cdot t_{bfl.i}^{\ 3}}{12} + w_{bfl.i} \cdot t_{bfl.i} \cdot \left(y_{s.0.i} - t_{tfl.i} - h_{web.i} - \frac{t_{bfl.i}}{2}\right)^2 = 0.035\ m^4$$

Outer:

$$y_{cg.0.o} := \frac{\left[\frac{A_c}{n_0} \cdot \left(h_c - 107mm\right) + t_{tfl.o} \cdot w_{tfl.o} \cdot \left(h_c + \frac{t_{tfl.o}}{2}\right) \ldots + h_{web.o} \cdot t_{web.o} \cdot \left(h_c + t_{tfl.o} + \frac{h_{web.o}}{2}\right) \ldots + t_{bfl.o} \cdot w_{bfl.o} \cdot \left(h_c + t_{tfl.o} + h_{web.o} + \frac{t_{bfl.o}}{2}\right)\right]}{\frac{A_c}{n_0} + A_{s.o}} = 0.367\ m$$

$y_{s.0.o} := y_{cg.0.o} - h_c = 0.097\ m$

$$I_{0.o} := \frac{\left(\frac{w_c}{n_0} \cdot h_c^{\ 3}\right)}{12} + \frac{A_c}{n_0} \cdot \left[y_{cg.0.o} - \left(h_c - 107mm\right)\right]^2 \ldots + \frac{w_{tfl.o} \cdot t_{tfl.o}^{\ 3}}{12} + w_{tfl.o} \cdot t_{tfl.o} \cdot \left(y_{s.0.o} - \frac{t_{tfl.o}}{2}\right)^2 \ldots + \frac{t_{web.o} \cdot h_{web.o}^{\ 3}}{12} + t_{web.o} \cdot h_{web.o} \cdot \left(y_{s.0.o} - t_{tfl.o} - \frac{h_{web.o}}{2}\right)^2 \ldots + \frac{w_{bfl.o} \cdot t_{bfl.o}^{\ 3}}{12} + w_{bfl.o} \cdot t_{bfl.o} \cdot \left(y_{s.0.o} - t_{tfl.o} - h_{web.o} - \frac{t_{bfl.o}}{2}\right)^2 = 0.03\ m^4$$

Self weight concrete

$\Psi_{L1} := 1.1 \qquad \varphi_{L1} := 2.83 \qquad n_{L1} := n_0 \cdot (1 + \Psi_{L1} \cdot \varphi_{L1}) = 25.404$

Inner:

$$y_{cg.L1.i} := \frac{\left[\begin{array}{l} \frac{A_c}{n_{L1}} \cdot (h_c - 107mm) + t_{tfl.i} \cdot w_{tfl.i} \cdot \left(h_c + \frac{t_{tfl.i}}{2}\right) ... \\ + h_{web.i} \cdot t_{web.i} \cdot \left(h_c + t_{tfl.i} + \frac{h_{web.i}}{2}\right) ... \\ + t_{bfl.i} \cdot w_{bfl.i} \cdot \left(h_c + t_{tfl.i} + h_{web.i} + \frac{t_{bfl.i}}{2}\right) \end{array}\right]}{\frac{A_c}{n_{L1}} + A_{s.i}} = 0.667\,m$$

$y_{s.L1.i} := y_{cg.L1.i} - h_c = 0.397\,m$

$$\begin{aligned} I_{L1.i} := & \frac{\left(\frac{w_c}{n_{L1}} \cdot h_c^{\,3}\right)}{12} + \frac{A_c}{n_{L1}} \cdot \left[y_{cg.L1.i} - (h_c - 107mm)\right]^2 ... \qquad = 0.025\,m^4 \\ & + \frac{w_{tfl.i} \cdot t_{tfl.i}^{\,3}}{12} + w_{tfl.i} \cdot t_{tfl.i} \cdot \left(y_{s.L1.i} - \frac{t_{tfl.i}}{2}\right)^2 ... \\ & + \frac{t_{web.i} \cdot h_{web.i}^{\,3}}{12} + t_{web.i} \cdot h_{web.i} \cdot \left(y_{s.L1.i} - t_{tfl.i} - \frac{h_{web.i}}{2}\right)^2 ... \\ & + \frac{w_{bfl.i} \cdot t_{bfl.i}^{\,3}}{12} + w_{bfl.i} \cdot t_{bfl.i} \cdot \left(y_{s.L1.i} - t_{tfl.i} - h_{web.i} - \frac{t_{bfl.i}}{2}\right)^2 \end{aligned}$$

Outer:

$$y_{cg.L1.o} := \frac{\left[\begin{array}{l} \frac{A_c}{n_{L1}} \cdot (h_c - 107mm) + t_{tfl.o} \cdot w_{tfl.o} \cdot \left(h_c + \frac{t_{tfl.o}}{2}\right) ... \\ + h_{web.o} \cdot t_{web.o} \cdot \left(h_c + t_{tfl.o} + \frac{h_{web.o}}{2}\right) ... \\ + t_{bfl.o} \cdot w_{bfl.o} \cdot \left(h_c + t_{tfl.o} + h_{web.o} + \frac{t_{bfl.o}}{2}\right) \end{array}\right]}{\frac{A_c}{n_{L1}} + A_{s.o}} = 0.633\,m$$

$y_{s.L1.o} := y_{cg.L1.o} - h_c = 0.363\,m$

$$I_{L1.o} := \frac{\left(\frac{w_c}{n_{L1}} \cdot h_c^{\,3}\right)}{12} + \frac{A_c}{n_{L1}} \cdot \left[y_{cg.L1.o} - \left(h_c - 107mm\right)\right]^2 \; ... \qquad = 0.022\ m^4$$

$$+ \frac{w_{tfl.o} \cdot t_{tfl.o}^{\,3}}{12} + w_{tfl.o} \cdot t_{tfl.o} \cdot \left(y_{s.L1.o} - \frac{t_{tfl.o}}{2}\right)^2 \; ...$$

$$+ \frac{t_{web.o} \cdot h_{web.o}^{\,3}}{12} + t_{web.o} \cdot h_{web.o} \cdot \left(y_{s.L1.o} - t_{tfl.o} - \frac{h_{web.o}}{2}\right)^2 \; ...$$

$$+ \frac{w_{bfl.o} \cdot t_{bfl.o}^{\,3}}{12} + w_{bfl.o} \cdot t_{bfl.o} \cdot \left(y_{s.L1.o} - t_{tfl.o} - h_{web.o} - \frac{t_{bfl.o}}{2}\right)^2$$

Shrinkage

$\Psi_{L2} := 0.55 \qquad \varphi_{L2} := 2.83 \qquad n_{L2} := n_0 \cdot \left(1 + \Psi_{L2} \cdot \varphi_{L2}\right) = 15.79$

Inner:

$$y_{cg.L2.i} := \frac{\left[\begin{aligned} &\frac{A_c}{n_{L2}} \cdot \left(h_c - 107mm\right) + t_{tfl.i} \cdot w_{tfl.i} \cdot \left(h_c + \frac{t_{tfl.i}}{2}\right) \; ... \\ &+ h_{web.i} \cdot t_{web.i} \cdot \left(h_c + t_{tfl.i} + \frac{h_{web.i}}{2}\right) \; ... \\ &+ t_{bfl.i} \cdot w_{bfl.i} \cdot \left(h_c + t_{tfl.i} + h_{web.i} + \frac{t_{bfl.i}}{2}\right) \end{aligned}\right]}{\frac{A_c}{n_{L2}} + A_{s.i}} = 0.573\ m$$

$y_{s.L2.i} := y_{cg.L2.i} - h_c = 0.303\ m$

$$I_{L2.i} := \frac{\left(\frac{w_c}{n_{L2}} \cdot h_c^{\,3}\right)}{12} + \frac{A_c}{n_{L2}} \cdot \left[y_{cg.L2.i} - \left(h_c - 107mm\right)\right]^2 \; ... \qquad = 0.029\ m^4$$

$$+ \frac{w_{tfl.i} \cdot t_{tfl.i}^{\,3}}{12} + w_{tfl.i} \cdot t_{tfl.i} \cdot \left(y_{s.L2.i} - \frac{t_{tfl.i}}{2}\right)^2 \; ...$$

$$+ \frac{t_{web.i} \cdot h_{web.i}^{\,3}}{12} + t_{web.i} \cdot h_{web.i} \cdot \left(y_{s.L2.i} - t_{tfl.i} - \frac{h_{web.i}}{2}\right)^2 \; ...$$

$$+ \frac{w_{bfl.i} \cdot t_{bfl.i}^{\,3}}{12} + w_{bfl.i} \cdot t_{bfl.i} \cdot \left(y_{s.L2.i} - t_{tfl.i} - h_{web.i} - \frac{t_{bfl.i}}{2}\right)^2$$

Outer:

$$y_{cg.L2.o} := \frac{\left[\begin{array}{l}\frac{A_c}{n_{L2}}\cdot(h_c - 107mm) + t_{tfl.o}\cdot w_{tfl.o}\cdot\left(h_c + \frac{t_{tfl.o}}{2}\right) ... \\ + h_{web.o}\cdot t_{web.o}\cdot\left(h_c + t_{tfl.o} + \frac{h_{web.o}}{2}\right) ... \\ + t_{bfl.o}\cdot w_{bfl.o}\cdot\left(h_c + t_{tfl.o} + h_{web.o} + \frac{t_{bfl.o}}{2}\right)\end{array}\right]}{\frac{A_c}{n_{L2}} + A_{s.o}} = 0.537\,m$$

$$y_{s.L2.o} := y_{cg.L2.o} - h_c = 0.267\,m$$

$$\begin{aligned}I_{L2.o} := {} & \frac{\left(\frac{w_c}{n_{L2}}\cdot h_c^{\,3}\right)}{12} + \frac{A_c}{n_{L2}}\cdot\left[y_{cg.L2.o} - (h_c - 107mm)\right]^2 ... \\ & + \frac{w_{tfl.o}\cdot t_{tfl.o}^{\,3}}{12} + w_{tfl.o}\cdot t_{tfl.o}\cdot\left(y_{s.L2.o} - \frac{t_{tfl.o}}{2}\right)^2 ... \\ & + \frac{t_{web.o}\cdot h_{web.o}^{\,3}}{12} + t_{web.o}\cdot h_{web.o}\cdot\left(y_{s.L2.o} - t_{tfl.o} - \frac{h_{web.o}}{2}\right)^2 ... \\ & + \frac{w_{bfl.o}\cdot t_{bfl.o}^{\,3}}{12} + w_{bfl.o}\cdot t_{bfl.o}\cdot\left(y_{s.L2.o} - t_{tfl.o} - h_{web.o} - \frac{t_{bfl.o}}{2}\right)^2\end{aligned} = 0.024\,m^4$$

Additonal self-weigth

$\Psi_{L3} := 1.1$ $\qquad \varphi_{L3} := 1.49$ $\qquad n_{L3} := n_0\cdot(1 + \Psi_{L3}\cdot\varphi_{L3}) = 16.3$

Inner:

$$y_{cg.L3.i} := \frac{\left[\begin{array}{l}\frac{A_c}{n_{L3}}\cdot(h_c - 107mm) + t_{tfl.i}\cdot w_{tfl.i}\cdot\left(h_c + \frac{t_{tfl.i}}{2}\right) ... \\ + h_{web.i}\cdot t_{web.i}\cdot\left(h_c + t_{tfl.i} + \frac{h_{web.i}}{2}\right) ... \\ + t_{bfl.i}\cdot w_{bfl.i}\cdot\left(h_c + t_{tfl.i} + h_{web.i} + \frac{t_{bfl.i}}{2}\right)\end{array}\right]}{\frac{A_c}{n_{L3}} + A_{s.i}} = 0.579\,m$$

$$y_{s.L3.i} := y_{cg.L3.i} - h_c = 0.309\,m$$

$$I_{L3.i} := \frac{\left(\frac{w_c}{n_{L3}} \cdot h_c^3\right)}{12} + \frac{A_c}{n_{L3}} \cdot \left[y_{cg.L3.i} - (h_c - 107mm)\right]^2 \ldots \qquad = 0.029\ m^4$$

$$+ \frac{w_{tfl.i} \cdot t_{tfl.i}^3}{12} + w_{tfl.i} \cdot t_{tfl.i} \cdot \left(y_{s.L3.i} - \frac{t_{tfl.i}}{2}\right)^2 \ldots$$

$$+ \frac{t_{web.i} \cdot h_{web.i}^3}{12} + t_{web.i} \cdot h_{web.i} \cdot \left(y_{s.L3.i} - t_{tfl.i} - \frac{h_{web.i}}{2}\right)^2 \ldots$$

$$+ \frac{w_{bfl.i} \cdot t_{bfl.i}^3}{12} + w_{bfl.i} \cdot t_{bfl.i} \cdot \left(y_{s.L3.i} - t_{tfl.i} - h_{web.i} - \frac{t_{bfl.i}}{2}\right)^2$$

Outer:

$$y_{cg.L3.o} := \frac{\left[\begin{array}{l} \frac{A_c}{n_{L3}} \cdot (h_c - 107mm) + t_{tfl.o} \cdot w_{tfl.o} \cdot \left(h_c + \frac{t_{tfl.o}}{2}\right) \ldots \\ + h_{web.o} \cdot t_{web.o} \cdot \left(h_c + t_{tfl.o} + \frac{h_{web.o}}{2}\right) \ldots \\ + t_{bfl.o} \cdot w_{bfl.o} \cdot \left(h_c + t_{tfl.o} + h_{web.o} + \frac{t_{bfl.o}}{2}\right) \end{array}\right]}{\frac{A_c}{n_{L3}} + A_{s.o}} = 0.544\ m$$

$$y_{s.L3.o} := y_{cg.L3.o} - h_c = 0.274\ m$$

$$I_{L3.o} := \frac{\left(\frac{w_c}{n_{L3}} \cdot h_c^3\right)}{12} + \frac{A_c}{n_{L3}} \cdot \left[y_{cg.L3.o} - (h_c - 107mm)\right]^2 \ldots \qquad = 0.024\ m^4$$

$$+ \frac{w_{tfl.o} \cdot t_{tfl.o}^3}{12} + w_{tfl.o} \cdot t_{tfl.o} \cdot \left(y_{s.L3.o} - \frac{t_{tfl.o}}{2}\right)^2 \ldots$$

$$+ \frac{t_{web.o} \cdot h_{web.o}^3}{12} + t_{web.o} \cdot h_{web.o} \cdot \left(y_{s.L3.o} - t_{tfl.o} - \frac{h_{web.o}}{2}\right)^2 \ldots$$

$$+ \frac{w_{bfl.o} \cdot t_{bfl.o}^3}{12} + w_{bfl.o} \cdot t_{bfl.o} \cdot \left(y_{s.L3.o} - t_{tfl.o} - h_{web.o} - \frac{t_{bfl.o}}{2}\right)^2$$

2. Fatigue Limit State

EC 1993 2 9.5

$t_{Ld} := 80$ — Design life of the bridge

$Q_{m1} := 300kN$ — Average gross weight of the lorries in the slow lane

$Q_0 := 480kN$

$N_{Obs} := 50000$ — Total number of lorries per year in the slow lane

$N_0 := 500000$

$\gamma_{Ff} := 1$ — Partial factor for equivalent constant amplitude stress range

$\gamma_{Mf} := 1.35$ — Partial factor for fatigue strength

$\gamma_{Mfs} := 1$ — Partial factor for fatigue strength - studs

Lambda coefficients for a span (f) and for a support (s)

EC 1993-2 9.5.2

$\lambda_{1.f} := 2.33$ — Factor for damage effect of traffic depending on length of the critical influenxe line Figure 9

$\lambda_{1.s} := 1.72$

$$\lambda_2 := \left(\frac{Q_{m1}}{Q_0}\right)\cdot\left(\frac{N_{Obs}}{N_0}\right)^{\frac{1}{5}} = 0.394$$

Factor for the traffic volume Eq. 9.10

$$\lambda_3 := \left(\frac{t_{Ld}}{100}\right)^{\frac{1}{5}} = 0.956$$

Factor for the design life of the bridge Table 9.2

$\lambda_4 := 1$ — Factor for traffic on other lanes from NA

$$\lambda_f := \min\left(\lambda_{1.f}\cdot\lambda_2\cdot\lambda_3\cdot\lambda_4, 2\right) = 0.879$$

Eq. 9.9

$$\lambda_s := \min\left(\lambda_{1.s}\cdot\lambda_2\cdot\lambda_3\cdot\lambda_4, 1.836\right) = 0.649$$

Figure 9.6

Lambda coefficients for the shear studs

EC 1994-2 6.8.6.2

EC 1994-2 6.8.6.2 (4)

$\lambda_{v.1} := 1.55$

$$\lambda_{v.2} := \left(\frac{Q_{m1}}{Q_0}\right)\cdot\left(\frac{N_{Obs}}{N_0}\right)^{\frac{1}{8}} = 0.469$$

$\lambda_{v.3} := \left(\frac{t_{Ld}}{100}\right)^{\frac{1}{8}} = 0.972$

$\lambda_{v.4} := 1$

$\lambda_v := \lambda_{v.1} \cdot \lambda_{v.2} \cdot \lambda_{v.3} \cdot \lambda_{v.4} = 0.706$

2.1 Load

$\Delta M_{FLS.16} := 2.55 MN \cdot m$ Moment due to fatigue loading at x = 16

$\Delta\sigma_{FLS.tfl.16} := \frac{\Delta M_{FLS.16}}{I_{0.i}} \cdot y_{s.0.i} = 8.963 \cdot MPa$

$\Delta\sigma_{FLS.tw.16} := \frac{\Delta M_{FLS.16}}{I_{0.i}} \cdot \left(y_{s.0.i} - t_{tfl.i}\right) = 7.161 \cdot MPa$

$\Delta\sigma_{FLS.bw.16} := \frac{\Delta M_{FLS.16}}{I_{0.i}} \cdot \left(h_s - y_{s.0.i} - t_{bfl.i}\right) = 90.644 \cdot MPa$

$\Delta\sigma_{FLS.bfl.16} := \frac{\Delta M_{FLS.16}}{I_{0.i}} \cdot \left(h_s - y_{s.0.i}\right) = 91.942 \cdot MPa$

$\Delta M_{FLS.9} := 2.13 MN \cdot m$ Moment due to fatigue loading at x = 9

$\Delta\sigma_{FLS.tfl.9} := \frac{\Delta M_{FLS.9}}{I_{0.o}} \cdot y_{s.0.o} = 6.911 \cdot MPa$

$\Delta\sigma_{FLS.tw.9} := \frac{\Delta M_{FLS.9}}{I_{0.o}} \cdot \left(y_{s.0.o} - t_{tfl.o}\right) = 5.48 \cdot MPa$

$\Delta\sigma_{FLS.bw.9} := \frac{\Delta M_{FLS.9}}{I_{0.o}} \cdot \left(h_s - y_{s.0.o} - t_{bfl.o}\right) = 92.304 \cdot MPa$

$\Delta\sigma_{FLS.bfl.9} := \frac{\Delta M_{FLS.9}}{I_{0.o}} \cdot \left(h_s - y_{s.0.o}\right) = 93.234 \cdot MPa$

$V_{FLS.16} := 0.295 MN$ Shear due to fatigue loading at x = 16

$V_{FLS.0} := 0.349 MN$ Shear due to fatigue loading at x = 0

2.2 Shear studs (Detail 1)

x = 16

$$S_{con.tfl} := \frac{A_c}{n_0} \cdot \left[y_{cg.0.o} - \left(h_c - 107mm \right) \right] = 2.181 \times 10^7 \cdot mm^3$$

$$\Delta F_{p.max} := V_{FLS.0} \cdot \frac{S_{con.tfl}}{I_{0.o}} = 255.591 \cdot \frac{kN}{m}$$

$\phi := 22mm$ Diameter of shear studs

$$\Delta F_{E2} := \lambda_v \cdot \Delta F_{p.max} = 180.569 \cdot \frac{kN}{m}$$

$$\Delta\tau_c := 90MPa$$

$$\Delta F_R := \Delta\tau_c \cdot \pi \cdot \frac{\phi^2}{4} = 34.212 \cdot kN$$

$$UR_{FLS.1} := \frac{\Delta F_{E2}}{\Delta F_R} = 5.278 \frac{1}{m}$$ Nr of studs/m < 10

2.3 Conneciton between flanges and web stiffeners (Detail 3)

x = 16

Top flange/web stiffener

$$\Delta\sigma_{E2.tf.ws.16} := \lambda_f \cdot \Delta\sigma_{FLS.tfl.16} = 7.876 \cdot MPa$$

$$\Delta\sigma_{c.tf.ws.16} := 80MPa$$

$$UR_{FLS.2} := \frac{\left(\gamma_{Ff} \cdot \Delta\sigma_{E2.tf.ws.16} \right)}{\left(\frac{\Delta\sigma_{c.tf.ws.16}}{\gamma_{Mf}} \right)} = 0.133$$

Bottom flange/web stiffener

$$\Delta\sigma_{E2.bf.ws.16} := \lambda_f \cdot \Delta\sigma_{FLS.bw.16} = 79.652 \cdot MP$$

$$\Delta\sigma_{c.bf.ws.16} := 112MPa$$

$$UR_{FLS.3} := \frac{\left(\gamma_{Ff} \cdot \Delta\sigma_{E2.bf.ws.16} \right)}{\left(\frac{\Delta\sigma_{c.bf.ws.16}}{\gamma_{Mf}} \right)} = 0.96$$

x = 8

Top flange/web stiffener

$\Delta\sigma_{E2.tf.ws.9} := \lambda_f \cdot \Delta\sigma_{FLS.tfl.9} = 6.073 \cdot MPa$

$\Delta\sigma_{c.tf.ws.9} := 80MPa$

$$UR_{FLS.4} := \frac{\left(\gamma_{Ff} \cdot \Delta\sigma_{E2.tf.ws.9}\right)}{\left(\frac{\Delta\sigma_{c.tf.ws.9}}{\gamma_{Mf}}\right)} = 0.102$$

Bottom flange/web stiffener

$\Delta\sigma_{E2.bf.ws.9} := \lambda_f \cdot \Delta\sigma_{FLS.bw.9} = 81.11 \cdot MPa$

$\Delta\sigma_{c.bf.ws.9} := 112MPa$

$$UR_{FLS.5} := \frac{\left(\gamma_{Ff} \cdot \Delta\sigma_{E2.bf.ws.9}\right)}{\left(\frac{\Delta\sigma_{c.bf.ws.9}}{\gamma_{Mf}}\right)} = 0.978$$

2.4 Connection between segments (Detail 4)

x = 9

Top flange/top flange

$\Delta\sigma_{E2.tf.tf.9} := \lambda_f \cdot \Delta\sigma_{FLS.tfl.9} = 6.073 \cdot MPa$

$\Delta\sigma_{c.tf.tf.9} := 80MPa$

$$UR_{FLS.6} := \frac{\left(\gamma_{Ff} \cdot \Delta\sigma_{E2.tf.tf.9}\right)}{\left(\frac{\Delta\sigma_{c.tf.tf.9}}{\gamma_{Mf}}\right)} = 0.102$$

Bottom flange/bottom flange

$\Delta\sigma_{E2.bf.bf.9} := \lambda_f \cdot \Delta\sigma_{FLS.bfl.9} = 81.927 \cdot MPa$

$\Delta\sigma_{c.bf.bf.9} := 112MPa$

$$UR_{FLS.7} := \frac{\left(\gamma_{Ff} \cdot \Delta\sigma_{E2.bf.bf.9}\right)}{\left(\frac{\Delta\sigma_{c.bf.bf.9}}{\gamma_{Mf}}\right)} = 0.988$$

2.5 Connection between flanges and web (Detail 5 + Detail 2)

$\Delta\sigma_{c.h} := 36MPa$

$l_h := 1.2m$

$F_h := 120kN$

$$\sigma_h := \frac{F_h}{t_{web.i} \cdot l_h} = 7.692 \cdot MPa$$

$$\Delta\sigma_{wf.max} := \left(\sigma_h^{\ 2} + \sigma_h^{\ 2}\right)^{0.5} = 10.879 \cdot MPa$$

$$\Delta\sigma_{E2.h} := \lambda_f \cdot \Delta\sigma_{wf.max} = 9.559 \cdot MPa$$

$$UR_{FLS.8} := \frac{\left(\gamma_{Ff} \cdot \Delta\sigma_{E2.h}\right)}{\left(\frac{\Delta\sigma_{c.h}}{\gamma_{Mf}}\right)} = 0.358$$

x = 16

Top flange/web

$$\Delta\sigma_{E2.tf.w.16} := \lambda_f \cdot \Delta\sigma_{FLS.tw.16} = 6.293 \cdot MPa$$

$$\Delta\sigma_{c.tf.w.16} := 112MPa$$

$$UR_{FLS.9} := \frac{\left(\gamma_{Ff} \cdot \Delta\sigma_{E2.tf.w.16}\right)}{\left(\frac{\Delta\sigma_{c.tf.w.16}}{\gamma_{Mf}}\right)} = 0.076$$

Bottom flange/web

$$\Delta\sigma_{E2.bf.w.16} := \lambda_f \cdot \Delta\sigma_{FLS.bw.16} = 79.652 \cdot MPa$$

$$\Delta\sigma_{c.bf.w.16} := 112MPa$$

$$UR_{FLS.10} := \frac{\left(\gamma_{Ff} \cdot \Delta\sigma_{E2.bf.w.16}\right)}{\left(\frac{\Delta\sigma_{c.bf.w.16}}{\gamma_{Mf}}\right)} = 0.96$$

x = 9

Top flange/web

$$\Delta\sigma_{E2.tf.w.9} := \lambda_f \cdot \Delta\sigma_{FLS.tw.9} = 4.816 \cdot MPa$$

$$\Delta\sigma_{c.tf.w.9} := 112MPa$$

$$UR_{FLS.11} := \frac{\left(\gamma_{Ff} \cdot \Delta\sigma_{E2.tf.w.9}\right)}{\left(\frac{\Delta\sigma_{c.tf.w.9}}{\gamma_{Mf}}\right)} = 0.058$$

Bottom flange/web

$$\Delta\sigma_{E2.bf.w.9} := \lambda_f \cdot \Delta\sigma_{FLS.bw.9} = 81.11 \cdot MPa$$

$$\Delta\sigma_{c.bf.w.9} := 112MPa$$

$$UR_{FLS.12} := \frac{\left(\gamma_{Ff} \cdot \Delta\sigma_{E2.bf.w.9}\right)}{\left(\frac{\Delta\sigma_{c.bf.w.9}}{\gamma_{Mf}}\right)} = 0.978$$

2.6 Connection between flanges and web (Detail 6)

$a := 5mm$ Height of the weld

$x = 16$

$\Delta\tau_{c.16} := 80MPa$

Top flange/web

$$S_{tfl.w.i} := \frac{A_c}{n_0} \cdot \left[y_{cg.0.i} - \left(h_c - 107mm \right) \right] + t_{tfl.i} \cdot w_{tfl.i} \cdot \left(y_{s.0.i} - \frac{t_{tfl.i}}{2} \right) = 2.618 \times 10^7 \cdot mm^3$$

$$\tau_{r1t.16} := \frac{\left(V_{FLS.16} \cdot S_{tfl.w.i} \right)}{I_{0.i} \cdot t_{web.i}} = 16.789 \cdot MPa$$

$$\Delta\tau_{E2.tfl.16} := \lambda_f \cdot \left(\frac{\tau_{r1t.16}}{2 \cdot a} \cdot t_{web.i} \right) = 19.179 \cdot MPa$$

$$UR_{FLS.13} := \frac{\left(\gamma_{Ff} \cdot \Delta\tau_{E2.tfl.16} \right)}{\left(\frac{\Delta\tau_{c.16}}{\gamma_{Mf}} \right)} = 0.324$$

Bottom flange/web

$$S_{bfl.w.i} := t_{bfl.i} \cdot w_{bfl.i} \cdot \left(h_s - y_{s.0.i} - \frac{t_{bfl.i}}{2} \right) = 1.596 \times 10^7 \cdot mm^3$$

$$\tau_{r1b.16} := \frac{\left(V_{FLS.16} \cdot S_{bfl.w.i} \right)}{I_{0.i} \cdot t_{web.i}} = 10.236 \cdot MPa$$

$$\Delta\tau_{E2.bfl.16} := \lambda_f \cdot \left(\frac{\tau_{r1b.16}}{2 \cdot a} \cdot t_{web.i} \right) = 11.694 \cdot MPa$$

$$UR_{FLS.14} := \frac{\left(\gamma_{Ff} \cdot \Delta\tau_{E2.bfl.16} \right)}{\left(\frac{\Delta\tau_{c.16}}{\gamma_{Mf}} \right)} = 0.197$$

x = 0

$\Delta\tau_{c.0} := 80\text{MPa}$

Top flange/web

$$S_{tfl.w.o} := \frac{A_c}{n_0} \cdot \left[y_{cg.0.o} - \left(h_c - 107\text{mm} \right) \right] + t_{tfl.o} \cdot w_{tfl.o} \cdot \left(y_{s.0.o} - \frac{t_{tfl.o}}{2} \right) = 2.259 \times 10^{7} \cdot \text{mm}^{3}$$

$$\tau_{r1t.0} := \frac{\left(V_{FLS.0} \cdot S_{tfl.w.o} \right)}{I_{0.o} \cdot t_{web.o}} = 20.364 \cdot \text{MPa}$$

$$\Delta\tau_{E2.tfl.0} := \lambda_s \cdot \left(\frac{\tau_{r1t.0}}{2 \cdot a} \cdot t_{web.o} \right) = 17.172 \cdot \text{MPa}$$

$$UR_{FLS.15} := \frac{\left(\gamma_{Ff} \cdot \Delta\tau_{E2.tfl.0} \right)}{\left(\frac{\Delta\tau_{c.0}}{\gamma_{Mf}} \right)} = 0.29$$

Bottom flange/web

$$S_{bfl.w.o} := t_{bfl.o} \cdot w_{bfl.o} \cdot \left(h_s - y_{s.0.o} - \frac{t_{bfl.o}}{2} \right) = 1.18 \times 10^{7} \cdot \text{mm}^{3}$$

$$\tau_{r1b.0} := \frac{\left(V_{FLS.0} \cdot S_{bfl.w.o} \right)}{I_{0.o} \cdot t_{web.o}} = 10.64 \cdot \text{MPa}$$

$$\Delta\tau_{E2.bfl.0} := \lambda_s \cdot \left(\frac{\tau_{r1b.0}}{2 \cdot a} \cdot t_{web.o} \right) = 8.973 \cdot \text{MPa}$$

$$UR_{FLS.16} := \frac{\left(\gamma_{Ff} \cdot \Delta\tau_{E2.bfl.0} \right)}{\left(\frac{\Delta\tau_{c.0}}{\gamma_{Mf}} \right)} = 0.151$$

3. Ultiate Limit State

3.1 Loads

The moment, shear and normal forces due to differnt loads are obtained from Appendix A and catigorized for different modular ratios. Self weight includes the self weigth of the steel and the concrete. Additional self weight includes the weight of the surfacing, the barriers and earth pressure. Shrinkage includes the weight due to shrinkage. Traffic includes the weight due to traffic and breaking loads. The self weight of the steel is calculated for different cross secitons adding 18% to account for cross beams.

Steel

$$\gamma_s := 77\frac{kN}{m^3}$$

$$q_{s.i} := 1.18\gamma_s \cdot A_{s.i} = 3.883\cdot\frac{kN}{m}$$

$$q_{s.o} := 1.18\gamma_s \cdot A_{s.o} = 3.259\cdot\frac{kN}{m}$$

$$R_s := \frac{\left(q_{s.i}\cdot 14m + q_{s.o}\cdot 19.6m\right)}{2} = 59.125\cdot kN$$

$$M_{steel.16} := -q_{s.i}\cdot 7m\cdot\left(\frac{7m}{2}\right) - q_{s.o}\cdot 9.8m\cdot\left(7m + \frac{9.8m}{2}\right) + R_s\cdot(7m + 9m) = 0.471\cdot MN\cdot m$$

$$M_{steel.9} := -q_{s.o}\cdot 9.8m\cdot\left(\frac{9.8m}{2}\right) + R_s\cdot 9m = 0.376\cdot MN\cdot m$$

$$V_{steel.9} := -q_{s.o}\cdot 9.8m + R_s = 0.027\cdot MN$$

$$V_{steel.0} := -q_{s.o}\cdot 0.8m + R_s = 0.057\cdot MN$$

x = 16

$$M_{self.16} := 1.2\cdot\left(M_{steel.16} + 2.693MN\cdot m\right) = 3.797\cdot MN\cdot m$$

$$M_{add.16} := 1.2\cdot\left(-1.149\times 10^{-1}MN\cdot m\right) + 1.32\cdot 7.852\times 10^{-1}MN\cdot m \ldots + 1\cdot\left(-5.270\times 10^{-2}\right)MN\cdot m = 0.846\cdot MN\cdot m$$

$$M_{shrinkage.16} := 1.2\cdot 1.188MN\cdot m = 1.426\cdot MN\cdot m$$

$$M_{traffic.16} := 1.5\cdot\left(\left(5.006MN\cdot m + 6.400\times 10^{-1}MN\cdot m\right)\right) + 1\cdot 0.75\cdot\left(1.596\times 10^{-6}MN\cdot m\right) = 8.469\cdot MN$$

$N_{self.16} := 0$

$N_{add.16} := 1\cdot\left(-4.990 \times 10^{-2} MN\right) = -0.05\cdot MN$

$N_{shrinkage.16} := 1.2\cdot(-2.289 MN) = -2.747\cdot MN$

$N_{traffic.16} := 1.5\cdot 0 + 1\cdot 0.75\cdot\left(-3.175\ 10^{-1} MN\right) = -0.238\cdot MN$

x = 9

$M_{self.9} := 1.2\cdot\left(M_{steel.9} + 2.124 MN\cdot m\right) = 3\cdot MN\cdot m$

$$M_{add.9} := 1.2\cdot\left(-9.286 \times 10^{-2} MN\cdot m\right) + 1.32\cdot 6.346 \times 10^{-1} MN\cdot m \ldots = 0.674\cdot MN\cdot m$$
$$+ 1\cdot\left(-5.270 \times 10^{-2} MN\cdot m\right)$$

$M_{shrinkage.9} := 1.2\cdot 1.101 MN\cdot m = 1.321\cdot MN\cdot m$

$M_{traffic.9} := 1.5\cdot\left(4.083 MN\cdot m + 5.175 \times 10^{-1} MN\cdot m\right) + 1\cdot 0.75\cdot\left(3.955 \times 10^{-3} MN\cdot m\right) = 6.904\cdot MN\cdot m$

$N_{self.9} := 0$

$N_{add.9} := 1\cdot\left(-4.990 \times 10^{-2} MN\right) = -0.05\cdot MN$

$N_{shrinkage.9} := 1.2\cdot(-2.289 MN) = -2.747\cdot MN$

$N_{traffic.9} := 1.5\cdot 0 + 1\cdot 0.75\cdot\left(-1.852\ 10^{-1} MN\right) = -0.139\cdot MN$

$V_{self.9} := 1.2\cdot\left(V_{steel.9} + 1.624 \times 10^{-1} MN\right) = 0.228\cdot MN$

$V_{add.9} := 1.2\cdot\left(-6.300 \times 10^{-3} MN\right) + 1.32\cdot 4.305 \times 10^{-2} MN + 1\cdot\left(-2.558 \times 10^{-9} MN\right) = 0.049\cdot MN$

$V_{shrinkage.9} := 1.2\cdot\left(-1.354 \times 10^{-8}\right) MN = -1.625 \times 10^{-8}\cdot MN$

$V_{traffic.9} := 1.5\cdot\left(4.144 \times 10^{-1} MN + 4.138\ 10^{-2} MN\right) + 1\cdot 0.75\cdot\left(1.180 \times 10^{-2} MN\right) = 0.693\cdot MN$

x = 0

$V_{self.0} := 1.2\cdot\left(V_{steel.0} + 3.712 \times 10^{-1} MN\right) = 0.513\cdot MN$

$V_{add.0} := 1.2\cdot\left(-1.440 \times 10^{-2} MN\right) + 1.32\cdot 9.840 \times 10^{-2} MN + 1\cdot\left(-5.924 \times 10^{-9} MN\right) = 0.113\cdot MN$

$V_{shrinkage.0} := 1.2\cdot\left(-1.354 \times 10^{-8}\right) MN = -1.625 \times 10^{-8}\cdot MN$

$V_{traffic.0} := 1.5\cdot\left(6.485 \times 10^{-1} MN + 8.000 \times 10^{-2} MN\right) + 1\cdot 0.75\cdot\left(1.186 \times 10^{-2} MN\right) = 1.102\cdot MN$

Stress ditribution

The stress due to moment and normal force is calculated for different modular ratios and summed to obtain the total stress acting at the edges of the flanges.

x = 16

Top flange

$$\sigma_{tfl.16} := \frac{M_{self.16}}{I_i}\cdot\left(-y_{cg.i}\right) + \frac{N_{self.16}}{A_{s.i} + A_c} = -182.686\cdot\frac{MN}{m^2}$$

$$\sigma_{tfl.0.16} := \frac{M_{traffic.16}}{I_{0.i}}\cdot\left(-y_{s.0.i}\right) + \frac{N_{traffic.16}}{A_{s.i} + \frac{A_c}{n_0}} = -31.357\cdot\frac{MN}{m^2}$$

$$\sigma_{tfl.L2.16} := \frac{M_{shrinkage.16}}{I_{L2.i}}\cdot\left(-y_{s.L2.i}\right) + \frac{N_{shrinkage.16}}{A_{s.i} + \frac{A_c}{n_{L2}}} = -47.432\cdot\frac{MN}{m^2}$$

$$\sigma_{tfl.L3.16} := \frac{M_{add.16}}{I_{L3.i}}\cdot\left(-y_{s.L3.i}\right) + \frac{N_{add.16}}{A_{s.i} + \frac{A_c}{n_{L3}}} = -9.748\cdot\frac{MN}{m^2}$$

$$\sigma_{tfl.tot.16} := \sigma_{tfl.16} + \sigma_{tfl.0.16} + \sigma_{tfl.L2.16} + \sigma_{tfl.L3.16} = -271.222\cdot\frac{MN}{m^2}$$

Top flange/web

$$\sigma_{tw.16} := \frac{M_{self.16}}{I_i}\cdot\left(-y_{cg.i} + t_{tfl.i}\right) + \frac{N_{self.16}}{A_{s.i} + A_c} = -176.199\cdot\frac{MN}{m^2}$$

$$\sigma_{tw.0.16} := \frac{M_{traffic.16}}{I_{0.i}}\cdot\left(-y_{s.0.i} + t_{tfl.i}\right) + \frac{N_{traffic.16}}{A_{s.i} + \frac{A_c}{n_0}} = -25.372\cdot\frac{MN}{m^2}$$

$$\sigma_{tw.L2.16} := \frac{M_{shrinkage.16}}{I_{L2.i}}\cdot\left(-y_{s.L2.i} + t_{tfl.i}\right) + \frac{N_{shrinkage.16}}{A_{s.i} + \frac{A_c}{n_{L2}}} = -46.194\cdot\frac{MN}{m^2}$$

$$\sigma_{tw.L3.16} := \frac{M_{add.16}}{I_{L3.i}}\cdot\left(-y_{s.L3.i} + t_{tfl.i}\right) + \frac{N_{add.16}}{A_{s.i} + \frac{A_c}{n_{L3}}} = -9.008\cdot\frac{MN}{m^2}$$

$$\sigma_{tw.tot.16} := \sigma_{tw.16} + \sigma_{tw.0.16} + \sigma_{tw.L2.16} + \sigma_{tw.L3.16} = -256.773\cdot\frac{MN}{m^2}$$

Bottom flange/web

$$\sigma_{bw.16} := \frac{M_{self.16}}{I_i} \cdot \left(h_s - y_{cg.i} - t_{bfl.i}\right) + \frac{N_{self.16}}{A_{s.i} + A_c} = 175.896 \cdot \frac{MN}{m^2}$$

$$\sigma_{bw.0.16} := \frac{M_{traffic.16}}{I_{0.i}} \cdot \left(h_s - y_{s.0.i} - t_{bfl.i}\right) + \frac{N_{traffic.16}}{A_{s.i} + \frac{A_c}{n_0}} = 299.457 \cdot \frac{MN}{m^2}$$

$$\sigma_{bw.L2.16} := \frac{M_{shrinkage.16}}{I_{L2.i}} \cdot \left(h_s - y_{s.L2.i} - t_{bfl.i}\right) + \frac{N_{shrinkage.16}}{A_{s.i} + \frac{A_c}{n_{L2}}} = 20.967 \cdot \frac{MN}{m^2}$$

$$\sigma_{bw.L3.16} := \frac{M_{add.16}}{I_{L3.i}} \cdot \left(h_s - y_{s.L3.i} - t_{bfl.i}\right) + \frac{N_{add.16}}{A_{s.i} + \frac{A_c}{n_{L3}}} = 31.165 \cdot \frac{MN}{m^2}$$

$$\sigma_{bw.tot.16} := \sigma_{bw.16} + \sigma_{bw.0.16} + \sigma_{bw.L2.16} + \sigma_{bw.L3.16} = 527.484 \cdot \frac{MN}{m^2}$$

Bottom flange

$$\sigma_{bfl.16} := \frac{M_{self.16}}{I_i} \cdot \left(h_s - y_{cg.i}\right) + \frac{N_{self.16}}{A_{s.i} + A_c} = 180.566 \cdot \frac{MN}{m^2}$$

$$\sigma_{bfl.0.16} := \frac{M_{traffic.16}}{I_{0.i}} \cdot \left(h_s - y_{s.0.i}\right) + \frac{N_{traffic.16}}{A_{s.i} + \frac{A_c}{n_0}} = 303.766 \cdot \frac{MN}{m^2}$$

$$\sigma_{bfl.L2.16} := \frac{M_{shrinkage.16}}{I_{L2.i}} \cdot \left(h_s - y_{s.L2.i}\right) + \frac{N_{shrinkage.16}}{A_{s.i} + \frac{A_c}{n_{L2}}} = 21.858 \cdot \frac{MN}{m^2}$$

$$\sigma_{bfl.L3.16} := \frac{M_{add.16}}{I_{L3.i}} \cdot \left(h_s - y_{s.L3.i}\right) + \frac{N_{add.16}}{A_{s.i} + \frac{A_c}{n_{L3}}} = 31.698 \cdot \frac{MN}{m^2}$$

$$\sigma_{bfl.tot.16} := \sigma_{bfl.16} + \sigma_{bfl.0.16} + \sigma_{bfl.L2.16} + \sigma_{bfl.L3.16} = 537.887 \cdot \frac{MN}{m^2}$$

x = 9

Top flange

$$\sigma_{tfl.9} := \frac{M_{self.9}}{I_o}\cdot\left(-y_{cg.o}\right) + \frac{N_{self.9}}{A_{s.o} + A_c} = -184.912\cdot\frac{MN}{m^2}$$

$$\sigma_{tfl.0.9} := \frac{M_{traffic.9}}{I_{0.o}}\cdot\left(-y_{s.0.o}\right) + \frac{N_{traffic.9}}{A_{s.o} + \frac{A_c}{n_0}} = -23.371\cdot\frac{MN}{m^2}$$

$$\sigma_{tfl.L2.9} := \frac{M_{shrinkage.9}}{I_{L2.o}}\cdot\left(-y_{s.L2.o}\right) + \frac{N_{shrinkage.9}}{A_{s.o} + \frac{A_c}{n_{L2}}} = -49.792\cdot\frac{MN}{m^2}$$

$$\sigma_{tfl.L3.9} := \frac{M_{add.9}}{I_{L3.o}}\cdot\left(-y_{s.L3.o}\right) + \frac{N_{add.9}}{A_{s.o} + \frac{A_c}{n_{L3}}} = -8.267\cdot\frac{MN}{m^2}$$

$$\sigma_{tfl.tot.9} := \sigma_{tfl.9} + \sigma_{tfl.0.9} + \sigma_{tfl.L2.9} + \sigma_{tfl.L3.9} = -266.342\cdot\frac{MN}{m^2}$$

Top flange/web

$$\sigma_{tw.9} := \frac{M_{self.9}}{I_o}\cdot\left(-y_{cg.o} + t_{tfl.o}\right) + \frac{N_{self.9}}{A_{s.o} + A_c} = -179.663\cdot\frac{MN}{m^2}$$

$$\sigma_{tw.0.9} := \frac{M_{traffic.9}}{I_{0.o}}\cdot\left(-y_{s.0.o} + t_{tfl.o}\right) + \frac{N_{traffic.9}}{A_{s.o} + \frac{A_c}{n_0}} = -18.734\cdot\frac{MN}{m^2}$$

$$\sigma_{tw.L2.9} := \frac{M_{shrinkage.9}}{I_{L2.o}}\cdot\left(-y_{s.L2.o} + t_{tfl.o}\right) + \frac{N_{shrinkage.9}}{A_{s.o} + \frac{A_c}{n_{L2}}} = -48.71\cdot\frac{MN}{m^2}$$

$$\sigma_{tw.L3.9} := \frac{M_{add.9}}{I_{L3.o}}\cdot\left(-y_{s.L3.o} + t_{tfl.o}\right) + \frac{N_{add.9}}{A_{s.o} + \frac{A_c}{n_{L3}}} = -7.711\cdot\frac{MN}{m^2}$$

$$\sigma_{tw.tot.9} := \sigma_{tw.9} + \sigma_{tw.0.9} + \sigma_{tw.L2.9} + \sigma_{tw.L3.9} = -254.818\cdot\frac{MN}{m^2}$$

Bottom flange/web

$$\sigma_{bw.9} := \frac{M_{self.9}}{I_o}\cdot\left(h_s - y_{cg.o} - t_{bfl.o}\right) + \frac{N_{self.9}}{A_{s.o} + A_c} = 179.114\cdot\frac{MN}{m^2}$$

$$\sigma_{bw.0.9} := \frac{M_{traffic.9}}{I_{0.o}}\cdot\left(h_s - y_{s.0.o} - t_{bfl.o}\right) + \frac{N_{traffic.9}}{A_{s.o} + \frac{A_c}{n_0}} = 298.203\cdot\frac{MN}{m^2}$$

$$\sigma_{bw.L2.9} := \frac{M_{shrinkage.9}}{I_{L2.o}}\cdot\left(h_s - y_{s.L2.o} - t_{bfl.o}\right) + \frac{N_{shrinkage.9}}{A_{s.o} + \frac{A_c}{n_{L2}}} = 25.278\cdot\frac{MN}{m^2}$$

$$\sigma_{bw.L3.9} := \frac{M_{add.9}}{I_{L3.o}}\cdot\left(h_s - y_{s.L3.o} - t_{bfl.o}\right) + \frac{N_{add.9}}{A_{s.o} + \frac{A_c}{n_{L3}}} = 30.311\cdot\frac{MN}{m^2}$$

$$\sigma_{bw.tot.9} := \sigma_{bw.9} + \sigma_{bw.0.9} + \sigma_{bw.L2.9} + \sigma_{bw.L3.9} = 532.906\cdot\frac{MN}{m^2}$$

Bottom flange

$$\sigma_{bfl.9} := \frac{M_{self.9}}{I_o}\cdot\left(h_s - y_{cg.o}\right) + \frac{N_{self.9}}{A_{s.o} + A_c} = 182.526\cdot\frac{MN}{m^2}$$

$$\sigma_{bfl.0.9} := \frac{M_{traffic.9}}{I_{0.o}}\cdot\left(h_s - y_{s.0.o}\right) + \frac{N_{traffic.9}}{A_{s.o} + \frac{A_c}{n_0}} = 301.217\cdot\frac{MN}{m^2}$$

$$\sigma_{bfl.L2.9} := \frac{M_{shrinkage.9}}{I_{L2.o}}\cdot\left(h_s - y_{s.L2.o}\right) + \frac{N_{shrinkage.9}}{A_{s.o} + \frac{A_c}{n_{L2}}} = 25.982\cdot\frac{MN}{m^2}$$

$$\sigma_{bfl.L3.9} := \frac{M_{add.9}}{I_{L3.o}}\cdot\left(h_s - y_{s.L3.o}\right) + \frac{N_{add.9}}{A_{s.o} + \frac{A_c}{n_{L3}}} = 30.673\cdot\frac{MN}{m^2}$$

$$\sigma_{bfl.tot.9} := \sigma_{bfl.9} + \sigma_{bfl.0.9} + \sigma_{bfl.L2.9} + \sigma_{bfl.L3.9} = 540.397\cdot\frac{MN}{m^2}$$

3.2 Classifications of cross section

x = 16 - Top flange

$a = 5 \cdot mm$

$$c_{tfl.i} := \frac{\left(w_{tfl.i} - t_{web.i} - 2\cdot\sqrt{2}\cdot a\right)}{2} = 236.429\cdot mm$$

$$\frac{c_{tfl.i}}{t_{tfl.i}} = 9.457$$

$$\varepsilon_{tfl.i} := \sqrt{\frac{235MPa}{f_{y.tfl.i}}} = 0.825$$

$$Class_{tfl.i} := \begin{cases} 1 & \text{if } \frac{c_{tfl.i}}{t_{tfl.i}} \le 9\cdot\varepsilon_{tfl.i} \\ 2 & \text{if } \frac{c_{tfl.i}}{t_{tfl.i}} \le 10\cdot\varepsilon_{tfl.i} \\ 3 & \text{if } \frac{c_{tfl.i}}{t_{tfl.i}} \le 14\cdot\varepsilon_{tfl.i} \\ 4 & \text{otherwise} \end{cases}$$

$Class_{tfl.i} = 3$

$\psi_{tfl.i} := 1$

$k_{\sigma.tfl.i} := 0.43$

$$\lambda_{p.tfl.i} := \frac{\left(\frac{c_{tfl.i}}{t_{tfl.i}}\right)}{28.4\cdot\varepsilon_{tfl.i}\cdot\sqrt{k_{\sigma.tfl.i}}} = 0.615$$

$$\rho_{tfl.i} := \begin{cases} 1 & \text{if } \lambda_{p.tfl.i} \le 0.748 \\ \frac{\left(\lambda_{p.tfl.i} - 0.188\right)}{\lambda_{p.tfl.i}^{2}} & \text{if } \lambda_{p.tfl.i} > 0.748 \end{cases}$$

$\rho_{tfl.i} = 1$

$b_{tfl.eff.i} := c_{tfl.i}\cdot\rho_{tfl.i} = 0.236\,m$

$w_{tfl.eff.i} := 2\cdot b_{tfl.eff.i} + t_{web.i} + 2\cdot\sqrt{2}\cdot a = 500\cdot mm$ No reduction x = 9 - Top flange

$$c_{tfl.o} := \frac{\left(w_{tfl.o} - t_{web.o} - 2\cdot\sqrt{2}\cdot a\right)}{2} = 211.429\cdot mm$$

$$\frac{c_{tfl.o}}{t_{tfl.o}} = 10.571$$

$$\varepsilon_{tfl.o} := \sqrt{\frac{235MPa}{f_{y.tfl.o}}} = 0.825$$

$$Class_{tfl.o} := \begin{array}{|l} 1 \ \text{ if } \frac{c_{tfl.o}}{t_{tfl.o}} \le 9\cdot\varepsilon_{tfl.o} \\ 2 \ \text{ if } \frac{c_{tfl.o}}{t_{tfl.o}} \le 10\cdot\varepsilon_{tfl.o} \\ 3 \ \text{ if } \frac{c_{tfl.o}}{t_{tfl.o}} \le 14\cdot\varepsilon_{tfl.o} \\ 4 \ \text{ otherwise} \end{array}$$

$$Class_{tfl.o} = 3$$

$$\psi_{tfl.o} := 1$$

$$k_{\sigma.tfl.o} := 0.43$$

$$\lambda_{p.tfl.o} := \frac{\left(\frac{c_{tfl.o}}{t_{tfl.o}}\right)}{28.4\cdot\varepsilon_{tfl.o}\cdot\sqrt{k_{\sigma.tfl.o}}} = 0.688$$

$$\rho_{tfl.o} := \begin{array}{|l} 1 \ \text{ if } \lambda_{p.tfl.o} \le 0.748 \\ \frac{\left(\lambda_{p.tfl.o} - 0.188\right)}{\lambda_{p.tfl.o}^{2}} \ \text{ if } \lambda_{p.tfl.o} > 0.748 \end{array}$$

$$\rho_{tfl.o} = 1$$

$$b_{tfl.eff.o} := c_{tfl.o}\cdot\rho_{tfl.o} = 0.211\ m$$

$$w_{tfl.eff.o} := 2\cdot b_{tfl.eff.o} + t_{web.o} + 2\cdot\sqrt{2}\cdot a = 450\cdot mm$$ No reduction

x = 0 - Bottom flange

$$c_{bfl.o} := \frac{\left(w_{bfl.o} - t_{web.o} - 2\cdot\sqrt{2}\cdot a\right)}{2} = 336.429\cdot mm$$

$$\frac{c_{bfl.o}}{t_{bfl.o}} = 25.879$$

$$\varepsilon_{bfl.o} := \sqrt{\frac{235MPa}{f_{y.bfl.o}}} = 0.56$$

$$Class_{bfl.o} := \begin{cases} 1 & \text{if } \frac{c_{bfl.o}}{t_{bfl.o}} \le 9\cdot\varepsilon_{bfl.o} \\ 2 & \text{if } \frac{c_{bfl.o}}{t_{bfl.o}} \le 10\cdot\varepsilon_{bfl.o} \\ 3 & \text{if } \frac{c_{bfl.o}}{t_{bfl.o}} \le 14\cdot\varepsilon_{bfl.o} \\ 4 & \text{otherwise} \end{cases}$$

$$Class_{bfl.o} = 4$$

$$\psi_{bfl.o} := 1$$

$$k_{\sigma.bfl.o} := 0.43$$

$$\lambda_{p.bfl.o} := \frac{\left(\frac{c_{bfl.o}}{t_{bfl.o}}\right)}{28.4\cdot\varepsilon_{bfl.o}\cdot\sqrt{k_{\sigma.bfl.o}}} = 2.483$$

$$\rho_{bfl.o} := \begin{cases} 1 & \text{if } \lambda_{p.bfl.o} \le 0.748 \\ \frac{\left(\lambda_{p.bfl.o} - 0.188\right)}{\lambda_{p.bfl.o}^{2}} & \text{if } \lambda_{p.bfl.o} > 0.748 \end{cases}$$

$$\rho_{bfl.o} = 0.372$$

$$b_{bfl.eff.o} := c_{bfl.o}\cdot\rho_{bfl.o} = 0.125\,m$$

$$w_{bfl.eff.o} := 2\cdot b_{bfl.eff.o} + t_{web.o} + 2\cdot\sqrt{2}\cdot a = 277.654\cdot mm$$ Reduction

3.3 Reduced cross section

Bottom flange at x = 0

$$A_{s.o.eff} := t_{tfl.o} \cdot w_{tfl.o} + h_{web.o} \cdot t_{web.o} + t_{bfl.o} \cdot w_{bfl.eff.o} = 0.03\,m^2$$

No interaction between steel and concrete

$$y_{cg.o.eff} := \frac{\left[t_{tfl.o} \cdot w_{tfl.o} \cdot \frac{t_{tfl.o}}{2} + h_{web.o} \cdot t_{web.o} \cdot \left(t_{tfl.o} + \frac{h_{web.o}}{2} \right) \ldots \atop + t_{bfl.o} \cdot w_{bfl.eff.o} \cdot \left(t_{tfl.o} + h_{web.o} + \frac{t_{bfl.o}}{2} \right) \right]}{A_{s.o.eff}} = 0.58\,m$$

$$I_{o.eff} := \frac{\left(w_{tfl.o} \cdot t_{tfl.o}^{\;3} \right)}{12} + w_{tfl.o} \cdot t_{tfl.o} \cdot \left(y_{cg.o.eff} - \frac{t_{tfl.o}}{2} \right)^2 \ldots = 8.352 \times 10^{\cdot}$$
$$+ \frac{t_{web.o} \cdot h_{web.o}^{\;3}}{12} + t_{web.o} \cdot h_{web.o} \cdot \left(y_{cg.o.eff} - t_{tfl.o} - \frac{h_{web.o}}{2} \right)^2 \ldots$$
$$+ \frac{w_{bfl.eff.o} \cdot t_{bfl.o}^{\;3}}{12} + w_{bfl.eff.o} \cdot t_{bfl.o} \cdot \left(y_{cg.o.eff} - t_{tfl.o} - h_{web.o} - \frac{t_{bfl.o}}{2} \right)^2$$

Interaction between steel and concrete

Short term

$$y_{cg.0.o.eff} := \frac{\left[\frac{A_c}{n_0} \cdot (h_c - 107mm) + t_{tfl.o} \cdot w_{tfl.o} \cdot \left(h_c + \frac{t_{tfl.o}}{2} \right) \ldots \atop {+ h_{web.o} \cdot t_{web.o} \cdot \left(h_c + t_{tfl.o} + \frac{h_{web.o}}{2} \right) \ldots \atop + t_{bfl.o} \cdot w_{bfl.eff.o} \cdot \left(h_c + t_{tfl.o} + h_{web.o} + \frac{t_{bfl.o}}{2} \right)} \right]}{\frac{A_c}{n_0} + A_{s.o.eff}} = 0.315\,m$$

$$y_{s.0.o.eff} := y_{cg.0.o.eff} - h_c = 0.045\,m$$

$$I_{0.o.eff} := \frac{\left(\frac{w_c}{n_0} \cdot h_c^{\,3}\right)}{12} + \frac{A_c}{n_0} \cdot \left[y_{cg.0.o.eff} - \left(h_c - 107mm\right)\right]^2 \ldots = 0.02\,m^4$$

$$+ \frac{w_{tfl.o} \cdot t_{tfl.o}^{\,3}}{12} + w_{tfl.o} \cdot t_{tfl.o} \cdot \left(y_{s.0.o.eff} - \frac{t_{tfl.o}}{2}\right)^2 \ldots$$

$$+ \frac{t_{web.o} \cdot h_{web.o}^{\,3}}{12} + t_{web.o} \cdot h_{web.o} \cdot \left(y_{s.0.o.eff} - t_{tfl.o} - \frac{h_{web.o}}{2}\right)^2 \ldots$$

$$+ \frac{w_{bfl.eff.o} \cdot t_{bfl.o}^{\,3}}{12} + w_{bfl.eff.o} \cdot t_{bfl.o} \cdot \left(y_{s.0.o.eff} - t_{tfl.o} - h_{web.o} - \frac{t_{bfl.o}}{2}\right)^2$$

Self weight concrete

$$y_{cg.L1.o.eff} := \frac{\left[\begin{array}{l} \frac{A_c}{n_{L1}} \cdot \left(h_c - 107mm\right) + t_{tfl.o} \cdot w_{tfl.o} \cdot \left(h_c + \frac{t_{tfl.o}}{2}\right) \ldots \\ + h_{web.o} \cdot t_{web.o} \cdot \left(h_c + t_{tfl.o} + \frac{h_{web.o}}{2}\right) \ldots \\ + t_{bfl.o} \cdot w_{bfl.eff.o} \cdot \left(h_c + t_{tfl.o} + h_{web.o} + \frac{t_{bfl.o}}{2}\right) \end{array}\right]}{\frac{A_c}{n_{L1}} + A_{s.o.eff}} = 0.533\,m$$

$$y_{s.L1.o.eff} := y_{cg.L1.o.eff} - h_c = 0.263\,m$$

$$I_{L1.o.eff} := \frac{\left(\frac{w_c}{n_{L1}} \cdot h_c^{\,3}\right)}{12} + \frac{A_c}{n_{L1}} \cdot \left[y_{cg.L1.o.eff} - \left(h_c - 107mm\right)\right]^2 \ldots = 0.015$$

$$+ \frac{w_{tfl.o} \cdot t_{tfl.o}^{\,3}}{12} + w_{tfl.o} \cdot t_{tfl.o} \cdot \left(y_{s.L1.o.eff} - \frac{t_{tfl.o}}{2}\right)^2 \ldots$$

$$+ \frac{t_{web.o} \cdot h_{web.o}^{\,3}}{12} + t_{web.o} \cdot h_{web.o} \cdot \left(y_{s.L1.o.eff} - t_{tfl.o} - \frac{h_{web.o}}{2}\right)^2 \ldots$$

$$+ \frac{w_{bfl.eff.o} \cdot t_{bfl.o}^{\,3}}{12} + w_{bfl.eff.o} \cdot t_{bfl.o} \cdot \left(y_{s.L1.o.eff} - t_{tfl.o} - h_{web.o} - \frac{t_{bfl.o}}{2}\right)^2$$

Shrinkage

$$y_{cg.L2.o.eff} := \frac{\left[\begin{array}{l}\frac{A_c}{n_{L2}}\cdot(h_c - 107mm) + t_{tfl.o}\cdot w_{tfl.o}\cdot\left(h_c + \frac{t_{tfl.o}}{2}\right) ... \\ + h_{web.o}\cdot t_{web.o}\cdot\left(h_c + t_{tfl.o} + \frac{h_{web.o}}{2}\right) ... \\ + t_{bfl.o}\cdot w_{bfl.eff.o}\cdot\left(h_c + t_{tfl.o} + h_{web.o} + \frac{t_{bfl.o}}{2}\right)\end{array}\right]}{\frac{A_c}{n_{L2}} + A_{s.o.eff}} = 0.452\,m$$

$$y_{s.L2.o.eff} := y_{cg.L2.o.eff} - h_c = 0.182\,m$$

$$\begin{aligned} I_{L2.o.eff} :=\ & \frac{\left(\frac{w_c}{n_{L2}}\cdot h_c^{\,3}\right)}{12} + \frac{A_c}{n_{L2}}\cdot\left[y_{cg.L2.o.eff} - (h_c - 107mm)\right]^2 ... \\ & + \frac{w_{tfl.o}\cdot t_{tfl.o}^{\,3}}{12} + w_{tfl.o}\cdot t_{tfl.o}\cdot\left(y_{s.L2.o.eff} - \frac{t_{tfl.o}}{2}\right)^2 ... \\ & + \frac{t_{web.o}\cdot h_{web.o}^{\,3}}{12} + t_{web.o}\cdot h_{web.o}\cdot\left(y_{s.L2.o.eff} - t_{tfl.o} - \frac{h_{web.o}}{2}\right)^2 ... \\ & + \frac{w_{bfl.eff.o}\cdot t_{bfl.o}^{\,3}}{12} + w_{bfl.eff.o}\cdot t_{bfl.o}\cdot\left(y_{s.L2.o.eff} - t_{tfl.o} - h_{web.o} - \frac{t_{bfl.o}}{2}\right)^2 \end{aligned} = 0.017$$

Additonal self-weigth

$$y_{cg.L3.o.eff} := \frac{\left[\begin{array}{l}\frac{A_c}{n_{L3}}\cdot(h_c - 107mm) + t_{tfl.o}\cdot w_{tfl.o}\cdot\left(h_c + \frac{t_{tfl.o}}{2}\right) ... \\ + h_{web.o}\cdot t_{web.o}\cdot\left(h_c + t_{tfl.o} + \frac{h_{web.o}}{2}\right) ... \\ + t_{bfl.o}\cdot w_{bfl.eff.o}\cdot\left(h_c + t_{tfl.o} + h_{web.o} + \frac{t_{bfl.o}}{2}\right)\end{array}\right]}{\frac{A_c}{n_{L3}} + A_{s.o.eff}} = 0.457\,m$$

$$y_{s.L3.o.eff} := y_{cg.L3.o.eff} - h_c = 0.187\,m$$

$$I_{L3.o.eff} := \frac{\left(\frac{w_c}{n_{L3}} \cdot h_c^{\ 3}\right)}{12} + \frac{A_c}{n_{L3}} \cdot \left[y_{cg.L3.o.eff} - \left(h_c - 107mm\right)\right]^2 \ ... = 0.017$$

$$+ \frac{w_{tfl.o} \cdot t_{tfl.o}^{\ 3}}{12} + w_{tfl.o} \cdot t_{tfl.o} \cdot \left(y_{s.L3.o.eff} - \frac{t_{tfl.o}}{2}\right)^2 \ ...$$

$$+ \frac{t_{web.o} \cdot h_{web.o}^{\ 3}}{12} + t_{web.o} \cdot h_{web.o} \cdot \left(y_{s.L3.o.eff} - t_{tfl.o} - \frac{h_{web.o}}{2}\right)^2 \ ...$$

$$+ \frac{w_{bfl.eff.o} \cdot t_{bfl.o}^{\ 3}}{12} + w_{bfl.eff.o} \cdot t_{bfl.o} \cdot \left(y_{s.L3.o.eff} - t_{tfl.o} - h_{web.o} - \frac{t_{bfl.o}}{2}\right)^2$$

3.4 Bending

Effect of different material in flange and web

The girders are hybryd beams whith a higher stregnth in the bottom flange than in the web. Full utilization in the flanges leaves theoritically a small part of the web plasticized, resulting in higher stress in the flanges. The effects are taken into account by adding the extra moment on the flanges.

At x = 16

$$h_{yweb.i} := t_{tfl.i} + h_{web.i} - y_{s.0.i} = 1.258\ m$$

Height of the web below cg

$$h_{pl.i} := h_{yweb.i} - \left(\frac{355MPa}{\sigma_{bw.tot.16}} \cdot h_{yweb.i}\right) = 0.411\ m$$

$$A_{pl.i} := h_{pl.i} \cdot t_{web.i} = 5.346 \times 10^{-3}\ m^2$$

$$F_{pl.16} := \left(\sigma_{bw.tot.16} - 355MPa\right) \cdot \frac{A_{pl.i}}{2} = 0.461 \cdot MN$$

$$M_{pl.16} := F_{pl.16} \cdot \left(h_{yweb.i} - \frac{h_{pl.i}}{3}\right) = 0.517 \cdot MN \cdot m$$

$$y_{cg.fl.i} := \frac{\left[t_{tfl.i} \cdot w_{tfl.i} \cdot \frac{t_{tfl.i}}{2} + t_{bfl.i} \cdot w_{bfl.i} \cdot \left(t_{tfl.i} + h_{web.i} + \frac{t_{bfl.i}}{2}\right)\right]}{t_{tfl.i} \cdot w_{tfl.i} + t_{bfl.i} \cdot w_{bfl.i}} = 0.704\ m$$

$$I_{fl.i} := \frac{\left(w_{tfl.i} \cdot t_{tfl.i}^{\ 3}\right)}{2} + w_{tfl.i} \cdot t_{tfl.i} \cdot \left(y_{cg.fl.i} - \frac{t_{tfl.i}}{2}\right)^2 \ ... = 0.012\ m^4$$

$$+ \frac{w_{bfl.i} \cdot t_{bfl.i}^{\ 3}}{2} + w_{bfl.i} \cdot t_{bfl.i} \cdot \left(y_{cg.fl.i} - t_{tfl.i} - h_{web.i} - \frac{t_{bfl.i}}{2}\right)^2$$

$$W_{tfl.i} := \frac{I_{fl.i}}{-y_{cg.fl.i}} = -0.017 \cdot m^3$$

$$W_{bfl.i} := \frac{I_{fl.i}}{h_s - y_{cg.fl.i}} = 0.017 \cdot m^3$$

$$\sigma_{tfl.add.16} := \frac{M_{pl.16}}{W_{tfl.i}} = -3.051 \times 10^7 \, Pa$$

$$\sigma_{bfl.add.16} := \frac{M_{pl.16}}{W_{bfl.i}} = 3.012 \times 10^7 \, Pa$$

$$\sigma_{tfl.tot.16.new} := \begin{vmatrix} \left(\sigma_{tfl.tot.16} + \sigma_{tfl.add.16}\right) & \text{if } h_{pl.i} > 0m \\ \sigma_{tfl.tot.16} & \text{otherwise} \end{vmatrix}$$

$$\sigma_{bfl.tot.16.new} := \begin{vmatrix} \left(\sigma_{bfl.tot.16} + \sigma_{bfl.add.16}\right) & \text{if } h_{pl.i} > 0m \\ \sigma_{bfl.tot.16} & \text{otherwise} \end{vmatrix}$$

At x = 9

$$h_{yweb.o} := t_{tfl.o} + h_{web.o} - y_{s.0.o} = 1.29 \, m$$

$$h_{pl.o} := h_{yweb.o} - \left(\frac{355MPa}{\sigma_{bw.tot.9}} \cdot h_{yweb.o}\right) = 0.431 \, m$$

$$A_{pl.o} := h_{pl.o} \cdot t_{web.o} = 5.6 \times 10^{-3} \, m^2$$

$$F_{pl.9} := \left(\sigma_{bw.tot.9} - 355MPa\right) \cdot \frac{A_{pl.o}}{2} = 0.498 \cdot MN$$

$$M_{pl.9} := F_{pl.9} \cdot \left(h_{yweb.o} - \frac{h_{pl.o}}{3}\right) = 0.571 \cdot MN \cdot m$$

$$y_{cg.fl.o} := \frac{\left[t_{tfl.o} \cdot w_{tfl.o} \cdot \frac{t_{tfl.o}}{2} + t_{bfl.o} \cdot w_{bfl.o} \cdot \left(t_{tfl.o} + h_{web.o} + \frac{t_{bfl.o}}{2}\right)\right]}{t_{tfl.o} \cdot w_{tfl.o} + t_{bfl.o} \cdot w_{bfl.o}} = 0.706 \, m$$

$$I_{fl.o} := \frac{\left(w_{tfl.o} \cdot t_{tfl.o}^3\right)}{2} + w_{tfl.o} \cdot t_{tfl.o} \cdot \left(y_{cg.fl.o} - \frac{t_{tfl.o}}{2}\right)^2 \ldots + \frac{w_{bfl.o} \cdot t_{bfl.o}^3}{2} + w_{bfl.o} \cdot t_{bfl.o} \cdot \left(y_{cg.fl.o} - t_{tfl.o} - h_{web.o} - \frac{t_{bfl.o}}{2}\right)^2 = 8.663 \times 10^{-3} \, m^4$$

$$W_{tfl.o} := \frac{I_{fl.o}}{-y_{cg.fl.o}} = -0.012 \cdot m^3$$

$$W_{bfl.o} := \frac{I_{fl.o}}{h_s - y_{cg.fl.o}} = 0.012 \cdot m^3$$

$$\sigma_{tfl.add.9} := \frac{M_{pl.9}}{W_{tfl.o}} = -4.653 \times 10^7 \, Pa$$

$$\sigma_{bfl.add.9} := \frac{M_{pl.9}}{W_{bfl.o}} = 4.579 \times 10^7 \, Pa$$

$$\sigma_{tfl.tot.9.new} := \begin{cases} (\sigma_{tfl.tot.9} + \sigma_{tfl.add.9}) & \text{if } h_{pl.o} > 0m \\ \sigma_{tfl.tot.9} & \text{otherwise} \end{cases}$$

$$\sigma_{bfl.tot.9.new} := \begin{cases} (\sigma_{bfl.tot.9} + \sigma_{bfl.add.9}) & \text{if } h_{pl.o} > 0m \\ \sigma_{bfl.tot.9} & \text{otherwise} \end{cases}$$

Bending verification at x = 16

Top flange

$\sigma_{tfl.tot.16} = -271.222 \cdot MPa$

$f_{y.tfl.i} = 345 \cdot MPa$

$$UR_{ULS.1} := \frac{|\sigma_{tfl.tot.16.new}|}{f_{y.tfl.i}} = 0.875$$

Bottom flange

$\sigma_{bfl.tot.16} = 537.887 \cdot MPa$

$f_{y.bfl.i} = 750 \cdot MPa$

$$UR_{ULS.2} := \frac{|\sigma_{bfl.tot.16.new}|}{f_{y.bfl.i}} = 0.757$$

Bending verification at x = 9

Top flange

$\sigma_{tfl.tot.9} = -266.342 \cdot MPa$

$f_{y.tfl.o} = 345 \cdot MPa$

$$UR_{ULS.3} := \frac{|\sigma_{tfl.tot.9.new}|}{f_{y.tfl.o}} = 0.907$$

Bottom flange

$\sigma_{bfl.tot.9} = 540.397 \cdot MPa$

$f_{y.bfl.o} = 750 \cdot MPa$

$$UR_{ULS.4} := \frac{|\sigma_{bfl.tot.9.new}|}{f_{y.bfl.o}} = 0.782$$

3.5 Buckling of top flange during casting

The top flange is checked for buckling during casting. The girders must be able to withstand the weight of the steel and the concrete.

x = 16

$$M_{b.self.16} := 1.35\cdot\left(M_{steel.16} + 2.693MN\cdot m\right) = 4.271\cdot MN\cdot m$$

$$\sigma_{b.tfl.16} := \frac{M_{b.self.16}}{I_i}\cdot\left(-y_{cg.i}\right) = -205.521\cdot\frac{MN}{m^2}$$

$$\sigma_{b.tw.16} := \frac{M_{b.self.16}}{I_i}\cdot\left(-y_{cg.i} + t_{tfl.i}\right) = -198.224\cdot\frac{MN}{m^2}$$

$$\sigma_{b.bw.16} := \frac{M_{b.self.16}}{I_i}\cdot\left(h_s - y_{cg.i} - t_{bfl.i}\right) = 197.882\cdot\frac{MN}{m^2}$$

$$\sigma_{b.bfl.16} := \frac{M_{b.self.16}}{I_i}\cdot\left(h_s - y_{cg.i}\right) = 203.137\cdot\frac{MN}{m^2}$$

$$\alpha_{b.16} := \frac{\sigma_{b.tw.16}}{\sigma_{b.tw.16} - \sigma_{b.bw.16}} = 0.5$$

$$\psi_{b.16} := \frac{\sigma_{b.bw.16}}{\sigma_{b.tw.16}} = -0.998$$

$$\varepsilon_{web.i} := \sqrt{\frac{235MPa}{f_{y.web.i}}} = 0.814$$

$$k_{\sigma.b.16} := \begin{cases} 4 & \text{if } \psi_{b.16} = 1 \\ \dfrac{8.2}{1.05 + \psi_{b.16}} & \text{if } 0 < \psi_{b.16} < 1 \\ 7.81 & \text{if } \psi_{b.16} = 0 \\ 7.81 - 6.29\cdot\psi_{b.16} + 9.78\cdot\psi_{b.16}^{\,2} & \text{if } -1 < \psi_{b.16} < 0 \\ 23.9 & \text{if } \psi_{b.16} = -1 \\ 5.98\cdot\left(1 - \psi_{b.16}\right)^2 & \text{if } -3 < \psi_{b.16} < -1 \\ 0 & \text{otherwise} \end{cases}$$

$$k_{\sigma.b.16} = 23.835$$

$$\lambda_{p.b.16} := \frac{\left(\frac{h_{web.i}}{t_{web.i}}\right)}{28.4 \cdot \varepsilon_{web.i} \cdot \sqrt{k_{\sigma.b.16}}} = 0.925$$

$$\rho_{b.16} := \begin{cases} 1 & \text{if } \lambda_{p.b.16} \le 0.673 \\ \frac{\left[\lambda_{p.b.16} - 0.055 \cdot \left(3 + \psi_{b.16}\right)\right]}{\lambda_{p.b.16}^{2}} & \text{if } \lambda_{p.b.16} > 0.748 \end{cases}$$

$$\rho_{b.16} = 0.952$$

$$b_{c.b.16} := \begin{cases} \frac{h_{web.i}}{1 - \psi_{b.16}} & \text{if } \psi_{b.16} < 0 \\ h_{web.i} & \text{otherwise} \end{cases}$$

$$b_{c.b.16} = 0.679\,m$$

$$b_{t.b.16} := h_{web.i} - b_{c.b.16} = 0.678\,m$$

$$b_{eff.b.16} := b_{c.b.16} \cdot \rho_{b.16} = 0.647\,m$$

$$b_{e1.b.16} := \begin{cases} 0.4 \cdot b_{eff.b.16} & \text{if } \psi_{b.16} < 0 \\ \frac{\left(2 \cdot b_{eff.b.16}\right)}{\left(5 - \psi_{b.16}\right)} & \text{if } 0 \le \psi_{b.16} < 1 \\ \left(0.5 \cdot b_{eff.b.16}\right) & \text{if } \psi_{b.16} = 1 \end{cases}$$

$$b_{e1.b.16} = 0.259\,m$$

$$b_{e2.b.16} := \begin{cases} 0.6 \cdot b_{eff.b.16} & \text{if } \psi_{b.16} < 0 \\ b_{eff.b.16} - b_{e1.b.16} & \text{if } 0 \le \psi_{b.16} < 1 \\ \left(0.5 \cdot b_{eff.b.16}\right) & \text{if } \psi_{b.16} = 1 \end{cases}$$

$$b_{e2.b.16} = 0.388\,m$$

$$A_{red.b.16} := t_{web.i} \cdot \left(y_{cg.i} - t_{tfl.i} - b_{e1.b.16} - b_{e2.b.16}\right) = 422.555 \cdot mm^{2}$$

$$A_{1.b.16} := t_{web.i} \cdot b_{e1.b.16} = 3.362 \times 10^{3} \cdot mm^{2}$$

$$A_{2.b.16} := t_{web.i} \cdot \left(b_{e2.b.16} + b_{t.b.16}\right) = 1.386 \times 10^{4} \cdot mm^{2}$$

$$y_{b.16} := \frac{\left[t_{tfl.i} \cdot w_{tfl.i} \cdot \frac{t_{tfl.i}}{2} + A_{1.b.16} \cdot \left(t_{tfl.i} + \frac{b_{e1.b.16}}{2} \right) ... + A_{2.b.16} \cdot \left[t_{tfl.i} + h_{web.i} - \left[\frac{\left(b_{e2.b.16} + b_{t.b.16}\right)}{2} \right] \right] ... + t_{bfl.i} \cdot w_{bfl.i} \cdot \left(t_{tfl.i} + h_{web.i} + \frac{t_{bfl.i}}{2} \right) \right]}{A_{s.i} - A_{red.b.16}} = 0.708\,m$$

$$I_{flanges.b.16} := \frac{\left(w_{tfl.i} \cdot t_{tfl.i}^{3}\right)}{12} + w_{tfl.i} \cdot t_{tfl.i} \cdot \left(y_{cg.i} - \frac{t_{tfl.i}}{2} \right)^{2} ... + \frac{w_{bfl.i} \cdot t_{bfl.i}^{3}}{12} + w_{bfl.i} \cdot t_{bfl.i} \cdot \left(y_{cg.i} - t_{tfl.i} - h_{web.i} - \frac{t_{bfl.i}}{2} \right)^{2} = 0.012\,m^{4}$$

$$I_{web.b.16} := \frac{t_{web.i} \cdot b_{e1.b.16}^{3}}{12} + A_{1.b.16} \cdot \left(y_{b.16} - t_{tfl.i} - \frac{b_{e1.b.16}}{2} \right)^{2} ... + \frac{t_{web.i} \cdot \left(b_{e2.b.16} + b_{t.b.16}\right)^{3}}{12} ... + A_{2.b.16} \cdot \left[t_{tfl.i} + h_{web.i} - y_{b.16} - \left(\frac{b_{e2.b.16} + b_{t.b.16}}{2} \right) \right]^{2} = 2.637 \times 10^{-3}\,m^{4}$$

$$I_{b.16} := I_{flanges.b.16} + I_{web.b.16} = 0.015\,m^{4}$$

$$\sigma_{b.tfl.16.new} := \frac{M_{b.self.16}}{I_{b.16}} \cdot \left(-y_{b.16}\right) = -207.694 \cdot MPa$$

$$\sigma_{b.tw.16.new} := \frac{M_{b.self.16}}{I_{b.16}} \cdot \left(-y_{b.16} + t_{tfl.i}\right) = -200.362 \cdot MPa$$

$$\sigma_{b.16.mean} := \frac{\left(\sigma_{b.tfl.16.new} + \sigma_{b.tw.16.new}\right)}{2} = -204.028 \cdot MPa$$

Buckling of top flange at x = 16

$$UR_{ULS.5} := \frac{\left|\sigma_{b.16.mean}\right|}{0.85 \cdot f_{y.tfl.i}} = 0.696$$

x = 9

$$M_{b.self.9} := 1.35 \cdot (M_{steel.9} + 2.124 MN \cdot m) = 3.374 \cdot MN \cdot m$$

$$\sigma_{b.tfl.9} := \frac{M_{b.self.9}}{I_o} \cdot (-y_{cg.o}) = -208.026 \cdot \frac{MN}{m^2}$$

$$\sigma_{b.tw.9} := \frac{M_{b.self.9}}{I_o} \cdot (-y_{cg.o} + t_{tfl.o}) = -202.12 \cdot \frac{MN}{m^2}$$

$$\sigma_{b.bw.9} := \frac{M_{b.self.9}}{I_o} \cdot (h_s - y_{cg.o} - t_{bfl.o}) = 201.503 \cdot \frac{MN}{m^2}$$

$$\sigma_{b.bfl.9} := \frac{M_{b.self.9}}{I_o} \cdot (h_s - y_{cg.o}) = 205.341 \cdot \frac{MN}{m^2}$$

$$\alpha_{b.9} := \frac{\sigma_{b.tw.9}}{\sigma_{b.tw.9} - \sigma_{b.bw.9}} = 0.501$$

$$\psi_{b.9} := \frac{\sigma_{b.bw.9}}{\sigma_{b.tw.9}} = -0.997$$

$$\varepsilon_{web.o} := \sqrt{\frac{235MPa}{f_{y.web.i}}} = 0.814$$

$$k_{\sigma.b.9} := \begin{cases} 4 & \text{if } \psi_{b.9} = 1 \\ \frac{8.2}{1.05 + \psi_{b.9}} & \text{if } 0 < \psi_{b.9} < 1 \\ 7.81 & \text{if } \psi_{b.9} = 0 \\ 7.81 - 6.29 \cdot \psi_{b.9} + 9.78 \cdot \psi_{b.9}^2 & \text{if } -1 < \psi_{b.9} < 0 \\ 23.9 & \text{if } \psi_{b.9} = -1 \\ 5.98 \cdot (1 - \psi_{b.9})^2 & \text{if } -3 < \psi_{b.9} < -1 \\ 0 & \text{otherwise} \end{cases}$$

$$k_{\sigma.b.9} = 23.801$$

$$\lambda_{p.b.9} := \frac{\left(\frac{h_{web.o}}{t_{web.o}}\right)}{28.4 \cdot \varepsilon_{web.o} \cdot \sqrt{k_{\sigma.b.9}}} = 0.933$$

$$\rho_{b.9} := \begin{cases} 1 & \text{if } \lambda_{p.b.9} \le 0.673 \\ \dfrac{\left[\lambda_{p.b.9} - 0.055\cdot\left(3 + \psi_{b.9}\right)\right]}{\lambda_{p.b.9}^{2}} & \text{if } \lambda_{p.b.9} > 0.748 \end{cases}$$

$\rho_{b.9} = 0.945$

$$b_{c.b.9} := \begin{cases} \dfrac{h_{web.o}}{1 - \psi_{b.9}} & \text{if } \psi_{b.9} < 0 \\ h_{web.o} & \text{otherwise} \end{cases}$$

$b_{c.b.9} = 0.685\,m$

$b_{t.b.9} := h_{web.o} - b_{c.b.9} = 0.682\,m$

$b_{eff.b.9} := b_{c.b.9}\cdot\rho_{b.9} = 0.647\,m$

$$b_{e1.b.9} := \begin{cases} 0.4\cdot b_{eff.b.9} & \text{if } \psi_{b.9} < 0 \\ \dfrac{\left(2\cdot b_{eff.b.9}\right)}{\left(5 - \psi_{b.9}\right)} & \text{if } 0 \le \psi_{b.9} < 1 \\ \left(0.5\cdot b_{eff.b.9}\right) & \text{if } \psi_{b.9} = 1 \end{cases}$$

$b_{e1.b.9} = 0.259\,m$

$$b_{e2.b.9} := \begin{cases} 0.6\cdot b_{eff.b.9} & \text{if } \psi_{b.9} < 0 \\ b_{eff.b.9} - b_{e1.b.9} & \text{if } 0 \le \psi_{b.9} < 1 \\ \left(0.5\cdot b_{eff.b.9}\right) & \text{if } \psi_{b.9} = 1 \end{cases}$$

$b_{e2.b.9} = 0.388\,m$

$A_{red.b.9} := t_{web.o}\cdot\left(y_{cg.o} - t_{tfl.o} - b_{e1.b.9} - b_{e2.b.9}\right) = 485.634\cdot mm^{2}$

$A_{1.b.9} := t_{web.o}\cdot b_{e1.b.9} = 3.365 \times 10^{3}\cdot mm^{2}$

$A_{2.b.9} := t_{web.o}\cdot\left(b_{e2.b.9} + b_{t.b.9}\right) = 1.392 \times 10^{4}\cdot mm^{2}$

$$y_{b.9} := \frac{\left[\begin{array}{l} t_{tfl.o} \cdot w_{tfl.o} \cdot \frac{t_{tfl.o}}{2} + A_{1.b.9} \cdot \left(t_{tfl.o} + \frac{b_{e1.b.9}}{2}\right) \ldots \\ + A_{2.b.9} \cdot \left[t_{tfl.o} + h_{web.o} - \left[\frac{(b_{e2.b.9} + b_{t.b.9})}{2}\right]\right] \ldots \\ + t_{bfl.o} \cdot w_{bfl.o} \cdot \left(t_{tfl.o} + h_{web.o} + \frac{t_{bfl.o}}{2}\right) \end{array}\right]}{A_{s.o} - A_{red.b.9}} = 0.71\,m$$

$$I_{flanges.b.9} := \frac{\left(w_{tfl.o} \cdot t_{tfl.o}^{3}\right)}{12} + w_{tfl.o} \cdot t_{tfl.o} \cdot \left(y_{cg.o} - \frac{t_{tfl.o}}{2}\right)^2 \ldots + \frac{w_{bfl.o} \cdot t_{bfl.o}^{3}}{12} + w_{bfl.o} \cdot t_{bfl.o} \cdot \left(y_{cg.o} - t_{tfl.o} - h_{web.o} - \frac{t_{bfl.o}}{2}\right)^2 = 8.661 \times 10^{-3}\,m$$

$$I_{web.b.9} := \frac{t_{web.o} \cdot b_{e1.b.9}^{3}}{12} + A_{1.b.9} \cdot \left(y_{b.9} - t_{tfl.o} - \frac{b_{e1.b.9}}{2}\right)^2 \ldots + \frac{t_{web.o} \cdot \left(b_{e2.b.9} + b_{t.b.9}\right)^3}{12} \ldots + A_{2.b.9} \cdot \left[t_{tfl.o} + h_{web.o} - y_{b.9} - \left(\frac{b_{e2.b.9} + b_{t.b.9}}{2}\right)\right]^2 = 2.685 \times 10^{-3}\,m^4$$

$$I_{b.9} := I_{flanges.b.9} + I_{web.b.9} = 0.011\,m^4$$

$$\sigma_{b.tfl.9.new} := \frac{M_{b.self.9}}{I_{b.9}} \cdot \left(-y_{b.9}\right) = -211.189 \cdot MPa$$

$$\sigma_{b.tw.9.new} := \frac{M_{b.self.9}}{I_{b.9}} \cdot \left(-y_{b.9} + t_{tfl.o}\right) = -205.241 \cdot MPa$$

$$\sigma_{b.9.mean} := \frac{\left(\sigma_{b.tfl.9.new} + \sigma_{b.tw.9.new}\right)}{2} = -208.215 \cdot MPa$$

Buckling of top flange at x = 9

$$UR_{ULS.6} := \frac{\left|\sigma_{b.9.mean}\right|}{0.85 \cdot f_{y.tfl.o}} = 0.71$$

3.6 Shear

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Shear resistance at x = 0

$\upsilon_s := 0.3$

$$\eta_{web.o} := \begin{cases} 1.2 & \text{if } f_{y.web.o} \leq 460MPa \\ 1.0 & \text{otherwise} \end{cases}$$

$\eta_{web.o} = 1.2$

$$\varepsilon_{web.o} := \sqrt{\frac{235MPa}{f_{y.web.o}}} = 0.814$$

$$\frac{h_{web.o}}{t_{web.o}} = 105.154$$

$$72 \cdot \frac{\varepsilon_{web.o}}{\eta_{web.o}} = 48.817$$

$$check_{shear.o} := \begin{cases} \text{"Check shear buckling"} & \text{if } \frac{h_{web.o}}{t_{web.o}} > 72 \cdot \frac{\varepsilon_{web.o}}{\eta_{web.o}} \\ \text{"Don't check shear buckling"} & \text{otherwise} \end{cases}$$

$check_{shear.o}$ = "Check shear buckling"

Contribution from web

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$$\sigma_{E.web.o} := \frac{\left(\pi^2 \cdot E_a \cdot t_{web.o}^{\ 2}\right)}{12 \cdot \left(1 - \upsilon_s^{\ 2}\right) \cdot h_{web.o}^{\ 2}} = 17.165 \cdot MPa$$

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$$k_{\tau.web.o} := \begin{cases} 5.34 + 4 \cdot \left(\frac{h_{web.o}}{a_{stiff}}\right)^2 & \text{if } \frac{a_{stiff}}{h_{web.o}} \geq 1 \\ 4.00 + 5.34 \cdot \left(\frac{h_{web.o}}{a_{stiff}}\right)^2 & \text{if } \frac{a_{stiff}}{h_{web.o}} \leq 1 \end{cases}$$

$k_{\tau.web.o} = 5.457$

$$\tau_{cr.web.o} := k_{\tau.web.o} \cdot \sigma_{E.web.o} = 93.666 \cdot MPa$$

$$\lambda_{web.o} := 0.76 \cdot \left(\frac{f_{y.web.o}}{\tau_{cr.web.o}} \right)^{0.5} = 1.48$$

$$\chi_{web.o} := \begin{cases} \eta_{web.o} & \text{if } \lambda_{web.o} < \dfrac{0.83}{\eta_{web.o}} \\ \dfrac{0.83}{\lambda_{web.o}} & \text{if } \dfrac{0.83}{\eta_{web.o}} \le \lambda_{web.o} < 1.08 \\ \dfrac{0.83}{\lambda_{web.o}} & \text{otherwise} \end{cases}$$

$$\chi_{web.o} = 0.561$$

$$\gamma_{M1} := 1$$

$$V_{b.web.Rd.o} := \frac{\left(\chi_{web.o} \cdot f_{y.web.o} \cdot h_{web.o} \cdot t_{web.o}\right)}{\sqrt{3} \cdot \gamma_{M1}} = 2.043 \times 10^{3} \cdot kN$$

Shear verification at x = 0

$$V_{Ed.0} := V_{self.0} + V_{traffic.0} + V_{shrinkage.0} + V_{add.0} = 1.728 \times 10^{6} N$$

$$UR_{ULS.7} := \frac{V_{Ed.0}}{V_{b.web.Rd.o}} = 0.845$$

Shear resistance at x = 9

$$\eta_{web.i} := \begin{cases} 1.2 & \text{if } f_{y.web.i} \le 460MPa \\ 1.0 & \text{otherwise} \end{cases}$$

$$\eta_{web.i} = 1.2$$

$$\varepsilon_{web.i} := \sqrt{\frac{235MPa}{f_{y.web.i}}} = 0.814$$

$$\frac{h_{web.i}}{t_{web.i}} = 104.385$$

$$72 \cdot \frac{\varepsilon_{web.i}}{\eta_{web.i}} = 48.817$$

$$check_{shear.i} := \begin{cases} \text{"Check shear buckling"} & \text{if } \frac{h_{web.i}}{t_{web.i}} > 72 \cdot \frac{\varepsilon_{web.i}}{\eta_{web.i}} \\ \text{"Don't check shear buckling"} & \text{otherwise} \end{cases}$$

$$check_{shear.i} = \text{"Check shear buckling"}$$

Contribution from web

EN1993-1-5 5.3

$$\sigma_{E.web.i} := \frac{\left(\pi^2 \cdot E_a \cdot t_{web.i}^{\ 2}\right)}{12 \cdot \left(1 - \upsilon_s^{\ 2}\right) \cdot h_{web.i}^{\ 2}} = 17.419 \cdot MPa$$

EN1993-1-5 A.1

$$k_{\tau.web.i} := \begin{cases} 5.34 + 4 \cdot \left(\frac{h_{web.i}}{a_{stiff}}\right)^2 & \text{if } \frac{a_{stiff}}{h_{web.i}} \ge 1 \\ 4.00 + 5.34 \cdot \left(\frac{h_{web.i}}{a_{stiff}}\right)^2 & \text{if } \frac{a_{stiff}}{h_{web.i}} \le 1 \end{cases}$$

EN1993-1-5 A.3

$$k_{\tau.web.i} = 5.455$$

$$\tau_{cr.web.i} := k_{\tau.web.i} \cdot \sigma_{E.web.i} = 95.022 \cdot MPa$$

$$\lambda_{web.i} := 0.76 \cdot \left(\frac{f_{y.web.i}}{\tau_{cr.web.i}}\right)^{0.5} = 1.469$$

$$\chi_{web.i} := \begin{cases} \eta_{web.i} & \text{if } \lambda_{web.i} < \dfrac{0.83}{\eta_{web.i}} \\ \dfrac{0.83}{\lambda_{web.i}} & \text{if } \dfrac{0.83}{\eta_{web.i}} \le \lambda_{web.i} < 1.08 \\ \dfrac{0.83}{\lambda_{web.i}} & \text{otherwise} \end{cases}$$

$$\chi_{web.i} = 0.565$$

$$\gamma_{M1} = 1$$

$$V_{b.web.Rd.i} := \frac{\left(\chi_{web.i} \cdot f_{y.web.i} \cdot h_{web.i} \cdot t_{web.i}\right)}{\sqrt{3} \cdot \gamma_{M1}} = 2.043 \times 10^{3} \cdot kN$$

Shear verification at x = 9

$$V_{Ed.9} := V_{self.9} + V_{traffic.9} + V_{shrinkage.9} + V_{add.9} = 9.693 \times 10^{5}\ N$$

$$UR_{ULS.8} := \frac{V_{Ed.9}}{V_{b.web.Rd.i}} = 0.474$$

3.6 Shear studs

EC 1994-2 6.6.3

$\phi = 0.022\ m$ — Diameter of the stud

$f_u := 450MPa$ — Ultimate tensile strength of the stud material

$f_{ck} := 35MPa$ — Characteristic cylinder compressive strenght of the concrete

$E_{cm} = 34 \cdot GPa$

$h_{sc} := 175mm$ — Height of the stud

$\gamma_v := 1.25$ — Partial factor

$$\alpha := \begin{cases} 0.2 \cdot \left(\frac{h_{sc}}{\phi} + 1 \right) & \text{if } 2 \le \frac{h_{sc}}{\phi} \le 4 \\ 1 & \text{if } 4 < \frac{h_{sc}}{\phi} \end{cases}$$

$\alpha = 1$

$$P_{Rd.1} := 0.8 \cdot f_u \cdot \pi \cdot \frac{\phi^2}{4 \cdot \gamma_v} = 109.478 \cdot kN$$

$$P_{Rd.2} := 0.29 \cdot \alpha \cdot \phi^2 \cdot \frac{\left(f_{ck} \cdot E_{cm} \right)^{0.5}}{\gamma_v} = 122.492 \cdot kN$$

$$P := \min\left(P_{Rd.1}, P_{Rd.2} \right) = 109.478 \cdot kN$$

Design resistance of the stud

The force acting on the studs is calculated for different modular ratios at x = 0

$S_{c.self.0} := 0$

$$S_{c.traffic.0} := \frac{A_c}{n_0} \cdot \left[y_{cg.0.o.eff} - \left(h_c - 107mm \right) \right] = 1.626 \times 10^7 \cdot mm^3$$

$$S_{c.shrinkage.0} := \frac{A_c}{n_{L2}} \cdot \left[y_{cg.L2.o.eff} - \left(h_c - 107mm \right) \right] = 1.21 \times 10^7 \cdot mm^3$$

$$S_{c.add.0} := \frac{A_c}{n_{L3}} \cdot \left[y_{cg.L3.o.eff} - \left(h_c - 107mm \right) \right] = 1.194 \times 10^7 \cdot mm^3$$

$F_{c.self.0} := 0$

$$F_{c.traffic.0} := V_{traffic.0} \cdot \frac{S_{c.traffic.0}}{I_{0.o.eff}} = 887.941 \cdot \frac{kN}{m}$$

$$F_{c.shrinkage.0} := V_{shrinkage.0} \cdot \frac{S_{c.shrinkage.0}}{I_{L2.o.eff}} = -1.162 \times 10^{-5} \cdot \frac{kN}{m}$$

$$F_{c.add.0} := V_{add.0} \cdot \frac{S_{c.add.0}}{I_{L3.o.eff}} = 80.015 \cdot \frac{kN}{m}$$

$$F_c := F_{c.self.0} + F_{c.traffic.0} + F_{c.shrinkage.0} + F_{c.add.0} = 967.955 \cdot \frac{kN}{m}$$

Shear stud verification at x = 0

$$UR_{ULS.9} := \frac{F_c}{P} = 8.842 \frac{1}{m}$$ Nr of studs/m < 10

4. Serviceability Limit State

Deflection is checked with Abaqus

Web breating

$$\frac{\frac{h_{web.i}}{t_{web.i}}}{(30m + 4 \cdot 32m)} = 0.661 \frac{1}{m}$$

Shear studs (Detail 1)

$UR_{FLS.1} = 5.278 \frac{1}{m}$

Flanges/Web stiffeners (Detail 3)

x = 16

Top flange/Web stiffener

$UR_{FLS.2} = 0.133$

Bottom flange/Web stiffener

$UR_{FLS.3} = 0.96$

x = 8

Top flange/Web stiffener

$UR_{FLS.4} = 0.102$

Bottom flange/Web stiffener

$UR_{FLS.5} = 0.978$

Segments (Detail 4)

x = 9

Top flange/Top flange

$UR_{FLS.6} = 0.102$

Bottom flange/Bottom flange

$UR_{FLS.7} = 0.988$

Flanges/Web (Detail 5 + Detail 2)

$UR_{FLS.8} = 0.358$

x = 16

Top flange/Web

$UR_{FLS.9} = 0.076$

Bottom flange/Web

$UR_{FLS.10} = 0.96$

x = 9

Top flange/Web

$UR_{FLS.11} = 0.058$

Bottom flange/Web

$UR_{FLS.12} = 0.978$

Flanges/Web (Detail 6)

x = 16

Top flange/Web

$UR_{FLS.13} = 0.324$

Bottom flange/Web

$UR_{FLS.14} = 0.197$

x = 0

Top flange/Web

$UR_{FLS.15} = 0.29$

Bottom flange/Web

$UR_{FLS.16} = 0.151$

Bending

x = 16

Top flange | Bottom flange

$UR_{ULS.1} = 0.875$ | $UR_{ULS.2} = 0.757$

x = 9

Top flange | Bottom flange

$UR_{ULS.3} = 0.907$ | $UR_{ULS.4} = 0.782$

Bucling of top flange

x = 16

$UR_{ULS.5} = 0.696$

x = 9

$UR_{ULS.6} = 0.71$

Shear

x = 0

$UR_{ULS.7} = 0.845$

x = 9

$UR_{ULS.8} = 0.474$

Shear studs

$UR_{ULS.9} = 8.842 \frac{1}{m}$

Appendix C

Calculations of different cross sections - Parametric study

Inner element

FAT class incr.	Thickness
0	32

Unreduced cross section

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	25	25	25	25	25
T.fl w (mm)	500	500	500	500	500
Web t (mm)	13	13	13	13	13
Web h (mm)	1343	1343	1343	1343	1343
B.fl t (mm)	32	32	32	32	32
B.fl w (mm)	700	700	700	700	700

n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	827	200	412	419	517
A (mm2)	0,05236	0,15946	0,09425	0,09294	0,07840
I (m4)	0,01817	0,04952	0,03874	0,03837	0,03351
Wtf	-0,0220	-0,2478	-0,0940	-0,0915	-0,0648
Wwt	-0,0226	-0,2833	-0,1001	-0,0973	-0,0681
Wwb	0,0336	0,0424	0,0405	0,0404	0,0394
Wbf	0,0317	0,0413	0,0392	0,0391	0,0379

Compressed top flange

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	25	25	25	25	25
T.fl w (mm)	500	500	500	500	500
Web t (mm)	13	13	13	13	13
Web h (mm)	1343	1343	1343	1343	1343
B.fl t (mm)	32	32	32	32	32
B.fl w (mm)	700	700	700	700	700

n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	827	200	412	419	517
A (mm2)	0,05236	0,15946	0,09425	0,09294	0,07840
I (m4)	0,01817	0,04952	0,03874	0,03837	0,03351
Wtf	-0,0220	-0,2478	-0,0940	-0,0915	-0,0648
Wwt	-0,0226	-0,2833	-0,1001	-0,0973	-0,0681
Wwb	0,0336	0,0424	0,0405	0,0404	0,0394
Wbf	0,0317	0,0413	0,0392	0,0391	0,0379

Compressed bottom flange

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	25	25	25	25	25
T.fl w (mm)	500	500	500	500	500
Web t (mm)	13	13	13	13	13
Web h (mm)	1343	1343	1343	1343	1343
B.fl t (mm)	32	32	32	32	32
B.fl w (mm)	700	700	700	700	700

n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	827	200	412	419	517
A (mm2)	0,05236	0,15946	0,09425	0,09294	0,07840
I (m4)	0,01817	0,04952	0,03874	0,03837	0,03351
Wtf	-0,0220	-0,2478	-0,0940	-0,0915	-0,0648
Wwt	-0,0226	-0,2833	-0,1001	-0,0973	-0,0681
Wwb	0,0336	0,0424	0,0405	0,0404	0,0394
Wbf	0,0317	0,0413	0,0392	0,0391	0,0379

FAT class incr.	Thickness
1	24

Unreduced cross section

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	25	25	25	25	25
T.fl w (mm)	500	500	500	500	500
Web t (mm)	13	13	13	13	13
Web h (mm)	1351	1351	1351	1351	1351
B.fl t (mm)	24	24	24	24	24
B.fl w (mm)	700	700	700	700	700
n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	763	158	353	359	453
A (mm2)	0,04686	0,15396	0,08876	0,08745	0,07290
I (m4)	0,01634	0,04169	0,03336	0,03307	0,02919
Wtf	-0,0214	-0,2640	-0,0946	-0,0920	-0,0645
Wwt	-0,0221	-0,3136	-0,1018	-0,0989	-0,0683
Wwb	0,0267	0,0342	0,0326	0,0325	0,0316
Wbf	0,0257	0,0336	0,0318	0,0318	0,0308

Compressed top flange

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	25	25	25	25	25
T.fl w (mm)	500	500	500	500	500
Web t (mm)	13	13	13	13	13
Web h (mm)	1351	1351	1351	1351	1351
B.fl t (mm)	24	24	24	24	24
B.fl w (mm)	700	700	700	700	700
n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	763	158	353	359	453
A (mm2)	0,04686	0,15396	0,08876	0,08745	0,07290
I (m4)	0,01634	0,04169	0,03336	0,03307	0,02919
Wtf	-0,0214	-0,2640	-0,0946	-0,0920	-0,0645
Wwt	-0,0221	-0,3136	-0,1018	-0,0989	-0,0683
Wwb	0,0267	0,0342	0,0326	0,0325	0,0316
Wbf	0,0257	0,0336	0,0318	0,0318	0,0308

Compressed bottom flange

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	25	25	25	25	25
T.fl w (mm)	500	500	500	500	500
Web t (mm)	13	13	13	13	13
Web h (mm)	1351	1351	1351	1351	1351
B.fl t (mm)	24	24	24	24	24
B.fl w (mm)	700	700	700	700	700
n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	763	158	353	359	453
A (mm2)	0,04686	0,15396	0,08876	0,08745	0,07290
I (m4)	0,01634	0,04169	0,03336	0,03307	0,02919
Wtf	-0,0214	-0,2640	-0,0946	-0,0920	-0,0645
Wwt	-0,0221	-0,3136	-0,1018	-0,0989	-0,0683
Wwb	0,0267	0,0342	0,0326	0,0325	0,0316
Wbf	0,0257	0,0336	0,0318	0,0318	0,0308

FAT class incr.	Thickness
2	21

Unreduced cross section

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	25	25	25	25	25
T.fl w (mm)	500	500	500	500	500
Web t (mm)	13	13	13	13	13
Web h (mm)	1354	1354	1354	1354	1354
B.fl t (mm)	21	21	21	21	21
B.fl w (mm)	700	700	700	700	700
n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	735	141	328	335	426
A (mm2)	0,04480	0,15190	0,08670	0,08539	0,07084
I (m4)	0,01553	0,03859	0,03114	0,03088	0,02737
Wtf	-0,0211	-0,2729	-0,0949	-0,0922	-0,0643
Wwt	-0,0219	-0,3315	-0,1027	-0,0997	-0,0683
Wwb	0,0241	0,0312	0,0296	0,0296	0,0287
Wbf	0,0234	0,0307	0,0291	0,0290	0,0281

Compressed top flange

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	25	25	25	25	25
T.fl w (mm)	500	500	500	500	500
Web t (mm)	13	13	13	13	13
Web h (mm)	1354	1354	1354	1354	1354
B.fl t (mm)	21	21	21	21	21
B.fl w (mm)	700	700	700	700	700
n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	735	141	328	335	426
A (mm2)	0,04480	0,15190	0,08670	0,08539	0,07084
I (m4)	0,01553	0,03859	0,03114	0,03088	0,02737
Wtf	-0,0211	-0,2729	-0,0949	-0,0922	-0,0643
Wwt	-0,0219	-0,3315	-0,1027	-0,0997	-0,0683
Wwb	0,0241	0,0312	0,0296	0,0296	0,0287
Wbf	0,0234	0,0307	0,0291	0,0290	0,0281

Compressed bottom flange

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	25	25	25	25	25
T.fl w (mm)	500	500	500	500	500
Web t (mm)	13	13	13	13	13
Web h (mm)	1354	1354	1354	1354	1354
B.fl t (mm)	21	21	21	21	21
B.fl w (mm)	700	700	700	700	700
n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	735	141	328	335	426
A (mm2)	0,04480	0,15190	0,08670	0,08539	0,07084
I (m4)	0,01553	0,03859	0,03114	0,03088	0,02737
Wtf	-0,0211	-0,2729	-0,0949	-0,0922	-0,0643
Wwt	-0,0219	-0,3315	-0,1027	-0,0997	-0,0683
Wwb	0,0241	0,0312	0,0296	0,0296	0,0287
Wbf	0,0234	0,0307	0,0291	0,0290	0,0281

FAT class incr.	Thickness
3	18

Unreduced cross section

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	25	25	25	25	25
T.fl w (mm)	500	500	500	500	500
Web t (mm)	13	13	13	13	13
Web h (mm)	1357	1357	1357	1357	1357
B.fl t (mm)	18	18	18	18	18
B.fl w (mm)	700	700	700	700	700

n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	704	124	303	309	397
A (mm2)	0,04274	0,14984	0,08463	0,08332	0,06878
I (m4)	0,01463	0,03538	0,02880	0,02857	0,02544
Wtf	-0,0208	-0,2845	-0,0952	-0,0925	-0,0641
Wwt	-0,0215	-0,3561	-0,1038	-0,1006	-0,0684
Wwb	0,0216	0,0281	0,0267	0,0266	0,0258
Wbf	0,0210	0,0277	0,0262	0,0262	0,0254

Compressed top flange

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	25	25	25	25	25
T.fl w (mm)	500	500	500	500	500
Web t (mm)	13	13	13	13	13
Web h (mm)	1357	1357	1357	1357	1357
B.fl t (mm)	18	18	18	18	18
B.fl w (mm)	700	700	700	700	700

n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	704	124	303	309	397
A (mm2)	0,04274	0,14984	0,08463	0,08332	0,06878
I (m4)	0,01463	0,03538	0,02880	0,02857	0,02544
Wtf	-0,0208	-0,2845	-0,0952	-0,0925	-0,0641
Wwt	-0,0215	-0,3561	-0,1038	-0,1006	-0,0684
Wwb	0,0216	0,0281	0,0267	0,0266	0,0258
Wbf	0,0210	0,0277	0,0262	0,0262	0,0254

Compressed bottom flange

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	25	25	25	25	25
T.fl w (mm)	500	500	500	500	500
Web t (mm)	13	13	13	13	13
Web h (mm)	1357	1357	1357	1357	1357
B.fl t (mm)	18	18	18	18	18
B.fl w (mm)	700	700	700	700	700

n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	704	124	303	309	397
A (mm2)	0,04274	0,14984	0,08463	0,08332	0,06878
I (m4)	0,01463	0,03538	0,02880	0,02857	0,02544
Wtf	-0,0208	-0,2845	-0,0952	-0,0925	-0,0641
Wwt	-0,0215	-0,3561	-0,1038	-0,1006	-0,0684
Wwb	0,0216	0,0281	0,0267	0,0266	0,0258
Wbf	0,0210	0,0277	0,0262	0,0262	0,0254

FAT class incr.	Thickness
4	15

Unreduced cross section

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	25	25	25	25	25
T.fl w (mm)	500	500	500	500	500
Web t (mm)	13	13	13	13	13
Web h (mm)	1360	1360	1360	1360	1360
B.fl t (mm)	15	15	15	15	15
B.fl w (mm)	700	700	700	700	700

n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	670	107	276	282	367
A (mm2)	0,04068	0,14778	0,08257	0,08126	0,06672
I (m4)	0,01363	0,03207	0,02634	0,02613	0,02337
Wtf	-0,0204	-0,3003	-0,0956	-0,0927	-0,0638
Wwt	-0,0211	-0,3920	-0,1051	-0,1018	-0,0684
Wwb	0,0191	0,0251	0,0237	0,0237	0,0229
Wbf	0,0187	0,0248	0,0234	0,0234	0,0226

Compressed top flange

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	25	25	25	25	25
T.fl w (mm)	500	500	500	500	500
Web t (mm)	13	13	13	13	13
Web h (mm)	1360	1360	1360	1360	1360
B.fl t (mm)	15	15	15	15	15
B.fl w (mm)	700	700	700	700	700

n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	670	107	276	282	367
A (mm2)	0,04068	0,14778	0,08257	0,08126	0,06672
I (m4)	0,01363	0,03207	0,02634	0,02613	0,02337
Wtf	-0,0204	-0,3003	-0,0956	-0,0927	-0,0638
Wwt	-0,0211	-0,3920	-0,1051	-0,1018	-0,0684
Wwb	0,0191	0,0251	0,0237	0,0237	0,0229
Wbf	0,0187	0,0248	0,0234	0,0234	0,0226

Compressed bottom flange

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	25	25	25	25	25
T.fl w (mm)	500	500	500	500	500
Web t (mm)	13	13	13	13	13
Web h (mm)	1360	1360	1360	1360	1360
B.fl t (mm)	15	15	15	15	15
B.fl w (mm)	700	700	700	700	700

n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	670	107	276	282	367
A (mm2)	0,04068	0,14778	0,08257	0,08126	0,06672
I (m4)	0,01363	0,03207	0,02634	0,02613	0,02337
Wtf	-0,0204	-0,3003	-0,0956	-0,0927	-0,0638
Wwt	-0,0211	-0,3920	-0,1051	-0,1018	-0,0684
Wwb	0,0191	0,0251	0,0237	0,0237	0,0229
Wbf	0,0187	0,0248	0,0234	0,0234	0,0226

Outer element

FAT class incr.	Thickness
0	25

Unreduced cross section

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	20	20	20	20	20
T.fl w (mm)	450	450	450	450	450
Web t (mm)	13	13	13	13	13
Web h (mm)	1355	1355	1355	1355	1355
B.fl t (mm)	25	25	25	25	25
B.fl w (mm)	700	700	700	700	700

n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	831	167	374	382	483
A (mm2)	0,04412	0,15122	0,08601	0,08470	0,07015
I (m4)	0,01450	0,04264	0,03365	0,03334	0,02906
Wtf	-0,0174	-0,2559	-0,0900	-0,0874	-0,0602
Wwt	-0,0179	-0,2908	-0,0950	-0,0922	-0,0628
Wwb	0,0266	0,0353	0,0336	0,0336	0,0326
Wbf	0,0255	0,0346	0,0328	0,0327	0,0317

Compressed top flange

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	20	20	20	20	20
T.fl w (mm)	450	450	450	450	450
Web t (mm)	13	13	13	13	13
Web h (mm)	1355	1355	1355	1355	1355
B.fl t (mm)	25	25	25	25	25
B.fl w (mm)	700	700	700	700	700

n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	831	167	374	382	483
A (mm2)	0,04412	0,15122	0,08601	0,08470	0,07015
I (m4)	0,01450	0,04264	0,03365	0,03334	0,02906
Wtf	-0,0174	-0,2559	-0,0900	-0,0874	-0,0602
Wwt	-0,0179	-0,2908	-0,0950	-0,0922	-0,0628
Wwb	0,0266	0,0353	0,0336	0,0336	0,0326
Wbf	0,0255	0,0346	0,0328	0,0327	0,0317

Compressed bottom flange

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	20	20	20	20	20
T.fl w (mm)	450	450	450	450	450
Web t (mm)	13	13	13	13	13
Web h (mm)	1355	1355	1355	1355	1355
B.fl t (mm)	25	25	25	25	25
B.fl w (mm)	599	599	599	599	599

n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	797	146	343	350	448
A (mm2)	0,04158	0,14868	0,08347	0,08216	0,06771
I (m4)	0,01411	0,03924	0,03142	0,03114	0,02738
Wtf	-0,0177	-0,2691	-0,0915	-0,0888	-0,0611
Wwt	-0,0182	-0,3119	-0,0972	-0,0942	-0,0640
Wwb	0,0244	0,0319	0,0305	0,0304	0,0295
Wbf	0,0120	0,0215	0,0193	0,0192	0,0180

FAT class incr.	Thickness
1	19

Unreduced cross section

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	20	20	20	20	20
T.fl w (mm)	450	450	450	450	450
Web t (mm)	13	13	13	13	13
Web h (mm)	1361	1361	1361	1361	1361
B.fl t (mm)	19	19	19	19	19
B.fl w (mm)	700	700	700	700	700

n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	775	133	324	331	427
A (mm2)	0,03999	0,14709	0,08189	0,08058	0,06603
I (m4)	0,01314	0,03642	0,02929	0,02904	0,02555
Wtf	-0,0170	-0,2745	-0,0905	-0,0878	-0,0598
Wwt	-0,0174	-0,3232	-0,0965	-0,0935	-0,0628
Wwb	0,0217	0,0292	0,0277	0,0276	0,0268
Wbf	0,0210	0,0287	0,0272	0,0272	0,0263

Compressed top flange

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	20	20	20	20	20
T.fl w (mm)	450	450	450	450	450
Web t (mm)	13	13	13	13	13
Web h (mm)	1361	1361	1361	1361	1361
B.fl t (mm)	19	19	19	19	19
B.fl w (mm)	700	700	700	700	700

n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	775	133	324	331	427
A (mm2)	0,03999	0,14709	0,08189	0,08058	0,06603
I (m4)	0,01314	0,03642	0,02929	0,02904	0,02555
Wtf	-0,0170	-0,2745	-0,0905	-0,0878	-0,0598
Wwt	-0,0174	-0,3232	-0,0965	-0,0935	-0,0628
Wwb	0,0217	0,0292	0,0277	0,0276	0,0268
Wbf	0,0210	0,0287	0,0272	0,0272	0,0263

Compressed bottom flange

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	20	20	20	20	20
T.fl w (mm)	450	450	450	450	450
Web t (mm)	13	13	13	13	13
Web h (mm)	1361	1361	1361	1361	1361
B.fl t (mm)	19	19	19	19	19
B.fl w (mm)	470	470	470	470	470

n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	699	94	263	270	358
A (mm2)	0,03562	0,14272	0,07751	0,07620	0,06175
I (m4)	0,01143	0,02944	0,02419	0,02400	0,02138
Wtf	-0,0164	-0,3129	-0,0919	-0,0890	-0,0598
Wwt	-0,0168	-0,3973	-0,0994	-0,0961	-0,0633
Wwb	0,0168	0,0229	0,0216	0,0216	0,0209
Wbf	0,0099	0,0168	0,0152	0,0152	0,0143

FAT class incr.	Thickness
2	16

Unreduced cross section

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	20	20	20	20	20
T.fl w (mm)	450	450	450	450	450
Web t (mm)	13	13	13	13	13
Web h (mm)	1364	1364	1364	1364	1364
B.fl t (mm)	16	16	16	16	16
B.fl w (mm)	700	700	700	700	700
n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	742	115	296	303	396
A (mm2)	0,03793	0,14503	0,07983	0,07852	0,06397
I (m4)	0,01233	0,03315	0,02692	0,02670	0,02361
Wtf	-0,0166	-0,2885	-0,0909	-0,0881	-0,0596
Wwt	-0,0171	-0,3492	-0,0975	-0,0944	-0,0628
Wwb	0,0192	0,0261	0,0247	0,0247	0,0239
Wbf	0,0187	0,0258	0,0244	0,0243	0,0235

Compressed top flange

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	20	20	20	20	20
T.fl w (mm)	450	450	450	450	450
Web t (mm)	13	13	13	13	13
Web h (mm)	1364	1364	1364	1364	1364
B.fl t (mm)	16	16	16	16	16
B.fl w (mm)	700	700	700	700	700
n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	742	115	296	303	396
A (mm2)	0,03793	0,14503	0,07983	0,07852	0,06397
I (m4)	0,01233	0,03315	0,02692	0,02670	0,02361
Wtf	-0,0166	-0,2885	-0,0909	-0,0881	-0,0596
Wwt	-0,0171	-0,3492	-0,0975	-0,0944	-0,0628
Wwb	0,0192	0,0261	0,0247	0,0247	0,0239
Wbf	0,0187	0,0258	0,0244	0,0243	0,0235

Compressed bottom flange

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	20	20	20	20	20
T.fl w (mm)	450	450	450	450	450
Web t (mm)	13	13	13	13	13
Web h (mm)	1364	1364	1364	1364	1364
B.fl t (mm)	16	16	16	16	16
B.fl w (mm)	389	389	389	389	389
n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	643	70	223	229	311
A (mm2)	0,03296	0,14006	0,07485	0,07354	0,05909
I (m4)	0,00999	0,02483	0,02063	0,02047	0,01836
Wtf	-0,0155	-0,3569	-0,0923	-0,0893	-0,0589
Wwt	-0,0160	-0,5009	-0,1014	-0,0978	-0,0630
Wwb	0,0135	0,0189	0,0178	0,0177	0,0171
Wbf	0,0088	0,0146	0,0133	0,0133	0,0126

FAT class incr.	Thickness
3	13

Unreduced cross section

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	20	20	20	20	20
T.fl w (mm)	450	450	450	450	450
Web t (mm)	13	13	13	13	13
Web h (mm)	1367	1367	1367	1367	1367
B.fl t (mm)	13	13	13	13	13
B.fl w (mm)	700	700	700	700	700
n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	705	97	267	274	363
A (mm2)	0,03587	0,14297	0,07776	0,07645	0,06191
I (m4)	0,01143	0,02978	0,02441	0,02422	0,02152
Wtf	-0,0162	-0,3082	-0,0913	-0,0885	-0,0593
Wwt	-0,0167	-0,3887	-0,0987	-0,0954	-0,0627
Wwb	0,0167	0,0231	0,0218	0,0218	0,0210
Wbf	0,0164	0,0228	0,0216	0,0215	0,0208

Compressed top flange

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	20	20	20	20	20
T.fl w (mm)	450	450	450	450	450
Web t (mm)	13	13	13	13	13
Web h (mm)	1367	1367	1367	1367	1367
B.fl t (mm)	13	13	13	13	13
B.fl w (mm)	700	700	700	700	700
n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	705	97	267	274	363
A (mm2)	0,03587	0,14297	0,07776	0,07645	0,06191
I (m4)	0,01143	0,02978	0,02441	0,02422	0,02152
Wtf	-0,0162	-0,3082	-0,0913	-0,0885	-0,0593
Wwt	-0,0167	-0,3887	-0,0987	-0,0954	-0,0627
Wwb	0,0167	0,0231	0,0218	0,0218	0,0210
Wbf	0,0164	0,0228	0,0216	0,0215	0,0208

Compressed bottom flange

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	20	20	20	20	20
T.fl w (mm)	450	450	450	450	450
Web t (mm)	13	13	13	13	13
Web h (mm)	1367	1367	1367	1367	1367
B.fl t (mm)	13	13	13	13	13
B.fl w (mm)	316	316	316	316	316
n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	593	50	190	195	272
A (mm2)	0,03087	0,13797	0,07277	0,07146	0,05701
I (m4)	0,00871	0,02110	0,01767	0,01755	0,01580
Wtf	-0,0147	-0,4250	-0,0930	-0,0898	-0,0581
Wwt	-0,0152	-0,7117	-0,1039	-0,1000	-0,0627
Wwb	0,0110	0,0158	0,0148	0,0147	0,0142
Wbf	0,0078	0,0128	0,0117	0,0116	0,0110

FAT class incr.	Thickness
4	11

Unreduced cross section

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	20	20	20	20	20
T.fl w (mm)	450	450	450	450	450
Web t (mm)	13	13	13	13	13
Web h (mm)	1369	1369	1369	1369	1369
B.fl t (mm)	11	11	11	11	11
B.fl w (mm)	700	700	700	700	700
n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	677	84	247	253	340
A (mm2)	0,03450	0,14160	0,07639	0,07508	0,06054
I (m4)	0,01076	0,02746	0,02265	0,02248	0,02005
Wtf	-0,0159	-0,3266	-0,0916	-0,0887	-0,0590
Wwt	-0,0164	-0,4286	-0,0997	-0,0963	-0,0627
Wwb	0,0151	0,0210	0,0198	0,0198	0,0191
Wbf	0,0149	0,0209	0,0197	0,0196	0,0189

Compressed top flange

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	20	20	20	20	20
T.fl w (mm)	450	450	450	450	450
Web t (mm)	13	13	13	13	13
Web h (mm)	1369	1369	1369	1369	1369
B.fl t (mm)	11	11	11	11	11
B.fl w (mm)	700	700	700	700	700
n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	677	84	247	253	340
A (mm2)	0,03450	0,14160	0,07639	0,07508	0,06054
I (m4)	0,01076	0,02746	0,02265	0,02248	0,02005
Wtf	-0,0159	-0,3266	-0,0916	-0,0887	-0,0590
Wwt	-0,0164	-0,4286	-0,0997	-0,0963	-0,0627
Wwb	0,0151	0,0210	0,0198	0,0198	0,0191
Wbf	0,0149	0,0209	0,0197	0,0196	0,0189

Compressed bottom flange

	Steel	Short Term	Shrinkage	Add. SW	SW concrete
T.fl t (mm)	20	20	20	20	20
T.fl w (mm)	450	450	450	450	450
Web t (mm)	13	13	13	13	13
Web h (mm)	1369	1369	1369	1369	1369
B.fl t (mm)	11	11	11	11	11
B.fl w (mm)	262	262	262	262	262
n0 or nL	1	6,2	15,8	16,3	25,4
CG (mm)	561	38	170	175	248
A (mm2)	0,02967	0,13677	0,07157	0,07026	0,05581
I (m4)	0,00789	0,01891	0,01589	0,01578	0,01425
Wtf	-0,0141	-0,4991	-0,0936	-0,0902	-0,0575
Wwt	-0,0146	-1,0574	-0,1060	-0,1018	-0,0625
Wwb	0,0095	0,0140	0,0130	0,0130	0,0125
Wbf	0,0072	0,0117	0,0107	0,0107	0,0102

Appendix D

Verification of different cross sections - Parametric study

Original design   Fat class = 80

Outer bottom flange: $t_{bfl.i} = 32 \cdot mm$ $f_{y.bfl.i} = 420 \cdot MPa$

Inner bottom flange: $t_{bfl.o} = 25 \cdot mm$ $f_{y.bfl.o} = 420 \cdot MPa$

$kg_{steel} = 2.46 \times 10^{4} \cdot kg$

$M_{steel.16} = 0.577 \cdot MN \cdot m$

$M_{steel.9} = 0.461 \cdot MN \cdot m$

$V_{steel.9} = 0.033 \cdot MN$

$V_{steel.0} = 0.069 \cdot MN$

Shear studs (Detail 1)

$UR_{FLS.1} = 4.954 \frac{1}{m}$

Flanges/Web stiffeners (Detail 3)

x = 16

Top flange/Web stiffener: $UR_{FLS.2} = 0.153$

Bottom flange/Web stiffener: $UR_{FLS.3} = 0.892$

x = 8

Top flange/Web stiffener: $UR_{FLS.4} = 0.123$

Bottom flange/Web stiffener: $UR_{FLS.5} = 0.895$

Segments (Detail 4)

x = 9

Top flange/Top flange: $UR_{FLS.6} = 0.123$

Bottom flange/Bottom flange: $UR_{FLS.7} = 0.914$

Flanges/Web (Detail 5 + Detail 2)

$UR_{FLS.8} = 0.358$

x = 16

Top flange/Web: $UR_{FLS.9} = 0.095$

Bottom flange/Web: $UR_{FLS.10} = 0.637$

x = 9

Top flange/Web	Bottom flange/Web
$UR_{FLS.11} = 0.078$	$UR_{FLS.12} = 0.639$

Flanges/Web (Detail 6)

x = 16

Top flange/Web	Bottom flange/Web
$UR_{FLS.13} = 0.311$	$UR_{FLS.14} = 0.234$

x = 0

Top flange/Web	Bottom flange/Web
$UR_{FLS.15} = 0.275$	$UR_{FLS.16} = 0.191$

Bending

x = 16

Top flange	Bottom flange
$UR_{ULS.1} = 0.778$	$UR_{ULS.2} = 0.889$

x = 9

Top flange	Bottom flange
$UR_{ULS.3} = 0.755$	$UR_{ULS.4} = 0.872$

Bucling of top flange

x = 16

$UR_{ULS.5} = 0.706$

x = 9

$UR_{ULS.6} = 0.714$

Shear

x = 0

$UR_{ULS.7} = 0.853$

x = 9

$UR_{ULS.8} = 0.478$

Case 1 - 1 FAT class increase: **Fat class = 90**

Outer bottom flange: $t_{bfl.i} = 24 \cdot mm$ $f_{y.bfl.i} = 500 \cdot MPa$

Inner bottom flange: $t_{bfl.o} = 25 \cdot mm$ $f_{y.bfl.o} = 420 \cdot MPa$

$kg_{steel} = 2.342 \times 10^{4} \cdot kg$

$M_{steel.16} = 0.534 \cdot MN \cdot m$

$M_{steel.9} = 0.429 \cdot MN \cdot m$

$V_{steel.9} = 0.03 \cdot MN$

$V_{steel.0} = 0.066 \cdot MN$

Shear studs (Detail 1)

$UR_{FLS.1} = 4.954 \frac{1}{m}$

Flanges/Web stiffeners (Detail 3)

x = 16

Top flange/Web stiffener: $UR_{FLS.2} = 0.143$

Bottom flange/Web stiffener: $UR_{FLS.3} = 0.982$

x = 8

Top flange/Web stiffener: $UR_{FLS.4} = 0.123$

Bottom flange/Web stiffener: $UR_{FLS.5} = 0.895$

Segments (Detail 4)

x = 9

Top flange/Top flange: $UR_{FLS.6} = 0.123$

Bottom flange/Bottom flange: $UR_{FLS.7} = 0.914$

Flanges/Web (Detail 5 + Detail 2)

$UR_{FLS.8} = 0.358$

x = 16

Top flange/Web: $UR_{FLS.9} = 0.086$

Bottom flange/Web: $UR_{FLS.10} = 0.789$

x = 9

Top flange/Web: $UR_{FLS.11} = 0.078$

Bottom flange/Web: $UR_{FLS.12} = 0.639$

Flanges/Web (Detail 6)

x = 16

Top flange/Web

$UR_{FLS.13} = 0.317$

Bottom flange/Web

$UR_{FLS.14} = 0.217$

x = 0

Top flange/Web

$UR_{FLS.15} = 0.275$

Bottom flange/Web

$UR_{FLS.16} = 0.191$

Bending

x = 16

Top flange

$UR_{ULS.1} = 0.803$

Bottom flange

$UR_{ULS.2} = 0.893$

x = 9

Top flange

$UR_{ULS.3} = 0.749$

Bottom flange

$UR_{ULS.4} = 0.868$

Bucling of top flange

x = 16

$UR_{ULS.5} = 0.702$

x = 9

$UR_{ULS.6} = 0.705$

Shear

x = 0

$UR_{ULS.7} = 0.851$

x = 9

$UR_{ULS.8} = 0.476$

Shear studs

$UR_{ULS.9} = 7.646 \frac{1}{m}$

Case 1 - 2 FAT class increase: **Fat class = 100**

Outer bottom flange: $t_{bfl.i} = 21 \cdot mm$ $f_{y.bfl.i} = 500 \cdot MPa$

Inner bottom flange: $t_{bfl.o} = 25 \cdot mm$ $f_{y.bfl.o} = 420 \cdot MPa$

$kg_{steel} = 2.297 \times 10^4 \cdot kg$

$M_{steel.16} = 0.517 \cdot MN \cdot m$

$M_{steel.9} = 0.418 \cdot MN \cdot m$

$V_{steel.9} = 0.028 \cdot MN$

$V_{steel.0} = 0.065 \cdot MN$

Shear studs (Detail 1)

$UR_{FLS.1} = 4.954 \frac{1}{m}$

Flanges/Web stiffeners (Detail 3)

x = 16

Top flange/Web stiffener: $UR_{FLS.2} = 0.139$

Bottom flange/Web stiffener: $UR_{FLS.3} = 0.97$

x = 8

Top flange/Web stiffener: $UR_{FLS.4} = 0.123$

Bottom flange/Web stiffener: $UR_{FLS.5} = 0.895$

Segments (Detail 4)

x = 9

Top flange/Top flange: $UR_{FLS.6} = 0.123$

Bottom flange/Bottom flange: $UR_{FLS.7} = 0.914$

Flanges/Web (Detail 5 + Detail 2)

$UR_{FLS.8} = 0.358$

x = 16

Top flange/Web: $UR_{FLS.9} = 0.081$

Bottom flange/Web: $UR_{FLS.10} = 0.866$

x = 9

Top flange/Web: $UR_{FLS.11} = 0.078$

Bottom flange/Web: $UR_{FLS.12} = 0.639$

Flanges/Web (Detail 6)

x = 16

Top flange/Web	Bottom flange/Web
$UR_{FLS.13} = 0.32$	$UR_{FLS.14} = 0.208$

x = 0

Top flange/Web	Bottom flange/Web
$UR_{FLS.15} = 0.275$	$UR_{FLS.16} = 0.191$

Bending

x = 16

Top flange	Bottom flange
$UR_{ULS.1} = 0.833$	$UR_{ULS.2} = 0.908$

x = 9

Top flange	Bottom flange
$UR_{ULS.3} = 0.747$	$UR_{ULS.4} = 0.867$

Bucling of top flange

x = 16

$UR_{ULS.5} = 0.702$

x = 9

$UR_{ULS.6} = 0.702$

Shear

x = 0

$UR_{ULS.7} = 0.85$

x = 9

$UR_{ULS.8} = 0.475$

Shear studs

$UR_{ULS.9} = 7.646 \frac{1}{m}$

Case 1 - 3 FAT class increase:

Fat class = 112

Outer bottom flange: $t_{bfl.i} = 18 \cdot mm$ $f_{y.bfl.i} = 550 \cdot MPa$

Inner bottom flange: $t_{bfl.o} = 25 \cdot mm$ $f_{y.bfl.o} = 420 \cdot MPa$

$kg_{steel} = 2.253 \times 10^4 \cdot kg$

$M_{steel.16} = 0.501 \cdot MN \cdot m$

$M_{steel.9} = 0.406 \cdot MN \cdot m$

$V_{steel.9} = 0.027 \cdot MN$

$V_{steel.0} = 0.063 \cdot MN$

Shear studs (Detail 1)

$UR_{FLS.1} = 4.954 \frac{1}{m}$

Flanges/Web stiffeners (Detail 3)

x = 16

Top flange/Web stiffener

$UR_{FLS.2} = 0.133$

Bottom flange/Web stiffener

$UR_{FLS.3} = 0.96$

x = 8

Top flange/Web stiffener

$UR_{FLS.4} = 0.123$

Bottom flange/Web stiffener

$UR_{FLS.5} = 0.895$

Segments (Detail 4)

x = 9

Top flange/Top flange

$UR_{FLS.6} = 0.123$

Bottom flange/Bottom flange

$UR_{FLS.7} = 0.914$

Flanges/Web (Detail 5 + Detail 2)

$UR_{FLS.8} = 0.358$

x = 16

Top flange/Web

$UR_{FLS.9} = 0.076$

Bottom flange/Web

$UR_{FLS.10} = 0.96$

x = 9

Top flange/Web

$UR_{FLS.11} = 0.078$

Bottom flange/Web

$UR_{FLS.12} = 0.639$

Flanges/Web (Detail 6)

x = 16

Top flange/Web

$UR_{FLS.13} = 0.324$

Bottom flange/Web

$UR_{FLS.14} = 0.197$

x = 0

Top flange/Web

$UR_{FLS.15} = 0.275$

Bottom flange/Web

$UR_{FLS.16} = 0.191$

Bending

x = 16

Top flange

$UR_{ULS.1} = 0.881$

Bottom flange

$UR_{ULS.2} = 0.95$

x = 9

Top flange

$UR_{ULS.3} = 0.744$

Bottom flange

$UR_{ULS.4} = 0.866$

Bucling of top flange

x = 16

$UR_{ULS.5} = 0.702$

x = 9

$UR_{ULS.6} = 0.699$

Shear

x = 0

$UR_{ULS.7} = 0.85$

x = 9

$UR_{ULS.8} = 0.474$

Shear studs

$UR_{ULS.9} = 7.646\,\frac{1}{m}$

Case 1 - 4 FAT class increase: **Fat class = 125**

Outer bottom flange: $t_{bfl.i} = 15 \cdot mm$ $f_{y.bfl.i} = 620 \cdot MPa$

Inner bottom flange: $t_{bfl.o} = 25 \cdot mm$ $f_{y.bfl.o} = 420 \cdot MPa$

$kg_{steel} = 2.209 \times 10^{4} \cdot kg$

$M_{steel.16} = 0.484 \cdot MN \cdot m$

$M_{steel.9} = 0.394 \cdot MN \cdot m$

$V_{steel.9} = 0.026 \cdot MN$

$V_{steel.0} = 0.062 \cdot MN$

Shear studs (Detail 1)

$UR_{FLS.1} = 4.954 \frac{1}{m}$

Flanges/Web stiffeners (Detail 3)

x = 16

Top flange/Web stiffener
$UR_{FLS.2} = 0.126$

Bottom flange/Web stiffener
$UR_{FLS.3} = 0.965$

x = 8

Top flange/Web stiffener
$UR_{FLS.4} = 0.123$

Bottom flange/Web stiffener
$UR_{FLS.5} = 0.895$

Segments (Detail 4)

x = 9

Top flange/Top flange
$UR_{FLS.6} = 0.123$

Bottom flange/Bottom flange
$UR_{FLS.7} = 0.914$

Flanges/Web (Detail 5 + Detail 2)

$UR_{FLS.8} = 0.358$

x = 16

Top flange/Web
$UR_{FLS.9} = 0.062$

Bottom flange/Web
$UR_{FLS.10} = 0.965$

x = 9

Top flange/Web
$UR_{FLS.11} = 0.07$

Bottom flange/Web
$UR_{FLS.12} = 0.573$

Flanges/Web (Detail 6)

x = 16

Top flange/Web	Bottom flange/Web
$UR_{FLS.13} = 0.328$	$UR_{FLS.14} = 0.184$

x = 0

Top flange/Web	Bottom flange/Web
$UR_{FLS.15} = 0.275$	$UR_{FLS.16} = 0.191$

Bending

x = 16

Top flange	Bottom flange
$UR_{ULS.1} = 0.952$	$UR_{ULS.2} = 0.972$

x = 9

Top flange	Bottom flange
$UR_{ULS.3} = 0.742$	$UR_{ULS.4} = 0.864$

Bucling of top flange

x = 16

$UR_{ULS.5} = 0.704$

x = 9

$UR_{ULS.6} = 0.695$

Shear

x = 0

$UR_{ULS.7} = 0.849$

x = 9

$UR_{ULS.8} = 0.474$

Shear studs

$UR_{ULS.9} = 7.646 \frac{1}{m}$

Case 1 - Summary

Girders

Incr.	Inner		Outer		kg	x=0 V [kN]	x=9 M [MNm]	x=9 V [kN]	x=16 M [MNm]
0	32	S420	25	S420	24604	0,0694	0,4608	0,0333	0,5773
1	24	S500	25	S420	23419	0,0659	0,4293	0,0298	0,5336
2	21	S500	25	S420	22975	0,0646	0,4175	0,0285	0,5172
3	18	S550	25	S420	22531	0,0633	0,4057	0,0272	0,5009
4	15	S620	25	S420	22086	0,0619	0,3939	0,0259	0,4845

FLS

Incr.	Fat Class	1	2	**3**	4	5	6	7	8	9	**10**	11	12	13	14	15	16
0	80	4,95	0,15	**0,89**	0,12	0,90	0,12	0,91	0,36	0,10	**0,64**	0,08	0,64	0,31	0,23	0,28	0,19
1	90	4,95	0,14	**0,98**	0,12	0,90	0,12	0,91	0,36	0,09	**0,79**	0,08	0,64	0,32	0,22	0,28	0,19
2	100	4,95	0,14	**0,97**	0,12	0,90	0,12	0,91	0,36	0,08	**0,87**	0,08	0,64	0,32	0,21	0,28	0,19
3	112	4,95	0,13	**0,96**	0,12	0,90	0,12	0,91	0,36	0,08	**0,96**	0,08	0,64	0,32	0,20	0,28	0,19
4	125	4,95	0,13	**0,96**	0,12	0,90	0,12	0,91	0,36	0,06	**0,96**	0,07	0,57	0,33	0,18	0,28	0,19

ULS

Incr.	fy	1	**2**	3	4	5	6	7	8	9
0	420	0,78	**0,89**	0,76	0,87	0,71	0,71	0,85	0,48	7,65
1	500	0,80	**0,89**	0,75	0,87	0,70	0,71	0,85	0,48	7,65
2	550	0,83	**0,91**	0,75	0,87	0,70	0,70	0,85	0,48	7,65
3	600	0,88	**0,95**	0,74	0,87	0,70	0,70	0,85	0,47	7,65
4	690	0,95	**0,97**	0,74	0,86	0,70	0,70	0,85	0,47	7,65

SLS

Incr.	x = 16
0	56%
1	64%
2	69%
3	76%
4	78%

Case 2 - 1 FAT class increase: **Fat class = 90**

Outer bottom flange: $t_{bfl.i} = 24 \cdot mm$ $f_{y.bfl.i} = 500 \cdot MPa$

Inner bottom flange: $t_{bfl.o} = 19 \cdot mm$ $f_{y.bfl.o} = 460 \cdot MPa$

$kg_{steel} = 2.218 \times 10^4 \cdot kg$

$M_{steel.16} = 0.519 \cdot MN \cdot m$

$M_{steel.9} = 0.414 \cdot MN \cdot m$

$V_{steel.9} = 0.03 \cdot MN$

$V_{steel.0} = 0.063 \cdot MN$

Shear studs (Detail 1)

$UR_{FLS.1} = 5.08 \frac{1}{m}$

Flanges/Web stiffeners (Detail 3)

x = 16

Top flange/Web stiffener $UR_{FLS.2} = 0.143$

Bottom flange/Web stiffener $UR_{FLS.3} = 0.982$

x = 8

Top flange/Web stiffener $UR_{FLS.4} = 0.115$

Bottom flange/Web stiffener $UR_{FLS.5} = 0.962$

Segments (Detail 4)

x = 9

Top flange/Top flange $UR_{FLS.6} = 0.115$

Bottom flange/Bottom flange $UR_{FLS.7} = 0.977$

Flanges/Web (Detail 5 + Detail 2)

$UR_{FLS.8} = 0.358$

x = 16

Top flange/Web $UR_{FLS.9} = 0.086$

Bottom flange/Web $UR_{FLS.10} = 0.789$

x = 9

Top flange/Web $UR_{FLS.11} = 0.07$

Bottom flange/Web $UR_{FLS.12} = 0.773$

Flanges/Web (Detail 6)

x = 16

Top flange/Web

$UR_{FLS.13} = 0.317$

Bottom flange/Web

$UR_{FLS.14} = 0.217$

x = 0

Top flange/Web

$UR_{FLS.15} = 0.281$

Bottom flange/Web

$UR_{FLS.16} = 0.175$

Bending

x = 16

Top flange

$UR_{ULS.1} = 0.801$

Bottom flange

$UR_{ULS.2} = 0.892$

x = 9

Top flange

$UR_{ULS.3} = 0.779$

Bottom flange

$UR_{ULS.4} = 0.973$

Bucling of top flange

x = 16

$UR_{ULS.5} = 0.699$

x = 9

$UR_{ULS.6} = 0.709$

Shear

x = 0

$UR_{ULS.7} = 0.849$

x = 9

$UR_{ULS.8} = 0.476$

Shear studs

$UR_{ULS.9} = 8.062 \frac{1}{m}$

Case 2 - 2 FAT class increasement: **Fat class = 100**

Outer bottom flange: $t_{bfl.i} = 21 \cdot mm$ $f_{y.bfl.i} = 500 \cdot MPa$

Inner bottom flange: $t_{bfl.o} = 16 \cdot mm$ $f_{y.bfl.o} = 500 \cdot MPa$

$kg_{steel} = 2.111 \times 10^{4} \cdot kg$

$M_{steel.16} = 0.495 \cdot MN \cdot m$

$M_{steel.9} = 0.395 \cdot MN \cdot m$

$V_{steel.9} = 0.028 \cdot MN$

$V_{steel.0} = 0.06 \cdot MN$

Shear studs (Detail 1)

$UR_{FLS.1} = 5.167 \frac{1}{m}$

Flanges/Web stiffeners (Detail 3)

x = 16

Top flange/Web stiffener
$UR_{FLS.2} = 0.139$

Bottom flange/Web stiffener
$UR_{FLS.3} = 0.97$

x = 8

Top flange/Web stiffener
$UR_{FLS.4} = 0.109$

Bottom flange/Web stiffener
$UR_{FLS.5} = 0.967$

Segments (Detail 4)

x = 9

Top flange/Top flange
$UR_{FLS.6} = 0.109$

Bottom flange/Bottom flange
$UR_{FLS.7} = 0.979$

Flanges/Web (Detail 5 + Detail 2)

$UR_{FLS.8} = 0.358$

x = 16

Top flange/Web
$UR_{FLS.9} = 0.081$

Bottom flange/Web
$UR_{FLS.10} = 0.866$

x = 9

Top flange/Web
$UR_{FLS.11} = 0.065$

Bottom flange/Web
$UR_{FLS.12} = 0.864$

Flanges/Web (Detail 6)

x = 16

Top flange/Web

$UR_{FLS.13} = 0.32$

Bottom flange/Web

$UR_{FLS.14} = 0.208$

x = 0

Top flange/Web

$UR_{FLS.15} = 0.285$

Bottom flange/Web

$UR_{FLS.16} = 0.165$

Bending

x = 16

Top flange

$UR_{ULS.1} = 0.829$

Bottom flange

$UR_{ULS.2} = 0.905$

x = 9

Top flange

$UR_{ULS.3} = 0.825$

Bottom flange

$UR_{ULS.4} = 0.983$

Bucling of top flange

x = 16

$UR_{ULS.5} = 0.697$

x = 9

$UR_{ULS.6} = 0.708$

Shear

x = 0

$UR_{ULS.7} = 0.847$

x = 9

$UR_{ULS.8} = 0.475$

Shear studs

$UR_{ULS.9} = 8.377 \frac{1}{m}$

Case 2 - 3 FAT class increase:

Fat class = 112

Outer bottom flange: $t_{bfl.i} = 18 \cdot mm$ $f_{y.bfl.i} = 550 \cdot MPa$

Inner bottom flange: $t_{bfl.o} = 13 \cdot mm$ $f_{y.bfl.o} = 550 \cdot MPa$

$kg_{steel} = 2.004 \times 10^{4} \cdot kg$

$M_{steel.16} = 0.471 \cdot MN \cdot m$

$M_{steel.9} = 0.376 \cdot MN \cdot m$

$V_{steel.9} = 0.027 \cdot MN$

$V_{steel.0} = 0.057 \cdot MN$

Shear studs (Detail 1)

$UR_{FLS.1} = 5.278 \frac{1}{m}$

Flanges/Web stiffeners (Detail 3)

x = 16

Top flange/Web stiffener
$UR_{FLS.2} = 0.133$

Bottom flange/Web stiffener
$UR_{FLS.3} = 0.96$

x = 8

Top flange/Web stiffener
$UR_{FLS.4} = 0.102$

Bottom flange/Web stiffener
$UR_{FLS.5} = 0.978$

Segments (Detail 4)

x = 9

Top flange/Top flange
$UR_{FLS.6} = 0.102$

Bottom flange/Bottom flange
$UR_{FLS.7} = 0.988$

Flanges/Web (Detail 5 + Detail 2)

$UR_{FLS.8} = 0.358$

x = 16

Top flange/Web
$UR_{FLS.9} = 0.076$

Bottom flange/Web
$UR_{FLS.10} = 0.96$

x = 9

Top flange/Web
$UR_{FLS.11} = 0.058$

Bottom flange/Web
$UR_{FLS.12} = 0.978$

Flanges/Web (Detail 6)

x = 16

Top flange/Web

$UR_{FLS.13} = 0.324$

Bottom flange/Web

$UR_{FLS.14} = 0.197$

x = 0

Top flange/Web

$UR_{FLS.15} = 0.29$

Bottom flange/Web

$UR_{FLS.16} = 0.151$

Bending

x = 16

Top flange

$UR_{ULS.1} = 0.875$

Bottom flange

$UR_{ULS.2} = 0.947$

x = 9

Top flange

$UR_{ULS.3} = 0.907$

Bottom flange

$UR_{ULS.4} = 0.977$

Bucling of top flange

x = 16

$UR_{ULS.5} = 0.696$

x = 9

$UR_{ULS.6} = 0.71$

Shear

x = 0

$UR_{ULS.7} = 0.845$

x = 9

$UR_{ULS.8} = 0.474$

Shear studs

$UR_{ULS.9} = 8.764 \frac{1}{m}$

Case 2 - 4 FAT class increase:

Fat class = 125

Outer bottom flange: $t_{bfl.i} = 15 \cdot mm$ $f_{y.bfl.i} = 620 \cdot MPa$

Inner bottom flange: $t_{bfl.o} = 11 \cdot mm$ $f_{y.bfl.o} = 620 \cdot MPa$

$kg_{steel} = 1.918 \times 10^4 \cdot kg$

$M_{steel.16} = 0.449 \cdot MN \cdot m$

$M_{steel.9} = 0.359 \cdot MN \cdot m$

$V_{steel.9} = 0.026 \cdot MN$

$V_{steel.0} = 0.054 \cdot MN$

Shear studs (Detail 1)

$UR_{FLS.1} = 5.37 \frac{1}{m}$

Flanges/Web stiffeners (Detail 3)

x = 16

Top flange/Web stiffener

$UR_{FLS.2} = 0.126$

Bottom flange/Web stiffener

$UR_{FLS.3} = 0.965$

x = 8

Top flange/Web stiffener

$UR_{FLS.4} = 0.097$

Bottom flange/Web stiffener

$UR_{FLS.5} = 0.96$

Segments (Detail 4)

x = 9

Top flange/Top flange

$UR_{FLS.6} = 0.097$

Bottom flange/Bottom flange

$UR_{FLS.7} = 0.969$

Flanges/Web (Detail 5 + Detail 2)

$UR_{FLS.8} = 0.358$

x = 16

Top flange/Web

$UR_{FLS.9} = 0.062$

Bottom flange/Web

$UR_{FLS.10} = 0.965$

x = 9

Top flange/Web

$UR_{FLS.11} = 0.047$

Bottom flange/Web

$UR_{FLS.12} = 0.96$

Flanges/Web (Detail 6)

x = 16

Top flange/Web

$UR_{FLS.13} = 0.328$

Bottom flange/Web

$UR_{FLS.14} = 0.184$

x = 0

Top flange/Web

$UR_{FLS.15} = 0.294$

Bottom flange/Web

$UR_{FLS.16} = 0.14$

Bending

x = 16

Top flange

$UR_{ULS.1} = 0.944$

Bottom flange

$UR_{ULS.2} = 0.967$

x = 9

Top flange

$UR_{ULS.3} = 0.987$

Bottom flange

$UR_{ULS.4} = 0.984$

Bucling of top flange

x = 16

$UR_{ULS.5} = 0.697$

x = 9

$UR_{ULS.6} = 0.712$

Shear

x = 0

$UR_{ULS.7} = 0.844$

x = 9

$UR_{ULS.8} = 0.474$

Shear studs

$UR_{ULS.9} = 9.046 \frac{1}{m}$

Case 2 - Summary

Girders

						x=0	x=9	x=9	x=16
Incr.	Inner		Outer		kg	V [kN]	M [MNm]	V [kN]	M [MNm]
0	32	S420	25	S420	24604	0,0694	0,4608	0,0333	0,5773
1	24	S500	19	S460	22175	0,0625	0,4143	0,0298	0,5186
2	21	S500	16	S500	21109	0,0595	0,3949	0,0285	0,4947
3	18	S550	13	S550	20042	0,0565	0,3756	0,0272	0,4708
4	15	S620	11	S620	19183	0,0541	0,3588	0,0259	0,4494

FLS

Incr.	Fat Class	1	2	**3**	4	**5**	6	**7**	8	9	**10**	11	**12**	13	14	15	16
0	80	4,95	0,15	**0,89**	0,12	**0,90**	0,12	**0,91**	0,36	0,10	**0,64**	0,08	**0,64**	0,31	0,23	0,28	0,19
1	90	5,08	0,14	**0,98**	0,12	**0,96**	0,12	**0,98**	0,36	0,09	**0,79**	0,07	**0,77**	0,32	0,22	0,28	0,18
2	100	5,17	0,14	**0,97**	0,11	**0,97**	0,11	**0,98**	0,36	0,08	**0,87**	0,06	**0,86**	0,32	0,21	0,28	0,16
3	112	5,28	0,13	**0,96**	0,10	**0,98**	0,10	**0,99**	0,36	0,08	**0,96**	0,06	**0,98**	0,32	0,20	0,29	0,15
4	125	5,37	0,13	**0,96**	0,10	**0,96**	0,10	**0,97**	0,36	0,06	**0,96**	0,05	**0,96**	0,33	0,18	0,29	0,14

ULS

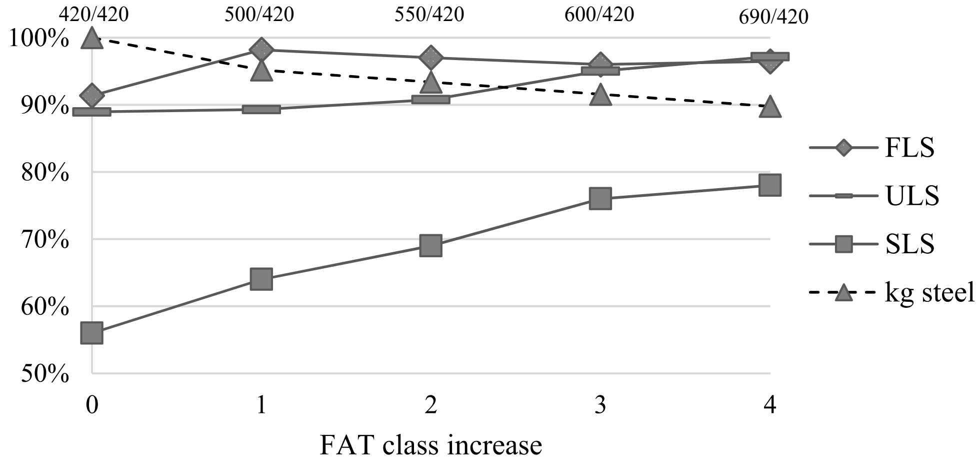
Incr.	fy	1	**2**	3	**4**	5	6	8	7	9
0	420	0,78	**0,89**	0,76	**0,87**	0,71	0,71	0,85	0,48	7,65
1	500/460	0,80	**0,89**	0,78	**0,97**	0,70	0,71	0,85	0,48	8,06
2	550/500	0,83	**0,91**	0,83	**0,98**	0,70	0,71	0,85	0,48	8,38
3	600	0,87	**0,95**	0,91	**0,98**	0,70	0,71	0,85	0,47	8,73
4	690	0,94	**0,97**	0,99	**0,98**	0,70	0,71	0,84	0,47	9,01

SLS

Incr.	x = 16
0	0,56
1	0,67
2	0,72
3	0,81
4	0,85

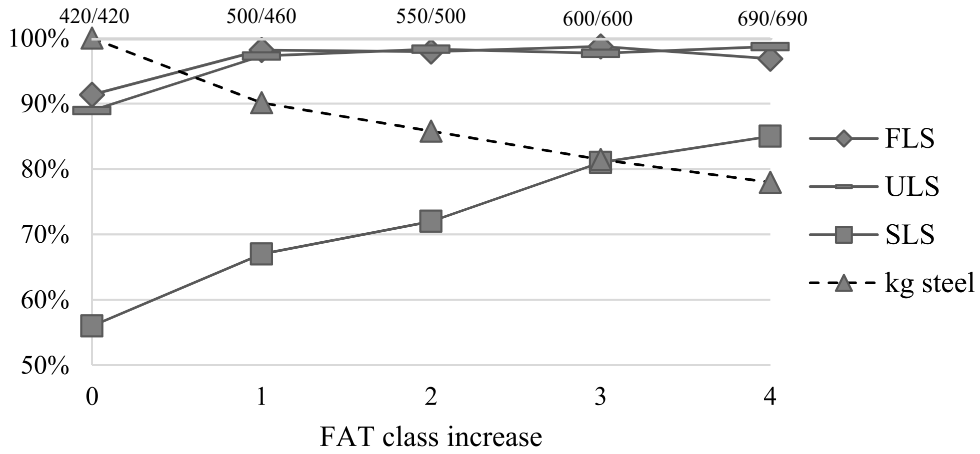
Case 1

Incr.	FLS	ULS	SLS	kg	% kg steel
0	91%	89%	56%	24604	100%
1	98%	89%	64%	23419	95%
2	97%	91%	69%	22975	93%
3	96%	95%	76%	22531	92%
4	96%	97%	78%	22086	90%



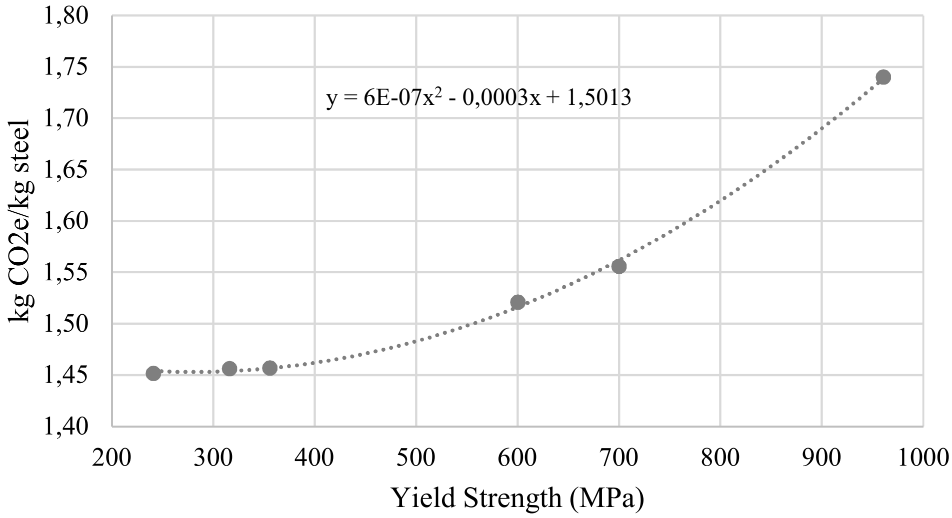
Case 2

Incr.	FLS	ULS	SLS	kg	% kg steel
0	91%	89%	56%	24604	100%
1	98%	97%	67%	22175	90%
2	98%	98%	72%	21109	86%
3	99%	98%	81%	20042	81%
4	97%	99%	85%	19183	78%

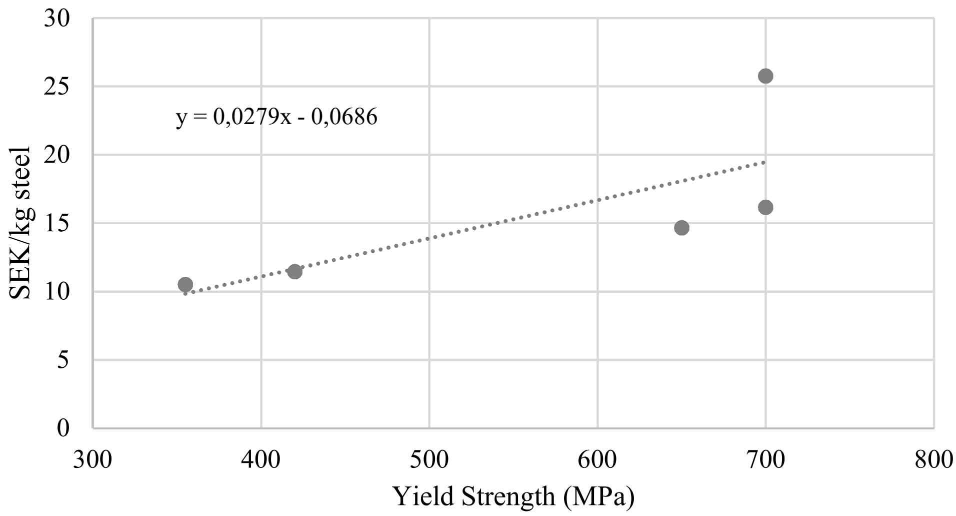


Appendix E
Impact and cost

CO2e



Raw material cost



Cost of HFMI

Price	
1 operator	2000 EUR/8 hr
2 operators	3400 EUR/ 8 hr

	SEK/min	min/m	SEK/m
One operator	39	20	773
	39	10	387
Two operators	66	10	657
	66	5	329

Appendix F

LCA & LCC - Case 1 and Case 2

Original

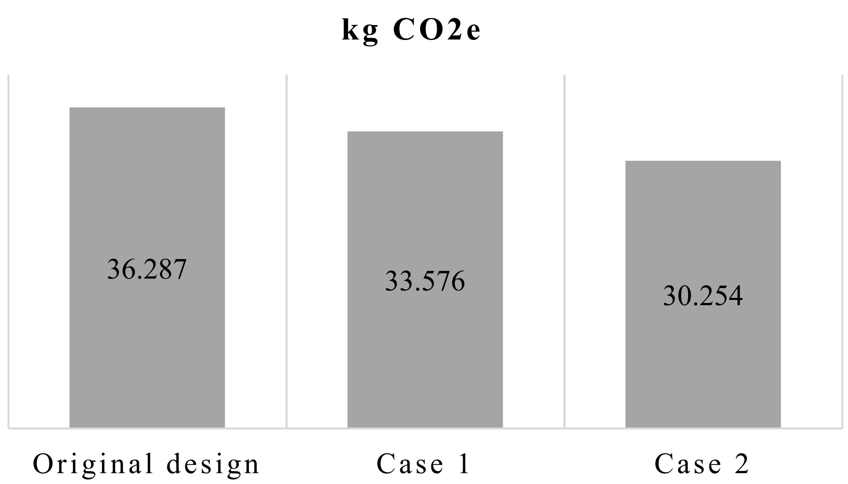
	A inner	A outer	V steel	kg steel	kr/kg	kr	CO2e/kg	CO2e
355	29.959	26.615	1,88	14.493	10	142.548	1,47	21.310
420	22.400	17.500	1,31	10.112	12	117.795	1,48	14.977
				24.604		260.343		36.287
				m HFMI	kr/m			
PWT				0	773	0		
						260.343		

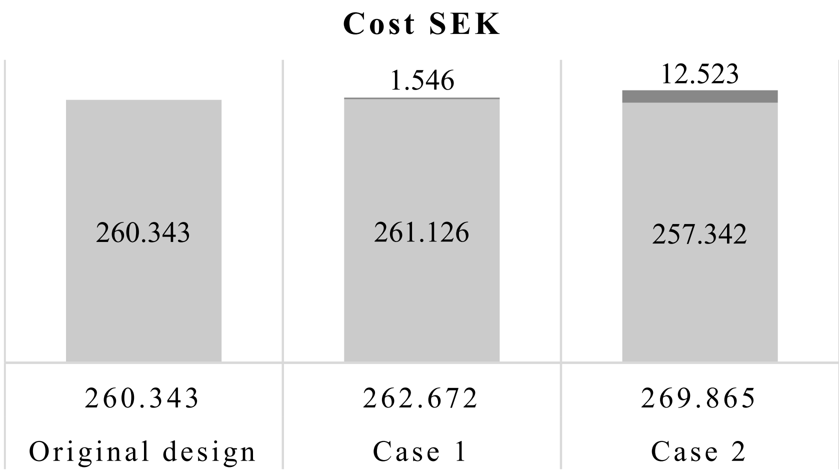
Case 1

	A inner	A outer	V steel	kg steel	kr/kg	kr	CO2e/kg	CO2e
355	30.141	26.615	1,89	14.532	10	142.934	1,47	21.368
420	0	17.500	0,69	5.282	12	61.534	1,48	7.824
750	12.600	0	0,35	2.717	21	56.658	1,61	4.384
				22.531		261.126		33.576
				m HFMI	kr/m			
PWT				2	773	1.546		
						262.672		

Case 2

	A inner	A outer	V steel	kg steel	kr/kg	kr	CO2e/kg	CO2e
355	30.141	26.771	1,89	14.579	10	143.397	1,47	21.437
750	12.600	9.100	0,71	5.463	21	113.945	1,61	8.817
				20.042		257.342		30.254
				m HFMI	kr/m			
PWT				16,2	773	12.523		
						269.865		




Cost SEK
1.546
12.523
260.343
261.126
257.342
260.343
262.672
269.865
Original design
Case 1
Case 2

Appendix G

LCA & LCC - Parametric study

Case 1

Incr. 0

	A inner	A outer	V steel	kg steel	kr/kg	kr	CO2e/kg	CO2e
355	29.959	26.615	1,88	14.493	9,84	142.548	1,47	21.310
420		17.500	0,69	5.282	11,65	61.534	1,48	7.824
420	22.400		0,63	4.829	11,65	56.260	1,48	7.153
				m HFMI	kr/m			
PWT				0	773	0		
				24.604		260.343		36.287
				100%		100%		100%

Incr. 1

	A inner	A outer	V steel	kg steel	kr/kg	kr	CO2e/kg	CO2e
355	30.063	26.615	1,89	14.515	9,84	142.769	1,47	21.343
420		17.500	0,69	5.282	11,65	61.534	1,48	7.824
500	16.800		0,47	3.622	13,88	50.280	1,50	5.438
				m HFMI	kr/m			
PWT				2	773	1.546		
				23.419		256.129		34.605
				95%		98%		95%

Incr. 2

	A inner	A outer	V steel	kg steel	kr/kg	kr	CO2e/kg	CO2e
355	30.102	26.615	1,89	14.523	9,84	142.851	1,47	21.356
420		17.500	0,69	5.282	11,65	61.534	1,48	7.824
550	14.700		0,41	3.169	15,28	48.416	1,52	4.810
				m HFMI	kr/m			
PWT				2	773	1.546		
				22.975		254.348		33.990
				93%		98%		94%

Incr. 3

	A inner	A outer	V steel	kg steel	kr/kg	kr	CO2e/kg	CO2e
355	30.141	26.615	1,89	14.532	9,84	142.934	1,47	21.368
420		17.500	0,69	5.282	11,65	61.534	1,48	7.824
600	12.600		0,35	2.717	16,67	45.289	1,54	4.176
				m HFMI	kr/m			
PWT				2	773	1.546		
				22.531		251.303		33.368
				92%		97%		92%

Incr. 4

	A inner	A outer	V steel	kg steel	kr/kg	kr	CO2e/kg	CO2e
355	30.180	26.615	1,89	14.540	9,84	143.017	1,47	21.380
420		17.500	0,69	5.282	11,65	61.534	1,48	7.824
690	10.500		0,29	2.264	19,18	43.425	1,58	3.577
				m HFMI	kr/m			
PWT				2	773	1.546		
				22.086		249.522		32.781
				90%		96%		90%

Case 2

Incr. 0

	A inner	A outer	V steel	kg steel	kr/kg	kr	CO2e/kg	CO2e
355	29.959	26.615	1,88	14.493	9,84	142.548	1,47	21.310
420		17.500	0,69	5.282	11,65	61.534	1,48	7.824
420	22.400		0,63	4.829	11,65	56.260	1,48	7.153
				m HFMI	kr/m			
PWT				0	773	0		
				24.604		260.343		36.287
				100%		100%		100%

Incr. 1

	A inner	A outer	V steel	kg steel	kr/kg	kr	CO2e/kg	CO2e
355	30.063	26.693	1,89	14.539	9,84	143.000	1,47	21.378
460		13.300	0,52	4.014	12,77	51.246	1,49	5.983
500	16.800		0,47	3.622	13,88	50.280	1,50	5.438
				m HFMI	kr/m			
PWT				16,2	773	12.523		
				22.175		257.049		32.798
				90%		99%		90%

Incr. 2

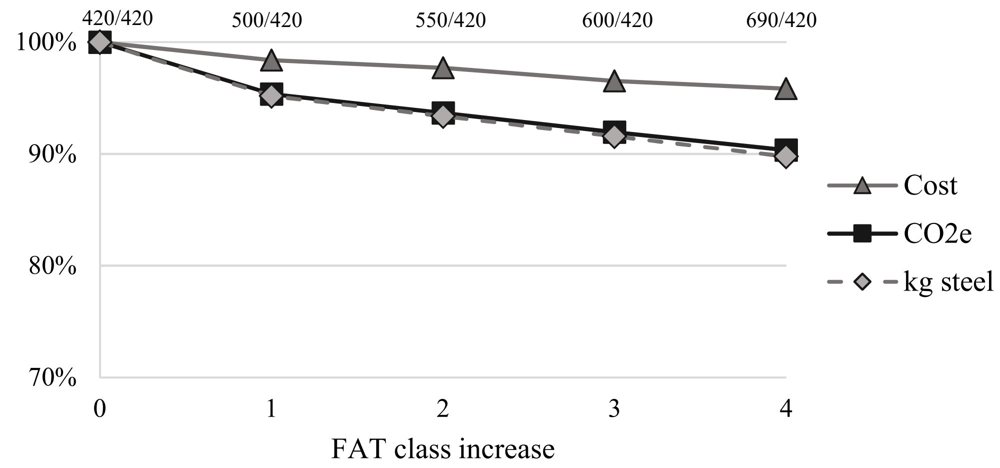
	A inner	A outer	V steel	kg steel	kr/kg	kr	CO2e/kg	CO2e
355	30.102	26.732	1,89	14.559	9,84	143.199	1,47	21.407
500		11.200	0,44	3.381	13,88	46.928	1,50	5.075
550	14.700		0,41	3.169	15,28	48.416	1,52	4.810
				m HFMI	kr/m			
PWT				16,2	773	12.523		
				21.109		251.065		31.293
				86%		96%		86%

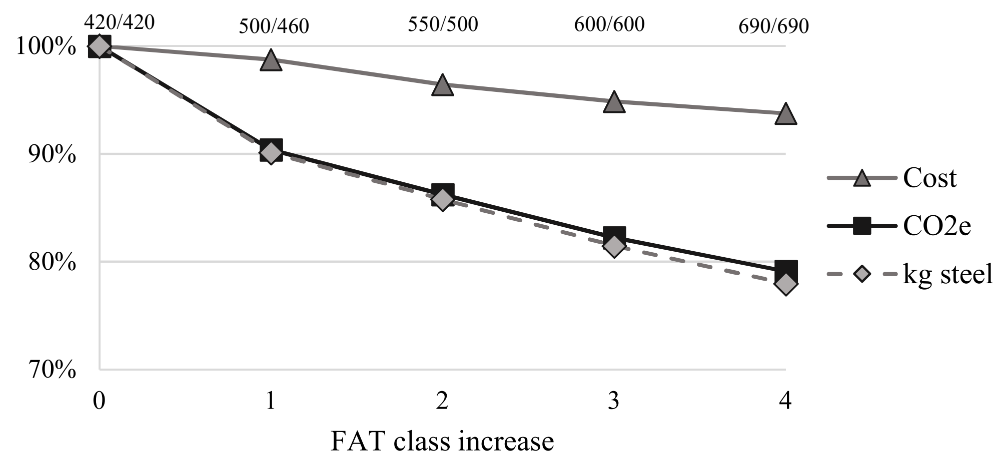
Incr. 3

	A inner	A outer	V steel	kg steel	kr/kg	kr	CO2e/kg	CO2e
355	30.141	26.771	1,89	14.579	9,84	143.397	1,47	21.437
600		9.100	0,36	2.747	16,67	45.792	1,54	4.223
600	12.600		0,35	2.717	16,67	45.289	1,54	4.176
				m HFMI	kr/m			
PWT				16,2	773	12.523		
				20.042		247.001		29.836
				81%		95%		82%

Incr. 4

	A inner	A outer	V steel	kg steel	kr/kg	kr	CO2e/kg	CO2e
355	30.180	26.797	1,90	14.595	9,84	143.557	1,47	21.461
690		7.700	0,30	2.324	19,18	44.583	1,58	3.672
690	10.500		0,29	2.264	19,18	43.425	1,58	3.577
				m HFMI	kr/m			
PWT				16,2	773	12.523		
				19.183		244.088		28710
				78%		94%		79%


420/420
500/420
550/420
600/420
690/420
100%
90%
80%
70%
0
1
2
3
4
FAT class increase
Cost
CO2e
kg steel


420/420
500/460
550/500
600/600
690/690
100%
90%
80%
70%
0
1
2
3
4
FAT class increase
Cost
CO2e
kg steel