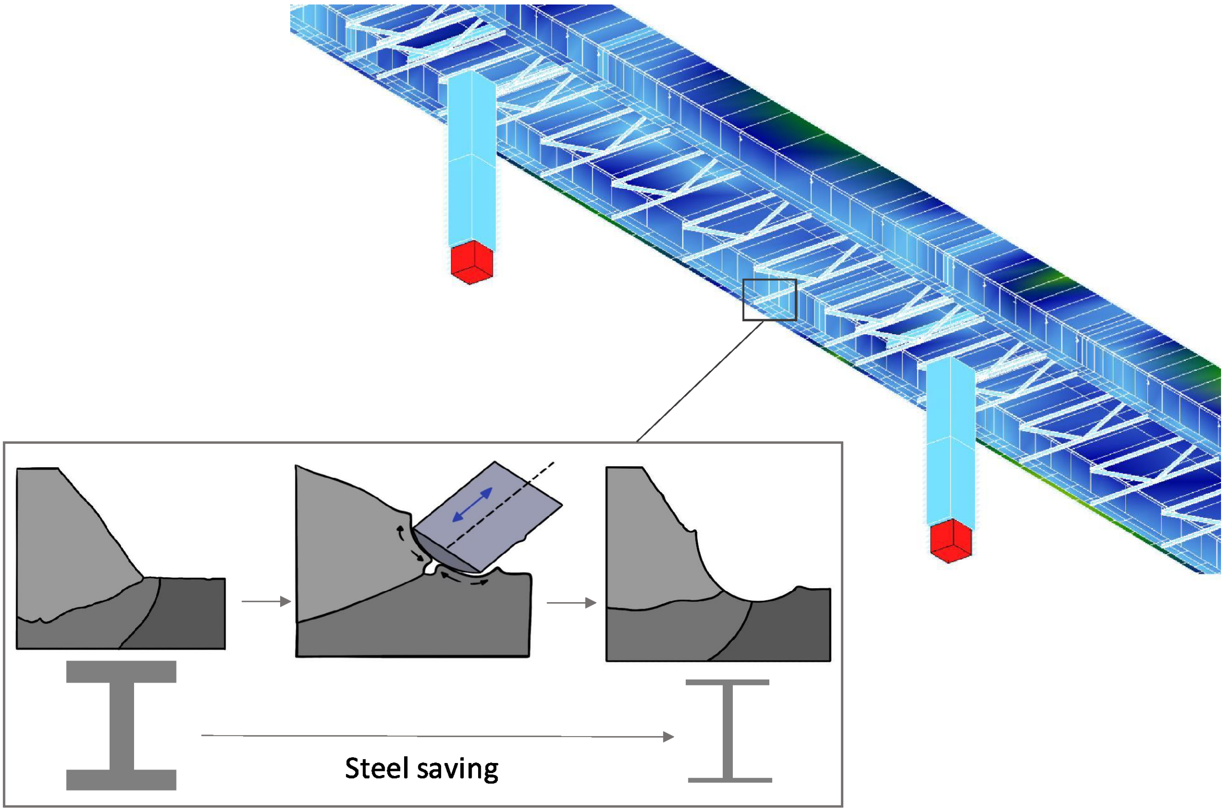

Composite bridge design optimisation using HFMI-treatment

Design and optimisation of composite bridges using high frequency mechanical impact (HFMI) treatment

Master's thesis in Master program Structural engineering and building technology

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Master's thesis ACEX30
Gothenburg, Sweden 2024

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Cover: An explanation of the change in geometry by applying HFMI-treatment on a welded bridge detail.

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Abstract

Bridges are structures that are usually subjected to repetitive loading which can cause fatigue damage. Welds are specifically sensitive when considering fatigue problems. Thus, a post-weld treatment called High Frequency Mechanical Impact treatment (HFMI-treatment) is one solution that has the potential to increase fatigue resistance. It can lead to reduced stress concentrations by improving the geometry and introducing counteracting stresses by the weld. Further, it can be useful to use high strength steel to increase the improvement even more.

The effect of using HFMI-treatment on new bridge design is still not thoroughly studied. Therefore, HFMI-treatment is investigated by optimising a steel bridge design using higher strength steel and also reducing material usage. A structural design of a road bridge is performed considering the effect of HFMI-treatment of the different welded joints. Additionally, the effect of implementing HFMI-treatment on site when the bridge already has been erected is studied and compared to when treatment is implemented in a workshop.

The study indicates that there is a significant decrease in utilisation ratios for fatigue limit states when HFMI-treatment is implemented. The effect of HFMI-treatment together with the use of higher steel grades resulted in enhanced fatigue performance and also remarkable material savings. The most economical option appears to be to use steel strength S460. On the other hand, S690 can help obtain a slender beam for nearly the same cost if the beam height is limited. However, high stress ranges can limit the improvement of HFMI which restricts the possibility of enhancing fatigue strength.

The thesis concludes that implementing HFMI-treatment and increasing steel strength, in new bridge designs, can be significantly beneficial. The cost of performing the treatment is insignificant, and there is good potential for material and cost savings. Furthermore, the best outcomes are obtained when the treatment is implemented after erection.

Keywords: Bridges, Fatigue, Welds, Post-weld treatment, High frequency mechanical impact treatment (HFMI-treatment), High strength steels, Optimisation.

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Cecilia Englund and Saffa Dagduk, Gothenburg, June 2024

Acronyms

AW - As-welded

CSC - Cross sectional class

FAT - Fatigue

FEM - Finite element method

FLM3 - Fatigue load model 3

FLM4 - Fatigue load model 4

FLS - Fatigue limit state

HFMI - High frequency mechanical impact

IIW - International institute of welding

LM1 - Load model 1

PWT - Post weld treatment

RS - Residual stresses

SLS - Serviceability limit state

ULS - Ultimate limit state

Notations

$\Delta\sigma$ - Stress range

$\Delta\sigma_c$ - Detail category (in as-welded condition)

$\Delta\sigma_{c,HFMI}$ - Detail category of HFMI-treated detail

$\Delta\sigma_{c,HFMI,ref}$ - Fatigue strength of an HFMI-treated detail prior to taking the material yield strength into consideration

$\Delta\sigma_D$ - Constant amplitude fatigue limit

$\Delta\sigma_L$ - Cut-off limit

$\Delta\sigma_p$ - Maximum stress range obtained for FLM3

$\Delta\sigma_s$ - Stress range that restrict the benefit of HFMI

f_1 - Factor accounting for the effect of yield strength of the material in the fatigue classification of a detail

f_y - Yield strength

γ_{Mf} - Partial factor for fatigue strength

λ_{HFMI} - Damage equivalent factor for R-ratio

$N_{min,HFMI}$ - Nr. of cycles that limit the benefit of HFMI

Φ - Factor that include stress effect from permanent loads

R - Stress ratio (R-ratio)

σ_{max} - Maximum stress

σ_{min} - Minimum stress

σ_{perm} - Stress from permanent loads

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1
Introduction

1.1 Background

Sweden is a relatively large country by area and its population of 10.5 million citizens are sparsely located (Statistikmyndigheten, 2022). The residents are therefore highly dependent on a well-functioning and safe infrastructure for transportation of individuals and goods. The Swedish Transport Administration, Trafikverket, is a public authority in charge of developing and maintaining an accessible, environmentally friendly and sustainable transport system (Trafikverket, 2022).

Bridges are an essential part of the infrastructure and should typically be designed for a long life expectancy of 120 years (Safi, 2014). In the period of 1999-2009, the investment and maintenance costs for bridges in Sweden, were estimated to be 8 billion SEK and 66 billion SEK respectively (Pantura, 2011). Furthermore, steel is a competitive building material for bridges in Sweden because of the quick erection and assembly (Stålbyggnadsinstitutet, 2020).

There are different metal joining methods in bridges, such as bolting, riveting and welding. Welding is however by far the most common joining method used in the bridge industry (Olofsson et al., 2008). That is mainly because it is effective, simple, cheap and environmentally friendly (Weman, 2011). In addition, compared to bolting and riveting, welding contributes to a stiffer behaviour of the structure (Tobias, n.d).

Despite the mentioned advantages of welding, welds are sensitive to a damaging phenomena called fatigue (Radaj et al., 2006). Fatigue is a progressive and localised process, that leads to permanent damage as a result of repeated loading, and it affects the structure even if the load level is below the material capacity. This makes the use of high strength steel less competitive since it is expensive but yet has the same fatigue strength. The result of this is that the ability of achieving effective constructions is restricted (Shams Hakimi et al., 2015).

Fatigue usually occurs due to material defects and high concentrated stresses in the welds (Al-Emrani, 2023). Additionally, tensile residual stresses arise as a result from the welding process which decreases the fatigue strength of the structure even more (Hobbacher, 2008). Therefore, fatigue resistance in welded steel details is often decisive in the design of steel and composite bridges. The conventional solution is to use thicker plates to reduce the nominal stresses, which thereby increases the fatigue life of welded structures (Shams Hakimi et al., 2021).

Post-weld treatment (PWT) is an alternative for increasing the fatigue strength in welded structures (Marquis & Barsoum, 2016). There are different families of PWTs depending on their effects. Some reduces the stress concentrations by improving the geometry, and others introduce compressive residual stresses to counteract the tensile stresses arising from welding. High Frequency Mechanical Impact-treatment (HFMI) is a post-weld treatment that contributes to both of these improvement mentioned. Moreover, the method is effective, simple, cheap and easy to implement. Applying HFMI-treatment has shown an outstanding improvement in the fatigue strength, and can therefore be used to achieve more profitable solutions leading to lighter structures and increased strength (Shams Hakimi et al., 2022). Furthermore, it can be implemented during the construction phase in workshop or on-site after the bridge has been erected. The potential for improvement is influenced by the method of implementation as further explained in the literature study.

HFMI-treatment is however only allowed during special technical permission in the industry (Gkatzogiannis et al., 2021). There is therefore not enough knowledge about its impact on bridge design. There are also no standards for HFMI-treatment for bridges in Eurocode, only design recommendations from different sources (Al-Karawi, 2023). Moreover, there is an increase in the use of HFMI-treatment and at the same time an ongoing development of higher strength steels (Marquis & Barsoum, 2016). Consequently, there is a need to investigate the potential of the improvement for fatigue design of composite bridges, and also the possibility of material savings using HFMI-treatment.

1.2 Aim

The aim of the thesis is to investigate and confirm the potential of design optimisation by enhancing the fatigue performance using HFMI treatment. The bridge analysed is a road bridge constructed in Söderköping, Sweden, and is a composite bridge with twin I-girders connected to a concrete slab.

1.3 Objectives

To fulfill the aim of the thesis, the following objectives must be achieved:

- Implementing the HFMI design rules on a existing bridge during design phase.
- Comparing the HFMI-treated bridge with the non-treated to determine the enhancement of fatigue performance.

- Investigating the effects of steel quality and loading conditions on the efficiency of HFMI-treatment on bridges.
- Analysing material and cost savings due to implementation of HFMI.
- Comparing the effect of HFMI implemented in workshop and on construction site.

1.4 Limitations

Due to restriction of time, limitations are to be implemented to achieve results within the scope of the thesis.

- The thesis is restricted to investigating a road bridge. No evaluation of HFMI-treatment on railway or pedestrian bridges is carried out.
- Only one composite bridge, consisting of a twin I-girder beam, is studied and designed.
- The design does not account for certain loads.

1.5 Method

The thesis consists of a literature study, design of the chosen bridge including FE-modelling and lastly a parametric study. The literature study is carried out focusing on the effect of HFMI-treatment considering fatigue strength enhancement. The literature study aims at gaining more knowledge on the topic from available literature, mostly reports made by experts in the field, in addition to guidelines and standards. It also aims to provide information about the design considerations when HFMI-treatment is applied on bridge components.

In the case study, the geometry, assigned loads and load combinations will be compiled in a document called RKFM, which describes the construction work method. The RKFM is presented in Appendix A.1. The road bridge will be designed using the FE-program Sofistik to calculate sectional forces and deflections. The bridge will then undergo design and verification in ultimate limit state, serviceability limit state, and fatigue limit state. Afterwards, HFMI treatment is incorporated into the design by considering relevant design guidelines. Further, the parametric study aims at changing the geometry to potentially achieve cost and material savings with an optimised design. Different steel qualities and plate thicknesses are to be investigated.

2

Fatigue and HFMI-treatment

2.1 Fatigue

Fatigue is a progressive and localised process, that leads to permanent damage as a result of repeated loading (Al-Emrani, 2023). Fatigue failure occurs usually because of plastic deformation in the form of micro-cracks. The micro-cracks further propagate upon loading and evolve into a larger dominant crack as presented in Figure 2.1. This can result in brittle failure which is dangerous and also contributes to economic losses. It is, therefore, crucial to acknowledge and consider all types of loading that can cause fatigue damage (Marquis & Barsoum, 2016).

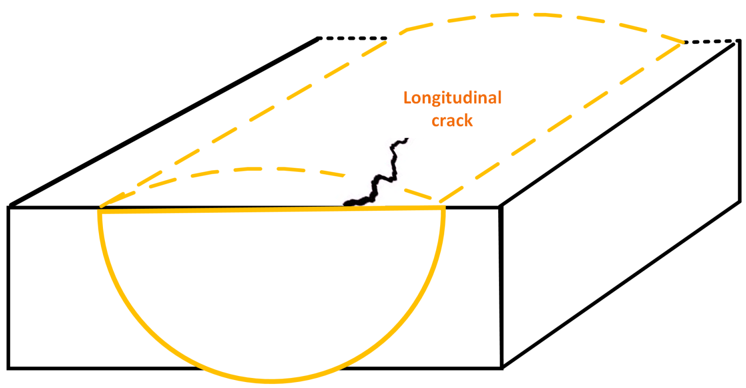

Figure 2.1: *Longitudinal cracking in weld.*

2.2 Fatigue strength

Static failure is often assumed in a structure if the maximum load is higher than the material capacity (Al-Emrani, 2023). However, fatigue failure can occur even if the load impact is significantly under the yield strength of the material. The stress limit for a specific number of cycles, without reaching failure, is called the fatigue strength (Corrosionpedia, 2020).

Furthermore, welds are critical details in fatigue (Hobbacher, 2008). The reason is that high tensile residual stresses appear from welding and together with local defects and high stress concentrations it can lead to initiation of cracks (Al-Emrani, 2023). Figure 2.2 shows a comparison between the fatigue strength in an as-welded detail and a non-welded detail.

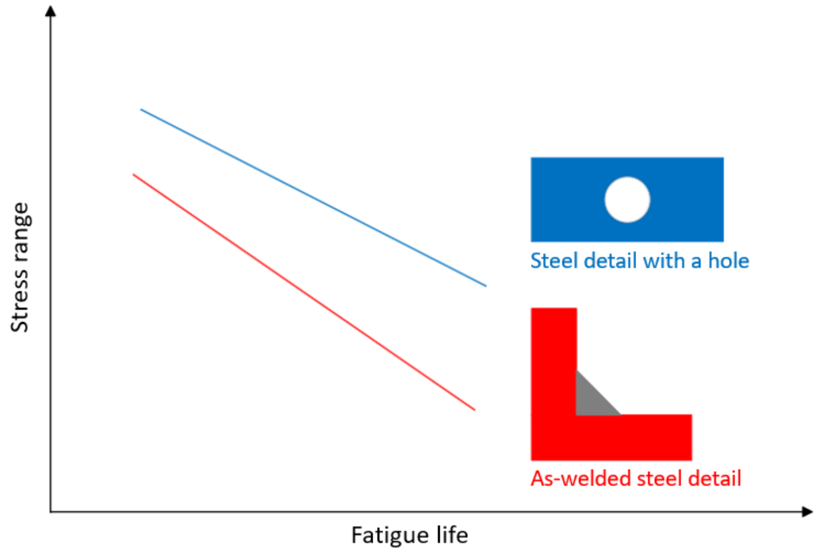

Figure 2.2: *Difference in fatigue life for an as-welded and a non-welded detail (Al-Emrani, 2023).*

In Eurocode, the characteristic fatigue strength for a steel detail is usually expressed by the stress range at $2 \cdot 10^6$ cycles. The fatigue strength is further represented by a S-N curve in Eurocode 3, which describes the logarithmic relation between the stress range and number of cycles to failure (Al-Emrani, 2023). The fatigue life for a certain detail related to a specific detail category, can be predicted with use of the S-N curve. Figure 2.3 gives an illustration of the S-N curves from Eurocode, with various lines representing different detail categories.

The constant amplitude fatigue limit $\Delta\sigma_D$, is at $5 \cdot 10^6$ cycles (EN, 2005). It is also called the CAFL and it indicates the maximum stress of a constant amplitude that the detail can experience for an infinite number of cycles. Furthermore, the cut-off limit $\Delta\sigma_L$ is at 10^8 number of cycles, and in that region, the stress does not contribute to fatigue damage.

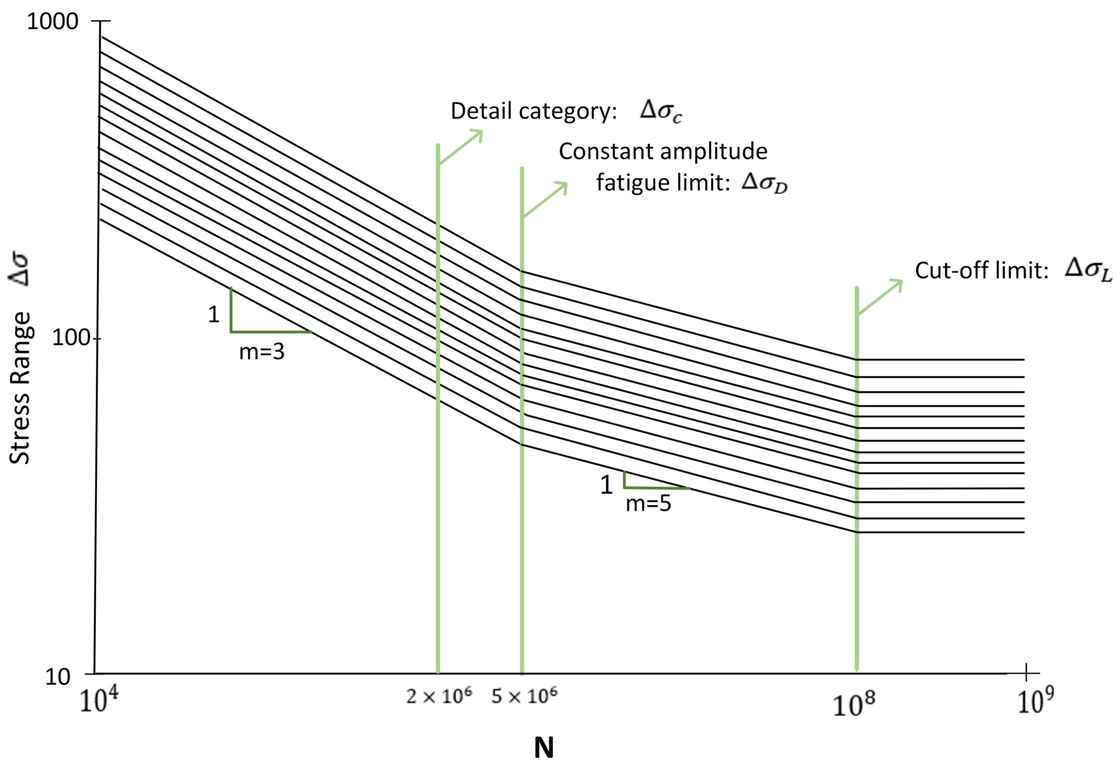

Figure 2.3: *Illustration of S-N curves diagram from Eurocode 3 (EN, 2005).*

There are two methods that can be used for fatigue assessment of bridges. In Eurocode the main methods are the Equivalent damage method (λ-coefficient method) and the Damage accumulation method, also called Palmgren-Miner damage rule (Al-Emrani & Aygül, 2014).

2.3 High strength steel

The use of high strength steel in structures is usually beneficial as it can result in a light structure because of the reduction of the material usage (de Jesus et al., 2012). In summary, the structure is to have a higher structural performance meanwhile using less material. However, the increase in steel strength in structures does not lead to an increase in fatigue resistance, which nevertheless makes the structure exposed to fatigue damage.

High strength steel is the term used to describe steel that has a quality of S420 or higher. There is a difference in fatigue resistance when comparing details in high strength steel and mild strength steel (de Jesus et al., 2012). The former results in higher resistance to fatigue crack initiation, meanwhile mild steel shows higher resistance to the crack propagation due to higher ductility. However, the initiation phase in welded details is negligible, which means that higher strength steel does not improve the fatigue strength (Shams Hakimi & Al-Emrani, 2014). Additionally, S690 costs nearly twice as much as S355 according to the steel manufacturing company SSAB (SSAB, 2022). This typically result in high strength steels being less competitive as it is expensive, and the potential of material savings will be constricted (Shams Hakimi et al., 2015).

2.4 Post weld treatment

There are plenty of post-weld treatments, where some of them refer to adjusting imperfections in the geometry by the transition to the weld (Marquis & Barsoum, 2016). Two examples of such are Burr-grinding and TIG re-melting, see Figure 2.4 for an illustration of the change in geometry of the weld. Other methods primarily focus on reducing the high tensile residual stresses in welds, where examples are hammer peening and needle peening. HFMI-treatment contributes to both of these improvements mentioned. Other examples of HFMI-treatment methods are ultrasonic impact treatment, ultrasonic peening, ultrasonic peening treatment, pneumatic impact treatment and ultrasonic needle peening. In the year of 2010 the International Institute of Welding (IIW) decided to use HFMI-treatment as a common term to describe several of these post-welding techniques (Marquis & Barsoum, 2016).

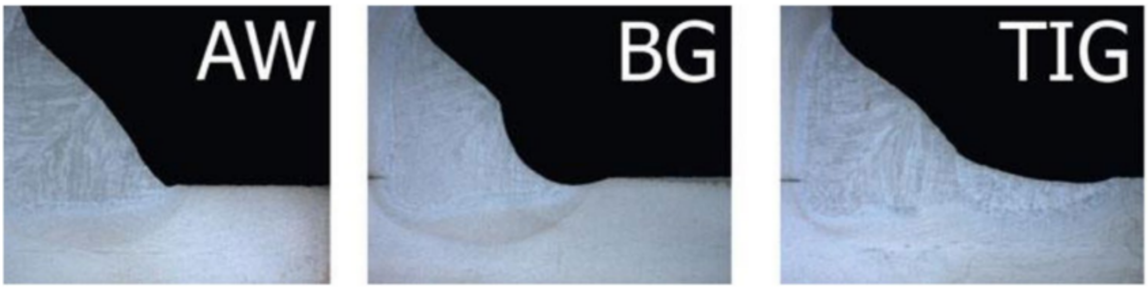

Figure 2.4: *Figure of an as-welded joint followed by the geometrical improvement with the use of Burr-grinding and TIG re-melting (Al-Karawi, 2023).*

A comparison between the various post-weld treatments is shown in Table 2.1, where HFMI-treatment is found to be the most effective. Firstly, the table presents what kind of main improvement it contributes to, whether the treatment is changing the geometry and if compressive residual stresses (RS) are induced (Marquis & Barsoum, 2016). Secondly, the application speed in an average value for burr-grinding, TIG re-melting and hammer peening is presented for application on similar detail types (Kirkhope et al., 1999). Lastly, the application speed for HFMI-treatment is stated and can be greater than 250 mm/min (Al-Karawi, 2023).

Table 2.1: *Comparison between different post weld treatments.*

PWT method	Main improvement	Application speed
Burr-grinding	Geometrical	162.7 mm/min
TIG re-melting	Geometrical	127.7 mm/min
Hammer/needle peening	Geometrical + RS	82.3 mm/min
HFMI-treatment	Geometrical + RS	≤250 mm/min

2.5 HFMI-treatment

High frequency mechanical impact (HFMI) is a post-weld treatment for improvement of the fatigue strength of welds in new and existing structures (Marquis & Barsoum, 2016). The treatment causes local geometrical and stress state changes to the material by the weld toe. To implement the HFMI-treatment on a structure, a tool with one or several indenters is used to make impressions with high frequency in the intersection between the weld and the base material. Figure 2.5 illustrates the tool and the geometrical effect of HFMI-treatment.

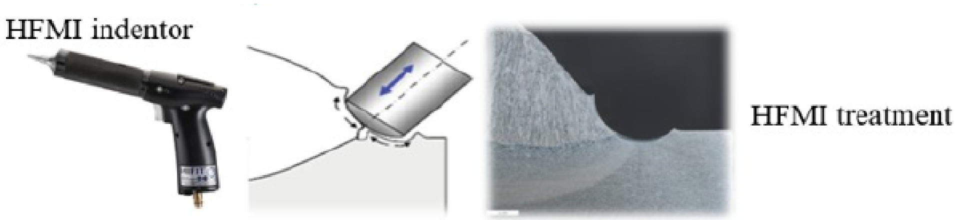

Figure 2.5: *The indenter and geometrical effect of applying HFMI-treatment (Al-karawi, 2023).*

Several parameters influence the improvement in fatigue strength class (FAT-class) due to HFMI-treatment (Marquis & Barsoum, 2016). Some are related to the adequacy of treatment applications, which can be assured if the treatment is done by a qualified operator. Other parameters are related to the steel type, loading conditions, and the geometry of the treated detail.

2.6 Benefits of HFMI-treatment

The method is described as easy to operate and the improvement of the fatigue strength is achieved through three main mechanisms, as described in the article by Shams-Hakimi et al. (2021). Firstly, it reduces stress concentrations by creating a smoother transition between the weld and the structural component. Secondly, it contributes to local hardening of the material through cold working. Lastly, it introduces compressive residual stresses by the weld toe, which is particularly crucial for improving the fatigue performance. Figure 2.6 illustrates the advantages of

HFMI and demonstrates the reduction in local stresses due to the increased radius (Al-Karawi, 2023).

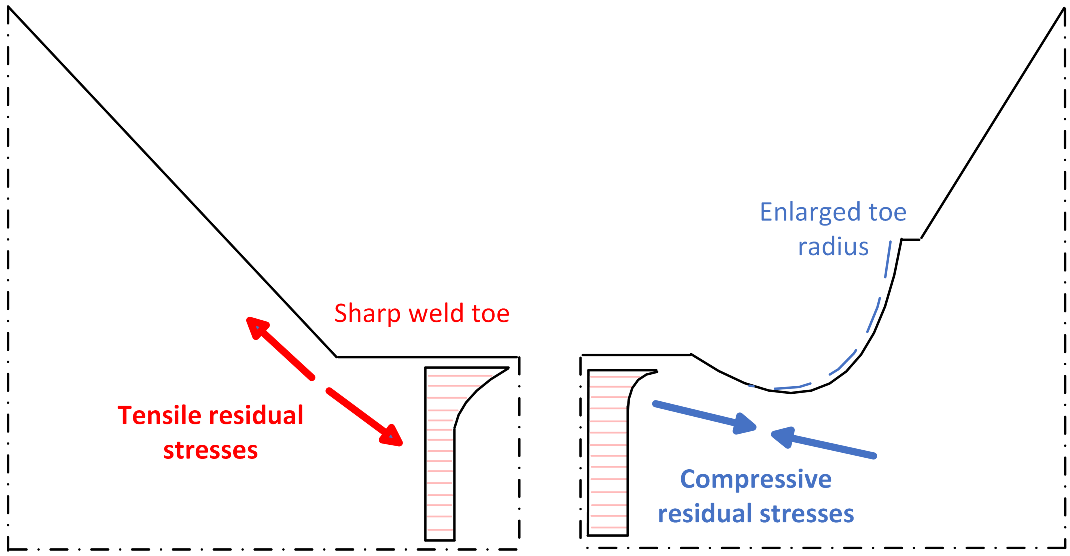

Figure 2.6: *Visual benefits of HFMI-treatment.*

The use of HFMI-treatment, at the welded area has proven to have a positive impact on the fatigue life (Weich et al., 2009). The change in material properties and introduction of compressive residual stresses can extend the crack initiation phase. Consequently, the use of high strength steel becomes relevant due to the potential of increasing the fatigue life even further (Shams Hakimi et al., 2015).

The International instutute of welding (IIW) have presented guidelines in 2016 for design using HFMI-treatment (Weinert et al., 2021). Furthermore, the German committee for steel construction, has published DASt-Guidline 026 which also is recommendations provided for design using HFMI. They both describe how to manage the increase in fatigue strength by HFMI-treatment in design. Furthermore, Chalmers University of Technology has recently published recommendations for the design of welded details in road and railway bridges (Al-Emrani et al., 2024). The publication is based on research from 2015-2023.

2.6.1 Influence of steel strength

According to the IIW, the fatigue strength classification of a weld subjected to HFMI-treatment can be enhanced up to 8 FAT-classes (Marquis & Barsoum, 2016). The extent of this improvement depends on factors such as the material strength and the geometry of the weld.

The improvement of the fatigue performance of an HFMI-treated weld is however closely connected to the increase in steel strength, which is proven experimentally

(Marquis & Barsoum, 2016). To take account for the steel strength, the IIW suggest that the FAT-class is increased by one step for every 200 MPa increase in yield strength. The relationship between the increase in FAT-class and the yield strength of the material is illustrated in Figure 2.7. Furthermore, the design recommendations on HFMI-treatment provided by the IIW are for plate thicknesses between 5-50 mm.

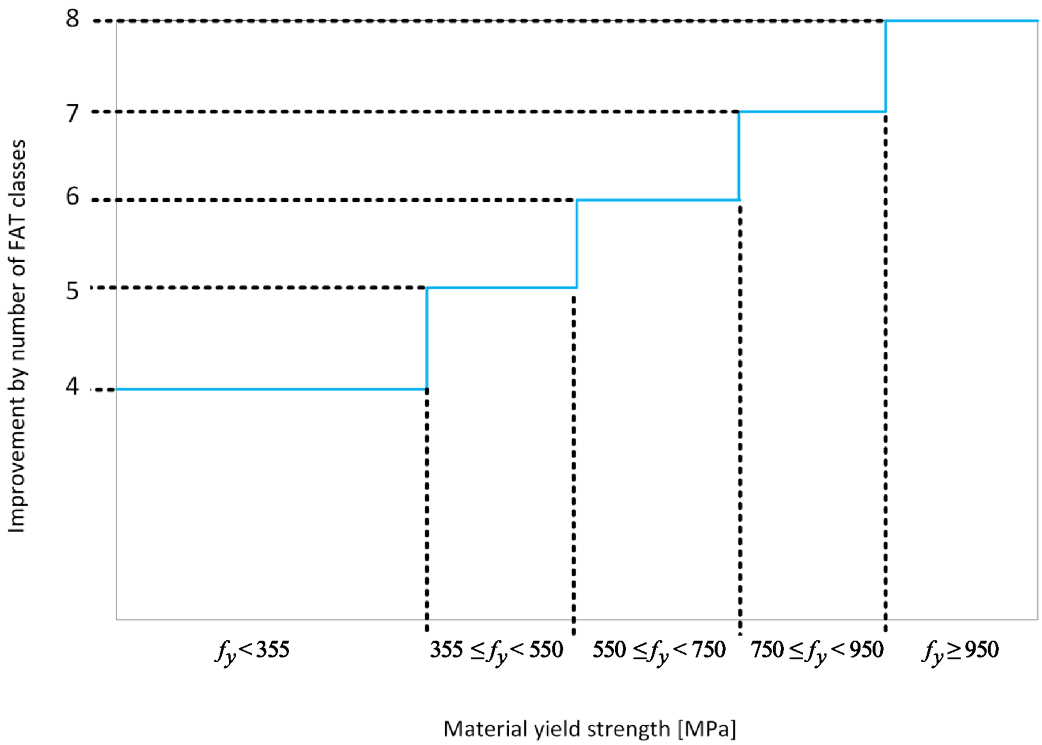

Figure 2.7: *Relationship between the increase in FAT-class and the yield strength of the material presented by IIW (Marquis & Barsoum, 2016).*

The DASt guidelines presents the improvement in fatigue strength classes for different bridge-specific welded details and for varying steel strengths. This information can be found in Tables 2.2-2.4. The welded details are depicted in Figure 2.8 and include butt-welds, transversal attachments and longitudinal attachments. The fatigue (FAT) values are provided for stress ratios of R=-1.0, R=0.1, and R=0.5.

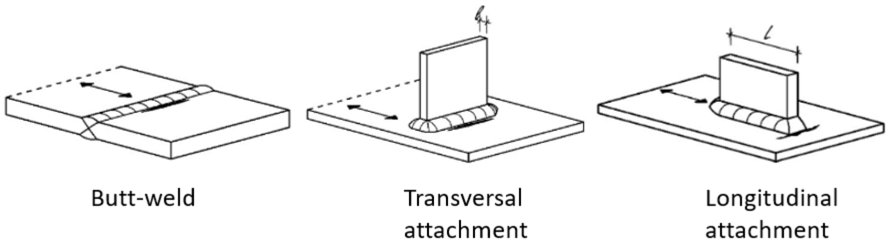

Figure 2.8: *Three different bridge-specific welded details (Kuhlmann et al., 2018).*

Table 2.2: *FAT-class for three different HFMI-treated details (R=-1.0) (Kuhlmann et al., 2018).*

Detail type	$f_y < 355MPa$	$355MPa < f_y < 550MPa$	$550MPa < f_y$
Butt-weld	Missing data	160	160
Transverse weld	100	160	160
Longitudinal weld	Missing data	112	125

Table 2.3: *FAT-class for three different HFMI-treated details (R=0.1) (Kuhlmann et al., 2018).*

Detail type	$f_y < 355MPa$	$355MPa < f_y < 550MPa$	$550MPa < f_y$
Butt-weld	Missing data	140	160
Transverse weld	100	140	140
Longitudinal weld	Missing data	112	125

Table 2.4: *FAT-class for three different HFMI-treated details (R=0.5) (Kuhlmann et al., 2018).*

Detail type	$f_y < 355MPa$	$355MPa < f_y < 550MPa$	$550MPa < f_y$
Butt-weld	Missing data	100	140
Transverse weld	80	90	90
Longitudinal weld	Missing data	80	80

Based on studies conducted between 2015 and 2023, Chalmers University of Technology is releasing recommendations for the design of bridges that include HFMI-treatment (Al-Emrani et al., 2024). Table 2.5 displays the reference values of the detail categories assigned to the three separate bridge specific details. The impact of steel strength is included in equations 2.1–2.2. In order to account for the yield strength of the material, a factor f1 is multiplied by the reference values. Resulting in the FAT-class for the treated details.

$$f_1 = 1 + \frac{0.1(f_y - 355)}{\Delta\sigma_{c,HFMI,ref}} \tag{2.1}$$

$$\Delta\sigma_{c,HFMI} = f_1 \Delta\sigma_{c,HFMI,ref} \tag{2.2}$$

Table 2.5: New FAT-classes for different bridge-specific details after HFMI-treatment (Al-Emrani et al., 2024).

Detail:	$\Delta\sigma_{c,HFMI,ref}$
Butt-weld	$k_s \times 160$
Transverse attachment	140
Longitudinal attachment	100

The k_s factor includes the impact of plate thickness. Equation 2.3 calculates the factor and it is used for plates thicker than 25 mm.

$$k_s = (\frac{25}{t})^{0.2} \tag{2.3}$$

2.6.2 Change in S-N curve

The IIW has further presented a modified S-N curve for an HFMI-treated detail where the slope is changed from m=3 in as-welded condition to m=5 in HFMI-treated condition (Marquis & Barsoum, 2016). After $1 \cdot 10^7$ cycles the slope is changed to m'=(2m-1)=9 for variable amplitude loading. Figure 2.9 is representing an example of the S-N curve for an as-welded detail and HFMI-treated detail, considering variable amplitude loading.

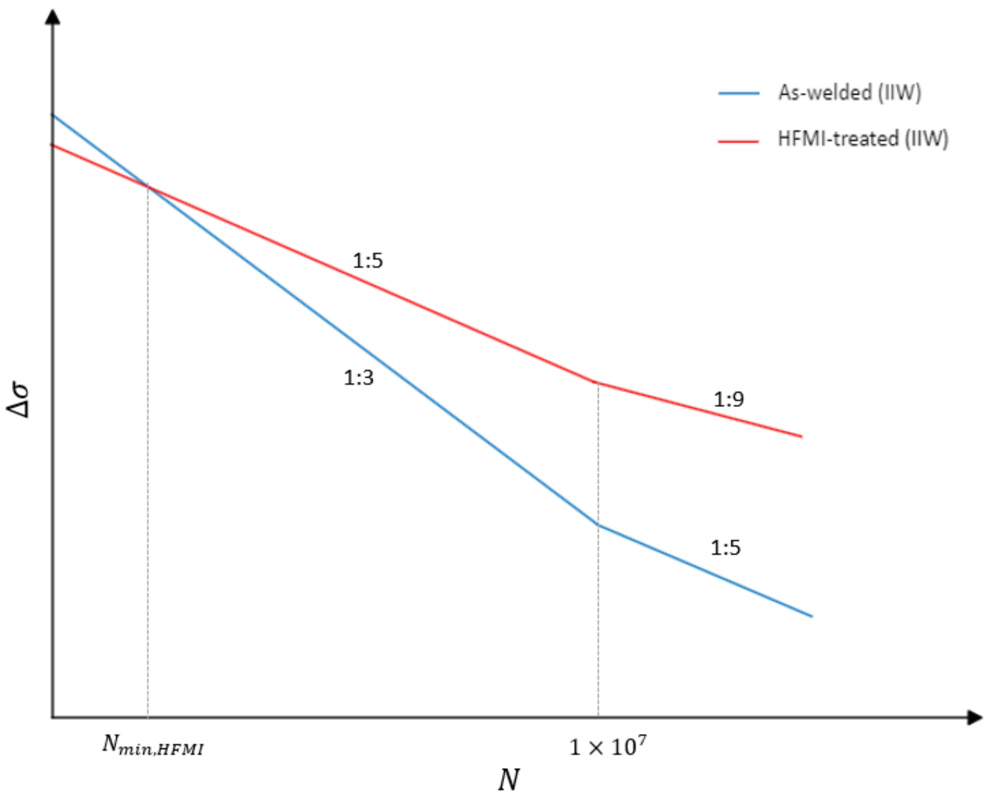

Figure 2.9: *S-N curve for an as-welded detail compared to an HFMI-treated welded detail according to the IIW recommendations (Marquis & Barsoum, 2016).*

The DASt-Guidlines do also have recommendation of the change in S-N curve after HFMI-treatment. The curve proposed adapts more to the same knee-points as in the Eurocode 3 (1-9) for an as-welded detail. The slope is changed from m=5 to m'=9 but now after $5 \cdot 10^6$ cycles instead (Kuhlmann et al., 2018). A comparison between the S-N curves by the IIW and DASt is presented in Figure 2.10 below.

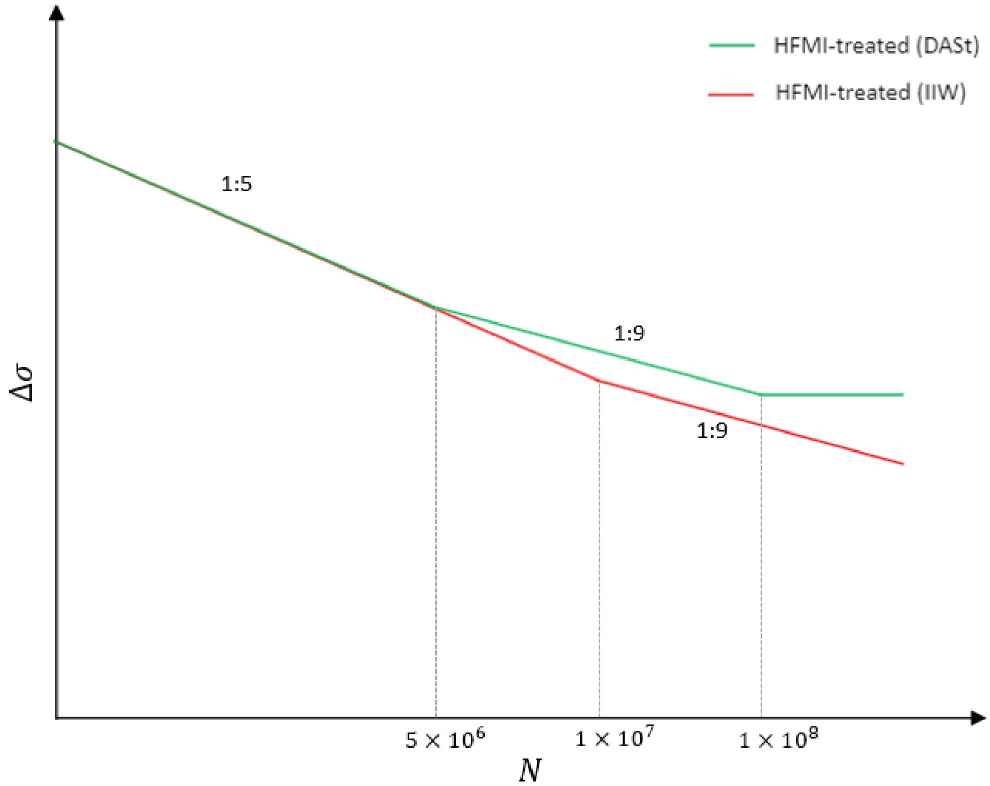

Figure 2.10: *S-N curves for an HFMI-treated detail by recommendation from the IIW and DASt. (Al-Karawi, 2023).*

Chalmers University of Technology's design suggestions additionally include a modified S-N-curve that shows the new states that should be followed while employing HFMI (Al-Emrani et al., 2024). The as-welded curve from Eurocode is shown in the same graph. Figure 2.11 shows an illustration of the S-N-curve.

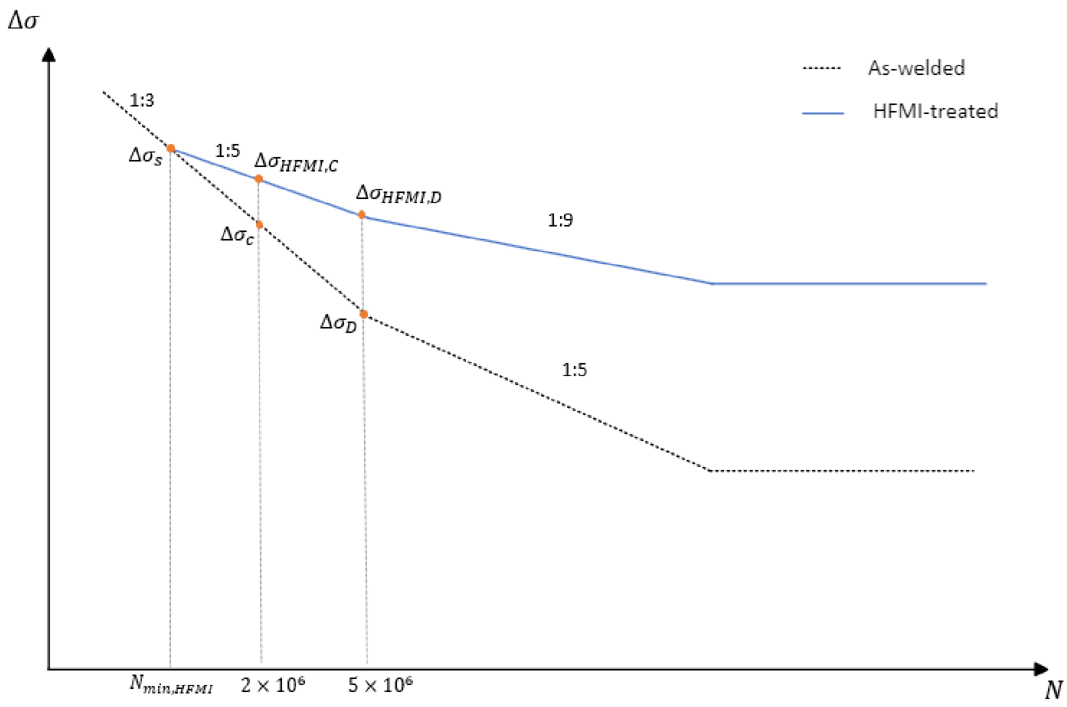

Figure 2.11: *S-N-curve presented in design recommendations from Chalmers University of Technology for an as-welded and HFMI-treated detail (Al-Emrani et al., 2024).*

Within the region for high applied stress ranges and low number of cycles, before $N_{min,HFMI}$, no improvement of fatigue strength can be expected. This is because the curve for HFMI can only be assured if the applied stress range and number of cycles meets the requirements presented in Equations 2.4 and 2.5.

$$\Delta\sigma < \frac{\Delta\sigma_s}{\gamma_{Mf}} \tag{2.4}$$

$$\text{where } \Delta\sigma_s = (\tfrac{\Delta\sigma^5_{c.HFMI}}{\Delta\sigma^3_c})^{0.5}$$

$$N < N_{min.HFMI} \tag{2.5}$$

$$\text{where } N_{min.HFMI} = 2 \cdot 10^6 \cdot (\tfrac{\Delta\sigma_{c.HFMI}}{\Delta\sigma_s})^5$$

2.7 Challenges with HFMI

For an as-welded joint, the fatigue strength is not significantly affected by the loading conditions (Shams Hakimi et al., 2021). This is due to the already high tensile stresses appearing at the weld. High load cycles, also called overloads, would cause relaxation of the tensile stresses from welding. This is caused by local yielding and is beneficial for the fatigue strength.

Following HFMI-treatment, compressive residual stresses are induced by the weld, as described in Section 2.6. The existence of these beneficial residual compressive stresses needs to remain through the service life (Al-Karawi et al., 2023). Otherwise, the increase in fatigue strength can not be guaranteed. The concern with high stresses arising in an HFMI-treated structure is that it can lead to relaxation of the beneficial compressive residual stresses. This can in turn have a negative impact on the fatigue performance of a treated joint. This is a challenge for road bridges as they are subjected to high and variable loading, which can give rise to high and varying mean stresses and overloads (Shams Hakimi et al., 2022).

2.7.1 Mean stress effect (R-ratio effect)

According to the recommendations from the IIW, the effect of stress ratio in design is implemented by decreasing the FAT-class (Marquis & Barsoum, 2016). Table 2.6 presents the reduction in FAT-class linked to the magnitude of the applied stress ratio (R-ratio). For the DASt-guidlines the details is assigned a lower FAT-class for higher stress ratios as seen in the Tables 2.2-2.4 above. The IIW and DASt recommendations are more adapted to constant amplitude loading, since the reduction is given for intervals or a specific value of the stress-ratio (Al-karawi, 2023). This is however not the case for bridges where the mean stress is fluctuating.

Table 2.6: *Minimum reduction in FAT-classes for the applied R-ratio recommended by IIW (Marquis & Barsoum, 2016)*

R-ratio	**Minimum reduction**
$R \leq 0.15$	No reduction
$0.15 < R \leq 0.28$	1 FAT class
$0.28 < R \leq 0.4$	2 FAT classes
$0.4 < R \leq 0.52$	3 FAT classes
$0.52 < R \leq 0.4$	Experimental data missing

According to the IIW, HFMI-treatment should not be implemented when the stress ratio is larger than R=0.5, or if $\sigma_{max} > 0.8 f_y$ (Marquis & Barsoum, 2016). This is since the favorable effect on the compressive residual stresses is thus uncertain.

A correction factor λ_{HFMI}, has been developed by Shams Hakimi et al. (2022) that takes the high and varying stress ratio into account in fatigue verification of road bridges. The factor is also included in the design recommendation from Chalmers University of Technology (Al-Emrani et al., 2024). It is used to increase the loading effect in fatigue verification of details treated with HFMI.

The factor is based on a large amount of experimental data from real traffic from both Sweden and the Netherlands (Al-Karawi, 2023). Further, an article by Al-Karawi et al. (2022) demostrated that the method was adequate for correcting the stress impact resulting from high mean stresses in Swedish traffic conditions. It also showed that the traffic loads did not have that much influence on the mean stress compared to the self-weight effect. This conclude that the proposed method can be used in different countries as well. The expression for the λ_{HFMI} differ depending on type of bridge, and also the details location on the bridge. For road bridges the factor is expressed in equations 2.6 and 2.7. The first equation is for details located in the mid-span section. The latter is for mid-support sections in continuous beams.

$$Mid-span : \lambda_{\text{HFMI}} = \frac{2.38\phi + 0.64}{\phi + 0.66} \geq 1.0 \tag{2.6}$$

$$Mid-support : \lambda_{\text{HFMI}} = \frac{2.38\phi + 0.06}{\phi + 0.40} \geq 1.0 \tag{2.7}$$

ϕ is a factor that includes the stress effect from permanent loads for road bridges, as seen in Equation 2.8 (Al-Karawi, 2023). Where σ_{perm} is the self-weight stress and $\Delta\sigma_p$ is the maximum stress range upcoming for FLM3.

$$\phi = \frac{\sigma_{perm}}{2\Delta\sigma_p} \tag{2.8}$$

The derived correction factor, λ_{HFMI} can be used in both the λ-coffieicent method and the Damage accumulation method for fatigue design (Al-Karawi, 2023). In the λ-coefficient method the factor is considered by multiplying it with the stress range from the traffic loads given by the load models in Eurocode. It increases the loading effect in the verification of the fatigue design. Furthermore, in the Damage accumulation method, the factor λ_{HFMI} accounts for the R-ratio in the magnified equivalent stress range. The equations for the methods can be found in the report "Fatigue design and assessment guidelines for high-frequency mechanical impact treatment applied on steel bridges" by Hassan Al-Karawi (2023).

2.7.2 Effect of overloads

To account for the effect of peak loads, also called overloads, the limitation of maximum stress for HFMI-treated welds $\sigma_{max} \leq 0.8 f_y$ is set by the IIW (Marquis & Barsoum, 2016). However, in the article by Al-Karawi et al. (2023) it is shown that the maximum stress that is allowed is dependent on the detail type. Three details mentioned and their limitation on maximum stresses are presented in Table 2.7 below. The different details are illustrated in the Figure 2.8 for a steel and concrete composite bridge.

Table 2.7: *Limitation on maximum stress given for three different welded details in a bridge (Al-Emrani et al., 2024).*

Detail type	Maximum stress limitations
Longitudinal attachment	$-0.5f_y < \sigma_{max} < f_y$
Transversal attachment	$-0.7f_y < \sigma_{max} < f_y$
Butt weld attachment	$-0.9f_y < \sigma_{max} < f_y$

The aforementioned limitations are used for the design of bridges (Al-Emrani et al., 2024). Al-Karawi et al. (2023) investigated which load combination is suitable for calibrating σ_{max} when compared for different limit states. The verification is made by comparing frequent load combination (SLS), characteristic load combination (SLS) and ULS with use of traffic data generated from road composite bridges in Sweden and the Netherlands. The characteristic combination is proved to be the best representation of the peak stresses appearing in an HFMI-treated weld.

Equation 2.9 and 2.10 present the characteristic combination for the calculation of maximum stress. The first equation includes the effect of shrinkage and results in higher stresses (Shams Hakimi et al., 2021). Further, the traffic model LM1 should be used for the traffic load (Al-Karawi et al., 2023).

$$\sigma_{max} = G + S + TS + UDL + 0.6 \cdot max(F_w, T_k) \leq C \cdot f_y \tag{2.9}$$

$$\sigma_{max} = G + TS + UDL + 0.6 \cdot max(F_w, T_k) \leq C \cdot f_y \tag{2.10}$$

G - Self-weight stresses
S - Stress rises due to concrete shrinkage
TS - Concentrated loads from traffic
UDL - Uniformly distributed loads from traffic
T_k - Thermal stresses
F_w - Wind loads
C - Constant that is multiplied with f_y

2.8 HFMI-treatment on bridges

Composite bridges are constructed by combining different materials, usually steel and concrete (Collings, 2005). One of the main benefits of composite bridges is that they are redundant (Hirt & Lebet, 2013). Furthermore, they are adjustable and can be used for different structures (Collings, 2005). However, the self-weight in a composite steel and concrete bridge is generally high due to the heavy concrete slab which contributes to a high mean stress effect (Shams Hakimi et al., 2021).

In addition to the high self-weight, bridges are often subjected to varying traffic which results in high and fluctuating stresses (Shams Hakimi et al., 2022). Figure 2.12 illustrates the effect on high mean stress (R-ratio). The R-ratio can further be calculated with Equation 2.11.

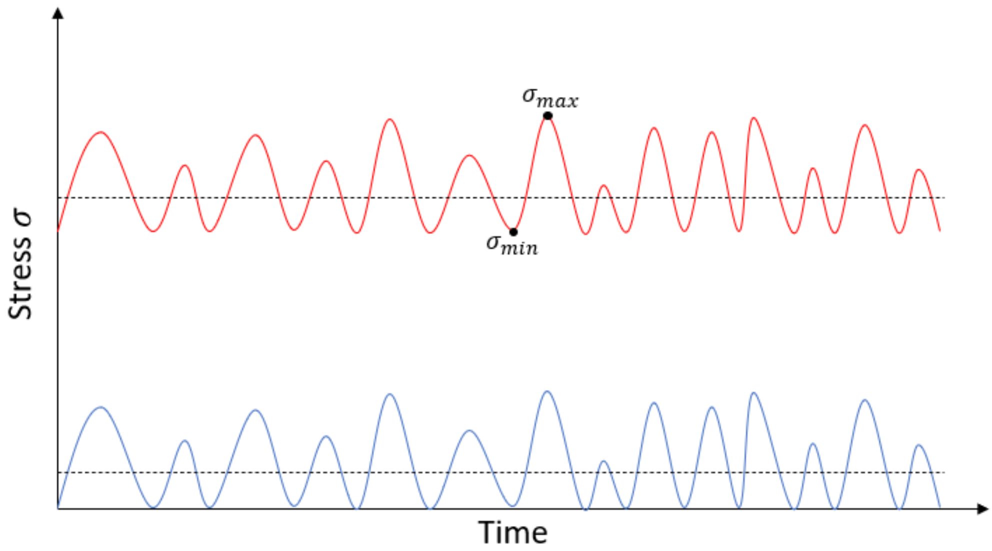

Figure 2.12: *The effect on mean stress with high applied self-weight.*

$$R = \frac{\sigma_{min}}{\sigma_{max}} \tag{2.11}$$

Moreover, fatigue can constitute a limiting state that governs the design of composite bridges which makes HFMI benefitial for bridges (Al-Karawi et al., 2023). Analysis of HFMI-treatment on steel and composite bridges have been performed, where Shams-Hakimi (2020) studied improvement of fatigue in steel bridges considering material savings and limitation of HFMI. Shams-Hakimi evaluated four different bridges by using the nominal stress method and comparing as-welded and HFMI-treated details. The analysis did however not verify if the maximum stresses are lower than the characteristic loads.

Furthermore, the mean stress was obtained according to the IIW guidelines, but on the other hand the steel strength was not reduced as the guidelines proposed (Shams Hakimi, 2020). Instead, the stress range was modified and extended. Additionally, the design analysis was not modified with the factor λ_{HFMI}, which takes into account the importance of correcting the mean stress with respect to stress ratio from variable loading and self-weight. The factor λ_{HFMI} and its properties is explained in Section 2.7.1.

2.9 Impact of application phase effect

Application of HFMI-treatment is most favourable if applied on site when the bridge already has been erected and the self-weight is applied (Shams Hakimi et al., 2022). The risk of executing HFMI-treatment before is that the compressive residual stresses implemented can be counteracted by the high stresses from the self-weight. In that case the self-weight will have a large influence on the mean stress arising in an HFMI-treated detail. On the other hand, there are several difficulties when implementing HFMI on-site (Al-Karawi, 2023). Firstly, it is more difficult to inspect the quality of the treatment considering for instance smoothness. Secondly, HFMI needs to be executed before painting of the steel, which usually is done in workshop.

Other treatment methods that can reduce the introduced compressive stresses after implementation of HFMI-treatment should be avoided (Marquis & Barsoum, 2016). Examples of such include heat treatment or hot-dip galvanizing. Furthermore, non-load-bearing welds that have undergone treatment can theoretically fail from the root, therefore fully penetrated welds and extra thick throats is preferable.

Furthermore, it is crucial that the executor requires appropriate practical education before applying HFMI on a structure (Marquis & Barsoum, 2016). If the treatment is wrongly applied or if incorrect indenter is used, the increase of fatigue strength can not be as high as promised.

3
Methodology

3.1 Design codes and standards

Bridges in Sweden are to be constructed in accordance with Eurocode SS-EN1990 to SS-EN1999 (Krona, 2019). The national choices in the Eurocode are to be extracted from the document TSFS 2018:57 by the Swedish Transport Agency. Design options are compiled into a document called RKFM, which describes the construction work method. The RKFM is found in Appendix A.1.

The design guidelines provided in the report "High Frequency Mechanical Impact Treatment - Recommendations for the design of welded details in road and railway bridges" published by Chalmers University of Technology, are to be used for fatigue design of welded details that have undergone HFMI-treatment (Al-Emrani et al., 2024).

3.2 Bridge geometry

This thesis examines a composite steel and concrete bridge that is 149.4 meters long overall, including the piers. The cross section is 14.5 wide and is made out of steel twin I-girder beams that have been welded together, and a 300 millimeter thick concrete slab. The cross section and used notations for the dimensions are shown in Figure 3.1.

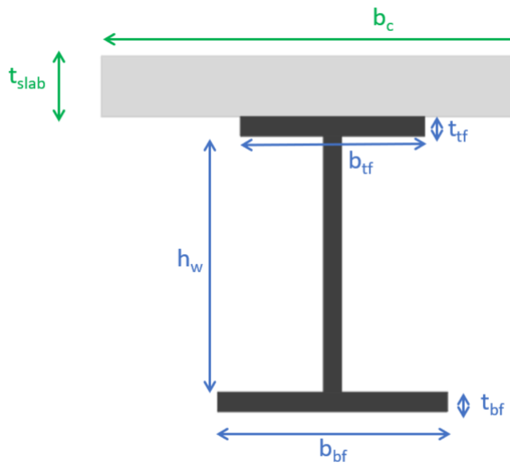

Figure 3.1: *Notations for the dimensions of the cross section.*

The steel beams are continuous over five supports with two abutments and two concrete pillars serving as inner supports. The two outer spans are 28.00 meters and the two inner are 38.75 meters as illustrated in Figure 3.2.

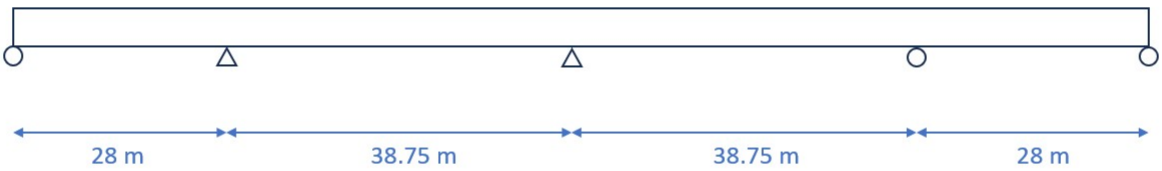

Figure 3.2: *Span lengths for the bridge.*

As shown in Table 3.1, the bridge is segmented into 14 different beams with varying dimensions for delivery purposes. Figure 3.3 displays the beam locations, where beams 3 and 5 are positioned above the support. The girders are designed with a constant beam height along the bridge. However, they are designed with other varying dimensions (thickness and width).

Table 3.1: The beam numbering over the length, where the green highlighting indicates support beams.

Sections and beams over the bridge		
Section	Length [m]	Beam number
Support 1	0 - 4.2	1
Span 1	4.2 - 23.8	2
Support 2	23.8 - 34.0	3
Span 2	34.0 - 60.5	4
Support 3	62.5 - 72.5	5
Span 3	72.5 - 99.5	4
Support 4	99.5 - 109.7	3
Span 4	109.7 - 129.3	2
Support 5	129.3 - 133.5	1

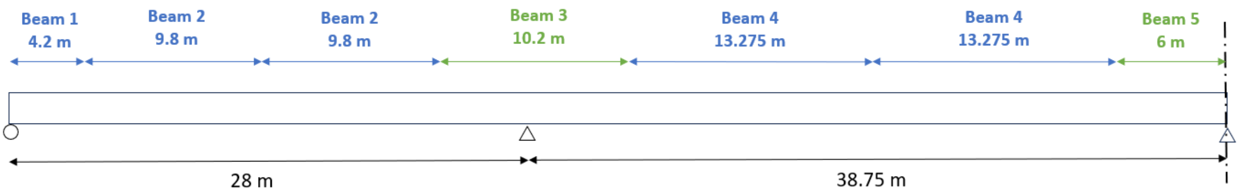

Figure 3.3: *The division of the main girders into smaller beams.*

The cross-section features transverse beams at each support section, and truss cross bracing sparingly placed in the middle of spans and closer to supports. This is presented in Figure 3.4.

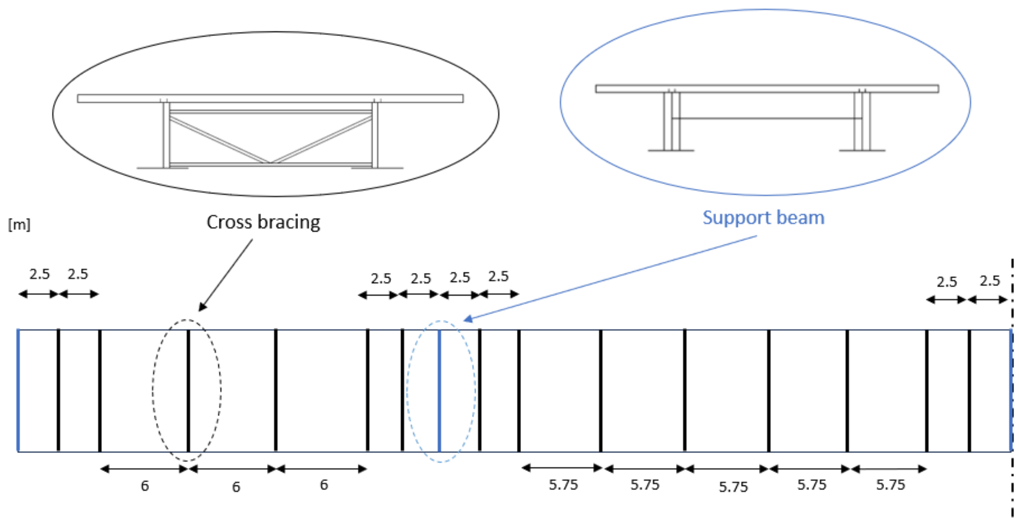

Figure 3.4: *The spacing of the support beams and cross bracing shown for half of the bridge length.*

3.2.1 Details

Welded details are extra sensitive to fatigue and must be distinguished across the bridge. Figure 3.5 displays the bridge details. The top flange is connected to the web by long butt welds, while fillet welds connect the web. Holes are designed in the main web to prevent multi-weld line intersections. The composite action is attained via shear studs connecting the concrete deck to the top flange. The shear studs are welded to the top flange. In addition, vertical stiffeners are welded to the flanges at every transverse beam and cross bracing, as shown earlier in Figure 3.4.As HFMI causes an increase in fatigue strength of welded details, the possibility of fatigue cracking initiating from the base metal is also considered. Table 3.2 contains the details and matching detail category in the as-welded condition, as well as the one to be assigned after HFMI-treatment.

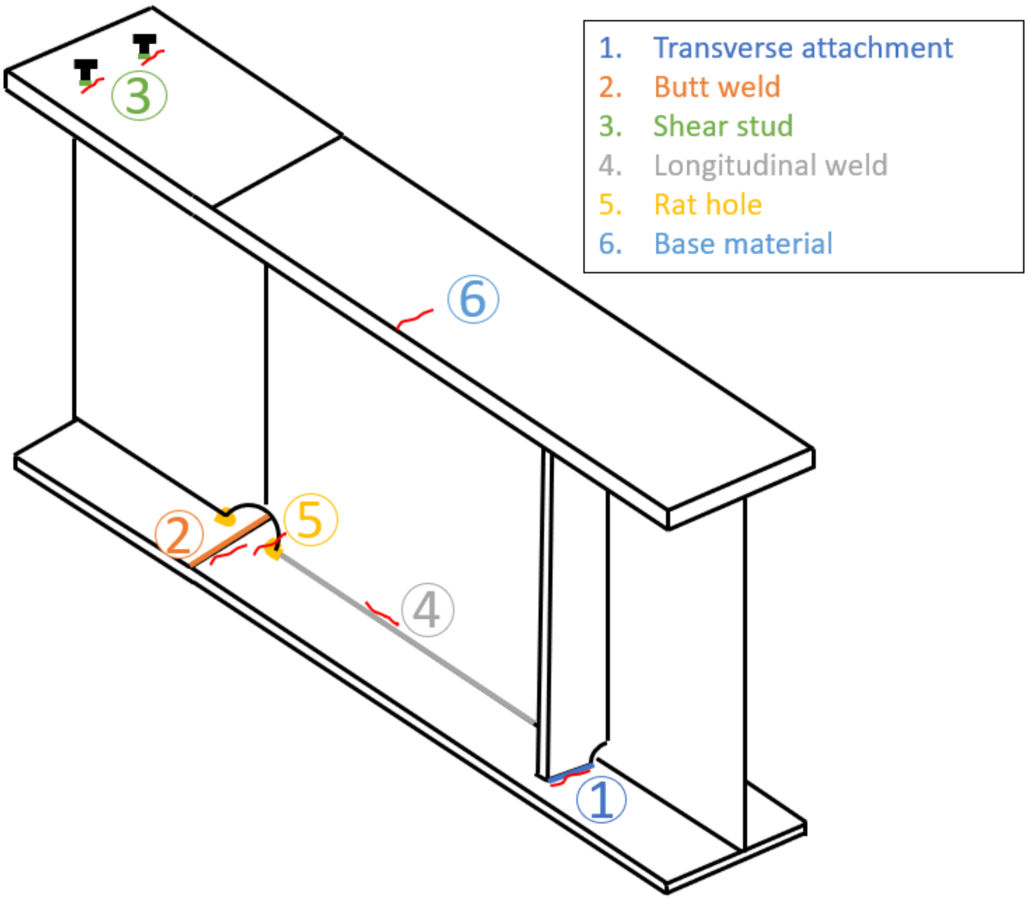

Figure 3.5: *Details within the bridge.*

Table 3.2: Fatigue detail categories for the studied details before and after HFMI-treatment for yield strength $f_y = 355$ MPa and $R = 0.1$.

Details subjected to normal stresses:	$\Delta\sigma_c$ [MPa]	$\Delta\sigma_{c,HFMI,ref}$ [MPa]
1. Transverse attachment	80	140
2. Butt-weld	112	160
4. Longitudinal weld	112	-
5. Rat-hole	71	100
6. Base metal	160	-
Details subjected to shear stresses:	$\Delta\tau_c$ [MPa]	$\Delta\tau_{c,HFMI,ref}$ [MPa]
3. Shear stud	90	-

3.3 Finite element model

The structural analysis is performed in the FE-based software SOFiSTiK 2022. The software is comprised of multiple modules for different purposes. Firstly, the structure geometry, cross sections and materials are defined using the AutoCAD add-in program Sofiplus. The bridge is further designed following EuroNorm bridge standards and safety class 3 in the program. Beam elements are used to create the main composite cross-section and quadrilateral shell elements for modelling the stiffness of the concrete slab. To facilitate the parameterising process, variables are defined in the program to represent the varying dimensions of the steel plates in the girders.

Consideration is also given to the effect of concrete cracking over the support, where the elastic modulus for the concrete is reduced to 0.3 GPa instead of 34 GPa. According to EN 1994-2:2005, cracked flexural stiffness is assigned to 15% of the span length on both sides of the internal supports, as seen in Figure 3.7 and 3.6.

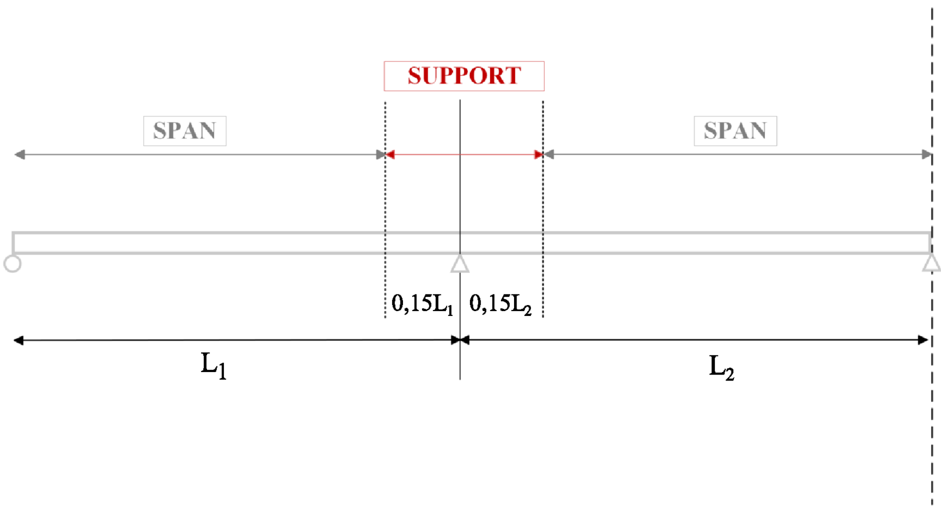

Figure 3.6: *Distribution of span and support sections over the bridge length.*

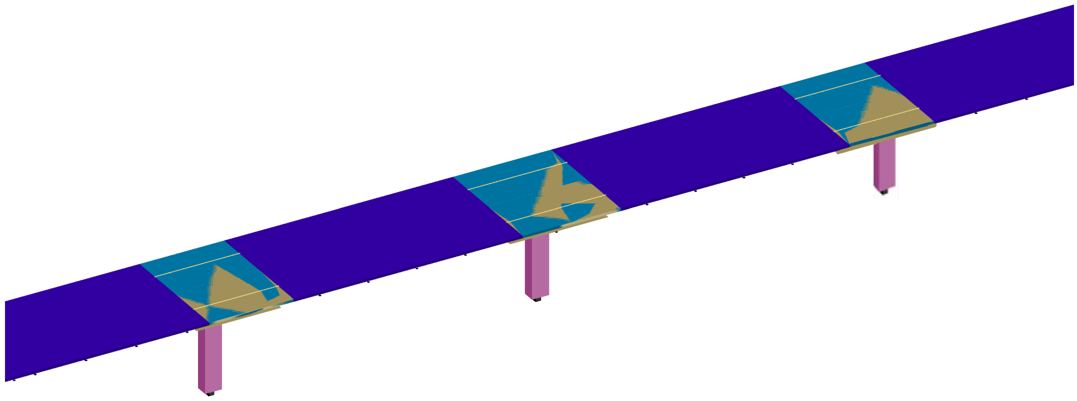

Figure 3.7: *Distribution of cracked sections.*

Figure 3.8 illustrates the support conditions along the bridge. The boundary conditions for translation in several directions are depicted in the figure. The support conditions are further defined with spring elements that have varying stiffnesses in different directions according to Figure 3.8.

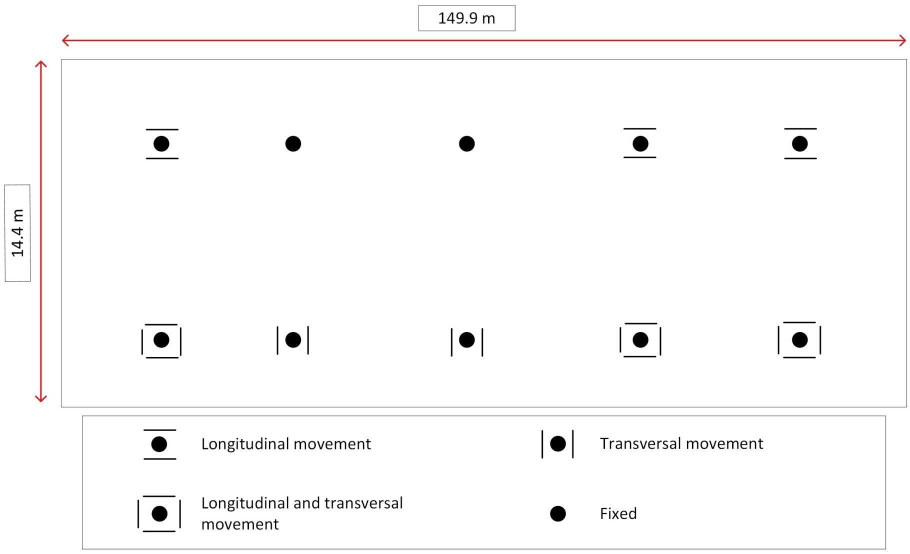

Figure 3.8: *Definition of support conditions.*

3.3.1 Actions and loads

The load case manager is used to define actions and load cases to apply additional loading on the structure. The program automatically calculates the self-weight of all components, including the I-girders, cross-beams, and concrete slab.

Line loads are added as railing along the length of the bridge on the left and right sides. The loading from the asphalt and waterproofing mat is converted to area loads and added to the slab. Additionally, linear temperature loads are applied to the structure based on the temperatures obtained in the RKFM in Appendix A.1. The traffic loads are assigned using the traffic loader task in Sofistik. Three lanes are automatically defined in accordance with the width of the concrete slab. The distribution of lanes is shown in Figure 3.9 and the dimensions of the lanes in Table 3.3. The traffic load is conducted for load model LM1, as well as fatigue load models FLM3 and FLM4.

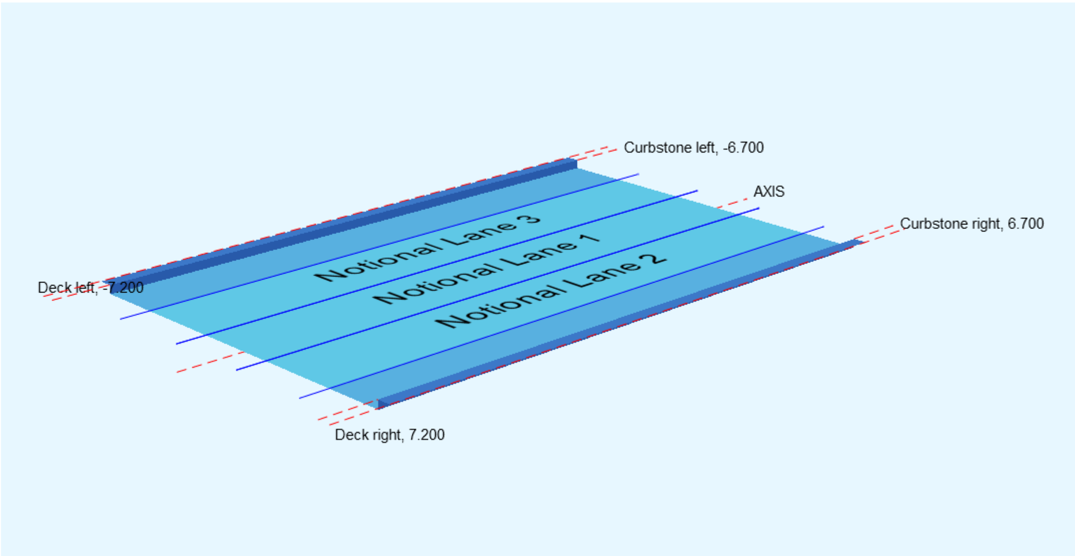

Figure 3.9: *Distribution of lanes in Sofistik.*

Lane number	Lane width [m]
1	3.0
2	5.2
3	5.2

Table 3.3: *Lane widths according to traffic loader in Sofistik.*

3.3.2 Verification of FE-model

The FE model created in Sofistik is verified to ensure the accuracy of the results. The verification is made considering a copied model with modified support conditions, where the internal supports are removed to simplify the verification process. The reaction forces and maximum span moment with respect to self-weight from the simplified model are obtained from Sofistik and compared with analytical calculations, which are detailed in Appendix A.5.

3.4 Calculation process

The study comprises of designing the steel I-girder beams for the Ultimate Limit State (ULS), Serviceability Limit State (SLS), and Fatigue Limit State (FLS). For ULS, bending and shear resistance are calculated, whereas deflection is evaluated for SLS. The critical details are checked in both ULS and FLS. The specific standards used will be specified in the respective calculations in the Appendix. Some simplifications for the calculations are stated below.

- Concrete and reinforcement design are out of the scope of the calculations, the thickness of the slab is assumed to be 300 mm and the material is C35/45.
- Lateral torsional buckling of flanges during production before casting of concrete is not considered.
- Wind loads are not taken into account to simplify the calculation process.
- The design vehicles (typfordon) which are given by TRVINFRA and TSFS are not used to generate traffic load for simplification purposes.
- The cross-bracing and support beams are not designed, the dimensions are assumed according to rule of thumb values.

To compute utilisation ratios along the bridge, the sectional forces and deflections obtained from Sofistik are exported and post-processed in Excel. Sectional forces for both short-term and long-term calculations are acquired. These forces are then collected in envelopes, consolidating the results from each node in the beam elements.

3.4.1 Ultimate limit state

The calculations are completed in envelopes along the bridge length. However, the calculations in the Appendix consider one point on the bridge. Initially, the flanges are reduced with respect to shear lag, and new stress distributions are calculated accordingly, see Appendix A.10. In addition, shear capacity is evaluated under the assumption that the web is carrying the entire shear force, see Appendix A.8 for calculations. The design verification and interaction between the bending moment and shear force are considered in the calculations. Further, stress distributions for gross cross-section are calculated in Appendix A.7

The cross-sectional class for the flanges is then determined as seen in Appendix A.6. If the flanges are in cross-sectional class 4 (CSC 4), they are reduced by local buckling based on the stress distributions obtained from shear lag reduction. Consideration of the reduction of the plates due to local buckling is presented in Appendix A.11 and A.12. The cross-sectional class calculation of the web is found in the latter. Calculations for the stress distributions are repeated if reduction is required.

The final stress distribution for the design is calculated for the reduced flanges and the web. The utilisation ratios for the bending in ultimate limit state are further calculated and verified from the final stress distribution. Additionally, Appendix A.14 shows how many shear studs are required for the structure and Appendix A.13 the longitudinal welds are examined in ULS.

3.4.2 Serviceability limit state

3.4.2.1 Deflection

In the Serviceability Limit State the deflection is verified. The deflections in envelopes are determined by the frequent SLS combination from traffic loads. The resulting deflections are validated with L/400 according to Trafikverket (Krona, 2019), where L is the theoretical span length. Calculations are found in Appendix A.9.

3.4.2.2 Verification of maximum stresses (for HFMI)

The characteristic stresses are obtained from Sofistik to check the effect of overloads, as mentioned in Section 2.7.2. The stresses will be verified according to the stress limitations in Table 2.7 as shown in Appendix A.17.

3.4.3 Fatigue limit state

All the critical details are checked in Fatigue Limit State. The details and their respective categories are listed in Table 3.2 in Section 3.2.1. The fatigue verification is conducted using the λ-coefficients method (for FLM3) as seen in Appendix A.15. Further, the damage accumulation method is used for FLM4, see Appendix A.16.

The number of heavy vehicles per year on the slow lane is determined based on the traffic categories in Table 4.5 of EN 1991-2:2003, where category 4 is assumed since it is the worst. It is then assumed that one cycle is equal to one lorry since the size of the lorries is smaller than the span lengths, thus only big cycles are generated. If smaller cycles are generated, their fatigue effect would be negligible as they will be lower than the cut of limit. The used parameters and calculations are further detailed in the Appendix for FLM4 A.16.

3.4.4 Fatigue limit state considering HFMI-treatment

The updated fatigue verification for HFMI adheres to the guidelines in *Recommendations for the design of welded details in road and railway bridges* published at Chalmers University of Technology (Al-Emrani et al., 2024). The process is similar to the verification for fatigue, but the calculations are changed with new FAT-classes and the correction factor λ_{HFMI}, as provided in equations 2.6 and 2.7. Table 3.2

shows the new FAT-classes for each detail, while Appendix A.18 shows the calculations for FLM3 and Appendix A.19 for FLM4. For the butt-weld, the FAT-class is changed with a thickness reduction factor, as indicated in Section 2.7.

The fatigue strength of butt-welds, transverse attachments and rat holes are altered to consider the effect of HFMI treatment. Furthermore, the details are checked for $N_{min,HFMI}$, according to figure 2.9, to check if the loading level is not high enough to cause relaxation of induced compressive residual stress. When improvements are not achievable, the impact of HFMI is not considered (Al-Emrani et al., 2024).

3.5 Parametric study (optimising geometry)

The original girder design is created using the steel material S355 and two different cross-sectional heights, L/20 and L/30, where "L" represents the longest span length. The approximate value for the girder height in a composite section is $h \approx L/25$ (Collin et al., 2008). Therefore two close values are chosen accordingly.

For the steel strength S355, the design of two welded I-girders, with different total heights, is optimised. The goal of the optimisation is to reduce the material usage using trial and error process until the utilisation ratios become close but not equal to 100%.

The thicknesses and widths of the plates are altered to change the geometry. Ratios for typical plate thicknesses in composite bridges are provided by the book "Steel Bridges" ((Hirt & Lebet, 2013)). The ratios used to produce accurate cross-sectional dimensions are displayed in Table 3.4. The height is maintained at the same level as the original beam designs (L/20 and L/30) during optimisation, as mentioned earlier.

Table 3.4: Typical dimensions for plate girders in composite bridges (Hirt & Lebet, 2013).

Dimension	Span	Support
Top flange thickness [mm]	15-40	20-70
Bottom flange thickness [mm]	20-70	40-90
Web thickness [mm]	10-18	12-22
Top flange width [mm]	300-700	300-1200
Bottom flange width [mm]	400-1200	500-1400

Further, the steel strength for the two beams is increased to S460, and the effect of HFMI-treatment is considered in the calculations. The HFMI is accounted for following the recommendations described in Sections 2.6-2.7. New optimised designs are created, to achieve a utilisation ratio near to 100% in the design limit states. The same method is repeated with an even higher steel grade, S690.

To compare the amount of material usage, the used steel volume and weight are calculated for each optimised beam design. To provide an accurate cost comparison, the cost of the girders is calculated to include an estimated cost of applying HFMI-treatment. The steel volume and cost of the main twin I-girders are the only steel elements that are compared, stiffeners and cross-beams are not considered. Table 3.5 displays the material costs in Swedish crowns (SEK) per kilogram that are used in the calculations.

Table 3.5: Material cost for plates in different steel strengths from Q4 2022 (SSAB, 2022).

Material	**Steel cost** [SEK/kg]
S355	10.00
S460	10.83
S690	19.24

The total length of the weld lines to be treated is evaluated to determine the approximate additional cost associated with HFMI-treatment. The cost is simplified to account for the HFMI device lease and operator hours (via the reported speed of the device). Certain pricing details could be obtained by directly contacting the company HiFIT (HiFIT, 2024). See the assumptions and calculations in Appendix A.20.

4

Results

4.1 Original design

The resulting dimensions for the original design (S355) with the cross sectional height limited to L/20 are presented in Table 4.1. The corresponding maximum utilisation ratios in the design limit states are presented in Table 4.2 for the different steel strengths S355, S460 and S690. The utilisation of S355 is governed by FLS (AW), followed by ULS.

Table 4.1: Dimensions for the beams in the original design with h=L/20.

Original design - h = L/20 = 1937.5 mm								
Beam	Nr. of beams	L [m]	t_{tf} [mm]	b_{tf} [mm]	t_w [mm]	h_w [mm]	t_{bf} [mm]	b_{bf} [mm]
1	2	4.2	35	700	18	1862.5	40	800
2	4	9.8	35	700	18	1864.5	38	780
3	2	10.2	55	800	20	1832.5	50	1100
4	4	13.3	35	725	18	1862.5	40	1250
5	2	6	55	800	20	1832.5	50	1100

Table 4.2: Maximum utilisation ratios for the original design with h=L/20 and for different steel strength.

Original design - h = L/20 = 1937.5 mm				
fy [MPa]	Umax ULS	Umax SLS	Umax FLS AW	Umax FLS HFMI
355	97.8%	24.7%	98.7%	84%
460	76.7%	24.7%	98.7%	78.1%
690	48.9%	24.7%	98.7%	67.8%

The dimensions and results of beam height L/30 are displayed in Tables 4.3 and 4.4. In comparison with the design having a height of L/20, the original S355 design's utilisation is determined by ULS instead of FLS. The governing usage changes to FLS (AW) when S460 is used instead. Further, the governing limit state changes to FLS (AW) for both heights.

Table 4.3: Dimensions for the beams in the original design with h=L/30.

h = L/30 = 1291.7 mm								
Beam	Nr. of beams	L [m]	t_{tf} [mm]	b_{tf} [mm]	t_w [mm]	h_w [mm]	t_{bf} [mm]	b_{bf} [mm]
1	2	4.2	35	700	18	1206.7	50	1100
2	4	9.8	35	700	18	1201.7	55	1000
3	2	10.2	55	800	20	1276.7	60	1250
4	4	13.3	35	725	18	1196.7	60	1050
5	2	6	55	800	20	1176.7	60	1250

Table 4.4: Maximum utilisation ratios for the original design with h=L/30 and different steel strength.

h = L/30 = 1291.7 mm				
fy [MPa]	Umax ULS	Umax SLS	Umax FLS AW	Umax FLS HFMI
355	97.5%	31.2%	93.7%	81.2%
460	76.7%	31.2%	93.7%	78.0%
690	50.8%	31.2%	93.7%	67.7%

Tables 4.2 and 4.4 show that increasing steel strength leads to lower utilisation ratios in ULS and FLS (HFMI), whereas FLS (AW) remains constant. Furthermore, there is no change in SLS (deflection), as the dimensions of the cross-section are maintained constant for the variable steel strengths.

The characteristic stresses are analysed for the top and bottom of the flanges over the bridge length. Figure 4.1 displays the results of the verification of characteristic stresses. As can be observed, there is no exceeding of the boundaries specified for the various details in Table 2.7.

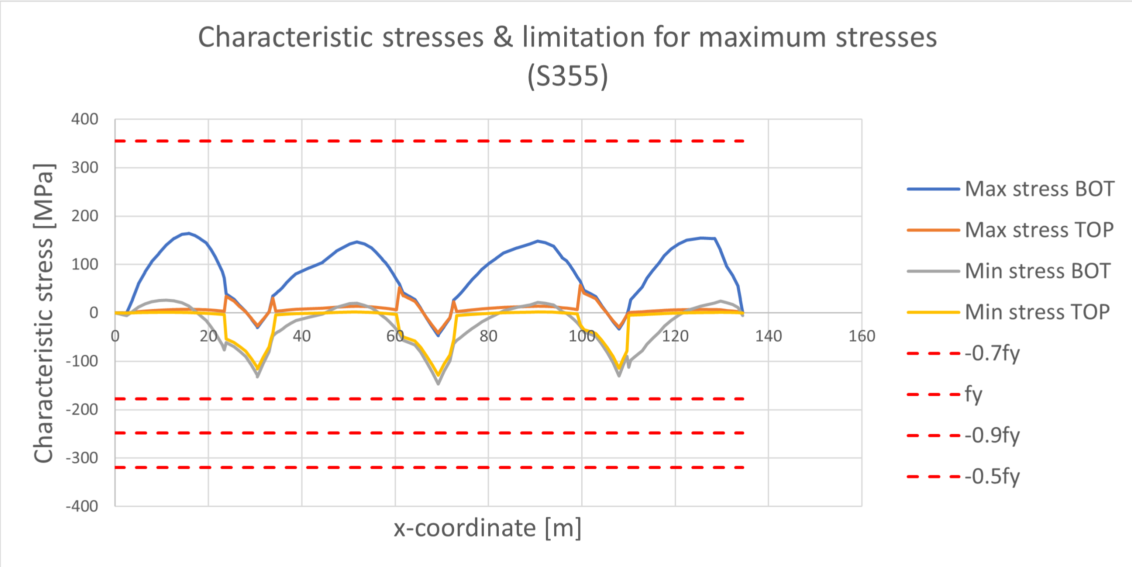

Figure 4.1: *The resulting characteristic stresses where the maximum limits are marked.*

4.1.1 Utilisation in envelopes

Figures 4.2-4.3 demonstrates the maximum utilisation in envelopes throughout the bridge for ULS, FLS (AW), and FLS (HFMI) for the two cross-sectional heights L/20 and L/30 individually. The FLS values are obtained using FLM3, as the load model generates the governing utilisation ratios for all points throughout the bridge length. The SLS utilisation envelope is not considered as it is found to be not governing in all cases.

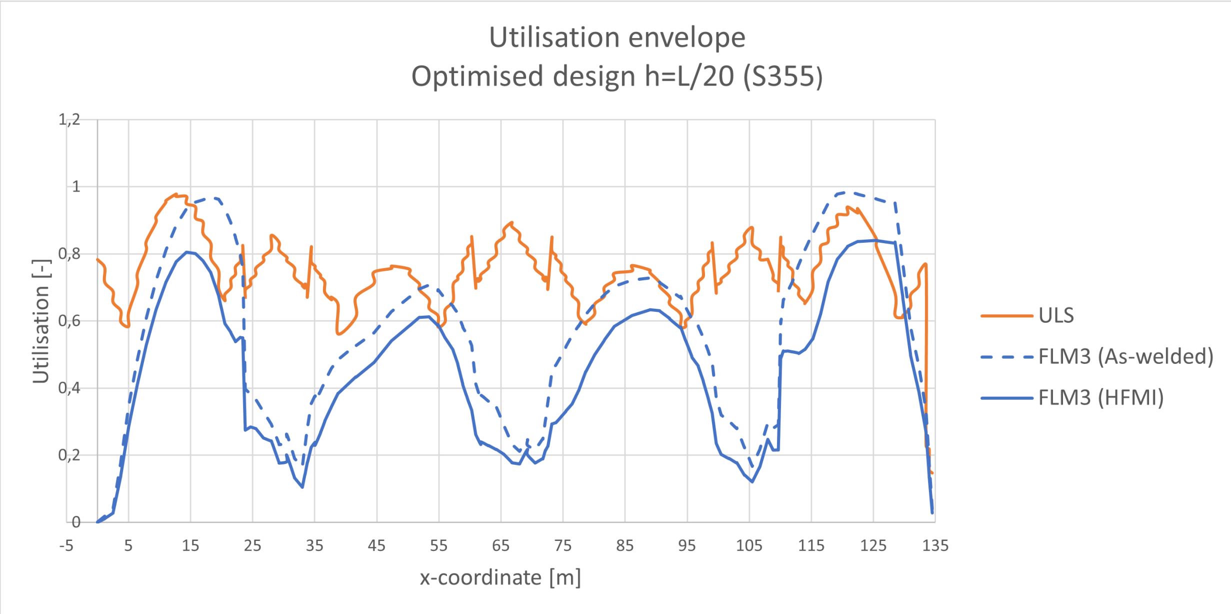

Figure 4.2: *The utilisation in ULS and FLS (FLM3) before and after HFMI over the bridge length for the original design (h=L/20).*

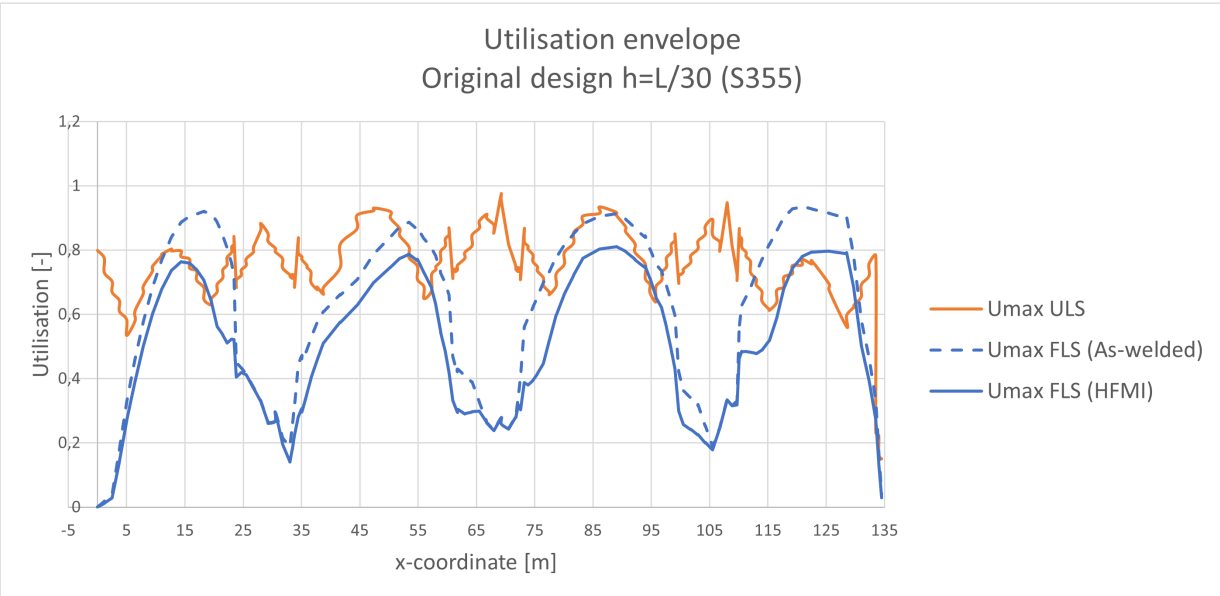

Figure 4.3: *The utilisation in ULS and FLS (FLM3) before and after HFMI over the bridge length for the original design (h=L/30).*

It can be seen in Figure 4.2 for the height L/20, that ULS is governing for most of the points over the bridge. On the other hand, FLS (AW) in the rightmost span has the highest utilisation ratio and is the governing failure mode. Another observation is that the utilisation in FLS (HFMI) is the lowest utilisation ratio in almost all parts of the bridge. Further, it can be noticed that the maximum utilisation, for the height L/30 in Figure 4.3, is in either ULS or FLS (AW) for different parts of the bridge.

4.1.2 Results for analysed details

This section presents the FLS utilisation ratios for all of the analysed details along the bridge length. The results consider utilisation for the as-welded state and after HFMI treatment. Figures 4.4-4.5 show the values of FLS (AW), whereas Figures 4.6-4.9 illustrate FLS (HFMI). The results are separately presented for the details located at the top and bottom of the cross-section and for the two different beam heights.

4.1.2.1 Utilisation before HFMI-treatment

As observed in Figures 4.4 and 4.5, the most critical points are located in the span section and the bottom attachments. Furthermore, detail 5 (rat-hole) is the governing detail in FLM3 in the bottom, throughout the bridge regardless of the height. At the top, detail 1 (transverse attachment) governs for both heights.

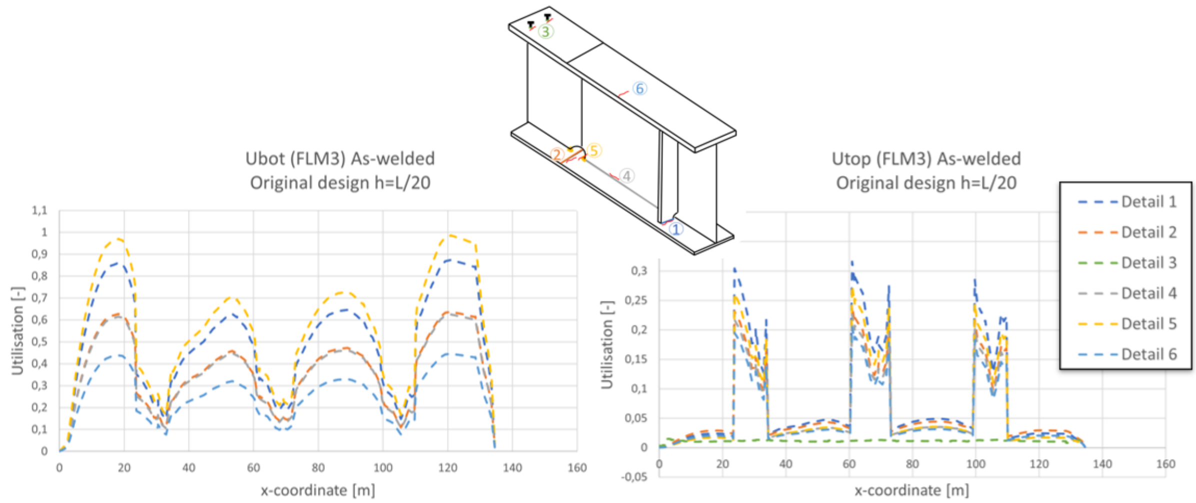

Figure 4.4: *The utilisation in bottom and in top for all details in as-welded state for S355 in the original design (h=L/20).*

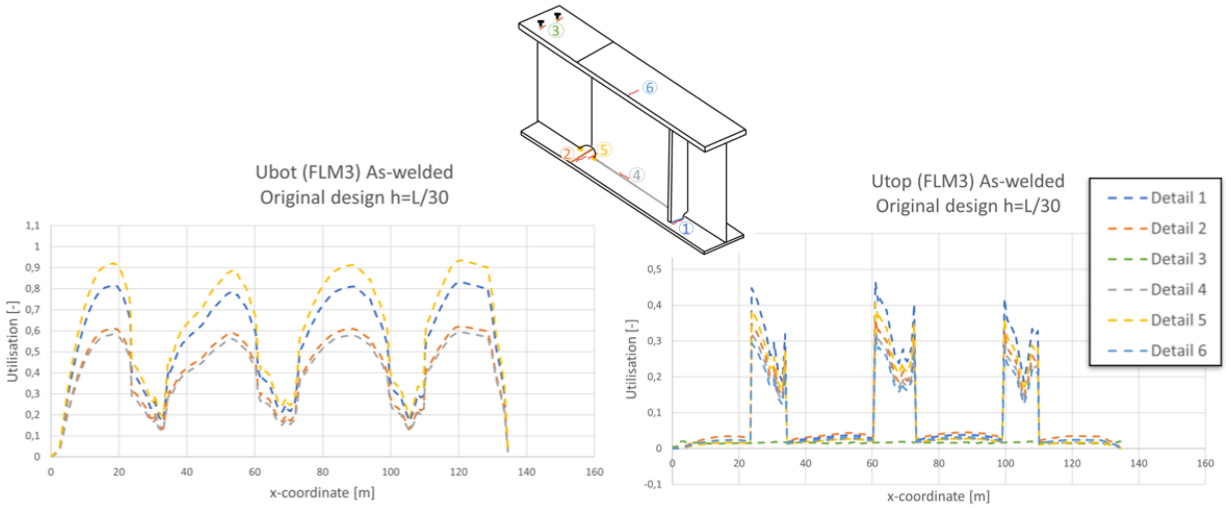

Figure 4.5: *The utilisation in bottom and in top for all details in as-welded state for S355 in the original design (h=L/30).*

4.1.2.2 Utilisation after HFMI-treatment

Following the implementation of HFMI-treatment, another detail is identified as the most critical. In this case, detail 1 (transverse attachment) is the most crucial at both top and bottom. This observation is further confirmed in Figure 4.12 and Figure 4.14 where detail 5 decreases the most in the bottom which makes detail 1 governing.

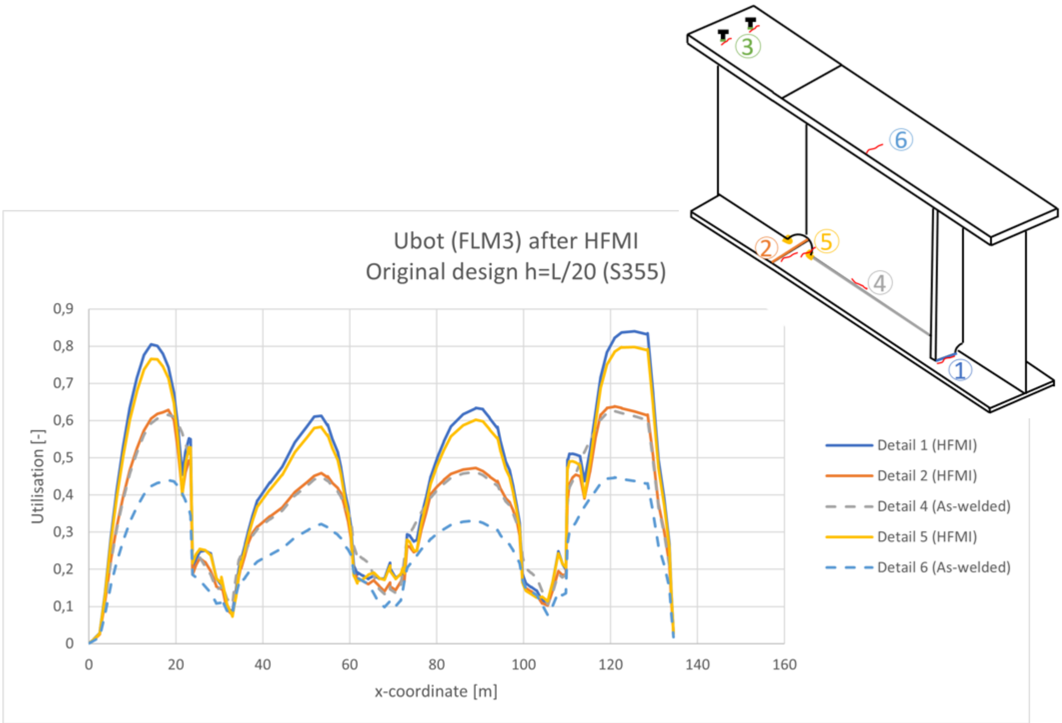

Figure 4.6: *The utilisation in the bottom for all details after HFMI-treatment for the original design (h=L/20). The dashed lines show the details that are not HFMI-treated.*

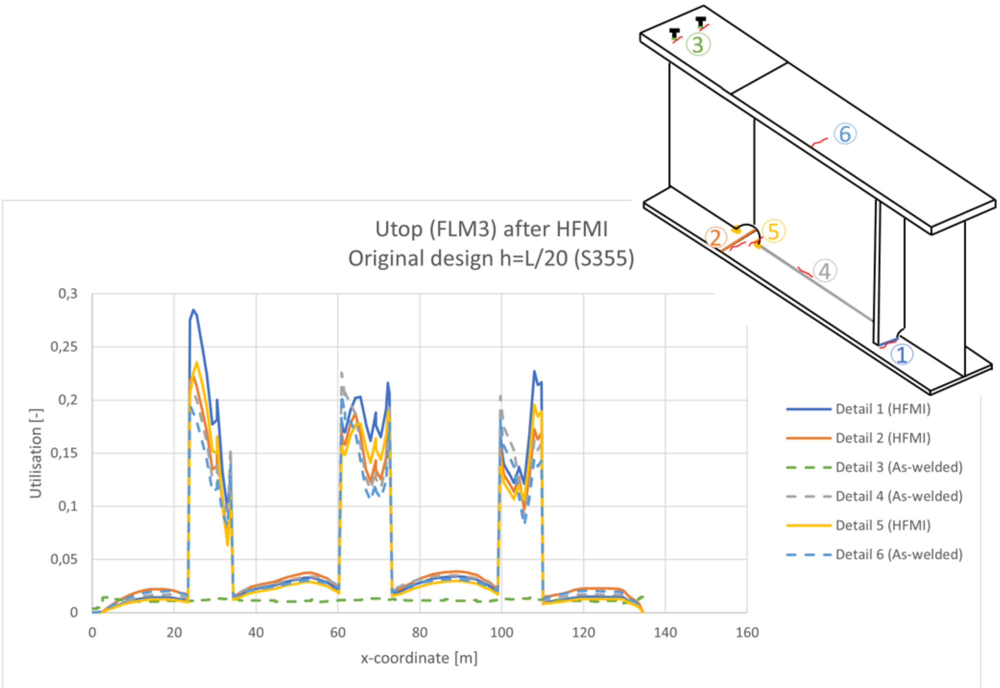

Figure 4.7: *The utilisation in top for all details after HFMI-treatment for the original design (h=L/20). The dashed lines show the details that are not HFMI-treated.*

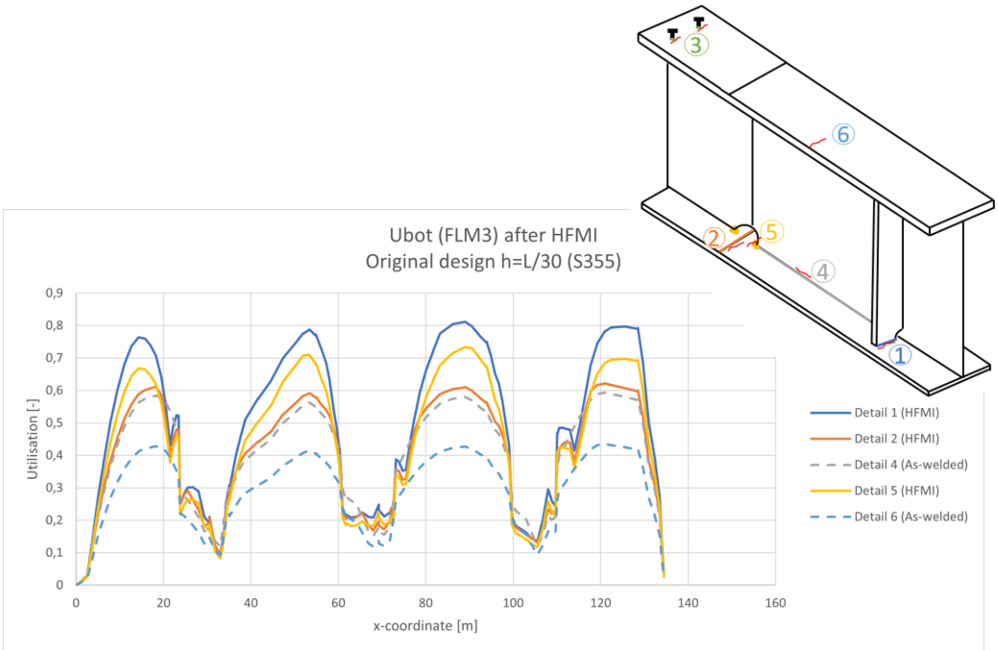

Figure 4.8: *The utilisation in the bottom for all details after HFMI-treatment for the original design (h=L/30). The dashed lines show the details that are not HFMI-treated.*

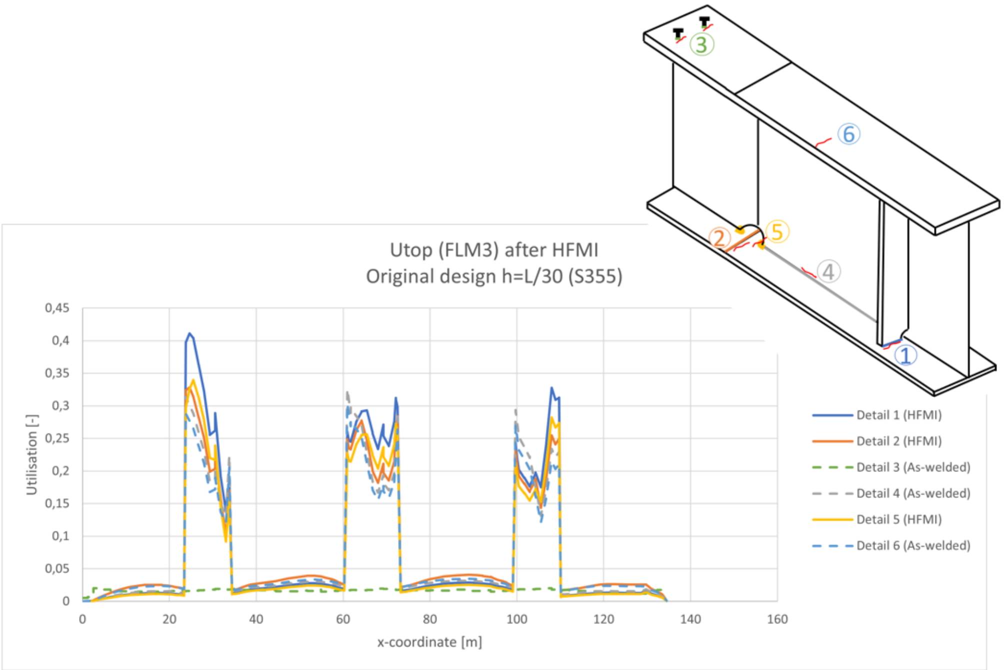

Figure 4.9: *The utilisation in top for all details after HFMI-treatment for the original design (h=L/30). The dashed lines show the details that are not HFMI-treated.*

Figures 4.10 and 4.11 show how the utilisation of FLS (HFMI) for all details is affected by higher steel strengths in the original design. It is evident that the utilisation for the HFMI-treated details decreases with higher steel strengths S460 and S690. Nevertheless, detail 1 is still governing in all cases.

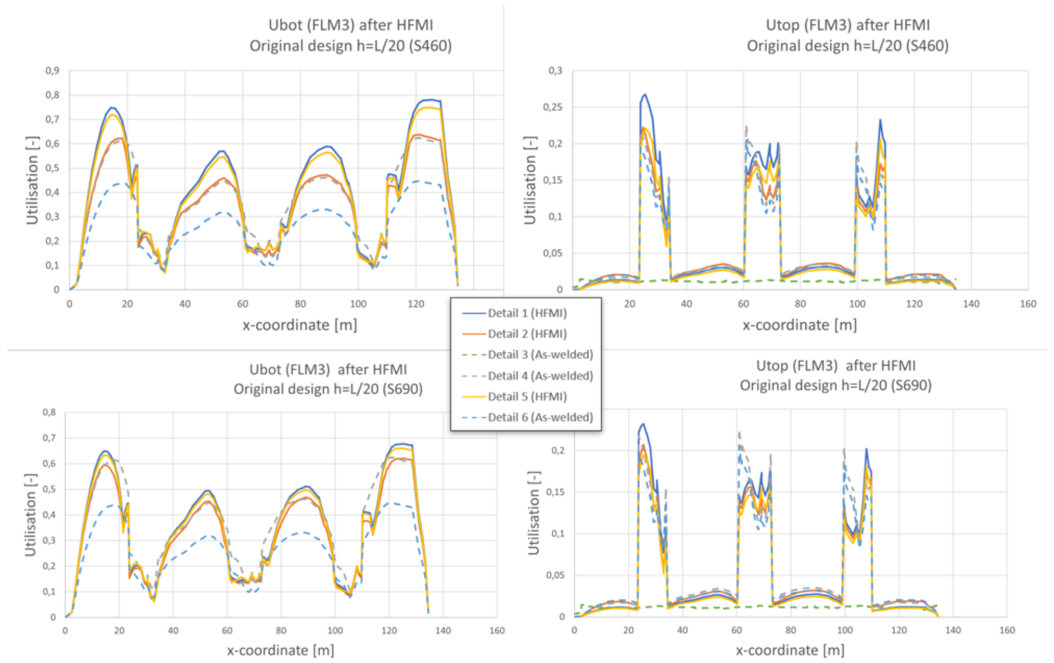

Figure 4.10: *The utilisation for all details in bottom and top after HFMI treatment for S460 and S690 in the original design (h=L/20). The dashed lines show the details that are not HFMI-treated.*

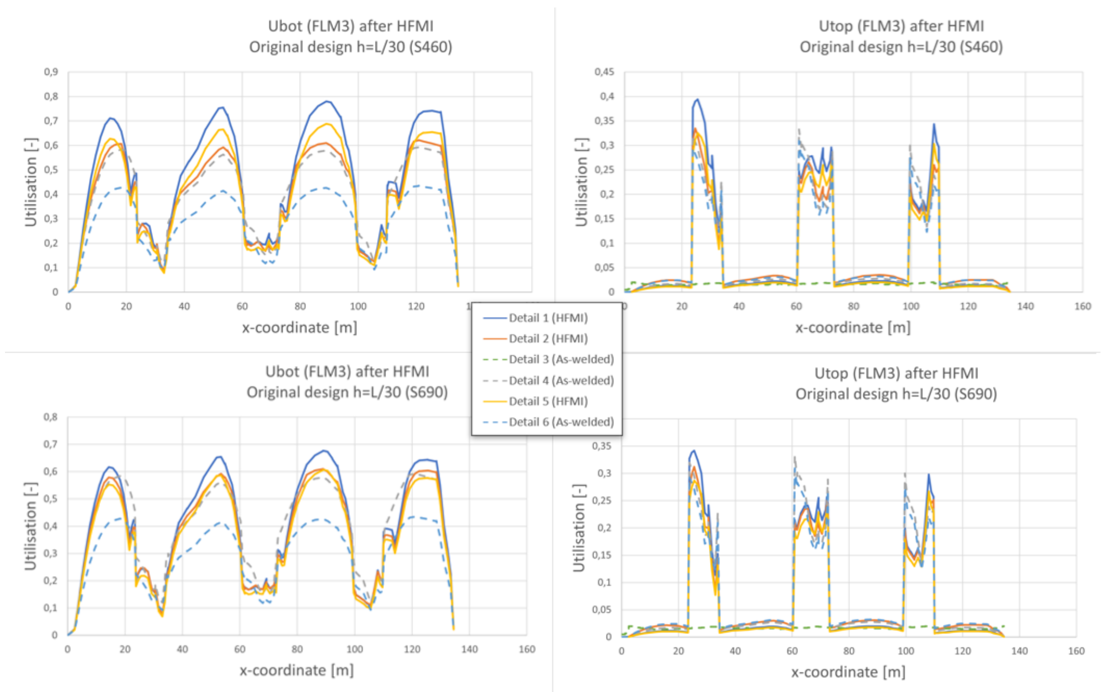

Figure 4.11: *The utilisation for all details in bottom and top after HFMI treatment for S460 and S690 in the original design (h=L/30). The dashed lines show the details that are not HFMI-treated.*

The utilisation for the details details with higher fatigue strength after HFMI treatment (transverse attachment, rat-hole and butt-weld) are presented in Figure 4.12-4.15 separately. The results are presented for the two different heights and for top and bottom individually. The results are also presented for utilisation in FLS (AW) and in FLS (HFMI) to observe the differences.. This allows for an easy comprehension of the influence of HFMI-treatment, in different parts of the bridge for the various details.

As observed in the figures, detail 5 (rat-hole) decreases significantly at both the top and the bottom. Detail 1 (transverse attachment) and detail 2 (butt-weld) does not decrease as much, thus detail 1 becomes governing. The reduction at the top is mainly noticeable at the highest peaks.

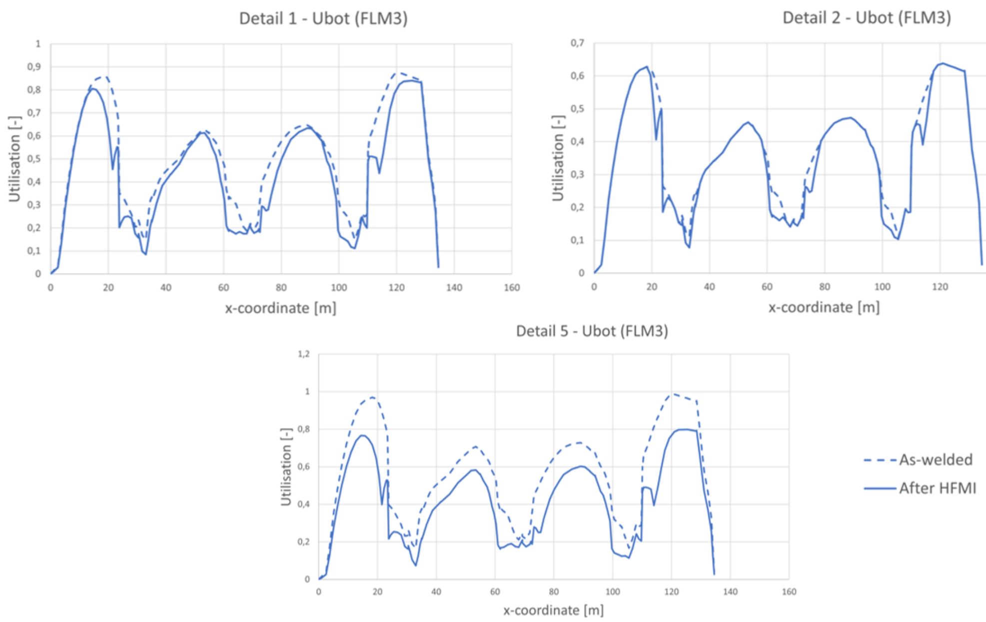

Figure 4.12: *The utilisation in the bottom in FLS (FLM3) for the HFMI-treated details 1, 2 and 5, over the bridge length. The result is presented for the original design with height h=L/20 and steel strength S355.*

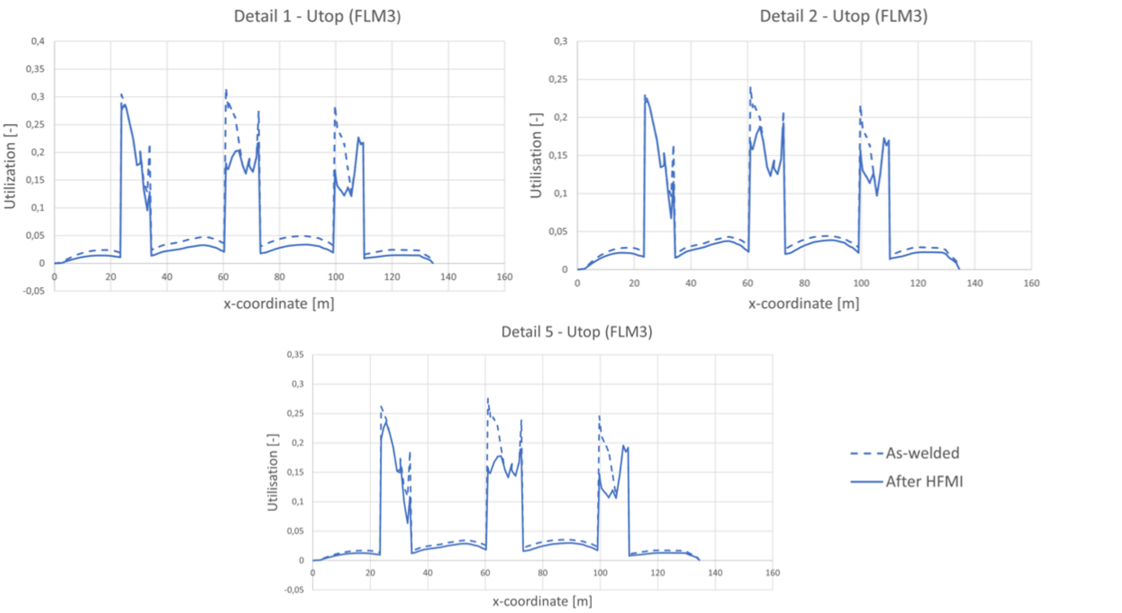

Figure 4.13: *The utilisation in top in FLS (FLM3) for the HFMI treated details 1, 2 and 5, over the bridge length. The result is presented for the original design with height h=L/20 and steel strength S355.*

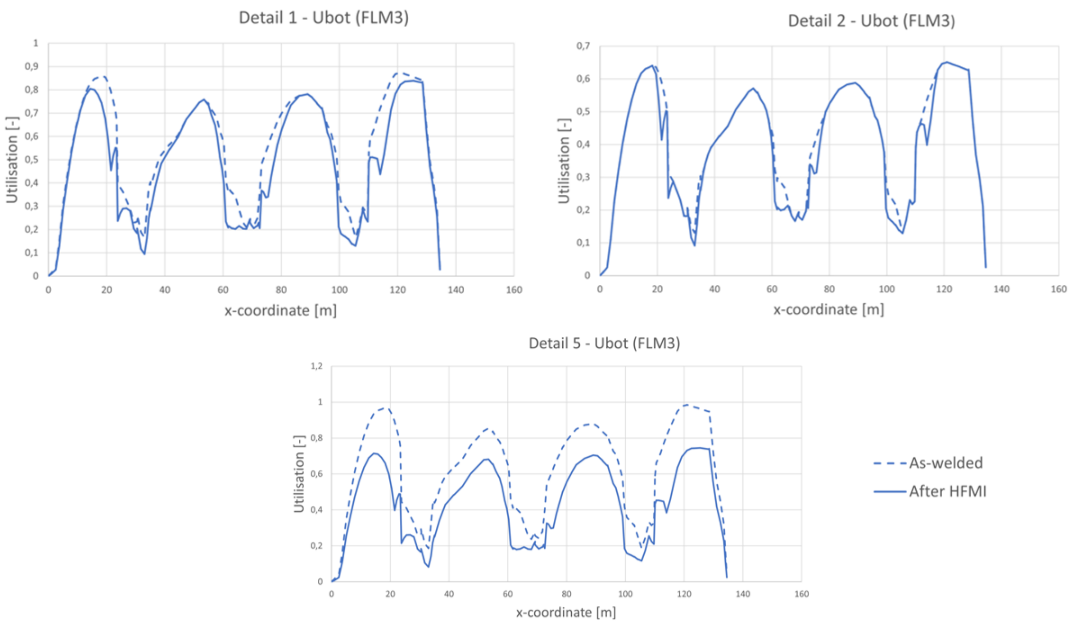

Figure 4.14: *The utilisation in the bottom in FLS (FLM3) for the HFMI treated details 1, 2 and 5, over the bridge length. The result is presented for the original design with height h=L/30 and steel strength S355.*

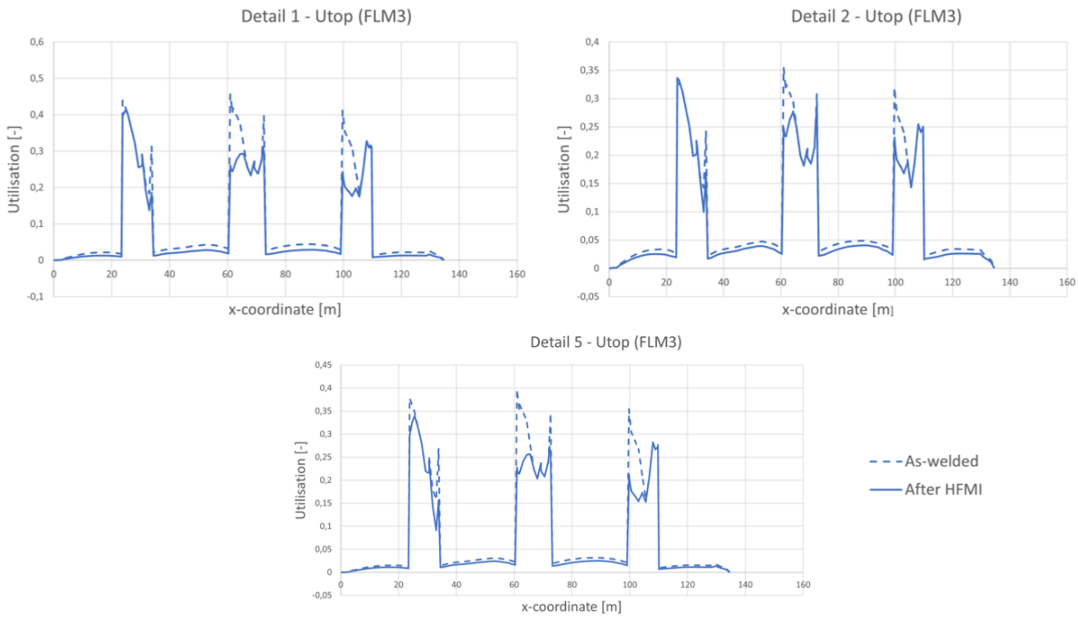

Figure 4.15: *The utilisation in top in FLS (FLM3) for the HFMI treated details 1, 2 and 5, over the bridge length. The result is presented for the original design with height h=L/30 and steel strength S355.*

4.2 New optimised design

A new optimised design is created based on the use of higher steel strengths S460 and S690. The optimisation aims to minimise the steel usage while achieving utilisation ratios close to 100% in design limit states. Tables A.1-A.4 in Appendix A.2 show the attained dimensions for the new designs.

Tables 4.5 and 4.6 present the maximum utilisation ratios for the new designs. For both designs, ULS is found to be the governing utilisation, followed by FLS (HFMI). FLS (AW) is further noticed to be significantly higher than 100%. Figure A.1-A.4 in Appendix A.3 shows the utilisation envelopes for ULS, FLS (AW), and FLS (HFMI).

Table 4.5: Utilisation ratios for the new design with h=L/20 for different steel strength.

h = L/20 = 1937.5 mm				
fy [MPa]	Umax ULS	Umax SLS	Umax FLS AW	Umax FLS HFMI
460	99.4%	25.6%	125.5%	99.4%
690	99.5%	52.0%	142.8%	99.0%

Table 4.6: Utilisation ratios for the new design with h=L/30 and different steel strength.

h = L/30 = 1291.7 mm				
fy [MPa]	Umax ULS	Umax SLS	Umax FLS AW	Umax FLS HFMI
460	99.5%	35.8%	115.9%	99.1%
690	98.8%	41.4%	142.9%	98.4%

4.2.1 HFMI-treatment on site (after bridge erection)

The same approach is followed when HFMI treatment is planned to be applied on-site after the bridge has been erected. As a result, the mean stress effects become negligible, as described in Section 2.9. Once again, new optimised designs were created for higher steel strengths S460 and S690. The utilisation ratios for the new designs are shown in Tables 4.7 and 4.8, and the new dimensions are presented in Tables A.5-A.8 in Appendix A.2.

As observed in Tables 4.7-4.8, ULS governs the design in all cases, except for when h=L/30 and steel strength is S690. Further, S460 has a lower utilisation in FLS (HFMI) than S690, whereas ULS is close to 100% in all different beam designs.

Table 4.7: Utilisation ratios for the new design with h=L/20 considering different steel strengths for HFMI-treatment after erection.

h = L/20 = 1937.5 mm AFTER ERECTION				
fy [MPa]	Umax ULS	Umax SLS	Umax FLS AW	Umax FLS HFMI
460	99.7%	29.3%	132.5%	84.0%
690	99.5%	30.4%	142.8%	99.0%

Table 4.8: Utilisation ratios for the new design with h=L/30 considering different steel strengths for HFMI-treatment after erection.

h = L/30 = 1291.7 mm AFTER ERECTION				
fy [MPa]	Umax ULS	Umax SLS	Umax FLS AW	Umax FLS HFMI
460	99.8%	39.0%	135.0%	85.6%
690	99.1%	47.8%	156.6%	99.3%

The utilisation envelope throughout the bridge considering before and after erection is presented in Figure 4.16 and 4.17. The figures shows a reduction in utilisation for FLS when comparing the curve for HFMI (before erection) and HMFI (after erection), which refers to implementation in workshop or on-site respectively.

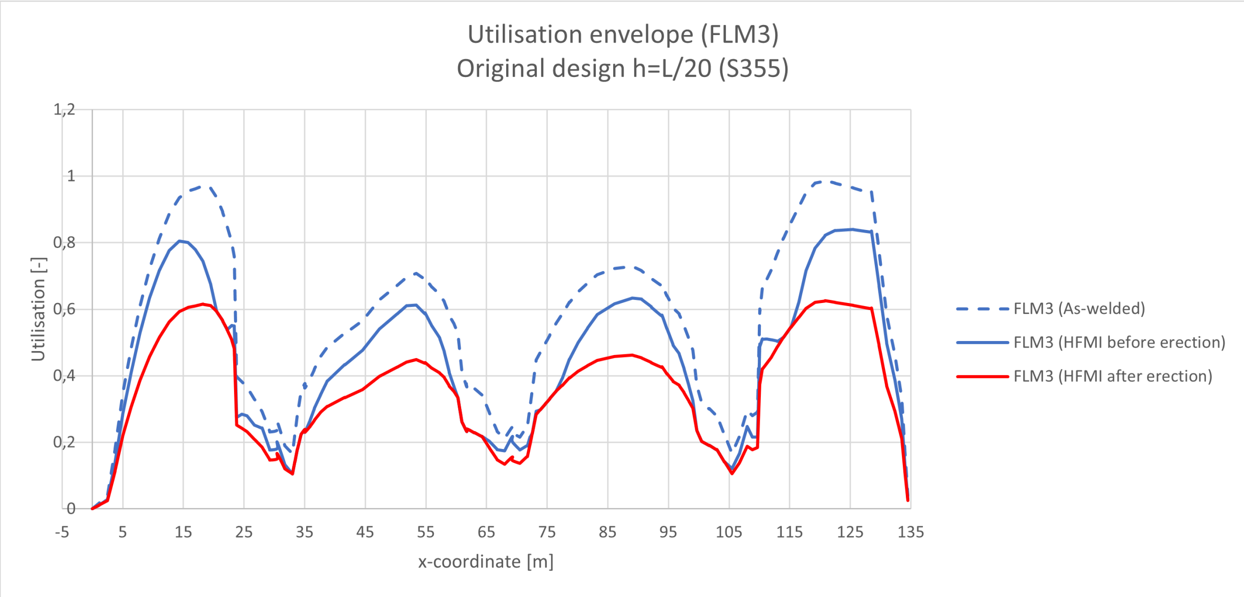

Figure 4.16: *The maximum utilisation in FLS (FLM3) for as-welded state, HFMI before erection and HFMI after erection for original design (h=L/20).*

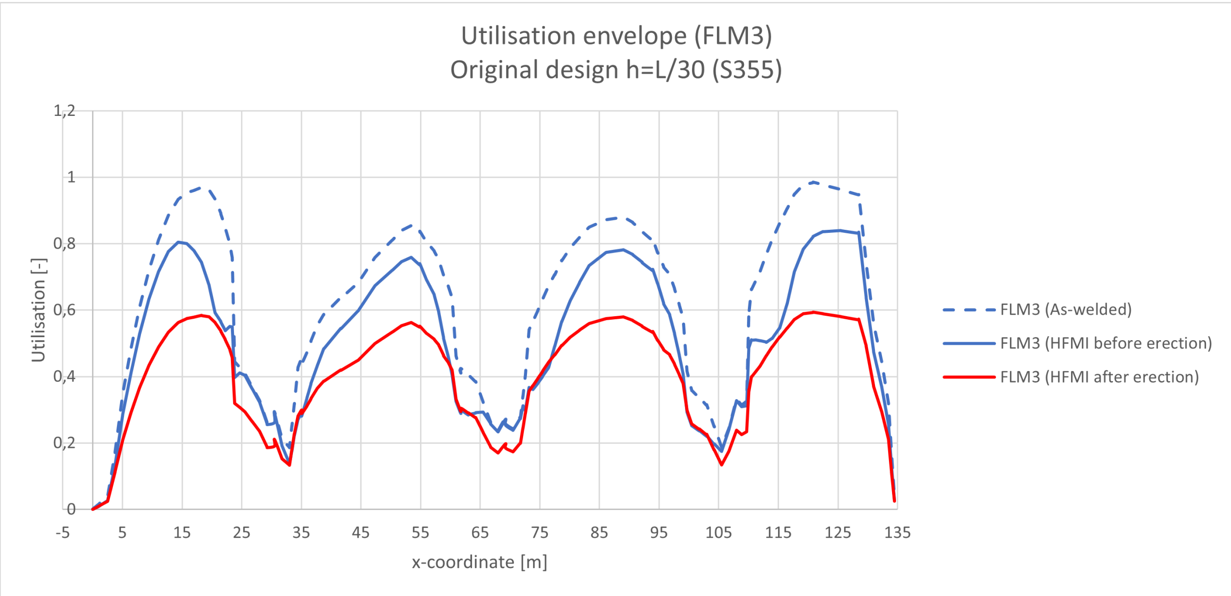

Figure 4.17: *The maximum utilisation in FLS (FLM3) for as-welded state, HFMI before erection and HFMI after erection for original design (h=L/30).*

4.3 Steel strength, HFMI and geometry effects

In this section, maximum utilisation ratios for ULS, FLS (AW) and FLS (HFMI) are presented in a step-wise diagrams. For every step, there is an additive modification, as described in Table 4.9.

Table 4.9: Description of the different steps in the step-wise modification.

Description of steps:	
1	Original design (S355, AW)
2	Increasing steel strength S460-S690 (AW)
3	Implementation of HFMI (S460-S690)
4	Optimisation of geometry

Results for the total beam height of h=L/20m are presented in Figure 4.18, and for h=L/30m in Figure 4.19. Utilisation in FLS (HFMI) for the original design (S355) is presented in step three, to easily compare the FLS-values for different steel strengths. The maximum utilisation in SLS is disregarded in the diagram since it is not governing in any case.

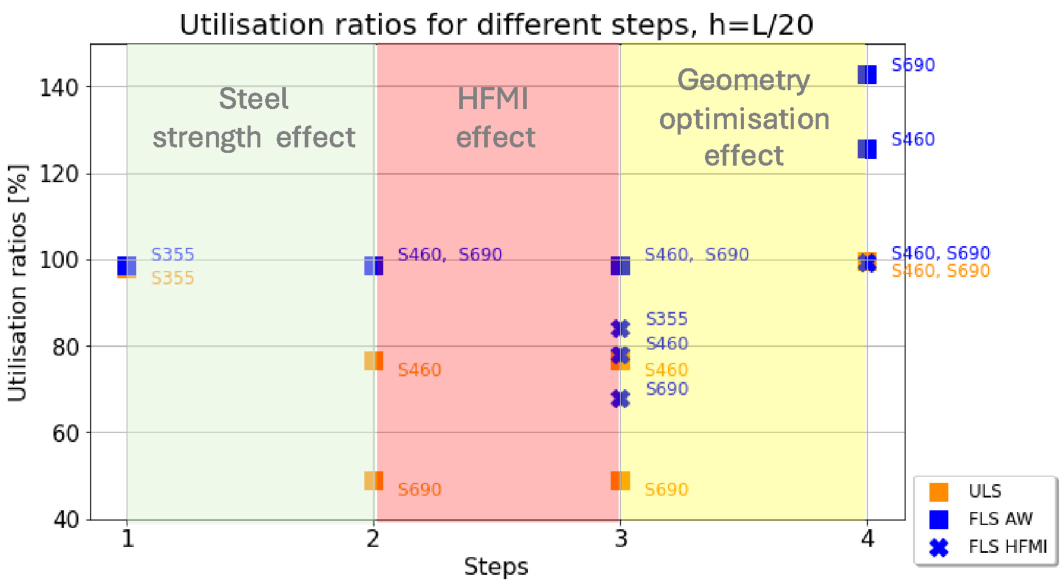

Figure 4.18: *Change in utilisation ratio for h=L/20 in different steps considering steel strength effect, HFMI effect and geometry optimisation effect.*

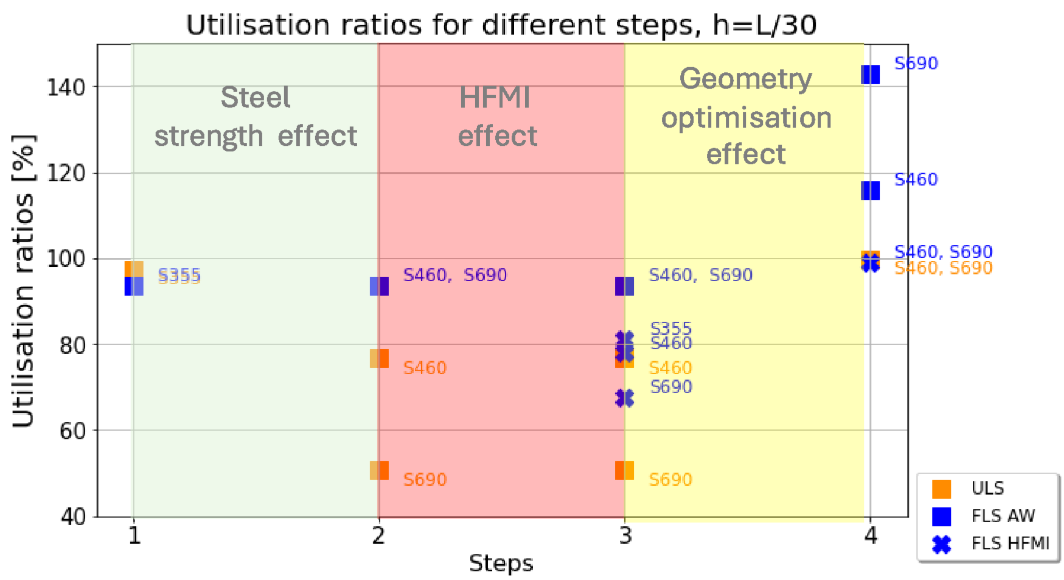

Figure 4.19: *Change in utilisation ratio for h=L/30 in different steps considering steel strength effect, HFMI effect and geometry optimisation effect.*

It can be seen, in Figure 4.18 and 4.19, that the utilisation ratio in ULS decreases with higher steel strength. The FLS (AW) value is constant when the steel material is changed. When implementing the HFMI-treatment in step three the FLS values (marked with a blue cross) decrease, where greater reduction is obtained for higher steel strengths. When the geometry is optimised in step 4, the utilisation in ULS and FLS (HFMI) is close to 100% again while the FLS (AW) values are well above 100%.

Figures 4.20 and 4.21 show the maximum utilisation ratio obtained if HFMI is applied after bridge erection for the two heights h=L/20mm and h=L/30mm, respectively. The change in utilisation in Figure 4.20 and 4.21 follows the same pattern as described before erection. However, it is noted that the effect on utilisation in step 3 for FLS (HFMI) is consistent for all steel strengths.

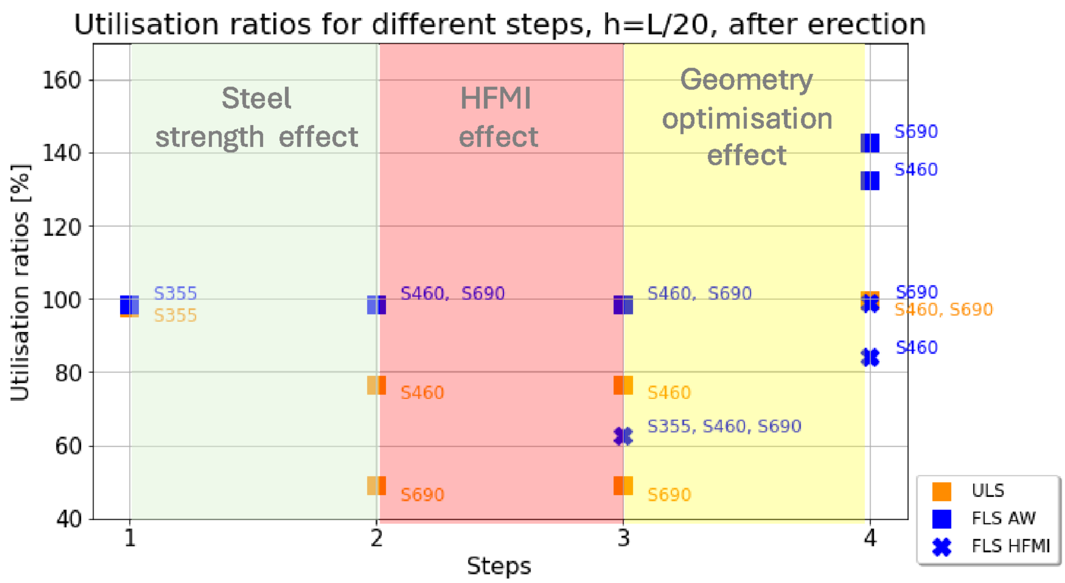

Figure 4.20: *Change in utilisation ratio for h=L/20 after erection, in different steps considering steel strength effect, HFMI effect and geometry optimisation effect.*

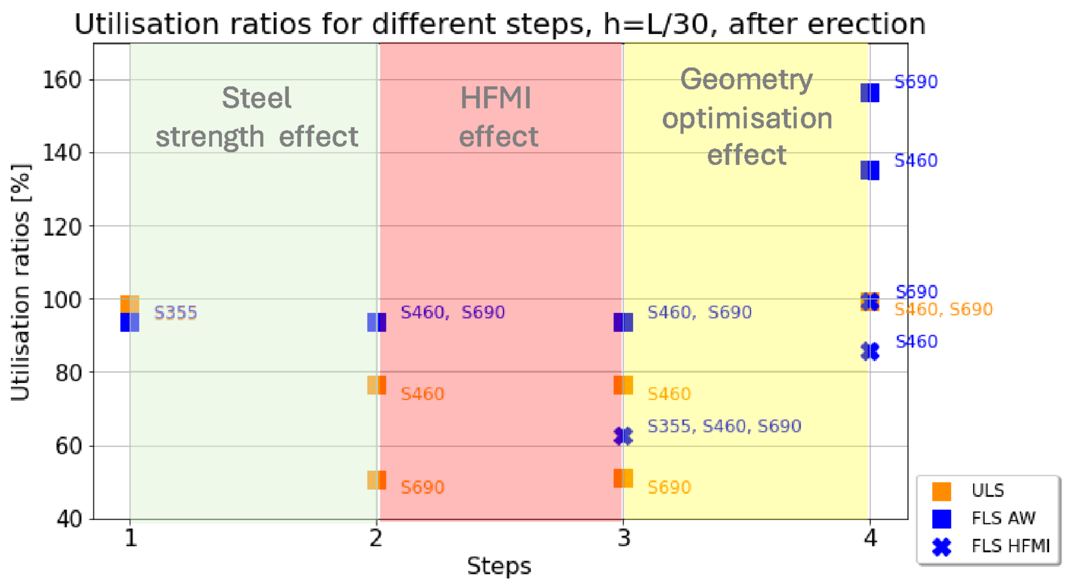

Figure 4.21: *Change in utilisation ratio for h=L/30 after erection, in different steps considering steel strength effect, HFMI effect and geometry optimisation effect.*

4.4 Material & cost savings

This section presents the cost and steel usage for the original and optimised designs in different steel strengths. The estimated cost of HFMI-treatment is presented in Table 4.10.

Table 4.10: Estimated cost of HFMI-treatment in relation to total cost of the main girder (including material cost and treatment cost).

Cost of HFMI [MSEK]	Percentage of total cost (L/20 S355)	Percentage of total cost (L/30 S355)
0.091	3.9 %	3.7 %

The possibility of achieving steel savings with the new optimised designs with higher steel strength is presented in Tables 4.11 and 4.11. The presented costs, for the designs where HFMI is implemented, includes the material cost and the estimated cost of HFMI-treatment. Furthermore, the price difference between the upgraded and original designs is shown. The green marks indicate a cost-saving while the red marks indicate an increase of the cost. The results for designs where HFMI is applied prior to erection are displayed below.

Table 4.11: Results for cost and steel usage for the main steel girder beams, considering original design (h=L/20) and optimised designs with different steel strengths.

h = L/20 = 1937.5 mm				
Design:	Steel usage [tone]	Steel saving [%]	Cost [MSEK]	Cost difference [%]
Original design (AW) (S355)	225.6	-	2.26	-
Optimised design (HFMI) (S460)	126.1	44.1	1.46	35.5
Optimised design (HFMI) (S690)	111.5	50.6	2.24	0.9

Table 4.12: Results for cost and steel usage for the main steel girder beams, considering original design (h=L/30) and optimised designs with different steel strengths.

h = L/30 = 1291.7 mm				
Design:	Steel usage [tone]	Steel saving [%]	Cost [MSEK]	Cost difference [%]
Original design (AW) (S355)	239.7	-	2.40	-
Optimised design (HFMI) (S460)	173.4	27.7	1.97	17.9
Optimised design (HFMI) (S690)	136.8	42.9	2.72	13.6

The same results as above are shown in Tables 4.13 and 4.14, however for the optimised designs when HFMI treatment is applied after bridge installation. The tables demonstrate how the new designs save a significant amount of material. However, the financial benefit of raising the steel strength to S690 is negligible or nonexistent. When steel S460 and the largest beam height of L/20 are used, the cost savings become the largest.

Table 4.13: Results for cost and steel usage for the main steel girder beams, considering original design (h=L/20) and optimised designs with different steel strengths and HFMI-treatment after erection.

HFMI after erection - h = L/20 = 1937.5 mm				
Design:	Steel usage [tone]	Steel saving [%]	Cost [MSEK]	Cost difference [%]
Original design (AW) (S355)	225.6	-	2.26	-
Optimised design (HFMI) (S460)	118.5	47.5	1.37	39.1
Optimised design (HFMI) (S690)	111.5	50.6	2.24	0.9

Table 4.14: Results for cost and steel usage for the main steel girder beams, considering original design (h=L/30) and optimised designs with different steel strengths and HFMI-treatment after erection.

HFMI after erection - h = L/30 = 1291.7 mm				
Design:	Steel usage [tone]	Steel saving [%]	Cost [%]	Cost difference [MSEK]
Original design (AW) (S355)	239.7	-	2.40	-
Optimised design (HFMI) (S460)	167.4	30.2	1.90	20.6
Optimised design (HFMI) (S690)	112.0	53.3	2.25	6.3

5
Discussion

The impact of HFMI treatment on bridge optimisation is investigated in this thesis. The effect is measured by first introducing an original design that is optimised in ULS and FLS (AW). Following that, adjustments are performed to account for steel strength, HFMI-treatment, and geometry optimisation effect. Steel strength is increased to 460 MPa and 690 MPa, and HFMI-treatment is investigated when applied before and after bridge installation which implies different mean stress effects. Moreover, geometry is optimised by adjusting the thicknesses and widths of the plates in the main steel girder.

The study results in a significant decrease in utilisation ratios in FLS when HFMI-treatment is applied. Since the utilisation is close to 100% in both ULS and FLS for the original design, both an increase in steel strength and HFMI-treatment are required to improve the geometry of the girder. The new optimised design provides a lower steel usage resulting in material savings. The maximum stresses in characteristic combination are analysed over the bridge and it is found that this is not limiting in either tension or compression members even for the lowest studied steel grade (S355). This concludes that there is no risk of relaxation of the induced compressive stresses by treatment.

A remarkable pattern when analysing the utilisation envelopes is that HFMI is more beneficial in span section compared to support section as defined in Figure 3.6. This is clearly seen in Figure 4.16 where the utilisation in span for both before and after erection benefits the most from HFMI. Additionally, HFMI-treatment results in lower utilisation ratios for all the studied details. This is determined by observing the change in utilisation for each specific detail individually. The largest improvement is seen for detail 5 (rat-hole), where the utilisation ratio reduces the most over the bridge. In some places of the bridge, the benefit of HFMI is limited by the high applied stress range. This is seen in Figure 4.6 where in some points there is no change in FLS (HFMI) utilisation in the detail envelope, especially for detail 1 and detail 2. The explanation is that the benefits of HFMI are limited and therefore the as-welded curve in the S-N diagram is followed, as seen in Figure 2.9. The fatigue strength curve of an HFMI-treated detail can only be used when the stress range is below $\Delta\sigma_s/\gamma_{Mf}$, as explained in Section 2.6.2.

Furthermore, there are nearly endless ways for optimising the girder geometry, which determines the behaviour of the structure. The primary goal of this study is to investigate the possibility of saving a significant amount of material by experimenting with various dimensions. The obtained design contributes to acceptable results. However, there may be several other geometries that might offer a better bridge design and reduce the amount of steel usage even more. It is important to note that the material savings mentioned only apply to the main girder beams. The percentage of the material saving would be smaller if the original steel volume included all of the steel details in the total amount of steel.

The dimensions of the cross-section (thicknesses and widths) can be significantly reduced throughout the geometry optimisation process, leading to substantial material savings. One limitation of the study is that it has not considered the influence of lateral torsional buckling (LT-buckling), which could affect the top flange thickness for composite bridges (Shams Hakimi, 2020). If LT-buckling is the primary cause of failure, then the top flange dimensions can not be reduced as much, resulting in less material savings. However, this can be avoided if lateral bracing is provided in the construction stage to provide lateral stability of the top flange.

Moreover, applying HFMI-treatment on-site results in the absolute maximum material savings. This confirms that the extent of increase in FAT-class from treatment is, as noted from the results, significantly influenced by the mean stress impact derived from self-weight. However, there are some challenges when implementing the treatment on-site. One important difficulty is establishing quality controls to ensure that the treatment has been implemented correctly. The promised improvement cannot be guaranteed if the treatment is not performed appropriately in accordance with the guidelines (Al-Emrani et al., 2024). Thus, implementing it in a workshop might be more advantageous.

When the steel strength is increased to 690 MPa, the largest material savings are attained. However, since the price of the material has almost doubled, implementing high steel strength S690 is resulting in negligible financial savings. Staying at a steel strength of S460 appears to be more cost-effective. However, it can be beneficial to use S690 when there are limitations on the beam heights. It provides an opportunity to obtain a slender beam with a relatively small height for the same material cost.

It should be emphasised that the estimation of the HFMI treatment cost is made under the presumption that every possible detail is treated throughout the bridge. This would most likely not be required. By looking at the diagram of the utilisation envelope for the details, it can be determined where it is more beneficial to implement the treatment. However, since HFMI is not expensive in relation to the total costs a shown in Table 4.10, there would be no significant difference in cost savings to leave out some details.

Furthermore, when HFMI is applied on-site, the girder utilisation reduces to the extent that an as-welded detail in FLS limits the design for the strength of S355 steel. In this case, it is the longitudinal weld between the flange and web, which has a FAT-class of 112 MPa. Hence, the FAT-class is restricted to that value. Consequently, if FLS (AW) is the governing failure limit, there is no need to raise the steel strength. Additionally, as the butt weld has a FAT-class of 112 in its as-welded state and cannot be improved, there is no need of HFMI-treating it.

The potential of lower utilisation is larger with FLM4 because is not as conservative as FLM3. This might result in even greater material savings, especially when combined with higher steel strengths than those studied in this thesis. Nonetheless, if ULS is the governing failure mode, then it would be irrelevant to use FLM4 as it does not lower the governing utilisation.

The most conservative traffic category in Eurocode is selected for the fatigue load models. In other countries where there is heavier traffic, and other standards are used, fatigue may be an even larger issue. In addition, since design vehicles are not included in the traffic loads, then the resulting axle loads may not provide the worst influence on fatigue. If they were to be incorporated, the fatigue limit state may be more governing, which would increase the significance of the topic in this thesis.

Additionally, the number of lanes affects the mean stress effect and this study only covers three lanes. More lanes lead to a wider slab width which increases the self-weight. This will lead to a further reduction of the HFMI effect. The type of concrete also affects the mean stress effect in the same way (light-weight concrete is an example). Furthermore, the mean stress effect reduces if the thickness of the concrete slab decreases, as this would also lead to a lower self-weight. In those cases, the motivation for implementing HFMI-treatment on-site to reduce the mean stress effect becomes stronger.

Compared to other studies, more effects are included in this study, for example, the mean stress effect and the effects of overloads. In addition, the analyses presented in this thesis are more detailed and less simplified. Despite that, the conclusions drawn by earlier studies mentioned in the literature, by for example Poja Shams-Hakimi and Hassan Al-Karawi, are correct that HFMI is beneficial and that material savings can be made. It is important to note that the obtained results are for specific case studies. Shams-Hakimi found that the material saving is 20% (Shams Hakimi, 2020) when implementing HFMI on a railway bridge without increasing steel strength. This study resulted in an even larger material saving of approximately 50% for a road bridge by implementing HFMI and increasing steel strength. It should however be noted that the material saving in this study is only calculated for the main girders.

6
Conclusion

The thesis aims to determine whether material savings can be gained by using HFMI treatment and enhancing steel strength. The goal is to obtain optimal design for new bridges. Design rules for HFMI-treatment are implemented and steel strength is increased on a caste study bridge, while also considering different application phases. After studying the effect of HFMI-treatment together with the use of higher steel grades, it can be concluded that fatigue performance is enhanced and there is remarkable material savings. Considering the results from the study:

- Implementing HFMI-treatment and increasing steel strength in new bridge design is highly advantageous. The steel usage for this case study is significantly reduced which produces a light structure. It reduces transportation costs and makes the installation easier. Furthermore, the material reductions create a more sustainable construction overall. For structures that have a cross-sectional height limit, there is still room for obtaining a slender girder structure.

- High stress ranges that exceed the limit for $\Delta\sigma_s$, can limit the improvement of HFMI for some details over the bridge. This is because the fatigue strength curve of an HFMI-treated detail can only be used when the stress range is below $\Delta\sigma_s/\gamma_{Mf}$. In addition, HFMI-treatment can reduce the utilisation to the extent that an as-welded detail in FLS limits the design. Hence, the FAT-class is restricted to the value of the as-welded detail. Consequently, increasing the steel strength is not necessary if FLS (AW) is the governing limit state.

- For this specific case study there is a remarkable potential for material savings up to 53.3%. The best steel strength option for material saving in design for this case study is 690 MPa. Additionally, implementing HFMI on-site provides the largest material savings. However, performing it in a workshop might be more advantageous because the complexity of applying treatment on-site is avoided, and the treatment quality control is easier. Thus, the most economical option is to choose a steel strength of S460 due to the significant cost savings that can be made. The cost savings for S690 can be negligible as the material cost is almost double compared to S355. Furthermore, the estimated cost of implementing HFMI is insignificant in relation to the total cost of the girders and can also be negligible.

- By analysing result envelopes it is observed that the reduction of utilisation is mostly beneficial over the span section. In addition, it can be determined where to implement the details and HFMI-treatment for maximum benefit.

- The thesis resulted in similar conclusions as earlier studies, even if it evaluated more effects that could have an impact on the benefit of HFMI. One of the effects is the overloads, however, it is not an issue for this bridge design as the applied characteristic stresses do not exceed the maximum stress limits in either the top or bottom. Therefore, HFMI can be implemented in all details.

Suggestions for further studies:

- The parameters of the study could be expanded to include a wider variety of materials and structural geometries.
- Consider different traffic volumes and codes. The traffic categories in this study are limited to Eurocode and the Swedish national regulations.
- Study other types of bridges, for example, truss, pedestrian and railway bridges.
- Evaluating HFMI in the construction phase, to investigate if there will be additional limitations.

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A
Appendix 1

A.1 RKFM

RKFM - Road bridge over Storån in Söderköping

Master Thesis
Saffa Dagduk
Cecilia Englund

Contents

1 Principle design

The bridge is a road bridge with twin I-girders made of steel and a slab made of concrete. A simplified cross-section is presented in Figure 1 and the static system in Figure 2.

Data input from original design plan:

- Total length of bridge: 149.4 m
- Width: 14.40 m
- Width between I-girders: 8.0 m
- Length betwen support 1 and 2: 28.00 m
- Length betwen support 2 and 3: 38.75 m
- Length betwen support 3 and 4: 38.75 m
- Length betwen support 4 and 5: 28.00 m

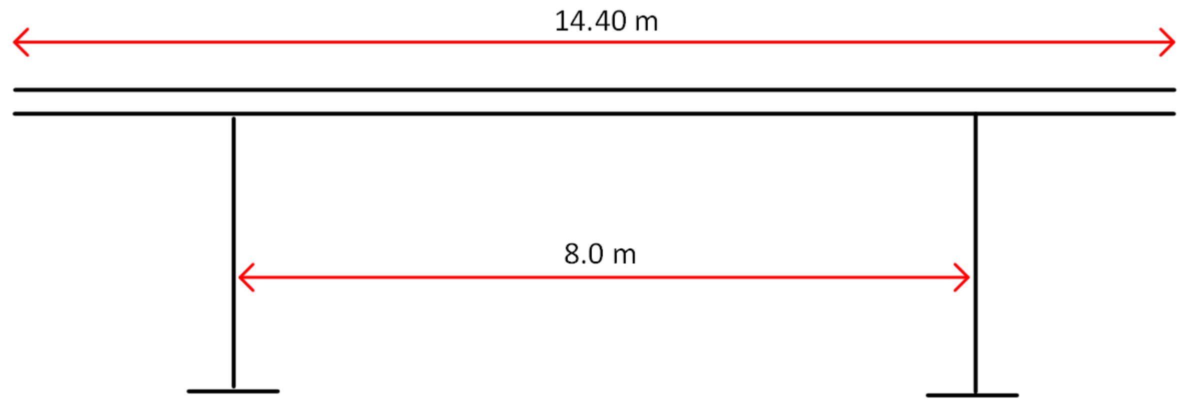


Figure 1: *Cross-sectional design of the bridge.*

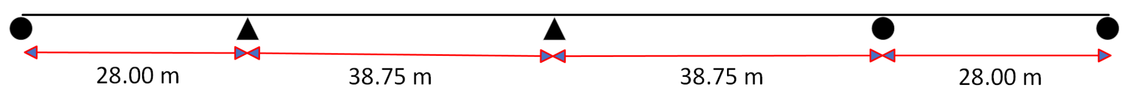


Figure 2: *Static system of the bridge.*

2 Material

Used materials will be steel and concrete. There is also asphalt coating and a waterproofing mat on the concrete slab. Additionally, a railing will be taken into consideration.

2.1 Steel

Table 1: Steel quality properties from Eurocode EN 10025-2:2004

Steel quality	**Nominal thickness [MPa]**	$R_{eH}(f_y)$ **[MPa]**	$R_M(f_u)$ **[MPa]**
S355J2	t$\leq$16mm	355	470
S355J2	16mm$<$ t $\leq$ 40mm	345	470
S355J2	40mm$<$ t $\leq$ 63mm	335	470

Table 2: Steel quality properties from Eurocode EN 10025-2:2004

Steel quality	**Nominal thickness [MPa]**	$R_{eH}(f_y)$ **[MPa]**	$R_M(f_u)$ **[MPa]**
S420	t$\leq$16mm	420	520
S420	16mm$<$ t $\leq$ 40mm	400	520
S420	40mm$<$ t $\leq$ 63mm	390	520

Table 3: Steel quality properties from Eurocode EN 10025-2:2004

Steel quality	**Nominal thickness [MPa]**	$R_{eH}(f_y)$ **[MPa]**	$R_M(f_u)$ **[MPa]**
S460	t$\leq$16mm	460	530
S460	16mm$<$ t $\leq$ 40mm	440	530
S460	40mm$<$ t $\leq$ 63mm	430	530

Table 4: Partial coefficients steel (EN1992 and EN1999).

Design situation	**Load bearing capacity**	**Instability**	**Tensile failure**	**Connections**
ULS	$\gamma_{M0} = 1.0$	$\gamma_{M1} = 1.0$	$\gamma_{M2} = 0.9f_u/f_y \leq 1.1$	$\gamma_{M2} = 1.25$
SLS	$\gamma_{M0} = 1.0$	$\gamma_{M1} = 1.0$	$\gamma_{M2} = 1.0$	$\gamma_{M2} = 1.0$
FLS	$\gamma_{Mf} = 1.35$	-	-	-

Other material parameters:
Modulus of elasticity: $E_s = 210$ GPa
Shear modulus: $G_s = 81$ GPa
Thermal expansion coefficient: $\alpha_s = 12 \cdot 10^{-6}$ 1/C (EN1991 1-5 - Table C.1) (For composite structures: the linear thermal expansion coefficient can be set to $\alpha_s = 10 \cdot 10^{-6}$ 1/C. This leads to that forces due to constraints can be neglected.

2.2 Concrete

Table 5: Properties of concrete from Eurocode 2

Class	$f_{ck}[MPa]$	$f_{cm}[MPa]$	$f_{ctk0.05}[MPa]$	$f_{ctm}[MPa]$	$f_{ctk0.95}[MPa]$	$E_{cm}[GPa]$
C35/45	35	43	2.2	3.2	4.2	34

Table 6: Partial coefficients concrete (SS-EN 1992-1-1 2.4.2.4, table 2.1N.

Design situation	Concrete γ_c
ULS	1.5
SLS	1.0
FAT	1.2

Other material parameters:
Thermal expansion coefficient: $\alpha_c = 10 \cdot 10^{-6} 1/C$ (EN1991 1-5 - table C.1)

2.3 Reinforcement

Table 7: Properties of reinforcement from Eurocode 2

Reinforcement	$f_{yk}[MPa]$	$E_s[GPa]$
Ks600S	600	200

Table 8: Partial coefficients reinforcement (SS-EN 1992-1-1 2.4.2.4, table 2.1N.

Design situation	Reinforcement γ_s
ULS	1.15
SLS	1.0
FAT	1.0

3 Safety categories, loads and load combinations

3.1 Safety categories

The safety class is retrieved from the stuctural plan of the bridge. The partial factors are from TSFS 2018:57, chapter 2, paragraph 8.

Table 9: *Safety classes and partial factors.*

Bridge	SK3	$\gamma_d = 1.0$
Geotecnical bearing capacity	SK2	$\gamma_d = 0.91$

3.2 Permanent loads

Self-weight for each material: (TRVINFRA-00331 table 8-1 and TRVINFRA-00227 chapter 7.1.6.1.1)

Steel: $\gamma = 78kN/m^3$

Concrete: $\gamma = 25kN/m^3$

Asphalt coating: $\gamma = 24kN/m^3$

Waterproofing mat: $\gamma = 22kN/m^3$

Railing: $\gamma = 1kN/m$

3.3 Variable loads

3.3.1 Traffic loads

The traffic loads are presented according to LM1 recommendations. Table 4.2, in Eurocode EN 1991-2, gives recommended values for traffic loads in form of point loads and distributed loads.

Table 10: *LM1 characteristic values*

Location	Axle loads Q_{ik} (kN)	Distributed loads q_{ik} (kN/m^2)	α_{Qi}	α_{qi}
Lane 1	300	9	0.9	0.8
Lane 2	200	2.5	0.9	1
Lane 3	100	2.5	0	1
Other lanes	0	2.5	0	1
Remaining area	0	2.5	0	1

3.3.2 Braking force

According to Eurocode 1991-2, chapter 4.4.1, the braking force should be calculated as following for LM1:

$$Q_{lk} = 0.6\alpha_{Q1} \cdot (2Q_{1k}) + 0.1\alpha_{q1} \cdot q_{1k} \cdot w_1 \cdot L \tag{1}$$

Where L i the length of deck and w_{l1} is the lane width.

Limitation for braking force:

$$180\alpha_{Q1}(kN) \leq Q_{lk} \leq 900(kN) \tag{2}$$

3.3.3 Temperature loads

Geographical location: Söderköping
Bridge type: 2 (steel and concrete composite bridge)

Uniform temperature:
Uniformly distributed temperature (according to SS-EN 1991-1-5 6.1.3).

- $T_{max} = 36°C$ Maximal air temperature (SS-EN 1991-1-5 figure 2a).
- $T_{min} = -32°C$ Minimal air temperature (SS-EN 1991-1-5 figure 2a).
- $T_0 = 10°C$ Installation temperature (SS-EN 1991-1-5 section A.1).
- $T_{e.max} = 40°C$ Maximum uniformly distributed temperature (SS-EN 1991-1-5 figure 6.1, type 2).
- $T_{e.min} = -27°C$ Minimum uniformly distributed temperature (SS-EN 1991-1-5 figure 6.1, type 2).
- $\Delta T_{N.con} = -(T_0 - T_{e.min}) = -37°C$ Contraction (SS-EN 1991-1-5 section 6.1.3.3 - equation 6.1).
- $\Delta T_{N.exp} = T_{e.max} - T_0 = 30°C$ Expansion (SS-EN 1991-1-5 section 6.1.3.3 - equation 6.2).
- $\Delta T_N = T_{e.max} - T_{e.min} = 72°C$ Total temperature difference (SS-EN 1991-1-5 section 6.1.3.3 - ANM.1).

Vertical, linear temperature change:
Method 1: (EN1991-1-5 6.1.4).

- $\Delta T_{M,heat} = 15°C$ Overside warmer then underside (SS-EN 1991-1-5 table 6.1).
- $\Delta T_{M,cool} = 18°C$ Underside warmer then overside (SS-EN 1991-1-5 table 6.1).

3.4 Load combinations

All actions considered unfavourable.

Table 11: *Design values for actions*

Load	Partial factor	Design value
Permanent	$\gamma_{G,j}$	1.35
Variable	$\gamma_{Q,1}$	1.5
Variable	$\gamma_{Q,i}$	1.5

Ultimate Limit State (ULS), worst case is the governing equation:

$$q_{d1} = \Sigma\gamma_{G,j}G_{k,j} + \gamma_P P + \gamma_{Q,1}\psi_{0.1}Q_{k,1} + \Sigma\gamma_{Q,i}\psi_{0,i}Q_{k,i} \tag{3}$$

$$q_{d2} = \Sigma\xi_j\gamma_{G,j}G_{k,j} + \gamma_P P + \gamma_{Q,1}Q_{k,1} + \Sigma\gamma_{Q,i}\psi_{0,i}Q_{k,i} \tag{4}$$

3.4.1 Serviceability limit state (SLS)

Characteristic combination:

$$\sum G_{k,j} + Q_{k,1} + \sum \psi_{0,i}Q_{k,i}j \geq 1; i > 1 \tag{5}$$

Frequent combination:

$$\sum G_{k,j} + \psi_{1,1}Q_{k,1} + \sum \psi_{2,i}Q_{k,i}j \geq 1; i > 1 \tag{6}$$

Quasi-permanent combination:

$$\sum G_{k,j} + \sum \psi_{2,i}Q_{k,i}j \geq 1; i > 1 \tag{7}$$

3.5 Fatigue limit state (FLS)

3.5.1 FLM3

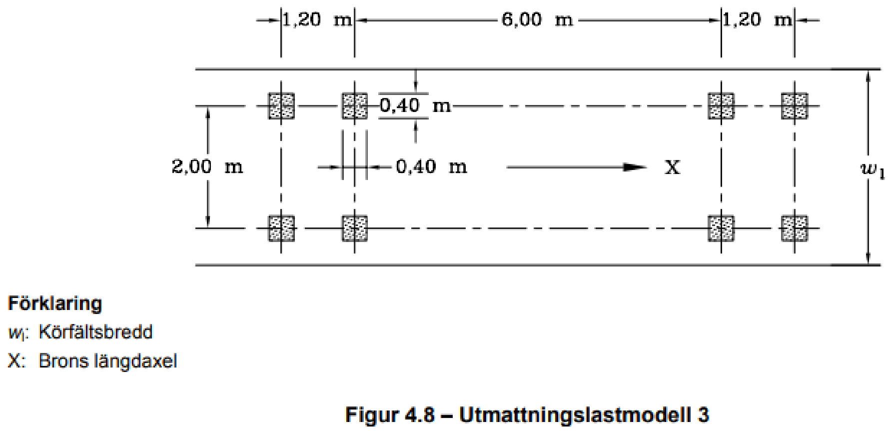


Figure 3: *FLM3 obtained from EN 1991-2:2003.*

Table 12: Axel loads according to FLM1, second vehicle on the same lane will have axel load Q_{F2}. According to EN 1991-2:2003.

Q_{F1} **[kN]**	Q_{F2} **[kN]**
120	36

3.5.2 FLM4

Minimum distance between centre of two vehicles:
$d \geq 40m$

Fatigue load model FLM4 (EN 1991-2:2003):

EN 1991-2:2003 (Sv)

Tabell 4.7 – Ekvivalenta lastfordon

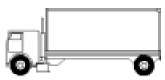
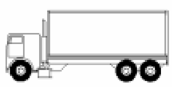
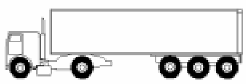
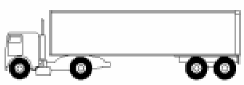
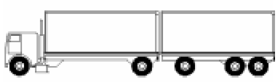
FORDONSTYP			TRAFIKTYP			
1	2	3	4	5	6	7
			Långväga	Regional	Lokaltrafik	
FORDON	Axelav-stånd (m)	Ekvivalent axellast (kN)	Procent-andel last-fordon	Procent-andel last-fordon	Procent-andel last-fordon	Hjul-typ
	4,5	70 130	20,0	40,0	80,0	A B
	4,20 1,30	70 120 120	5,0	10,0	5,0	A B B
	3,20 5,20 1,30 1,30	70 150 90 90 90	50,0	30,0	5,0	A B C C C
	3,40 6,00 1,80	70 140 90 90	15,0	15,0	5,0	A B B B
	4,80 3,60 4,40 1,30	70 130 90 80 80	10,0	5,0	5,0	A B C C C

Figure 4: FLM4 obtained from EN 1991-2:2003.

4 Assumptions and limitations

- Assuming there is no curve in the bridge and it is completely straight.
- Wind loads are neglected.
- Lateral torsional buckling is not considered.
- No design vehicles according to Trafikverket and Transportstyrelsen.
- Dynamic effects are taken into consideration in LM1.
- Sectional forces will be obtained from FE-program Sofistik.

A.2 Geometry

Table A.1: Dimensions for the beams in the new optimised beam with h=L/20 and fy=460 MPa.

Optimised design (S460) - h = L/20 = 1937.5 mm							
Beam	L [m]	t_{tf} [mm]	b_{tf} [mm]	t_w [mm]	h_w [mm]	t_{bf} [mm]	b_{bf} [mm]
1	4.2	20	400	14	1881.5	36	550
2	9.8	20	400	12	1881.5	36	680
3	10.2	20	400	14	1879.5	38	850
4	13.275	20	400	12	1885.5	32	950
5	6	25	400	14	1874.5	38	850

Table A.2: Dimensions for the beams in the new optimised beam with h=L/20 and fy=690 MPa.

Optimised design (S690) - h = L/20 = 1937.5 mm							
Beam	L [m]	t_{tf} [mm]	b_{tf} [mm]	t_w [mm]	h_w [mm]	t_{bf} [mm]	b_{bf} [mm]
1	4.2	15	300	14	1891.5	35	480
2	9.8	15	300	14	1894.5	35	550
3	10.2	20	300	16	1894.5	40	500
4	13.275	15	300	14	1892.5	32	750
5	6	20	300	16	1885.5	40	505

Table A.3: Dimensions for the beams in the new optimised beam with h=L/30 and fy=460 MPa.

Optimised design (S460) - h = L/30 = 1291.7 mm							
Beam	L [m]	t_{tf} [mm]	b_{tf} [mm]	t_w [mm]	h_w [mm]	t_{bf} [mm]	b_{bf} [mm]
1	4.2	20	400	18	1211.7	60	750
2	9.8	20	400	18	1211.7	60	750
3	10.2	35	680	20	1201.7	55	1000
4	13.275	20	400	18	1211.7	60	800
5	6	35	730	20	1201.7	55	1000

Table A.4: Dimensions for the beams in the new optimised beam with h=L/30 and fy=690 MPa.

Optimised design (S690) - h = L/30 = 1291.7 mm							
Beam	L [m]	t_{tf} [mm]	b_{tf} [mm]	t_w [mm]	h_w [mm]	t_{bf} [mm]	b_{bf} [mm]
1	4.2	15	300	16	1236.7	40	750
2	9.8	15	300	16	1236.7	40	850
3	10.2	20	300	18	1216.7	55	900
4	13.275	15	300	16	1221.7	55	750
5	6	20	300	18	1216.7	55	900

Table A.5: Dimensions for the beams after erection in the new optimised beam with h=L/20 and fy=460 MPa.

Optimised design (S460) - h = L/20 = 1937.5 mm AFTER ERECTION							
Beam	L [m]	t_{tf} [mm]	b_{tf} [mm]	t_w [mm]	h_w [mm]	t_{bf} [mm]	b_{bf} [mm]
1	4.2	15	300	12	1902.5	35	650
2	9.8	15	300	12	1887.5	35	650
3	10.2	25	320	13	1870.5	42	800
4	13.275	15	300	12	1887.5	35	860
5	6	25	370	13	1872.5	40	800

Table A.6: Dimensions for the beams after erection in the new optimised beam with h=L/20 and fy=690 MPa.

Optimised design (S690) - h = L/20 = 1937.5 mm AFTER ERECTION							
Beam	L [m]	t_{tf} [mm]	b_{tf} [mm]	t_w [mm]	h_w [mm]	t_{bf} [mm]	b_{bf} [mm]
1	4.2	15	300	14	1887.5	35	480
2	9.8	15	300	14	1887.5	35	550
3	10.2	20	300	16	1877.5	40	500
4	13.275	15	300	14	1890.5	32	750
5	6	20	300	16	1877.5	40	505

Table A.7: Dimensions for the beams after erection in the new optimised beam with h=L/30 and fy=460 MPa.

Optimised design (S460) - h = L/30 = 1291.7 mm AFTER ERECTION							
Beam	L [m]	t_{tf} [mm]	b_{tf} [mm]	t_w [mm]	h_w [mm]	t_{bf} [mm]	b_{bf} [mm]
1	4.2	20	300	16	1226.7	45	700
2	9.8	30	450	16	1216.7	45	810
3	10.2	40	600	18	1196.7	55	920
4	13.275	35	450	16	1206.7	50	920
5	6	50	550	18	1186.7	55	920

Table A.8: Dimensions for the beams after erection in the new optimised beam with h=L/30 and fy=690 MPa.

Optimised design (S690) - h = L/30 = 1291.7 mm AFTER ERECTION							
Beam	L [m]	t_{tf} [mm]	b_{tf} [mm]	t_w [mm]	h_w [mm]	t_{bf} [mm]	b_{bf} [mm]
1	4.2	15	300	10	1221.7	55	600
2	9.8	15	300	10	1221.7	55	600
3	10.2	20	300	12	1211.7	60	600
4	13.275	15	300	10	1221.7	55	700
5	6	20	300	12	1211.7	60	600

A.3 Utilisation envelopes for optimised designs

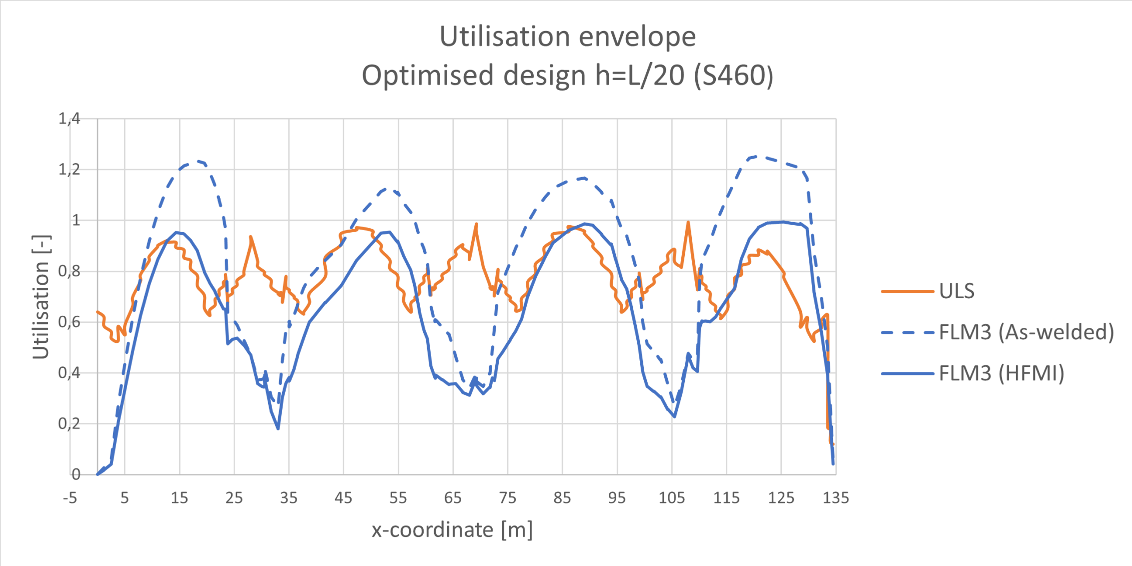


Figure A.1: *The maximal utilisation in FLS (FLM3) for as-welded state, HFMI before erection and HFMI after erection for original design (h=L/30).*

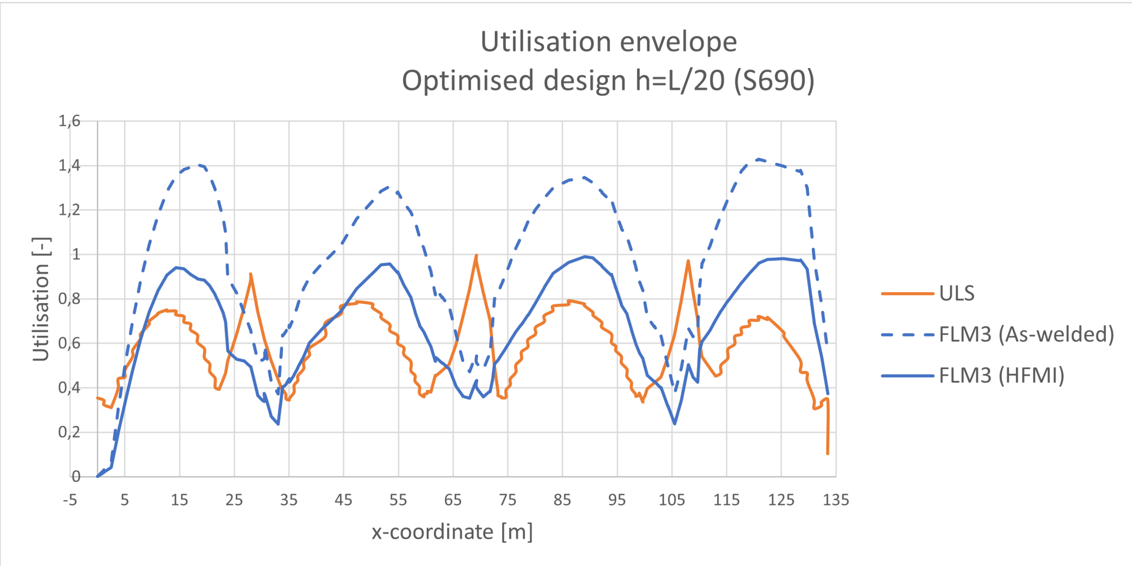


Figure A.2: *The maximal utilisation in FLS (FLM3) for as-welded state, HFMI before erection and HFMI after erection for original design (h=L/30).*

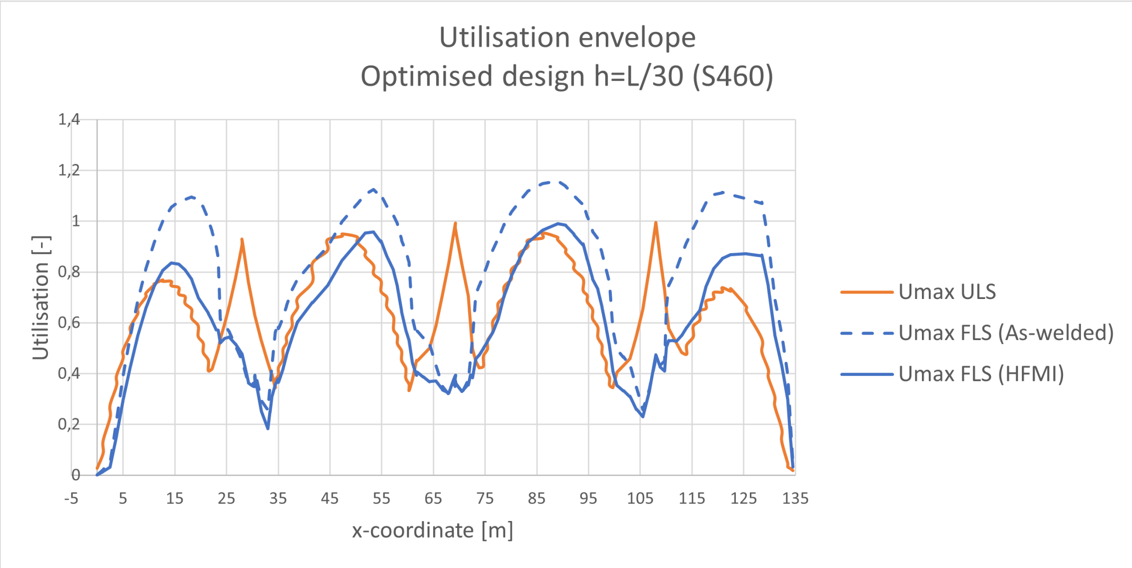


Figure A.3: *The maximal utilisation in FLS (FLM3) for as-welded state, HFMI before erection and HFMI after erection for original design (h=L/30).*

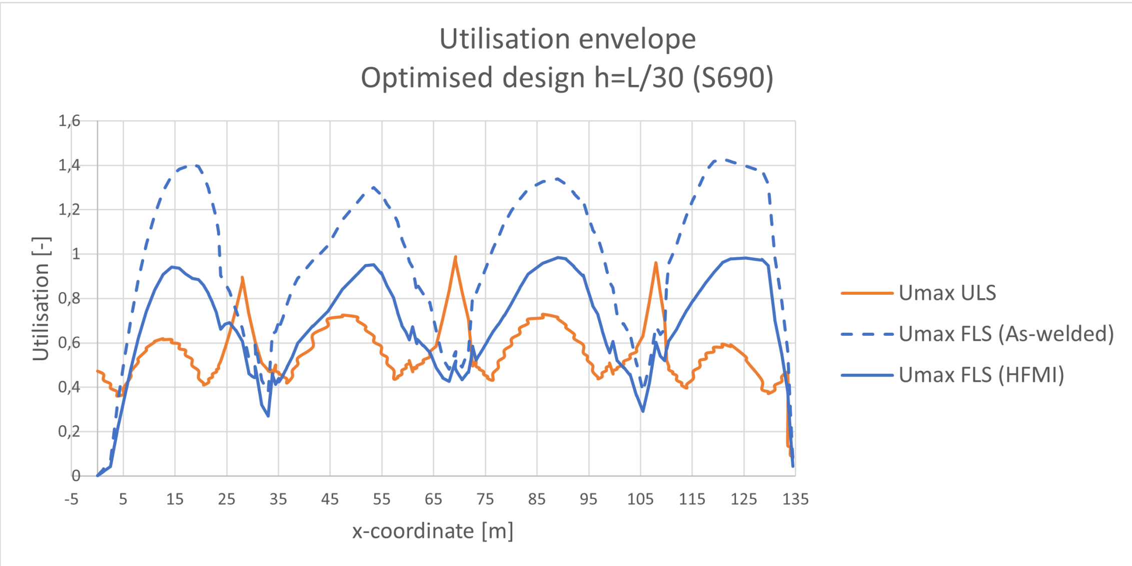


Figure A.4: *The maximal utilisation in FLS (FLM3) for as-welded state, HFMI before erection and HFMI after erection for original design (h=L/30).*

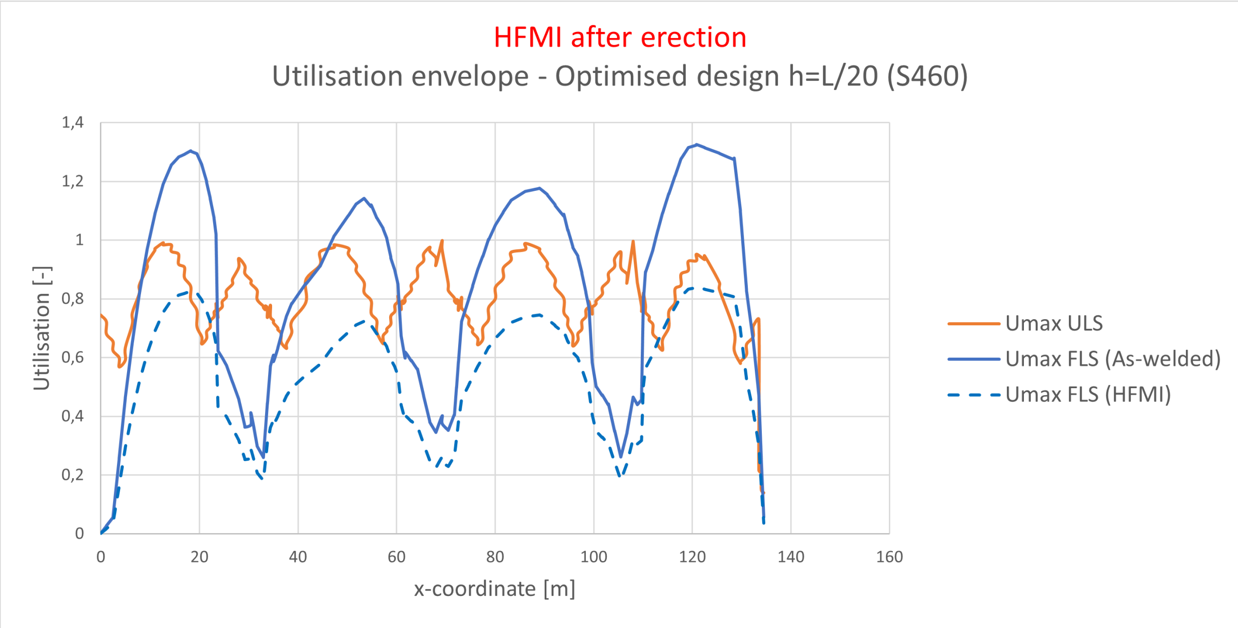


Figure A.5: *The maximal utilisation in FLS (FLM3) for as-welded state, HFMI before erection and HFMI after erection for original design (h=L/30).*

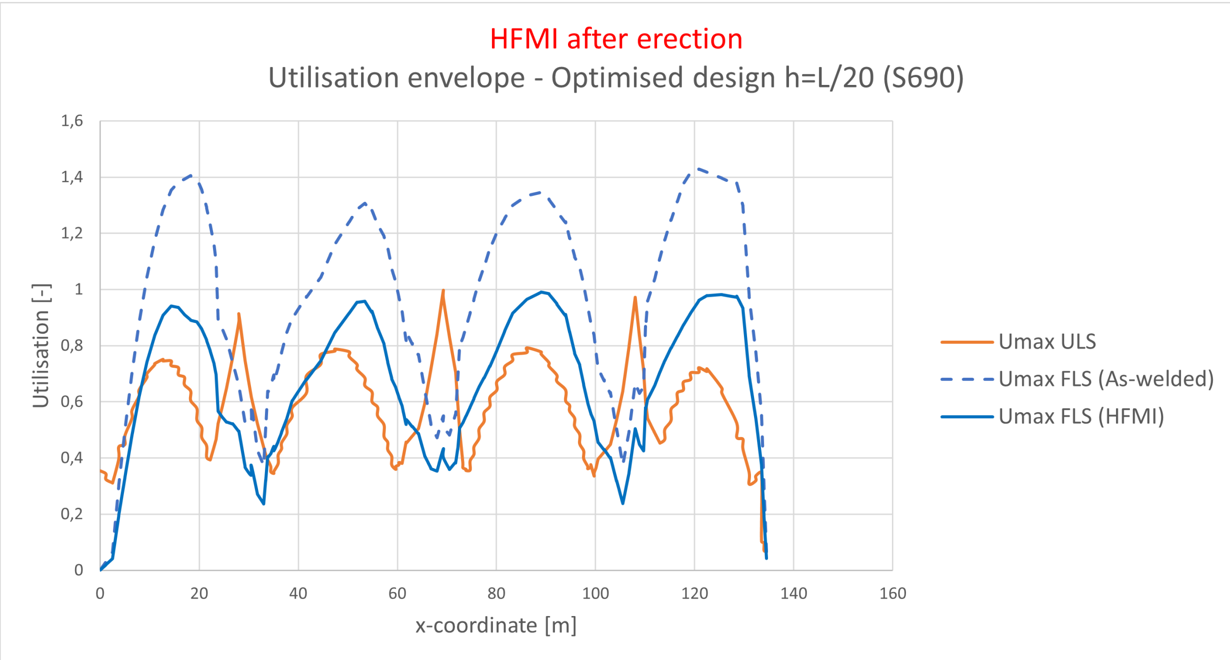


Figure A.6: *The maximal utilisation in FLS (FLM3) for as-welded state, HFMI before erection and HFMI after erection for original design (h=L/30).*

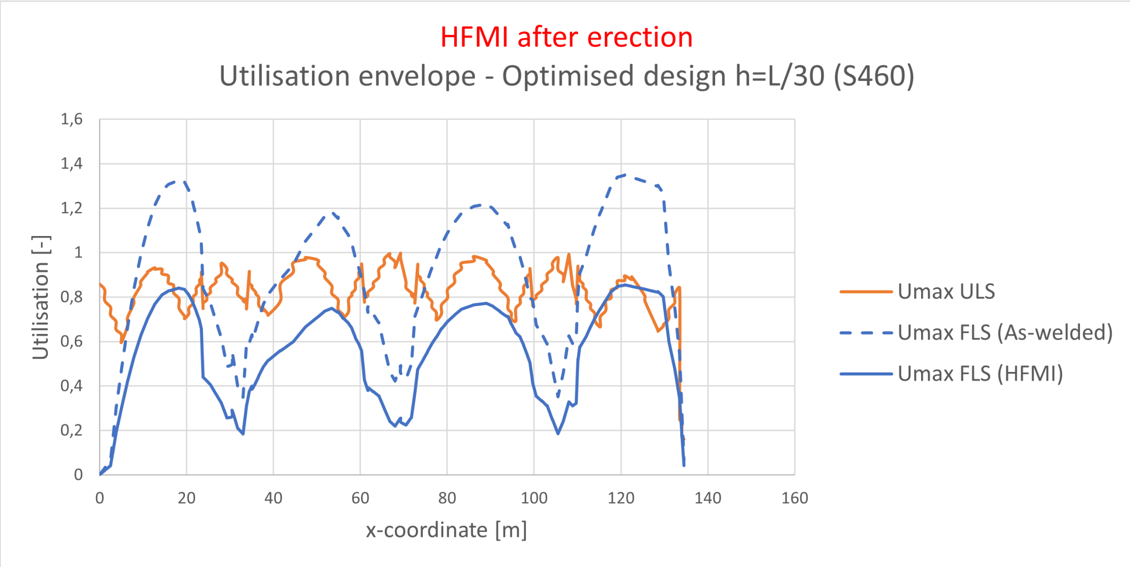


Figure A.7: *The maximal utilisation in FLS (FLM3) for as-welded state, HFMI before erection and HFMI after erection for original design (h=L/30).*

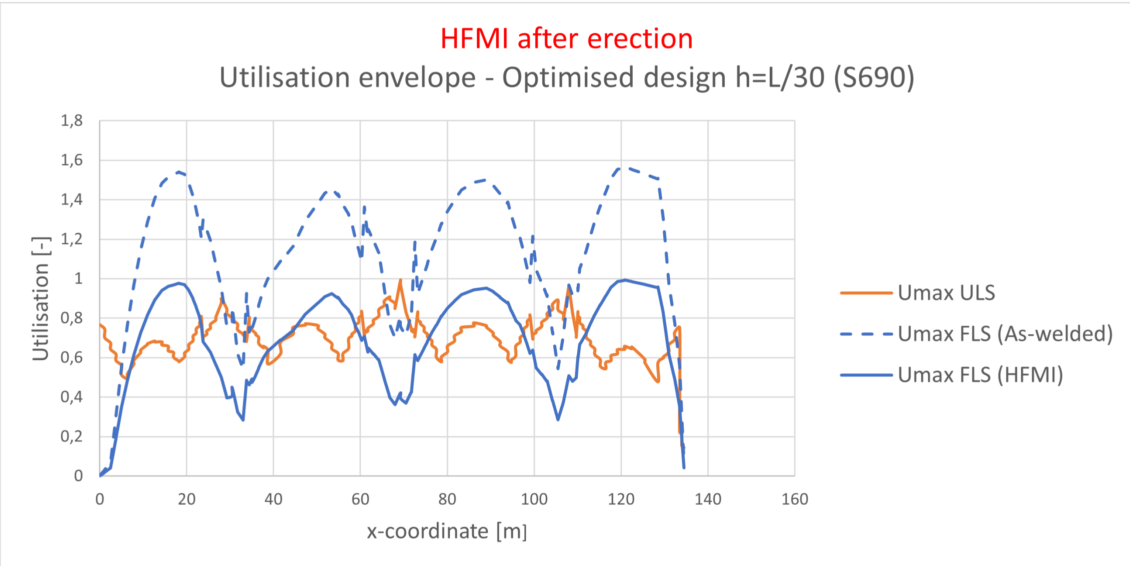


Figure A.8: *The maximal utilisation in FLS (FLM3) for as-welded state, HFMI before erection and HFMI after erection for original design (h=L/30).*

A.4 HFMI-treatment after bridge erection

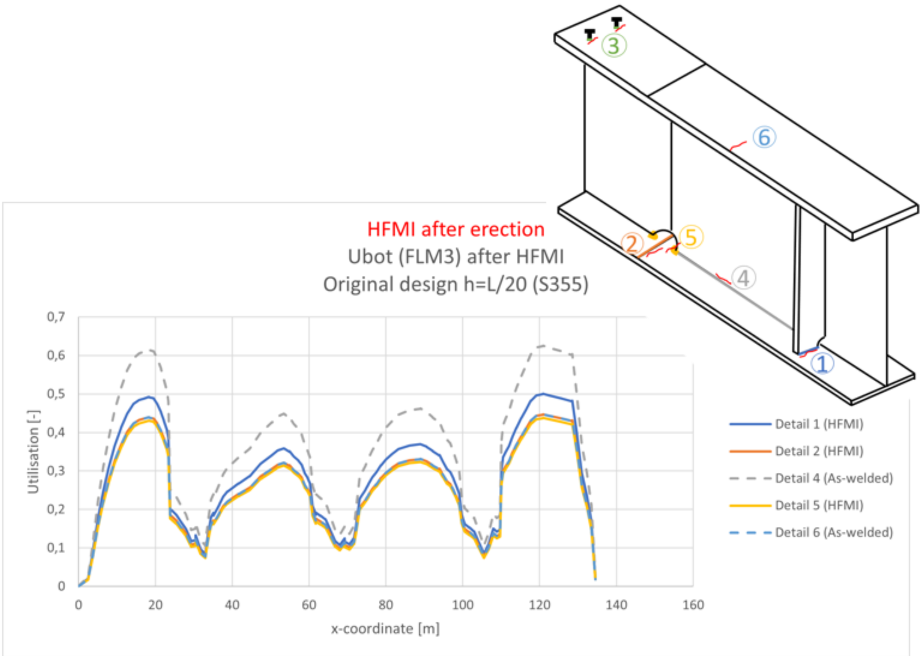


Figure A.9: *Utilisation in FLS in bot for details in the original design after HFMI-treatment for h=L/20*

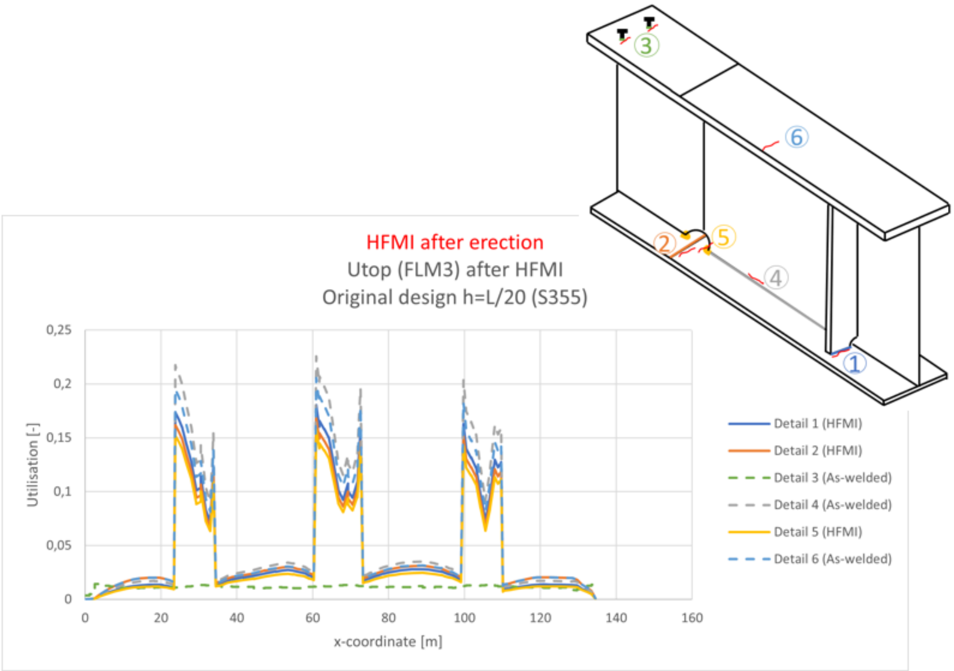


Figure A.10: *Utilisation in FLS in top for details in the original design after HFMI-treatment for h=L/20*

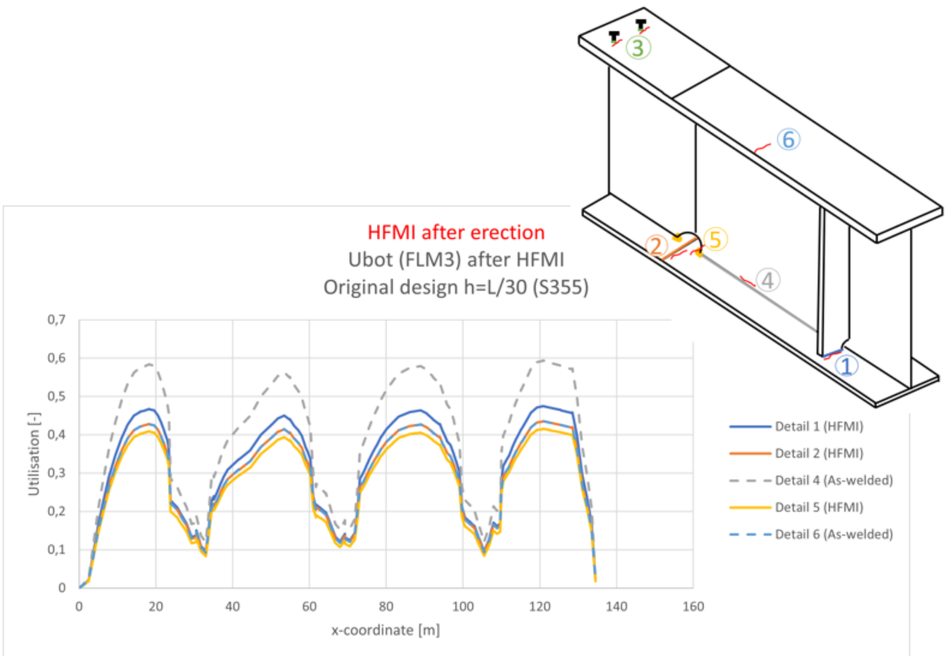


Figure A.11: *Utilisation in FLS in bot for details in the original design after HFMI-treatment for h=L/30*

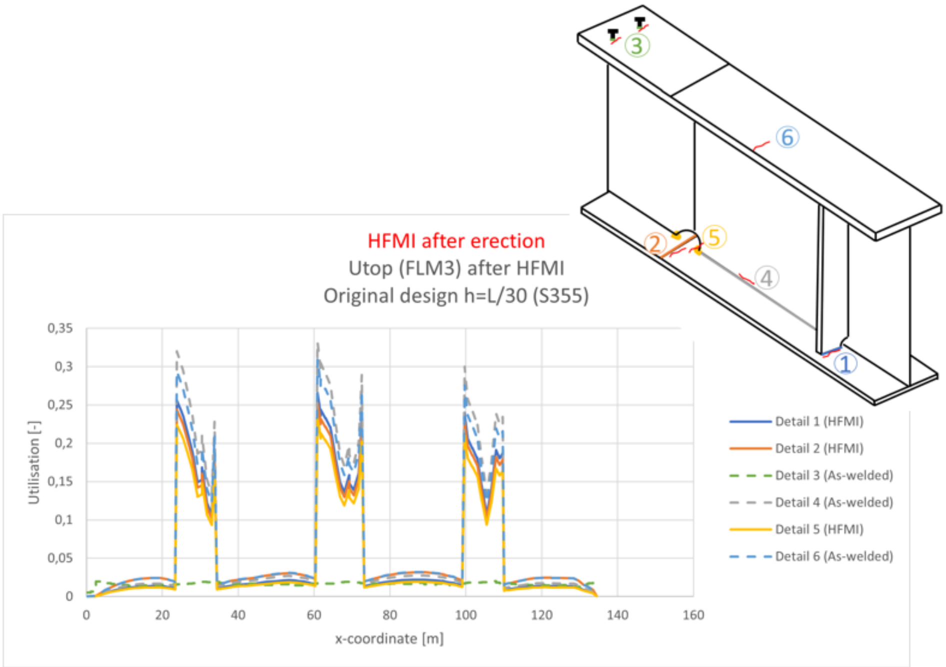


Figure A.12: *Utilisation in FLS in top for details in the original design after HFMI-treatment for h=L/30*

A.5 Verification of FE-model

Verification of model:

Weights:

$\gamma_s := 78\ \dfrac{kN}{m^3}$ Steel weight

$\gamma_c := 25\ \dfrac{kN}{m^3}$ Concrete weight

$g_{girder} := \gamma_s \cdot A_{tot.girder} = 8.494\ \dfrac{kN}{m}$ Selfweight I-girder beam

$g_{concrete} := \gamma_c \cdot b \cdot t_{slab} = 108\ \dfrac{kN}{m}$ Selfweight concrete slab

Selfweight for verification of reaktionforces (only LC "Selfweight" in Sofistik)

$$g_{tot.self} := g_{girder} \cdot 2 + g_{concrete} = 124.988\ \frac{kN}{m}$$

Selfweight of one gider beam and half of the concrete deck (For verification of handcalc. of moment):

$$g_{tot} := g_{girder} + \frac{g_{concrete}}{2} = 62.494\ \frac{kN}{m}$$

Verification of reaction forces (simply supported beam):

$R := g_{tot} \cdot L_{tot} = \left(8.343 \cdot 10^3\right)\ kN$ Hand calculation

$R_{sof.simply.supp} := 4275.2\ kN + 4283.3\ kN = \left(8.559 \cdot 10^3\right)\ kN$ From sofisitik

$$\frac{R}{R_{sof.simply.supp}} = 0.975$$

Verification of the model in Sofistik with simply supported beam (one long span - removed middle supports)

simply supported beam in one span $L_{tot} = 133.5\ m$

$$M_{hand.max} := \frac{g_{tot} \cdot L_{tot}^{\ 2}}{8} = 139.223\ MN \cdot m$$

Hand calculation

$$M_{sof.max} := 118.41311\ MN \cdot m$$

Max moment from Sofistik

$$e_{sof.N} := 286.4871\ mm$$

Eccentricity from the center of gravity of the composite cross section to the middle of the concrete slab in Sofistik

$$N_{sof.max} := 47333\ kN$$

Max normal force from Sofistik

$$M_{sof.tot} := M_{sof.max} + \left(N_{sof.max} \cdot e_{sof.N}\right) = \left(1.32 \cdot 10^{5}\right)\ kN \cdot m$$

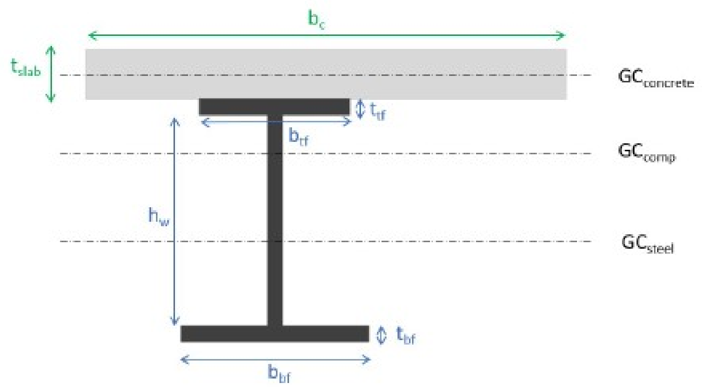
$$\frac{M_{hand.max}}{M_{sof.tot}} = 1.055$$

A.6 Geometry and cross-sectional class

Below follows an example of calculation for one section over the bridge, x=50.25 m which is in the middle of one of the longest spans.

At x=50.25m the cross section consists of beam 4. The calculation is shown for the beam with cross sectional height of L/20.

Geometry of the cross section and span lengths:



$L_{span1} := 28\ m$	$L_{span2} := 38.75\ m$	Span lengths
$L_{tot} := L_{span1} \cdot 2 + L_{span2} \cdot 2 = 133.5\ m$		Total length
$b := 14.4\ m$		Width of the concrete deck
$t_{slab} := 300\ mm$		Slab thickness
$t_{ac} := 90\ mm$		Thickness of asphalt layer
$t_{wm} := 5\ mm$		Thickness of water proofing mat

Geometry steel I-girders (main beams): (Beam 4)

$b_{tf} := 725\ mm$	$b_{bf} := 1250\ mm$	Width of the flanges
$t_{tf} := 35\ mm$	$t_{bf} := 40\ mm$	Thickness of the flanges

$h_{tot} := \frac{L_{span2}}{20} = 1.938\ m$ Total height of cross section

$h_w := h_{tot} - t_{tf} - t_{bf} = 1.863\ m$ Height of the web

$t_w := 0.018\ m$ Thickness of the web

$A_w := h_w \cdot t_w = 0.034\ m^2$ Area of the web

$A_{tf} := b_{tf} \cdot t_{tf} = 0.025\ m^2$ Area of the top flange

$A_{bf} := b_{bf} \cdot t_{bf} = 0.05\ m^2$ Area of the bottom flange

$A_{tot.girder} := A_w + A_{tf} + A_{bf} = 0.109\ m^2$ Total area of CS (I-girder)

$a := 5\ mm$ Assumed fillet weld in top

Partial safety factors carbon steel:

$\gamma_{M0} := 1.0$ TSFS 2018:57

$\gamma_{M1} := 1.0$ TSFS 2018:57

$\gamma_{M2} := min\left(0.9 \cdot \left(\frac{f_u}{f_y}\right), 1.1\right) = 1.1$ TSFS 2018:57

Partial factors concrete:

$\gamma_c := 1.5$ $\alpha_{cc} := 1.0$ $\alpha_{cct} := 1.0$ EN 1992-1-1

Material parameters:

$E_s := 210\ GPa$ E-modulus of steel

$E_{cm} := 34\ GPa$ E-modulus of concrete $E_c := E_{cm} \cdot 1.05 = 35.7\ GPa$

$f_{cm} := 43\ MPa$ $f_{ck} := 35\ MPa$ C35/45

$f_{cd} := \alpha_{cc} \cdot \frac{f_{ck}}{\gamma_c} = 23.333\ MPa$

Creep coefficient: EN 1992-1-1:2004 Annex B

Assume cement class N t0=28 days

$RH := 70 \quad \%$

$h_{0.slab} := 300 \quad mm$

$t := 365 \cdot 120 = 4.38 \cdot 10^4 \quad days$

$t_0 := 28 \quad days$ Days of curing

$b_c := \frac{b}{2} = 7.2 \ m$ Width of half of the slab

$A_{conc} := b_c \cdot t_{slab} = 2.16 \ m^2$ Area of half of the slab

$u := b \cdot 2 + L_{tot} \cdot 2 = 295.8 \ m$

$\alpha_1 := \left(\frac{35 \ MPa}{f_{cm}}\right)^{0.7} = 0.866$ $\alpha_2 := \left(\frac{35 \ MPa}{f_{cm}}\right)^{0.2} = 0.96$ $\alpha_3 := \left(\frac{35 \ MPa}{f_{cm}}\right)^{0.5} = 0.902$

$\beta_H := 1.5 \cdot \left(1 + (0.012 \cdot RH)^{18}\right) \cdot h_{0.slab} + 250 \cdot \alpha_3 = 695.058 \quad \le \quad 1500 \cdot \alpha_3 = 1.353 \cdot 10^3$

$\beta_c := \left(\frac{(t - t_0)}{\beta_H + t - t_0}\right)^{0.3} = 0.995$

$h_{01} := \frac{2 \cdot A_{conc}}{u} = 14.604 \ mm$ $h_0 := 14.604 \quad mm$

$\beta_{t0} := \frac{1}{\left(0.1 + t_0^{0.20}\right)} = 0.488$

$\beta_{fcm} := \frac{16.8}{\sqrt{43}} = 2.562$

$\varphi_{RH} := \left(1 + \left(\frac{1 - \frac{RH}{100}}{0.1 \cdot \sqrt[3]{h_0}}\right) \cdot \alpha_1\right) \cdot \alpha_2 = 1.979$

$\varphi_0 := \varphi_{RH} \cdot \beta_{fcm} \cdot \beta_{t0} = 2.477$

$\varphi_t := \varphi_0 \cdot \beta_c = 2.465$

$$E_{c.eff} := \frac{E_{cm}}{1 + \varphi_t} = 9.811\ GPa$$

Shrinkage is neglected in the calculations.

Yield strength plates:

Minimum thickness of plate: 4mm (Krav brobyggande)

$f_y := 355\ MPa$

$f_u := 490\ MPa$

Yield strength of flanges dependent on plate thickness: EN 10025-2:2004

$$f_{y.f.top} := \begin{array}{l} \text{if } t_{tf} < 16\ mm \\ \quad f_y \\ \text{if } t_{tf} \ge 16\ mm \\ \quad 345\ MPa \\ \text{if } t_{tf} \ge 40\ mm \\ \quad 335\ MPa \\ \text{if } t_{tf} \ge 63\ mm \\ \quad 325\ MPa \\ \text{if } t_{tf} \ge 80\ mm \\ \quad 315\ MPa \\ \text{if } t_{tf} \ge 100\ mm \\ \quad 295\ MPa \end{array}$$

$$f_{y.f.bot} := \begin{array}{l} \text{if } t_{bf} < 16\ mm \\ \quad f_y \\ \text{if } t_{bf} \ge 16\ mm \\ \quad 345\ MPa \\ \text{if } t_{bf} \ge 40\ mm \\ \quad 335\ MPa \\ \text{if } t_{bf} \ge 63\ mm \\ \quad 325\ MPa \\ \text{if } t_{bf} \ge 80\ mm \\ \quad 315\ MPa \\ \text{if } t_{bf} \ge 100\ mm \\ \quad 295\ MPa \end{array}$$

Yield strength of web dependent on plate thickness: EN 10025-2:2004

$$f_{y.w} := \begin{array}{l} \text{if } t_w < 16\ mm \\ \quad f_y\ MPa \\ \text{if } t_w \ge 16\ mm \\ \quad 345\ MPa \\ \text{if } t_w \ge 40\ mm \\ \quad 335\ MPa \\ \text{if } t_w \ge 63\ mm \\ \quad 325\ MPa \\ \text{if } t_w \ge 80\ mm \\ \quad 315\ MPa \\ \text{if } t_w \ge 100\ mm \\ \quad 295\ MPa \end{array}$$

$f_{y.f.top} = 345\ MPa$

$f_{y.f.bot} = 335\ MPa$

$f_{y.w} = 345\ MPa$

Cross sectional class of flanges:

$$\varepsilon_{f.top} := \sqrt{\frac{235\ MPa}{f_{y.f.top}}} = 0.825$$

$$\varepsilon_{f.bot} := \sqrt{\frac{235\ MPa}{f_{y.f.bot}}} = 0.838$$

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

$$c_{tf} := \frac{b_{tf}}{2} - \frac{t_w}{2} = 0.354\ m$$

Butt-weld in top

$$c_{bf} := \frac{b_{bf}}{2} - \frac{t_w}{2} - \sqrt{2} \cdot a = 0.609\ m$$

Fillet weld in bottom

$$\frac{c_{tf}}{t_{tf}} = 10.1$$

$$\frac{c_{bf}}{t_{bf}} = 15.223$$

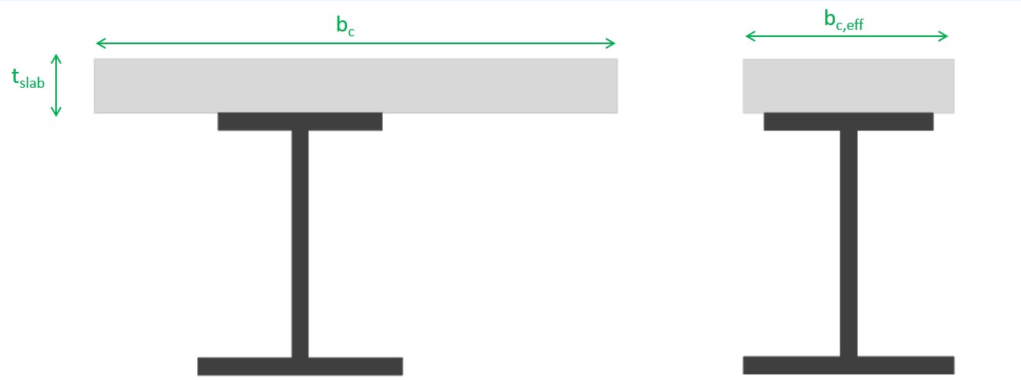
$$CS_{class.flange.top} := \left\| \begin{array}{l} \text{if } \dfrac{c_{tf}}{t_{tf}} \le 9 \cdot \varepsilon_{f.top} \\ \quad \| 1 \\ \text{if } 9 \cdot \varepsilon_{f.top} < \dfrac{c_{tf}}{t_{tf}} \le 10 \cdot \varepsilon_{f.top} \\ \quad \| 2 \\ \text{if } 10 \cdot \varepsilon_{f.top} < \dfrac{c_{tf}}{t_{tf}} \le 14 \cdot \varepsilon_{f.top} \\ \quad \| 3 \\ \text{if } 14 \cdot \varepsilon_{f.top} < \dfrac{c_{tf}}{t_{tf}} \\ \quad \| 4 \end{array} \right.$$

$$CS_{class.flange.top} = 3$$

$$CS_{class.flange.bot} := \left\| \begin{array}{l} \text{if } \dfrac{c_{bf}}{t_{bf}} \le 9 \cdot \varepsilon_{f.bot} \\ \quad \| 1 \\ \text{if } 9 \cdot \varepsilon_{f.bot} < \dfrac{c_{bf}}{t_{bf}} \le 10 \cdot \varepsilon_{f.bot} \\ \quad \| 2 \\ \text{if } 10 \cdot \varepsilon_{f.bot} < \dfrac{c_{bf}}{t_{bf}} \le 14 \cdot \varepsilon_{f.bot} \\ \quad \| 3 \\ \text{if } 14 \cdot \varepsilon_{f.bot} < \dfrac{c_{bf}}{t_{bf}} \\ \quad \| 4 \end{array} \right.$$

$$CS_{class.flange.bot} = 4$$

Equivalent steel section:



Modular ratio - Composite section:
EN 1994-2:2005 Section 5.4.2.2

$\Psi_L := 1.1$ Permanent loads

$n_0 := \dfrac{E_s}{E_{cm}} = 6.176$ Modular ratio between steel and concrete (short-term)

$n_L := n_0 \cdot \left(1 + \Psi_L \cdot \varphi_t\right) = 22.927$ EN1994-2:2005 Eq. (5.6) (Long-term)

$n_{cr} := 100$ Assume 1% of the concrete area consists of reinforcement bars

A.7 Stress gross cross-section

Bending resistance:

Cross sectional constants:

$A_{tf}=0.025\ m^2$ $A_w=0.034\ m^2$ $A_{bf}=0.05\ m^2$

$n_0=6.176$ $n_L=22.927$ $n_{cr}=100$

$b_c=7.2\ m$ $t_{slab}=0.3\ m$

Distance from top to gravity centre (GC) of each part:
(GC is calculated from top of steel girder)

$e_{tf}:=\frac{t_{tf}}{2}=0.018\ m$ $e_w:=t_{tf}+\frac{h_w}{2}=0.966\ m$ $e_{bf}:=t_{tf}+h_w+\frac{t_{bf}}{2}=1.918\ m$

$e_c:=\frac{-t_{slab}}{2}=-0.15\ m$

Calculations of Gravity centre (GC):

$Ae_{tf}:=A_{tf}\cdot e_{tf}=\left(4.441\cdot 10^{-4}\right)\ m^3$

$Ae_w:=A_w\cdot e_w=0.032\ m^3$

$Ae_{bf}:=A_{bf}\cdot e_{bf}=0.096\ m^3$

$I_{0.tf}:=\frac{b_{tf}\cdot t_{tf}^{\ 3}}{12}=\left(2.59\cdot 10^{-6}\right)\ m^4$

$I_{0.w}:=\frac{t_w\cdot h_w^{\ 3}}{12}=0.01\ m^4$

$I_{0.bf}:=\frac{b_{bf}\cdot t_{bf}^{\ 3}}{12}=\left(6.667\cdot 10^{-6}\right)\ m^4$

Short term calculations: $n_0 = 6.176$

$$A_c := \frac{t_{slab} \cdot b_c}{n_0} = 0.35\ m^2$$

$$t_c := \frac{A_c}{b_c} = 0.049\ m$$

$$Ae_c := A_c \cdot e_c = -0.052\ m^3$$

$$I_{0.c} := \frac{b_c \cdot t_c^{\ 3}}{12} = \left(6.875 \cdot 10^{-5}\right)\ m^4$$

$$y_{tp} := \frac{Ae_{tf} + Ae_w + Ae_{bf} + Ae_c}{A_{tf} + A_w + A_{bf} + A_c} = 0.166\ m$$

$$I_{tf} := I_{0.tf} + A_{tf} \cdot \left(e_{tf} - y_{tp}\right)^2 = \left(5.642 \cdot 10^{-4}\right)\ m^4$$

$$I_w := I_{0.w} + A_w \cdot \left(e_w - y_{tp}\right)^2 = 0.031\ m^4$$

$$I_{bf} := I_{0.bf} + A_{bf} \cdot \left(e_{bf} - y_{tp}\right)^2 = 0.153\ m^4$$

$$I_c := I_{0.c} + A_c \cdot \left(e_c - y_{tp}\right)^2 = 0.035\ m^4$$

$$I_{tot} := I_{tf} + I_w + I_{bf} + I_c = 0.22\ m^4$$

$$A_{tot} := A_{tf} + A_w + A_{bf} + A_c = 0.459\ m^2$$

$$e_{top} := y_{tp} = 0.166\ m$$

$$e_{bot} := h_{tot} - y_{tp} = 1.771\ m$$

$$W_{top} := \frac{I_{tot}}{e_{top}} = 1.324\ m^3$$

$$W_{bot} := \frac{I_{tot}}{e_{bot}} = 0.124\ m^3$$

Stress distribution (gross cross section) - Short term

$M_{max.short} := 17131.5\ kN \cdot m$ Sectional forces from Sofistik

$N_{max.short} := 747.6\ kN$

$\sigma_{max.short.top} := \frac{M_{max.short}}{W_{top}} + \frac{N_{max.short}}{A_{tot}} = 14.572\ MPa$

$\sigma_{max.short.bot} := \frac{M_{max.short}}{W_{bot}} + \frac{N_{max.short}}{A_{tot}} = 139.489\ MPa$

$M_{min.short} := -1030.1\ kN \cdot m$ Sectional forces from Sofistik

$N_{min.short} := -731.2\ kN$

$\sigma_{min.short.top} := \frac{M_{min.short}}{W_{top}} + \frac{N_{min.short}}{A_{tot}} = -2.373\ MPa$

$\sigma_{min.short.bot} := \frac{M_{min.short}}{W_{bot}} + \frac{N_{min.short}}{A_{tot}} = -9.884\ MPa$

Long term calculations:

$n_L = 22.927$

$$\boxed{A_c} := \frac{t_{slab} \cdot b_c}{n_L} = 0.094\ m^2$$

$$\boxed{t_c} := \frac{A_c}{b_c} = 0.013\ m$$

$$\boxed{Ae_c} := A_c \cdot e_c = -0.014\ m^3$$

$$\boxed{I_{0.c}} := \frac{b_c \cdot t_c^{\ 3}}{12} = \left(1.344 \cdot 10^{-6}\right)\ m^4$$

$$\boxed{y_{tp}} := \frac{Ae_{tf} + Ae_w + Ae_{bf} + Ae_c}{A_{tf} + A_w + A_{bf} + A_c} = 0.564\ m$$

$$\boxed{I_{tf}} := I_{0.tf} + A_{tf} \cdot \left(e_{tf} - y_{tp}\right)^2 = 0.008\ m^4$$

$$\boxed{I_w} := I_{0.w} + A_w \cdot \left(e_w - y_{tp}\right)^2 = 0.015\ m^4$$

$$\boxed{I_{bf}} := I_{0.bf} + A_{bf} \cdot \left(e_{bf} - y_{tp}\right)^2 = 0.092\ m^4$$

$$\boxed{I_c} := I_{0.c} + A_c \cdot \left(e_c - y_{tp}\right)^2 = 0.048\ m^4$$

$$\boxed{I_{tot}} := I_{tf} + I_w + I_{bf} + I_c = 0.162\ m^4$$

$$\boxed{A_{tot}} := A_{tf} + A_w + A_{bf} + A_c = 0.203\ m^2$$

$$\boxed{e_{top}} := y_{tp} = 0.564\ m$$

$$\boxed{e_{bot}} := h_{tot} - y_{tp} = 1.373\ m$$

$$\boxed{W_{top}} := \frac{I_{tot}}{e_{top}} = 0.288\ m^3$$

$$\boxed{W_{bot}} := \frac{I_{tot}}{e_{bot}} = 0.118\ m^3$$

Stress distribution (gross cross section) - long term

$M_{max.long} := 8834.96\ kN \cdot m$ Sectional forces from Sofistik

$N_{max.long} := 6.7\ kN$

$\sigma_{max.long.top} := \frac{M_{max.long}}{W_{top}} + \frac{N_{max.long}}{A_{tot}} = 30.735\ MPa$

$\sigma_{max.long.bot} := \frac{M_{max.long}}{W_{bot}} + \frac{N_{max.long}}{A_{tot}} = 74.779\ MPa$

$M_{min.long} := 6031.17\ kN \cdot m$ Sectional forces from Sofistik

$N_{min.long} := -67.7\ kN$

$\sigma_{min.long.top} := \frac{M_{min.long}}{W_{top}} + \frac{N_{min.long}}{A_{tot}} = 20.625\ MPa$

$\sigma_{min.long.bot} := \frac{M_{min.long}}{W_{bot}} + \frac{N_{min.long}}{A_{tot}} = 50.692\ MPa$

Total stesses:

$\sigma_{tot.top.max} := \sigma_{max.short.top} + \sigma_{max.long.top} = 45.307\ MPa$

$\sigma_{tot.top.min} := \sigma_{min.short.top} + \sigma_{min.long.top} = 18.253\ MPa$

$\sigma_{tot.bot.max} := \sigma_{max.short.bot} + \sigma_{max.long.bot} = 214.268\ MPa$

$\sigma_{tot.bot.min} := \sigma_{min.short.bot} + \sigma_{min.long.bot} = 40.808\ MPa$

For cracked sections the calculations are the same but with use of $n_{cr} = 100$

A.8 Shear capacity ULS

Check of shear resistance

Input data:

$h_w = 1.863\ m$ $\quad t_w = 0.018\ m$ $\quad \varepsilon_w = 0.825$

$f_{y.w} = 345\ MPa$ $\quad \gamma_{M1} = 1$ $\quad \gamma_{M0} = 1$

Check of shear buckling:

$$\eta := \text{if } f_{y.w} \le 460\ MPa \;\Big\|\; 1.2 \;\; \text{if } f_{y.w} > 460\ MPa \;\Big\|\; 1$$

EN 1993-1-5 - Chapter 5

$\eta = 1.2$

$a_{stiff} := 6\ m$

Shear buckling coefficient

$$\frac{a_{stiff}}{h_w} = 3.221$$

$$k_t := 5.34 + 4 \cdot \left(\frac{h_w}{a_{stiff}}\right)^2 = 5.725$$

EN 1993-1-5 - Eq. A.5

$$\frac{31}{\eta} \cdot \varepsilon_w \cdot \sqrt[2]{k_t} = 51.016$$

$$\frac{h_w}{t_w} = 103.472$$

$$\frac{h_w}{t_w} > \frac{31}{\eta} \cdot \varepsilon_w \cdot \sqrt[2]{k_t}$$

-> Need to check shear buckling resistance!

Checking slenderness

$v := 0.3$

$$\sigma_E := \frac{\pi^2 \cdot E_s \cdot t_w^{\ 2}}{12\left(1-v^2\right) \cdot h_w^{\ 2}} = 17.728\ MPa$$

Eq. A.1. EN 1993-1-5

$$\tau_{cr} := k_t \cdot \sigma_E = 101.498\ MPa$$

Eq. 5.4, EN 1993-1-5

$$\lambda_w := 0.76 \cdot \sqrt{\frac{f_{y.w}}{\tau_{cr}}} = 1.401$$

Eq. 5.3, EN 1993-1-5

Non-rigid end post:

Table 5.1, EN 1993-1-5

$$\chi_w := \begin{cases} \eta & \text{if } \lambda_w < \dfrac{0.83}{\eta} \\ \dfrac{0.83}{\lambda_w} & \text{if } \dfrac{0.83}{\eta} \le \lambda_w < 1.08 \\ \dfrac{0.83}{\lambda_w} & \text{if } \lambda_w \ge 1.08 \end{cases}$$

$\chi_w = 0.592$

$$V_{bw.Rd} := \frac{\chi_w \cdot f_{y.w} \cdot h_w \cdot t_w}{\sqrt[2]{3} \cdot \gamma_{M1}} = 3.956\ MN$$

Shear resistance

Forces from Sofistik:

$V_{Ed.max.short} := 864.6\ kN$ $V_{Ed.min.short} := -1076.1\ kN$ short term shear force

$V_{Ed.max.long} := -236.8\ kN$ $V_{Ed.min.long} := -324.5\ kN$ long term shear force

$V_{Ed.max} := V_{Ed.max.short} + V_{Ed.max.long} = 627.8\ kN$

$V_{Ed.min} := V_{Ed.min.short} + V_{Ed.min.long} = -1.401 \cdot 10^{3}\ kN$

Utilisation:

$$U_{Vmax} := \mathrm{abs}\left(\frac{V_{Ed.max}}{V_{bw.Rd}}\right) = 0.159$$

$$U_{Vmin} := \mathrm{abs}\left(\frac{V_{Ed.min}}{V_{bw.Rd}}\right) = 0.354$$

check of interaction between moment and shear force: EN 1993-1-2005

$A_v := \eta \cdot A_w = 0.04\ m^2$ Section 6.2.6 (3) d)

$$V_{pl.Rd} := A_v \cdot \frac{\left(\frac{f_{y.w}}{\sqrt{3}}\right)}{\gamma_{M0}} = \left(8.013 \cdot 10^{3}\right)\ kN \qquad (6.18)$$

$V_{pl.Rd.0.5} := 0.5 \cdot V_{pl.Rd} = \left(4.007 \cdot 10^{3}\right)\ kN$

$$check.max := \frac{\mathrm{abs}\left(V_{Ed.max}\right)}{V_{pl.Rd.0.5}} = 0.157$$

$$check.min := \frac{\mathrm{abs}\left(V_{Ed.min}\right)}{V_{pl.Rd.0.5}} = 0.35$$

```
if check.max > 0.5                  = "No reduction needed"
  ‖ "fy needs to be reduced"
else
  ‖ "fy needs to be reduced"
  ‖ "No reduction needed"
```

```
if check.min > 0.5                  = "No reduction needed"
  ‖ "fy needs to be reduced"
else
  ‖ "fy needs to be reduced"
  ‖ "No reduction needed"
```

A.9 SLS deflection

Deflection SLS

Deflection is obtained from Sofistik
x=50.25m
$L_{span} := 38.75\ m$

$u_z := 22.95\ mm$

Requirement:

$u_{max} := \frac{L_{span}}{400} = 96.875\ mm$ (Krav brobyggande)

Verification:

$U := \frac{u_z}{u_{max}} = 0.237$ < 1 OK!

A.10 Reduction due to shear lag

SHEAR LAG EFFECT:

shear lag in flanges may be neglected if b0<Le/50 where b0 is taken as the flange outstand of half the width of an internal element and Le is the legnth between the zero bending moment (EN1993-1-5)

Shear lag concrete flange:

Effective width of concrete flanges for shear lag EN 1994-2:2005 - Section 5.4.1.2

Equivalent spans, for effective width of concrete flange EN 1994-2:2005 Figure 5.1

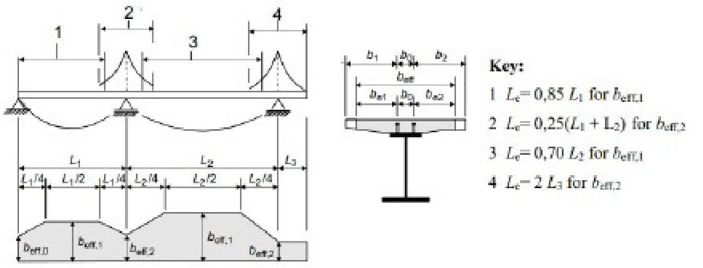


Figure 5.1: Equivalent spans, for effective width of concrete flange

$L_e := 0.7 \cdot L_{span2} = 27.125\ m$

$b_1 := 3\ m$ Left side of shear connector

$b_2 := 3.8\ m$ Right side of shear connector

<u>Effective width at midspan or at internal support:</u>

$b_{eff} = b_0 + \sum b_{ei}$ (Eq. 5.3)

Distance between the centres of the outstand shear connectors b_0:

$\geq 5\ d$ $d_{stud} := 22\ mm$ Assumed diameter of stud

$b_0 := 0.4\ m$ Dist. between shear studs

Minimum distance: 4d Steel Concrete Composite Bridges book - p.96)

Effective width of concrete flange on each side of the web b_{ei}: 5.4.1.2 (5):

$$\frac{L_e}{8} = 3.391\ m$$

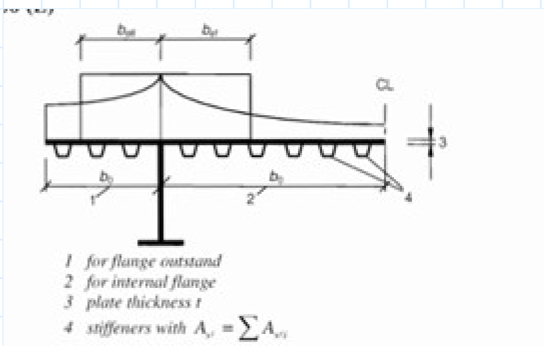
$$b_{e1} := \begin{cases} \text{if } \dfrac{L_e}{8} \le b_1 \\ \quad \dfrac{L_e}{8} \\ \text{else} \\ \quad b_1 \end{cases} = 3\ m \qquad b_{e2} := \begin{cases} \text{if } \dfrac{L_e}{8} \le b_2 \\ \quad \dfrac{L_e}{8} \\ \text{else} \\ \quad b_2 \end{cases} = 3.391\ m$$

Total effective width of concrete flange:

$$b_{eff.tot} := b_0 + b_{e1} + b_{e2} = 6.791\ m$$

Shear lag steel flanges:

Effective width for elastic shear lag EN 1993-1-5 Section 3.2



$$b_{eff} = \beta \cdot b_0 \qquad \text{(Eq. 3.1)}$$

Figure 3.2:

$$b_{0.tf} := \frac{b_{tf}}{2} = 0.363\ m \qquad b_{0.bf} := \frac{b_{bf}}{2} = 0.625\ m$$

$$\frac{L_e}{50} = 0.543\ m$$

If b0<Le/50 - shear lag does not need to be considered

Top flange:

$$check.tf := \begin{array}{l} \text{if } b_{0.tf} < \dfrac{L_e}{50} \\ \quad \| \text{"no need to consider"} \\ \text{else} \\ \quad \| \text{"need to consider"} \end{array} = \text{"no need to consider"}$$

$$b_{eff.tf.pos} := b_{tf} = 0.725\ m$$

$$b_{eff.tf.neg} := b_{tf} = 0.725\ m$$

Bottom flange:

$$check.bf := \begin{array}{l} \text{if } b_{0.bf} < \dfrac{L_e}{50} \\ \quad \| \text{"no need to consider"} \\ \text{else} \\ \quad \| \text{"need to consider"} \end{array} = \text{"need to consider"}$$

Table 3.1:

$A_{sl.bf} := 0\ m^2$ Area of longitudinal stiffeners

$$\alpha_{0.bf} := \left(1 + \frac{A_{sl.bf}}{b_{0.bf} \cdot t_{bf}}\right) = 1$$

$$\kappa_{bf} := \frac{\alpha_{0.bf} \cdot b_{0.bf}}{L_e} = 0.023$$

Sagging moment (positive):

$$\beta_{bf.pos} := \begin{array}{l} \text{if } \kappa_{bf} \le 0.02 \\ \quad \| 1 \end{array} = 0.997$$

$$\text{also if } 0.02 < \kappa_{bf} \le 0.7$$
$$\left\| \frac{1}{1+6.4 \cdot \kappa_{bf}^{2}} \right.$$
$$\text{also if } \kappa_{bf} > 0.7$$
$$\left\| \frac{1}{5.9 \cdot \kappa_{bf}} \right.$$

Hogging moment (negative):

$$\beta_{bf.neg} := \text{if } \kappa_{bf} \le 0.02 \quad = 0.966$$
$$\left\| 1 \right.$$
$$\text{also if } 0.02 < \kappa_{bf} \le 0.7$$
$$\left\| \frac{1}{1+6.0 \cdot \left(\kappa_{bf} - \frac{1}{2500 \cdot \kappa_{bf}}\right) + 1.6 \cdot \kappa_{bf}^{2}} \right.$$
$$\text{also if } \kappa_{bf} > 0.7$$
$$\left\| \frac{1}{8.6 \cdot \kappa_{bf}} \right.$$

$$b_{eff.bf.pos} := 2 \cdot b_{0.bf} \cdot \beta_{bf.pos} = 1.246 \ m$$

$$b_{eff.bf.neg} := 2 \cdot b_{0.bf} \cdot \beta_{bf.neg} = 1.208 \ m$$

A.11 Reduction due to local buckling (flanges)

Reduction buckling flanges for X=105.5m

Total stresses:

$\sigma_{tot.top.max} := -11.4\ MPa$

$\sigma_{bot.max} := -4.5\ MPa$

SS-EN 1993-1-5:2006.

Top flange:

$f_{y.top} := 345\ MPa$

$t_{top.flange} := 35\ mm$

$a := 5\ mm$

$t_w := 18\ mm$

EN 1993-1-1

$c_{top.flange} := 353.50\ mm$ Table 5.2 EN 1993-1-1

SS-EN 1993-1-5:2006

$\psi := \frac{\sigma_{bot.max}}{\sigma_{tot.top.max}} = 0.395$ Table 4.1 SS-EN 1993-1-5:2006

$k_\sigma := \frac{0.578}{(\psi + 0.34)} = 0.787$

$\varepsilon := \sqrt{\frac{235\ MPa}{f_{y.top}}} = 0.825$

$\lambda_p := \frac{\left(\frac{c_{top.flange}}{t_{top.flange}}\right)}{28.4 \cdot \varepsilon \cdot \sqrt{k_\sigma}} = 0.486$

$\rho := 1$ outstand compression elements: $\rho = 1{,}0$ for $\bar{\lambda}_p \le 0{,}748$

$b_{eff.top} := \rho \cdot c_{top.flange} = 0.354\ m$

$b_{eff.top.total} := b_{eff.top} \cdot 2 + 2 \cdot \sqrt{2} \cdot a + t_w = 0.739\ m$

Bot flange:

$f_{y.bot} := 345\ MPa$

$t_{bot.flange} := 40\ mm$

EN 1993-1-1

$c_{bot.flange} := 608.93\ mm$ Table 5.2 EN 1993-1-1

$\psi_{bot} := \dfrac{\sigma_{bot.max}}{\sigma_{tot.top.max}} = 0.395$ Table 4.1 SS-EN 1993-1-5:2006

$k_{\sigma.bot} := \dfrac{0.578}{(\psi + 0.34)} = 0.787$

SS-EN 1993-1-5:2006

$\varepsilon_{bot} := \sqrt{\dfrac{235\ MPa}{f_{y.bot}}} = 0.825$

$\lambda_{p.bot} := \dfrac{\left(\dfrac{c_{bot.flange}}{t_{bot.flange}}\right)}{28.4 \cdot \varepsilon_{bot} \cdot \sqrt{k_{\sigma.bot}}} = 0.732$

$\rho_{bot} := 1$

outstand compression elements:
$\rho = 1{,}0$ for $\overline{\lambda}_p \le 0{,}748$

$b_{eff.bot} := \rho_{bot} \cdot c_{bot.flange} = 0.609\ m$

$b_{eff.bot.total} := b_{eff.bot} \cdot 2 + 2 \cdot \sqrt{2} \cdot a + t_w = 1.25\ m$

A.12 Reduction due to local buckling (web)

Check for local buckling (web)

Calculations follow for the section x=50.25m

Mmax - Sagging moment (positive)

Input data:

$h_{tot} = 1.938\ m$ $\qquad a = 0.005\ m$

$\sigma_{top.max} := 45.66\ MPa$

$\sigma_{bot.max} := 216.60\ MPa$

From stress distribution after reduction for plate buckling of flanges

$c_w := h_w - \left(2 \cdot \sqrt{2} \cdot a\right) = 1.848\ m$

$h_{comp.Mmax} := 0\ m$ $\qquad \sigma_{top.max} > 0$ $\qquad \sigma_{bot.max} > 0$

No part of the web in compression -> no reduction needed for local buckling

Calculations follow for the section x=105.5m

$a = 5\ mm$

$h_{w.new.x} := 1832.5\ mm$ $\qquad t_{w.new.x} := 20\ mm$ $\qquad t_{tf.new.x} := 55\ mm$

$c_{w.new.x} := h_{w.new.x} - \left(2 \cdot \sqrt{2} \cdot a\right) = 1.818\ m$

Mmax

Input data:

$h_{tot} = 1.938\ m$ $\quad a = 0.005\ m$

$\boxed{\sigma_{top.max}} := -11.30\ MPa$

From stress distribution after reduction for plate buckling of flanges

$\boxed{\sigma_{bot.max}} := -13.22\ MPa$

Internal compression element (compression positive)

$\sigma_1 := -\sigma_{bot.max} = 13.22\ MPa$ EN1993-1-5 - Table 4.1

$\sigma_2 := -\sigma_{top.max} = 11.3\ MPa$

$$\psi := \frac{\sigma_2}{\sigma_1} = 0.855$$

Check CSC class: (Part subjected to bending and compression)

$$GC := h_{tot} - \left(\frac{h_{tot}}{\text{abs}\left(\sigma_{top.max}\right) + \text{abs}\left(\sigma_{bot.max}\right)}\right) \cdot \text{abs}\left(\sigma_{bot.max}\right) = 0.893\ m$$

$h_{comp} := c_{w.new.x} = 1.818\ m$ All part of the web is compressed

$$\alpha := \frac{h_{comp}}{c_{w.new.x}} = 1 \qquad \alpha > 0.5$$

If $\alpha > 0.5$ & $\psi > -1$

$$CS_{class.web} := \begin{array}{l} \text{if } \dfrac{c_{w.new.x}}{t_{w.new.x}} \le \dfrac{396 \cdot \varepsilon_w}{13 \cdot \alpha - 1} \\ \quad 1 \\ \text{if } \dfrac{396 \cdot \varepsilon_w}{13 \cdot \alpha - 1} < \dfrac{c_{w.new.x}}{t_{w.new.x}} \le \dfrac{456 \cdot \varepsilon_w}{13 \cdot \alpha - 1} \\ \quad 2 \\ \text{if } \dfrac{456 \cdot \varepsilon_w}{13 \cdot \alpha - 1} < \dfrac{c_{w.new.x}}{t_{w.new.x}} \le \dfrac{42 \cdot \varepsilon_w}{0.67 + 0.33 \cdot \psi} \\ \quad 3 \\ \text{if } \dfrac{42 \cdot \varepsilon_w}{0.67 + 0.33 \cdot \psi} < \dfrac{c_{w.new.x}}{t_{w.new.x}} \\ \quad 4 \end{array} = 4$$

EN1993-1-5 - Table 4.1

$$k_\sigma := \frac{8.2}{(1.05+\psi)} = 4.305$$

$$b_{bar} := c_{w.new.x} = 1.818\ m$$

$$f_{y.w} = 345\ MPa$$

$$\varepsilon := \sqrt{\frac{235\ MPa}{f_{y.w}}} = 0.825$$

EN1993-1-5 - section 4.4

$$\lambda_p := \frac{\dfrac{b_{bar}}{t_{w.new.x}}}{28.4 \cdot \varepsilon \cdot \sqrt{k_\sigma}} = 1.869$$

$$limit := 0.5 + \sqrt{0.085 - 0.055 \cdot \psi} = 0.695$$

$$\lambda_p > limit$$

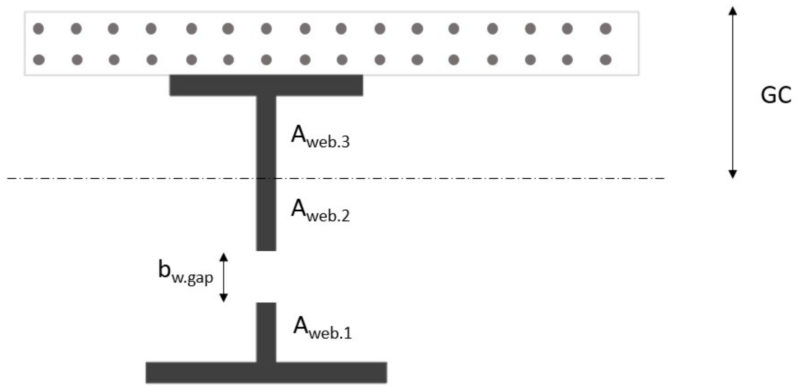
$$\rho := \frac{\lambda_p - 0.055 \cdot (3+\psi)}{{\lambda_p}^2} = 0.474$$

EN1993-1-5 - Table 4.1

$$b_{eff} := \rho \cdot h_{comp} = 0.862\ m$$

$$b_{e1} := \frac{2}{5-\psi} \cdot b_{eff} = 0.416\ m \qquad b_{e2} := b_{eff} - b_{e1} = 0.446\ m$$

$$b_{w.gap} := h_{comp} - b_{e1} - b_{e2} = 0.956\ m$$



Stress distribution is calculated with reduced plates if in compression and in CSC 4.

Mmin

Input data:

$h_{tot} = 1.938\ m$ $\qquad a = 0.005\ m$

$\sigma_{top.max} := -41.79\ MPa$ From stress distribution after reduction for plate buckling of flanges

$\sigma_{bot.max} := -50.91\ MPa$

Internal compression element (compression positive)

$\sigma_1 := -\sigma_{bot.max} = 50.91\ MPa$ EN1993-1-5 - Table 4.1

$\sigma_2 := -\sigma_{top.max} = 41.79\ MPa$

$$\psi := \frac{\sigma_2}{\sigma_1} = 0.821$$

Check CSC class: (Part subjected to bending and compression)

$$GC := h_{tot} - \left(\frac{h_{tot}}{\mathrm{abs}\left(\sigma_{top.max}\right) + \mathrm{abs}\left(\sigma_{bot.max}\right)} \right) \cdot \mathrm{abs}\left(\sigma_{bot.max}\right) = 0.873\ m$$

$h_{comp} := c_{w.new.x} = 1.818\ m$ All part of the web is compressed

$$\alpha := \frac{n_{comp}}{c_{w.new.x}} = 1 \qquad \alpha > 0.5$$

If $\alpha > 0.5$ & $\psi > -1$

$$CS_{class.web} := \begin{array}{l} \text{if } \dfrac{c_{w.new.x}}{t_{w.new.x}} \le \dfrac{396 \cdot \varepsilon_w}{13 \cdot \alpha - 1} \\ \quad \| \; 1 \\ \text{if } \dfrac{396 \cdot \varepsilon_w}{13 \cdot \alpha - 1} < \dfrac{c_{w.new.x}}{t_{w.new.x}} \le \dfrac{456 \cdot \varepsilon_w}{13 \cdot \alpha - 1} \\ \quad \| \; 2 \\ \text{if } \dfrac{456 \cdot \varepsilon_w}{13 \cdot \alpha - 1} < \dfrac{c_{w.new.x}}{t_{w.new.x}} \le \dfrac{42 \cdot \varepsilon_w}{0.67 + 0.33 \cdot \psi} \\ \quad \| \; 3 \\ \text{if } \dfrac{42 \cdot \varepsilon_w}{0.67 + 0.33 \cdot \psi} < \dfrac{c_{w.new.x}}{t_{w.new.x}} \\ \quad \| \; 4 \end{array} = 4$$

EN1993-1-5 - Table 4.1

$$k_\sigma := \frac{8.2}{(1.05 + \psi)} = 4.383$$

$$b_{bar} := c_{w.new.x} = 1.818 \; m$$

$$f_{y.w} = 345 \; MPa$$

$$\varepsilon := \sqrt{\frac{235 \; MPa}{f_{y.w}}} = 0.825$$

EN1993-1-5 - section 4.4

$$\lambda_p := \frac{\dfrac{b_{bar}}{t_{w.new.x}}}{28.4 \cdot \varepsilon \cdot \sqrt{k_\sigma}} = 1.853$$

$$limit := 0.5 + \sqrt{0.085 - 0.055 \cdot \psi} = 0.7$$

$$\lambda_p > limit$$

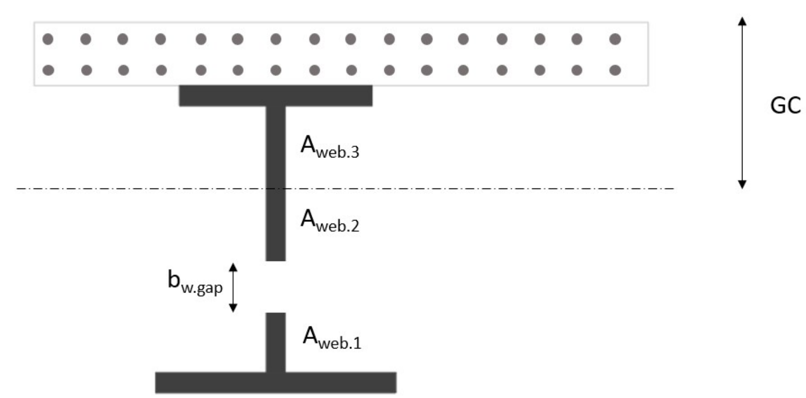
$$\rho := \frac{\lambda_p - 0.055 \cdot (3 + \psi)}{{\lambda_p}^2} = 0.479$$

EN1993-1-5 - Table 4.1

$$b_{eff} := \rho \cdot h_{comp} = 0.87\ m$$

$$b_{e1} := \frac{2}{5 - \psi} \cdot b_{eff} = 0.416\ m \qquad b_{e2} := b_{eff} - b_{e1} = 0.454\ m$$

$$b_{w.gap} := h_{comp} - b_{e1} - b_{e2} = 0.948\ m$$



Stress distribution is calculated with reduced plates if in compression and in CSC 4.

A.13 Verification of welds in ULS

Welds ULS

According to EN 1993-1-8

$\tau_{II.max} := 48.8\ MPa$

$\tau_{II.min} := 25.9\ MPa$

$f_u := 470\ MPa$

$\beta := 0.9$ Table 4.1

$\gamma_{M2} := 1.25$

$$\tau_{Rd} := \frac{\left(\frac{f_u}{\sqrt{3}}\right)}{\beta \cdot \gamma_{M2}} = 241.204\ MPa$$

Verification:

$$U_{max} := \frac{\tau_{II.max}}{\tau_{Rd}} = 0.202$$

$$U_{min} := \frac{\tau_{II.min}}{\tau_{Rd}} = 0.107$$ < 1 OK!

A.14 Shear studs calculation

Shear connector

Steel and composite bridges Section 4.9

x=50.25m

$t_{.top.flange} := 35\ mm$

$f_{.y.top.flange} := 345\ MPa$

Design of shear studs (ULS)

$\phi := 22\ mm$ $\phi 19,\ \phi 22,\ \phi 25$ is standard diameters

$f_{uk} := 450\ MPa$ Ultimate tensile strength of the material of the stud (<500MPa)

$\gamma_v := 1.25$ EN 1994-1-1

$$P_{Rd1} := \frac{0.8 \cdot f_{uk} \cdot \frac{(\pi \cdot \phi^2)}{4}}{\gamma_v} = 109.478\ kN$$

$h_{sc} := \frac{t_{slab}}{2} = 0.15\ m$ Height of stud

$$\alpha_{ss} := \begin{array}{|l} \text{if } 3 \le \frac{h_{sc}}{\phi} \le 4 \\ \quad \left\| 0.2 \cdot \left(\frac{h_{sc}}{\phi} + 1\right) \right. \\ \text{if } 4 < \frac{h_{sc}}{\phi} \\ \quad \| 1 \end{array} = 1$$

$$P_{Rd2} := \frac{0.29 \cdot \alpha_{ss} \cdot \phi^2 \cdot \sqrt{f_{ck} \cdot E_{cm}}}{\gamma_v} = 122.492\ kN$$

$$P_{Rd} := min\left(P_{Rd1}, P_{Rd2}\right) = 109.478\ kN$$ Design shear resistance

Minimum/maximum distances:

$$b_{0.min} := min(4 \cdot \phi) = 0.088\ m$$ Minimum center distance between studs

$$b_{edge.stud.min} := min(50\ mm) = 0.05\ m$$ Minimum distance from edge of flange to center of stud

<u>Choose:</u>

$$b_0 := 0.4\ m$$

$$b_{edge.stud} := \frac{b_{tf} - b_0}{2} = 0.3\ m$$ $> b_{edge.stud.min}$ -> OK

$$c_{long.stud.max} := 22 \cdot t_{.top.flange} \cdot \sqrt{\frac{235\ MPa}{f_{.y.top.flange}}} = 0.635\ m$$ EN 1994-2:2005 6.6.5.5

$$c_{long.stud.max} := \max(600\ mm) = 0.6\ m$$ Distance between studs in longitudinal direction

$$c_{long.stud.min} := min(5 \cdot \phi) = 0.11\ m$$

$$c_{long.stud} := \text{mean}\left(c_{long.stud.min}, c_{long.stud.max}\right) = 0.355\ m$$

Sectional constants for x=50.25 m

Long term:

$$V_{Ed.max.long} := -236.79\ kN$$

$$V_{Ed.min.long} := -324.48\ kN$$

$$e_{long} := 0.564\ m$$

$$A_{long} := 0.203\ m^2$$

$$I_{long} := 0.162\ m^4$$

Short term:

$V_{Ed.max.short} := 864.59\ kN$

$V_{Ed.min.short} := -1076.08\ kN$

$e_{short} := 0.166\ m$

$A_{short} := 0.459\ m^2$

$I_{short} := 0.220\ m^4$

Concentrated shear force transferred to distrubuted shear force per meter length of the beam:

$$F_{sd.max} := \frac{V_{Ed.max.long} \cdot e_{long} \cdot A_{long}}{I_{long}} + \frac{V_{Ed.max.short} \cdot e_{short} \cdot A_{short}}{I_{short}} = 132.09\ \frac{kN}{m}$$

$$F_{sd.min} := \frac{V_{Ed.min.long} \cdot e_{long} \cdot A_{long}}{I_{long}} + \frac{V_{Ed.min.short} \cdot e_{short} \cdot A_{short}}{I_{short}} = -602.009\ \frac{kN}{m}$$

$$n_{studs.max} := \left| \frac{F_{sd.max}}{P_{Rd}} \right| = 1.207\ \frac{1}{m}$$

Pair of studs per meter

$$n_{studs.min} := \left| \frac{F_{sd.min}}{P_{Rd}} \right| = 5.499\ \frac{1}{m}$$

A.15 FLS verification (FLM3)

EN 1993-2: 2006 - Section 9.5.2

λ-coefficient method for FLM3

EN 1991-2:2003 Indicative nr of heavy veichles expected per year and per slow lange - Table 4.5

$N_{obs} := 0.05 \cdot 10^6$ Roads and motorways with medium flow rates of lorries

EN 1993-2:2006 - Section 9.5.2

$Q_0 := 480\ kN$

$N_0 := 0.5 \cdot 10^6$

$Q_{M1} := 445.5\ kN$ The average gross weight of the lorries in the slow lane

Factor for traffic volume:

$$\lambda_2 := \frac{Q_{M1}}{Q_0} \cdot \left(\frac{N_{obs}}{N_0}\right)^{\frac{1}{5}} = 0.586 \qquad \text{Eq. (9.10)}$$

Factor for design life of the bridge:

$\lambda_3 := 1.037$ Table 9.2 (Design life 120 year)

Factor for the traffic on other lanes:

$\lambda_4 := 1.0$ Assuming $Eq.(9.12)$ TSFS 2018:57

EN 1993-2 - Section 9.5.2 (2)

$L_{span1} := 28\ m$

$L_{span2} := 38.75\ m$

$L_{supp1} := 0.15 \cdot L_{span1} = 4.2\ m$ $L_{supp2} := 0.15 \cdot L_{span2} = 5.813\ m$

λ_1: Figure 9.5 EN 1993-2:2006

$$L_{span1.new} := L_{span1} - L_{supp1} = 23.8\ m$$

$$L_{span2.new} := L_{span2} - 2 \cdot L_{supp2} = 27.125\ m$$

$$\lambda_{1.span1} := 2.55 - 0.7 \cdot \left(\frac{L_{span1.new} - 10\ m}{70\ m} \right) = 2.412$$

$$\lambda_{1.span2} := 2.55 - 0.7 \cdot \left(\frac{L_{span2.new} - 10\ m}{70\ m} \right) = 2.379$$

$$\lambda_{1.supp1} := 2 - 0.3 \cdot \left(\frac{\left(L_{supp1} + L_{supp2}\right) - 10\ m}{20\ m} \right) = 2$$

$$\lambda_{1.supp2} := 2 - 0.3 \cdot \left(\frac{\left(2 \cdot L_{supp2}\right) - 10\ m}{20\ m} \right) = 1.976$$

<u>Maximum λ-value taking account of the fatigue limit:</u>

λ_{max}: EN 1993-2 - Section 9.5.2 (7) Span longer than 25 m

$$\lambda_{max.span1} := 2$$

$$\lambda_{max.span2} := 2$$

$$\lambda_{max.supp1} := 1.8$$

$$\lambda_{max.supp2} := 1.8$$

Span section:

$\lambda_{span1} := \lambda_{1.span1} \cdot \lambda_2 \cdot \lambda_3 \cdot \lambda_4 = 1.465$ Equation 9.13

$\lambda_{span2} := \lambda_{1.span2} \cdot \lambda_2 \cdot \lambda_3 \cdot \lambda_4 = 1.445$

$\lambda_{supp1} := \lambda_{1.supp1} \cdot \lambda_2 \cdot \lambda_3 \cdot \lambda_4 = 1.214$

$\lambda_{supp2} := \lambda_{1.supp2} \cdot \lambda_2 \cdot \lambda_3 \cdot \lambda_4 = 1.2$

$$\lambda_{span11} := \left| \begin{array}{l} \text{if } \lambda_{span1} \le \lambda_{max.span1} \\ \quad \| \lambda_{span1} \\ \text{else} \\ \quad \| \lambda_{max.span1} \end{array} \right. = 1.465$$

$$\lambda_{span22} := \left| \begin{array}{l} \text{if } \lambda_{span2} \le \lambda_{max.span2} \\ \quad \| \lambda_{span2} \\ \text{else} \\ \quad \| \lambda_{max.span2} \end{array} \right. = 1.445$$

$$\lambda_{supp11} := \left| \begin{array}{l} \text{if } \lambda_{supp1} \le \lambda_{max.supp1} \\ \quad \| \lambda_{supp1} \\ \text{else} \\ \quad \| \lambda_{max.supp1} \end{array} \right. = 1.214$$

$$\lambda_{supp22} := \left| \begin{array}{l} \text{if } \lambda_{supp2} \le \lambda_{max.supp2} \\ \quad \| \lambda_{supp2} \\ \text{else} \\ \quad \| \lambda_{max.supp2} \end{array} \right. = 1.2$$

FLM3 EN 1993-1-9 : 2005 (E)

$\phi_2 := 1.0$ Dynamic amplification factor (already included in FLM3)

$H := 1937.5\ mm$

$t_{top.flange} := 35\ mm$

$\Delta M := 3109.24\ kN \cdot m$

$GC := 166.27\ mm$

$I_{tot} := 2.2 \cdot 10^{11}\ mm^4$

Detail 1: Transversal stiffeners

$\Delta\sigma_{c1} := 80\ MPa$

$e_{1.bot} := H - GC = 1.771\ m$

$e_{1.top} := GC - t_{top.flange} = 0.131\ m$

Bottom flange: EN 1993-2: 2006 Section 9.4

$$\sigma_{1.bot} := \frac{\Delta M}{\left(\frac{I_{tot}}{e_{1.bot}}\right)} = 25.033\ MPa$$

$\sigma_{E.1.bot} := \sigma_{1.bot} \cdot \lambda_{span22} = 36.161\ MPa$

Verification: EN 1993-1-9 : 2005 Section 8

$\gamma_{Ff} := 1$
$\gamma_{Mf} := 1.35$

$$\frac{\sigma_{E.1.bot} \cdot \gamma_{Ff}}{\frac{\Delta\sigma_{c1}}{\gamma_{Mf}}} = 0.61$$ < 1 OK!

Top flange:

$$\sigma_{1.top} := \frac{\Delta M}{\left(\frac{I_{tot}}{e_{1.top}}\right)} = 1.855\ MPa$$

$$\sigma_{E.1.top} := \sigma_{1.top} \cdot \lambda_{span22} = 2.68\ MPa$$

Verification:

$$\frac{\sigma_{E.1.top} \cdot \gamma_{Ff}}{\frac{\Delta\sigma_{c1}}{\gamma_{Mf}}} = 0.045$$ < 1 OK!

Detail 2: Butt-weld

$$\Delta\sigma_{c2} := 112\ MPa$$

$$e_{2.bot} := H - GC = 1.771\ m$$
$$e_{2.top} := GC = 0.166\ m$$

Bottom flange:

$$\sigma_{2.bot} := \frac{\Delta M}{\left(\frac{I_{tot}}{e_{2.bot}}\right)} = 25.033\ MPa$$

$$\sigma_{E.2.bot} := \sigma_{2.bot} \cdot \lambda_{span22} = 36.161\ MPa$$

Verification:

$$\frac{\sigma_{E.2.bot} \cdot \gamma_{Ff}}{\frac{\Delta\sigma_{c2}}{\gamma_{Mf}}} = 0.436$$ < 1 OK!

Top flange:

$$\sigma_{2.top} := \frac{\Delta M}{\left(\frac{I_{tot}}{e_{2.top}}\right)} = 2.35\ MPa$$

$$\sigma_{E.2.top} := \sigma_{2.top} \cdot \lambda_{span22} = 3.395\ MPa$$

Verification:

$$\frac{\sigma_{E.2.top} \cdot \gamma_{Ff}}{\frac{\Delta\sigma_{c2}}{\gamma_{Mf}}} = 0.041$$ < 1 OK!

Detail 3: Shear stud

<u>Fatigue verification of shear studs 1994-2:2003</u>

x=50.25m

$$\Delta V := 345.95\ kN$$

$\lambda_{v.1} := 1.55$ For road bridges of span up to 100m (EN 1994-2:2003 - Section 6.8.6.2 (4))

EN 1994-2:2005 Section 6.8.6.2

$$\lambda_{v.2} := \frac{Q_{M1}}{Q_0} \cdot \left(\frac{N_{obs}}{N_0}\right)^{\frac{1}{8}} = 0.696$$

EN1993-2:2006 - Section 9.5.2 (3) but 1/5 replaced by 1/8 in the expression

$$\lambda_{v.3} := \left(\frac{120}{100}\right)^{\frac{1}{8}} = 1.023$$

EN1993-2:2006 - Section 9.5.2 (4) but 1/5 replaced by 1/8 in the expression

$\lambda_{v.4} := 1$ TSFS 2018:57

$$\lambda_v := \lambda_{v.1} \cdot \lambda_{v.2} \cdot \lambda_{v.3} \cdot \lambda_{v.4} = 1.104$$

Shear stress:

$\Delta\tau_c := 90\ MPa$

$A_{btg} := 349714.3\ mm^2$

$e_{btg} := -150\ mm$

$n := 6.18$
$\phi_3 := 22\ mm$

$$S_c := \frac{A_{btg} \cdot \left(GC - \left(e_{btg}\right)\right)}{n} = \left(1.79 \cdot 10^7\right)\ mm^3$$

$$\Delta\tau_1 := \frac{\Delta V \cdot S_c}{I_{tot} \cdot \phi_3 \cdot 2} = 0.64\ MPa$$

$$\Delta\tau_{E.1} := \Delta\tau_1 \cdot \lambda_v = 0.706\ MPa$$

Verification:

$\gamma_{Ff} \cdot \Delta\tau_{E.1} = 0.706\ MPa$

$$\frac{\gamma_{Ff} \cdot \Delta\tau_{E.1}}{\dfrac{\Delta\tau_c}{\gamma_{Mf}}} = 0.011$$ < 1 OK!

Detail 4: Flange to web longitudinal weld

$\Delta\sigma_{c4} := 112\ MPa$

$e_{4.bot} := H - GC = 1.771\ m$
$e_{4.top} := GC - t_{top.flange} = 0.131\ m$

Bottom flange:

$$\sigma_{4.bot} := \frac{\Delta M}{\left(\frac{I_{tot}}{e_{4.bot}}\right)} = 25.033\ MPa$$

$$\sigma_{E.4.bot} := \sigma_{4.bot} \cdot \lambda_{span22} = 36.161\ MPa$$

Verification:

$$\frac{\sigma_{E.4.bot} \cdot \gamma_{Ff}}{\frac{\Delta\sigma_{c4}}{\gamma_{Mf}}} = 0.436$$ < 1 OK!

Top flange:

$$\sigma_{4.top} := \frac{\Delta M}{\left(\frac{I_{tot}}{e_{4.top}}\right)} = 1.855\ MPa$$

$$\sigma_{E.4.top} := \sigma_{4.top} \cdot \lambda_{span22} = 2.68\ MPa$$

Verification:

$$\frac{\sigma_{E.4.top} \cdot \gamma_{Ff}}{\frac{\Delta\sigma_{c4}}{\gamma_{Mf}}} = 0.032$$ < 1 OK!

Detail 5: Rat-hole (notch)

$\Delta\sigma_{c5} := 71\ MPa$

$e_{5.bot} := H - GC = 1.771\ m$
$e_{5.top} := GC - t_{top.flange} = 0.131\ m$

Bottom flange:

$$\sigma_{5.bot} := \frac{\Delta M}{\left(\frac{I_{tot}}{e_{5.bot}}\right)} = 25.033\ MPa$$

$$\sigma_{E.5.bot} := \sigma_{5.bot} \cdot \lambda_{span22} = 36.161\ MPa$$

Verification:

$$\frac{\sigma_{E.5.bot} \cdot \gamma_{Ff}}{\frac{\Delta\sigma_{c5}}{\gamma_{Mf}}} = 0.688$$ < 1 OK!

Top flange:

$$\sigma_{5.top} := \frac{\Delta M}{\left(\frac{I_{tot}}{e_{5.top}}\right)} = 1.855\ MPa$$

$$\sigma_{E.5.top} := \sigma_{5.top} \cdot \lambda_{span22} = 2.68\ MPa$$

Verification:

$$\frac{\sigma_{E.5.top} \cdot \gamma_{Ff}}{\frac{\Delta\sigma_{c5}}{\gamma_{Mf}}} = 0.051$$ < 1 OK!

Detail 6: Base metal

$\Delta\sigma_{c6} := 160\ MPa$

$e_{6.bot} := H - GC = 1.771\ m$
$e_{6.top} := GC = 0.166\ m$

Bottom flange:

$$\sigma_{6.bot} := \frac{\Delta M}{\left(\frac{I_{tot}}{e_{6.bot}}\right)} = 25.033\ MPa$$

$$\sigma_{E.6.bot} := \sigma_{6.bot} \cdot \lambda_{span22} = 36.161\ MPa$$

Verification:

$$\frac{\sigma_{E.6.bot} \cdot \gamma_{Ff}}{\frac{\Delta\sigma_{c6}}{\gamma_{Mf}}} = 0.305 \ < 1 \text{ OK!}$$

Top flange:

$$\sigma_{6.top} := \frac{\Delta M}{\left(\frac{I_{tot}}{e_{6.top}}\right)} = 2.35\ MPa$$

$$\sigma_{E.6.top} := \sigma_{6.top} \cdot \lambda_{span22} = 3.395\ MPa$$

Verification:

$$\frac{\sigma_{E.6.top} \cdot \gamma_{Ff}}{\frac{\Delta\sigma_{c6}}{\gamma_{Mf}}} = 0.029 \ < 1 \text{ OK!}$$

A.16 FLS verification (FLM4)

Damage accumulation method FLM4

EN 1991-2:2003, 4.6.5

For road bridges: FLM4 should be uses to calculate total fatigue damage accumulated trough the design service life of the bridge

$\gamma_{Ff} := 1.0$ $\gamma_{Mf} := 1.35$ EN 1993-1-9:2005

$\gamma_{Mf.s} := 1.0$ For shear studs - EN 1994-2 2.4.1.2 (6)

Safe life method - TRVFS 2011:12 Design life 120 years

$c := 8000\ mm$ $e := 3200\ mm$

$LDF := 0.5 + \frac{e}{c} = 0.9$ Load distribution factor (Fatigue design of steel bridges)

EN 1991-2:2003 Indicative nr of heavy veichles expected per year and per slow lange Table 4.5

$N_{obs} := 0.05 \cdot 10^6$ Roads and motorways with medium flow rates of lorries

EN 1993-2:2006 - Section 9.5.2

$Q_0 := 480\ kN$

$N_0 := 0.5 \cdot 10^6$

EN 1991-2 - Table 4.7 - Set of equivalent lorries

Lorry:		n/year	n in 120 years
Lorrie 1 20%	$p_1 := 0.2$	$n_{11} := p_1 \cdot N_{obs} = 1 \cdot 10^4$	$n_1 := n_{11} \cdot 120 = 1.2 \cdot 10^6$
Lorrie 2 5%	$p_2 := 0.05$	$n_{22} := p_2 \cdot N_{obs} = 2.5 \cdot 10^3$	$n_2 := n_{22} \cdot 120 = 3 \cdot 10^5$
Lorrie 3 50%	$p_3 := 0.5$	$n_{33} := p_3 \cdot N_{obs} = 2.5 \cdot 10^4$	$n_3 := n_{33} \cdot 120 = 3 \cdot 10^6$

Lorrie 4 15%	$p_4 := 0.15$	$n_{44} := p_4 \cdot N_{obs} = 7.5 \cdot 10^3$	$n_4 := n_{44} \cdot 120 = 9 \cdot 10^5$
Lorrie 5 10%	$p_5 := 0.1$	$n_{55} := p_5 \cdot N_{obs} = 5 \cdot 10^3$	$n_5 := n_{55} \cdot 120 = 6 \cdot 10^5$

Weight of each veichles:

$$Q_1 := (70 + 130)\ kN = 200\ kN$$

$$Q_2 := (70 + 120 + 120)\ kN = 310\ kN$$

$$Q_3 := (70 + 150 + 90 + 90 + 90)\ kN = 490\ kN$$

$$Q_4 := (70 + 140 + 90 + 90)\ kN = 390\ kN$$

$$Q_5 := (70 + 130 + 90 + 80 + 80)\ kN = 450\ kN$$

$$Q_{M1} := \left(\frac{n_{11} \cdot Q_1^{\ 5} + n_{22} \cdot Q_2^{\ 5} + n_{33} \cdot Q_3^{\ 5} + n_{44} \cdot Q_4^{\ 5} + n_{55} \cdot Q_5^{\ 5}}{(n_{11} + n_{22} + n_{33} + n_{44} + n_{55})} \right)^{\left(\frac{1}{5}\right)} = 445.404\ kN$$

The average gross weight of the lorries in the slow lane (källa FAT design composite bridge)

Assuming 1 veichle = 1 cycle

The following calculations are for section x=50.25 m

$h_{tot} = 1.938\ m$ $\qquad$ $I_{tot} := 0.22\ m^4$

$y_{tp} := 0.166\ m$ $\qquad$ (Short term calculations of GC)

Detail 1 - Transverse attachment

EN 1993-1-9:

$\Delta\sigma_{C.1} := 80\ MPa$ Detail category (detail 1)

$\Delta\sigma_{D.1} := 0.737 \cdot \Delta\sigma_{C.1} = 58.96\ MPa$ CAFL

$\Delta\sigma_{L.1} := 0.549 \cdot \Delta\sigma_{D.1} = 32.369\ MPa$ Cut-off limit

Sectional properties:

$e_{d1.bot} := h_{tot} - y_{tp} - t_{bf} = 1.732\ m$ Dist. from GC to top of bottom flange (where the transverse stiffener is attached)

$e_{d1.top} := y_{tp} - t_{tf} = 0.131\ m$ Dist. from GC to bot of top flange (where the transverse stiffener is attached)

$$I\_e_{d1.bot} := \frac{I_{tot}}{e_{d1.bot}} = 0.127\ m^3$$

$$I\_e_{d1.top} := \frac{I_{tot}}{e_{d1.top}} = 1.679\ m^3$$

Stress history:

Lorry 1:

$M_{1.max} := 1327.68\ kN \cdot m$ From Sofisitk (FLM4)

$M_{1.min} := -138.54\ kN \cdot m$

$$\Delta M_1 := \text{abs}\left(M_{1.max}\right) + \text{abs}\left(M_{1.min}\right) = \left(1.466 \cdot 10^3\right)\ kN \cdot m$$

$$\Delta\sigma_{1.d1.bot} := \frac{\Delta M_1}{I\_e_{d1.bot}} = 11.54\ MPa$$

$$\Delta\sigma_{1.d1.top} := \frac{\Delta M_1}{I\_e_{d1.top}} = 0.873\ MPa$$

Lorry 2:

$M_{2.max} := 2096.80\ kN \cdot m$ From Sofisitk (FLM4)

$M_{2.min} := -214.82\ kN \cdot m$

$\Delta M_2 := \text{abs}\left(M_{2.max}\right) + \text{abs}\left(M_{2.min}\right) = \left(2.312 \cdot 10^3\right)\ kN \cdot m$

$$\Delta\sigma_{2.d1.bot} := \frac{\Delta M_2}{I\_e_{d1.bot}} = 18.194\ MPa$$

$$\Delta\sigma_{2.d1.top} := \frac{\Delta M_2}{I\_e_{d1.top}} = 1.376\ MPa$$

Lorry 3:

$M_{3.max} := 2853.87\ kN \cdot m$ From Sofisitk (FLM4)

$M_{3.min} := -316.38\ kN \cdot m$

$\Delta M_3 := \text{abs}\left(M_{3.max}\right) + \text{abs}\left(M_{3.min}\right) = \left(3.17 \cdot 10^3\right)\ kN \cdot m$

$$\Delta\sigma_{3.d1.bot} := \frac{\Delta M_3}{I\_e_{d1.bot}} = 24.951\ MPa$$

$$\Delta\sigma_{3.d1.top} := \frac{\Delta M_3}{I\_e_{d1.top}} = 1.888\ MPa$$

Lorry 4:

$M_{4.max} := 2158.08\ kN \cdot m$ From Sofisitk (FLM4)

$M_{4.min} := -248.88\ kN \cdot m$

$\Delta M_4 := \text{abs}\left(M_{4.max}\right) + \text{abs}\left(M_{4.min}\right) = \left(2.407 \cdot 10^3\right)\ kN \cdot m$

$$\Delta\sigma_{4.d1.bot} := \frac{\Delta M_4}{I\_e_{d1.bot}} = 18.944\ MPa$$

$$\Delta\sigma_{4.d1.top} := \frac{\Delta M_4}{I\_e_{d1.top}} = 1.433\ MPa$$

Lorry 5:

$M_{5.max} := 2418.59\ kN \cdot m$ From Sofisitk (FLM4)

$M_{5.min} := -275.53\ kN \cdot m$

$\Delta M_5 := \text{abs}\left(M_{5.max}\right) + \text{abs}\left(M_{5.min}\right) = \left(2.694 \cdot 10^3\right)\ kN \cdot m$

$$\Delta\sigma_{5.d1.bot} := \frac{\Delta M_5}{I\_e_{d1.bot}} = 21.204\ MPa$$

$$\Delta\sigma_{5.d1.top} := \frac{\Delta M_5}{I\_e_{d1.top}} = 1.604\ MPa$$

Damage calculation (BOTTOM):

Lorry 1:

$$N_{1.d1.bot} := \begin{cases} 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{1.d1.bot} \cdot \gamma_{Ff}}\right)^3 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d1.bot} \ge \dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}} \\ 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{1.d1.bot} \cdot \gamma_{Ff}}\right)^5 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d1.bot} \ge \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \\ \infty & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d1.bot} < \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \end{cases} = 1 \cdot 10^{307}$$

$$D_{1.d1.bot} := \frac{n_1}{N_{1.d1.bot}} = 1.2 \cdot 10^{-301}$$

Lorry 2:

$$N_{2.d1.bot} := \begin{cases} 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{1.d1.bot} \cdot \gamma_{Ff}} \right)^3 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d1.bot} \geq \dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}} \\ 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{2.d1.bot} \cdot \gamma_{Ff}} \right)^5 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d1.bot} \geq \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \\ \infty & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d1.bot} < \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \end{cases} = 1 \cdot 10^{307}$$

$$D_{2.d1.bot} := \frac{n_2}{N_{2.d1.bot}} = 3 \cdot 10^{-302}$$

Lorry 3:

$$N_{3.d1.bot} := \begin{cases} 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{3.d1.bot} \cdot \gamma_{Ff}} \right)^3 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d1.bot} \geq \dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}} \\ 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{3.d1.bot} \cdot \gamma_{Ff}} \right)^5 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d1.bot} \geq \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \\ \infty & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d1.bot} < \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \end{cases} = 8.215 \cdot 10^{7}$$

$$D_{3.d1.bot} := \frac{n_3}{N_{3.d1.bot}} = 0.037$$

Lorry 4:

$$N_{4.d1.bot} := \begin{cases} 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{4.d1.bot} \cdot \gamma_{Ff}} \right)^3 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d1.bot} \geq \dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}} \\ 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{4.d1.bot} \cdot \gamma_{Ff}} \right)^5 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d1.bot} \geq \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \\ \infty & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d1.bot} < \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \end{cases} = 1 \cdot 10^{307}$$

$$D_{4.d1.bot} := \frac{n_4}{N_{4.d1.bot}} = 9 \cdot 10^{-302}$$

Lorry 5:

$$N_{5.d1.bot} := \begin{cases} 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{5.d1.bot} \cdot \gamma_{Ff}} \right)^3 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d1.bot} \geq \dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}} \\ 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{5.d1.bot} \cdot \gamma_{Ff}} \right)^5 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d1.bot} \geq \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \\ \infty & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d1.bot} < \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \end{cases} = 1 \cdot 10^{307}$$

$$D_{5.d1.bot} := \frac{n_5}{N_{5.d1.bot}} = 6 \cdot 10^{-302}$$

$$D_{d1.bot} := D_{1.d1.bot} + D_{2.d1.bot} + D_{3.d1.bot} + D_{4.d1.bot} + D_{5.d1.bot} = 0.037$$

Damage calculation (TOP):

Lorry 1:

$$N_{1.d1.top} := \left\| \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d1.top} \geq \dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}} \\ \quad \left\| \, 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{1.d1.top} \cdot \gamma_{Ff}} \right)^3 \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d1.top} \geq \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \\ \quad \left\| \, 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{1.d1.top} \cdot \gamma_{Ff}} \right)^5 \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d1.top} < \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \\ \quad \left\| \, \infty \right. \end{array} \right. = 1 \cdot 10^{307} \qquad D_{1.d1.top} := \frac{n_1}{N_{1.d1.top}} = 1.2 \cdot 10^{-301}$$

Lorry 2:

$$N_{2.d1.top} := \left\| \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d1.top} \geq \dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}} \\ \quad \left\| \, 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{1.d1.top} \cdot \gamma_{Ff}} \right)^3 \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d1.top} \geq \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \\ \quad \left\| \, 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{2.d1.top} \cdot \gamma_{Ff}} \right)^5 \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d1.top} < \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \\ \quad \left\| \, \infty \right. \end{array} \right. = 1 \cdot 10^{307} \qquad D_{2.d1.top} := \frac{n_2}{N_{2.d1.top}} = 3 \cdot 10^{-302}$$

Lorry 3:

$$N_{3.d1.top} := \begin{cases} 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{3.d1.top} \cdot \gamma_{Ff}} \right)^3 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d1.top} \geq \dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}} \\ 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{3.d1.top} \cdot \gamma_{Ff}} \right)^5 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d1.top} \geq \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \\ \infty & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d1.top} < \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \end{cases} = 1 \cdot 10^{307}$$

$$D_{3.d1.top} := \frac{n_3}{N_{3.d1.top}} = 3 \cdot 10^{-301}$$

Lorry 4:

$$N_{4.d1.top} := \begin{cases} 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{4.d1.top} \cdot \gamma_{Ff}} \right)^3 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d1.top} \geq \dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}} \\ 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{4.d1.top} \cdot \gamma_{Ff}} \right)^5 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d1.top} \geq \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \\ \infty & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d1.top} < \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \end{cases} = 1 \cdot 10^{307}$$

$$D_{4.d1.top} := \frac{n_4}{N_{4.d1.top}} = 9 \cdot 10^{-302}$$

Lorry 5:

$$N_{5.d1.top} := \begin{cases} 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{5.d1.top} \cdot \gamma_{Ff}} \right)^{3} & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d1.top} \geq \dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}} \\ 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{5.d1.top} \cdot \gamma_{Ff}} \right)^{5} & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d1.top} \geq \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \\ \infty & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d1.top} < \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \end{cases} = 1 \cdot 10^{307}$$

$$D_{5.d1.top} := \frac{n_5}{N_{5.d1.top}} = 6 \cdot 10^{-302}$$

$$D_{d1.top} := D_{1.d1.top} + D_{2.d1.top} + D_{3.d1.top} + D_{4.d1.top} + D_{5.d1.top} = 6 \cdot 10^{-301}$$

Detail 2 - Butt weld

EN 1993-1-9:

$\Delta\sigma_{C.2} := 112\ MPa$ — Detail category (detail 2)

$\Delta\sigma_{D.2} := 0.737 \cdot \Delta\sigma_{C.2} = 82.544\ MPa$ — CAFL

$\Delta\sigma_{L.2} := 0.549 \cdot \Delta\sigma_{D.2} = 45.317\ MPa$ — Cut-off limit

Sectional properties:

$e_{d2.bot} := h_{tot} - y_{tp} = 1.772\ m$ — Dist. from GC to outer most fiber in bot flange (where the transverse stiffener is attached)

$e_{d2.top} := y_{tp} = 0.166\ m$ — Dist. from GC to outer most fiber in top flange (where the transverse stiffener is attached)

$$I\_e_{d2.bot} := \frac{I_{tot}}{e_{d2.bot}} = 0.124\ m^3$$

$$I\_e_{d2.top} := \frac{I_{tot}}{e_{d2.top}} = 1.325\ m^3$$

Stress history:

Lorry 1:

$$\Delta\sigma_{1.d2.bot} := \frac{\Delta M_1}{I\_e_{d2.bot}} = 11.806\ MPa$$

$$\Delta\sigma_{1.d2.top} := \frac{\Delta M_1}{I\_e_{d2.top}} = 1.106\ MPa$$

Lorry 2:

$$\Delta\sigma_{2.d2.bot} := \frac{\Delta M_2}{I\_e_{d2.bot}} = 18.614\ MPa$$

$$\Delta\sigma_{2.d2.top} := \frac{\Delta M_2}{I\_e_{d2.top}} = 1.744\ MPa$$

Lorry 3:

$$\Delta\sigma_{3.d2.bot} := \frac{\Delta M_3}{I\_e_{d2.bot}} = 25.528\ MPa$$

$$\Delta\sigma_{3.d2.top} := \frac{\Delta M_3}{I\_e_{d2.top}} = 2.392\ MPa$$

Lorry 4:

$$\Delta\sigma_{4.d2.bot} := \frac{\Delta M_4}{I\_e_{d2.bot}} = 19.381\ MPa$$

$$\Delta\sigma_{4.d2.top} := \frac{\Delta M_4}{I\_e_{d2.top}} = 1.816\ MPa$$

Lorry 5:

$$\Delta\sigma_{5.d2.bot} := \frac{\Delta M_5}{I\_e_{d2.bot}} = 21.694\ MPa$$

$$\Delta\sigma_{5.d2.top} := \frac{\Delta M_5}{I\_e_{d2.top}} = 2.033\ MPa$$

Damage calculation (BOTTOM):

Lorry 1:

$$N_{1.d2.bot} := \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d2.bot} \geq \dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}} \\ \quad 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{1.d2.bot} \cdot \gamma_{Ff}} \right)^3 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d2.bot} \geq \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \\ \quad 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{1.d2.bot} \cdot \gamma_{Ff}} \right)^5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d2.bot} < \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \\ \quad \infty \end{array} = 1 \cdot 10^{307}$$

$$D_{1.d2.bot} := \frac{n_1}{N_{1.d2.bot}} = 1.2 \cdot 10^{-301}$$

Lorry 2:

$$N_{2.d2.bot} := \begin{cases} 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{1.d2.bot} \cdot \gamma_{Ff}} \right)^3 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d2.bot} \geq \dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}} \\ 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{2.d2.bot} \cdot \gamma_{Ff}} \right)^5 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d2.bot} \geq \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \\ \infty & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d2.bot} < \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \end{cases} = 1 \cdot 10^{307}$$

$$D_{2.d2.bot} := \frac{n_2}{N_{2.d2.bot}} = 3 \cdot 10^{-302}$$

Lorry 3:

$$N_{3.d2.bot} := \begin{cases} 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{3.d2.bot} \cdot \gamma_{Ff}} \right)^3 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d2.bot} \geq \dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}} \\ 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{3.d2.bot} \cdot \gamma_{Ff}} \right)^5 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d2.bot} \geq \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \\ \infty & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d2.bot} < \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \end{cases} = 7.329 \cdot 10^7$$

$$D_{3.d2.bot} := \frac{n_3}{N_{3.d2.bot}} = 0.041$$

Lorry 4:

$$N_{4.d2.bot} := \left\| \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d2.bot} \ge \dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{4.d2.bot} \cdot \gamma_{Ff}} \right)^{3} \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d2.bot} \ge \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{4.d2.bot} \cdot \gamma_{Ff}} \right)^{5} \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d2.bot} < \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \\ \quad \left\| \; \infty \right. \end{array} \right. = 1 \cdot 10^{307}$$

$$D_{4.d2.bot} := \frac{n_4}{N_{4.d2.bot}} = 9 \cdot 10^{-302}$$

Lorry 5:

$$N_{5.d2.bot} := \left\| \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d2.bot} \ge \dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{5.d2.bot} \cdot \gamma_{Ff}} \right)^{3} \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d2.bot} \ge \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.1}}{\gamma_{Mf}}}{\Delta\sigma_{5.d2.bot} \cdot \gamma_{Ff}} \right)^{5} \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d2.bot} < \dfrac{\Delta\sigma_{L.1}}{\gamma_{Mf}} \\ \quad \left\| \; \infty \right. \end{array} \right. = 1 \cdot 10^{307}$$

$$D_{5.d2.bot} := \frac{n_5}{N_{5.d2.bot}} = 6 \cdot 10^{-302}$$

$$D_{d2.bot} := D_{1.d2.bot} + D_{2.d2.bot} + D_{3.d2.bot} + D_{4.d2.bot} + D_{5.d2.bot} = 0.041$$

Damage calculation (TOP):

Lorry 1:

$$N_{1.d2.top} := \left\| \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d2.top} \ge \dfrac{\Delta\sigma_{D.2}}{\gamma_{Mf}} \\ \quad \left\| \, 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.2}}{\gamma_{Mf}}}{\Delta\sigma_{1.d2.top} \cdot \gamma_{Ff}} \right)^3 \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d2.top} \ge \dfrac{\Delta\sigma_{L.2}}{\gamma_{Mf}} \\ \quad \left\| \, 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.2}}{\gamma_{Mf}}}{\Delta\sigma_{1.d2.top} \cdot \gamma_{Ff}} \right)^5 \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d2.top} < \dfrac{\Delta\sigma_{L.2}}{\gamma_{Mf}} \\ \quad \left\| \, \infty \right. \end{array} \right. = 1 \cdot 10^{307}$$

$$D_{1.d2.top} := \frac{n_1}{N_{1.d2.top}} = 1.2 \cdot 10^{-301}$$

Lorry 2:

$$N_{2.d2.top} := \left\| \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d2.top} \ge \dfrac{\Delta\sigma_{D.2}}{\gamma_{Mf}} \\ \quad \left\| \, 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.2}}{\gamma_{Mf}}}{\Delta\sigma_{1.d2.top} \cdot \gamma_{Ff}} \right)^3 \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d2.top} \ge \dfrac{\Delta\sigma_{L.2}}{\gamma_{Mf}} \\ \quad \left\| \, 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.2}}{\gamma_{Mf}}}{\Delta\sigma_{2.d2.top} \cdot \gamma_{Ff}} \right)^5 \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d2.top} < \dfrac{\Delta\sigma_{L.2}}{\gamma_{Mf}} \\ \quad \left\| \, \infty \right. \end{array} \right. = 1 \cdot 10^{307}$$

$$D_{2.d2.top} := \frac{n_2}{N_{2.d2.top}} = 3 \cdot 10^{-302}$$

Lorry 3:

$$N_{3.d2.top} := \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d2.top} \ge \dfrac{\Delta\sigma_{D.2}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.2}}{\gamma_{Mf}}}{\Delta\sigma_{3.d2.top} \cdot \gamma_{Ff}} \right)^3 \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d2.top} \ge \dfrac{\Delta\sigma_{L.2}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.2}}{\gamma_{Mf}}}{\Delta\sigma_{3.d2.top} \cdot \gamma_{Ff}} \right)^5 \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d2.top} < \dfrac{\Delta\sigma_{L.2}}{\gamma_{Mf}} \\ \quad \| \; \infty \end{array} = 1 \cdot 10^{307} \qquad D_{3.d2.top} := \frac{n_3}{N_{3.d2.top}} = 3 \cdot 10^{-301}$$

Lorry 4:

$$N_{4.d2.top} := \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d2.top} \ge \dfrac{\Delta\sigma_{D.2}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.2}}{\gamma_{Mf}}}{\Delta\sigma_{4.d2.top} \cdot \gamma_{Ff}} \right)^3 \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d2.top} \ge \dfrac{\Delta\sigma_{L.2}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.2}}{\gamma_{Mf}}}{\Delta\sigma_{4.d2.top} \cdot \gamma_{Ff}} \right)^5 \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d2.top} < \dfrac{\Delta\sigma_{L.2}}{\gamma_{Mf}} \\ \quad \| \; \infty \end{array} = 1 \cdot 10^{307} \qquad D_{4.d2.top} := \frac{n_4}{N_{4.d2.top}} = 9 \cdot 10^{-302}$$

Lorry 5:

$$N_{5.d2.top} := \left\| \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d2.top} \geq \dfrac{\Delta\sigma_{D.2}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.2}}{\gamma_{Mf}}}{\Delta\sigma_{5.d2.top} \cdot \gamma_{Ff}} \right)^3 \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d2.top} \geq \dfrac{\Delta\sigma_{L.2}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.2}}{\gamma_{Mf}}}{\Delta\sigma_{5.d2.top} \cdot \gamma_{Ff}} \right)^5 \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d2.top} < \dfrac{\Delta\sigma_{L.2}}{\gamma_{Mf}} \\ \quad \left\| \; \infty \right. \end{array} \right. = 1 \cdot 10^{307} \qquad D_{5.d2.top} := \frac{n_5}{N_{5.d2.top}} = 6 \cdot 10^{-302}$$

$$D_{d2.top} := D_{1.d2.top} + D_{2.d2.top} + D_{3.d2.top} + D_{4.d2.top} + D_{5.d2.top} = 6 \cdot 10^{-301}$$

Detail 4 - Flange to web connection

EN 1993-1-9:

$\Delta\sigma_{C.4} := 112 \; MPa$ — Detail category (detail 4)

$\Delta\sigma_{D.4} := 0.737 \cdot \Delta\sigma_{C.4} = 82.544 \; MPa$ — CAFL

$\Delta\sigma_{L.4} := 0.549 \cdot \Delta\sigma_{D.4} = 45.317 \; MPa$ — Cut-off limit

Sectional properties:

$e_{d4.bot} := h_{tot} - y_{tp} - t_{bf} = 1.732 \; m$ — Dist. from GC to outer most fiber in bot flange

$e_{d4.top} := y_{tp} - t_{tf} = 0.131 \; m$ — Dist. from GC to outer most fiber in top flange

$$I\_e_{d4.bot} := \frac{I_{tot}}{e_{d4.bot}} = 0.127\ m^3$$

$$I\_e_{d4.top} := \frac{I_{tot}}{e_{d4.top}} = 1.679\ m^3$$

Stress history:

Lorry 1:

$$\Delta\sigma_{1.d4.bot} := \frac{\Delta M_1}{I\_e_{d4.bot}} = 11.54\ MPa$$

$$\Delta\sigma_{1.d4.top} := \frac{\Delta M_1}{I\_e_{d4.top}} = 0.873\ MPa$$

Lorry 2:

$$\Delta\sigma_{2.d4.bot} := \frac{\Delta M_2}{I\_e_{d4.bot}} = 18.194\ MPa$$

$$\Delta\sigma_{2.d4.top} := \frac{\Delta M_2}{I\_e_{d4.top}} = 1.376\ MPa$$

Lorry 3:

$$\Delta\sigma_{3.d4.bot} := \frac{\Delta M_3}{I\_e_{d4.bot}} = 24.951\ MPa$$

$$\Delta\sigma_{3.d4.top} := \frac{\Delta M_3}{I\_e_{d4.top}} = 1.888\ MPa$$

Lorry 4:

$$\Delta\sigma_{4.d4.bot} := \frac{\Delta M_4}{I\_e_{d4.bot}} = 18.944\ MPa$$

$$\Delta\sigma_{4.d4.top} := \frac{\Delta M_4}{I\_e_{d4.top}} = 1.433\ MPa$$

Lorry 5:

$$\Delta\sigma_{5.d4.bot} := \frac{\Delta M_5}{I\_e_{d4.bot}} = 21.204\ MPa$$

$$\Delta\sigma_{5.d4.top} := \frac{\Delta M_5}{I\_e_{d4.top}} = 1.604\ MPa$$

Damage calculation (BOTTOM):

Lorry 1:

$$N_{1.d4.bot} := \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d4.bot} \geq \dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}}}{\Delta\sigma_{1.d4.bot} \cdot \gamma_{Ff}} \right)^3 \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d4.bot} \geq \dfrac{\Delta\sigma_{L.4}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}}}{\Delta\sigma_{1.d4.bot} \cdot \gamma_{Ff}} \right)^5 \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d4.bot} < \dfrac{\Delta\sigma_{L.4}}{\gamma_{Mf}} \\ \quad \left\| \; \infty \right. \end{array} = 1 \cdot 10^{307}$$

$$D_{1.d4.bot} := \frac{n_1}{N_{1.d4.bot}} = 1.2 \cdot 10^{-301}$$

Lorry 2:

$$N_{2.d4.bot} := \begin{array}{|l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d4.bot} \geq \dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}} \\ \quad \left\| \, 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}}}{\Delta\sigma_{1.d4.bot} \cdot \gamma_{Ff}} \right)^{3} \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d4.bot} \geq \dfrac{\Delta\sigma_{L.4}}{\gamma_{Mf}} \\ \quad \left\| \, 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}}}{\Delta\sigma_{2.d4.bot} \cdot \gamma_{Ff}} \right)^{5} \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d4.bot} < \dfrac{\Delta\sigma_{L.4}}{\gamma_{Mf}} \\ \quad \| \, \infty \end{array} = 1 \cdot 10^{307}$$

$$D_{2.d4.bot} := \frac{n_2}{N_{2.d4.bot}} = 3 \cdot 10^{-302}$$

Lorry 3:

$$N_{3.d4.bot} := \begin{array}{|l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d4.bot} \geq \dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}} \\ \quad \left\| \, 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}}}{\Delta\sigma_{3.d4.bot} \cdot \gamma_{Ff}} \right)^{3} \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d4.bot} \geq \dfrac{\Delta\sigma_{L.4}}{\gamma_{Mf}} \\ \quad \left\| \, 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}}}{\Delta\sigma_{3.d4.bot} \cdot \gamma_{Ff}} \right)^{5} \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d4.bot} < \dfrac{\Delta\sigma_{L.4}}{\gamma_{Mf}} \\ \quad \| \, \infty \end{array} = 1 \cdot 10^{307}$$

$$D_{3.d4.bot} := \frac{n_3}{N_{3.d4.bot}} = 3 \cdot 10^{-301}$$

Lorry 4:

$$N_{4.d4.bot} := \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d4.bot} \geq \dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}}}{\Delta\sigma_{4.d4.bot} \cdot \gamma_{Ff}} \right)^{3} \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d4.bot} \geq \dfrac{\Delta\sigma_{L.4}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}}}{\Delta\sigma_{4.d4.bot} \cdot \gamma_{Ff}} \right)^{5} \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d4.bot} < \dfrac{\Delta\sigma_{L.4}}{\gamma_{Mf}} \\ \quad \left\| \; \infty \right. \end{array} = 1 \cdot 10^{307}$$

$$D_{4.d4.bot} := \frac{n_4}{N_{4.d4.bot}} = 9 \cdot 10^{-302}$$

Lorry 5:

$$N_{5.d4.bot} := \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d4.bot} \geq \dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}}}{\Delta\sigma_{5.d4.bot} \cdot \gamma_{Ff}} \right)^{3} \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d4.bot} \geq \dfrac{\Delta\sigma_{L.4}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}}}{\Delta\sigma_{5.d4.bot} \cdot \gamma_{Ff}} \right)^{5} \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d4.bot} < \dfrac{\Delta\sigma_{L.4}}{\gamma_{Mf}} \\ \quad \left\| \; \infty \right. \end{array} = 1 \cdot 10^{307}$$

$$D_{5.d4.bot} := \frac{n_5}{N_{5.d4.bot}} = 6 \cdot 10^{-302}$$

$$D_{d4.bot} := D_{1.d4.bot} + D_{2.d4.bot} + D_{3.d4.bot} + D_{4.d4.bot} + D_{5.d4.bot} = 6 \cdot 10^{-301}$$

Damage calculation (TOP):

Lorry 1:

$$N_{1.d4.top} := \left\| \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d4.top} \geq \dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}} \\ \quad \left\| 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}}}{\Delta\sigma_{1.d4.top} \cdot \gamma_{Ff}} \right)^3 \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d4.top} \geq \dfrac{\Delta\sigma_{L.4}}{\gamma_{Mf}} \\ \quad \left\| 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}}}{\Delta\sigma_{1.d4.top} \cdot \gamma_{Ff}} \right)^5 \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d4.top} < \dfrac{\Delta\sigma_{L.4}}{\gamma_{Mf}} \\ \quad \left\| \infty \right. \end{array} \right. = 1 \cdot 10^{307} \qquad D_{1.d4.top} := \frac{n_1}{N_{1.d4.top}} = 1.2 \cdot 10^{-301}$$

Lorry 2:

$$N_{2.d4.top} := \left\| \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d4.top} \geq \dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}} \\ \quad \left\| 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}}}{\Delta\sigma_{1.d4.top} \cdot \gamma_{Ff}} \right)^3 \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d4.top} \geq \dfrac{\Delta\sigma_{L.4}}{\gamma_{Mf}} \\ \quad \left\| 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}}}{\Delta\sigma_{2.d4.top} \cdot \gamma_{Ff}} \right)^5 \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d4.top} < \dfrac{\Delta\sigma_{L.4}}{\gamma_{Mf}} \\ \quad \left\| \infty \right. \end{array} \right. = 1 \cdot 10^{307} \qquad D_{2.d4.top} := \frac{n_2}{N_{2.d4.top}} = 3 \cdot 10^{-302}$$

Lorry 3:

$$N_{3.d4.top} := \begin{cases} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d4.top} \geq \dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}} \\ \quad 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}}}{\Delta\sigma_{3.d4.top} \cdot \gamma_{Ff}} \right)^3 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d4.top} \geq \dfrac{\Delta\sigma_{L.4}}{\gamma_{Mf}} \\ \quad 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}}}{\Delta\sigma_{3.d4.top} \cdot \gamma_{Ff}} \right)^5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d4.top} < \dfrac{\Delta\sigma_{L.4}}{\gamma_{Mf}} \\ \quad \infty \end{cases} = 1 \cdot 10^{307} \qquad D_{3.d4.top} := \frac{n_3}{N_{3.d4.top}} = 3 \cdot 10^{-301}$$

Lorry 4:

$$N_{4.d4.top} := \begin{cases} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d4.top} \geq \dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}} \\ \quad 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}}}{\Delta\sigma_{4.d4.top} \cdot \gamma_{Ff}} \right)^3 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d4.top} \geq \dfrac{\Delta\sigma_{L.4}}{\gamma_{Mf}} \\ \quad 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}}}{\Delta\sigma_{4.d4.top} \cdot \gamma_{Ff}} \right)^5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d4.top} < \dfrac{\Delta\sigma_{L.4}}{\gamma_{Mf}} \\ \quad \infty \end{cases} = 1 \cdot 10^{307} \qquad D_{4.d4.top} := \frac{n_4}{N_{4.d4.top}} = 9 \cdot 10^{-302}$$

Lorry 5:

$$N_{5.d4.top} := \begin{cases} 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}}}{\Delta\sigma_{5.d4.top} \cdot \gamma_{Ff}} \right)^3 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d4.top} \geq \dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}} \\ 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.4}}{\gamma_{Mf}}}{\Delta\sigma_{5.d4.top} \cdot \gamma_{Ff}} \right)^5 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d4.top} \geq \dfrac{\Delta\sigma_{L.4}}{\gamma_{Mf}} \\ \infty & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d4.top} < \dfrac{\Delta\sigma_{L.4}}{\gamma_{Mf}} \end{cases} = 1 \cdot 10^{307}$$

$$D_{5.d4.top} := \frac{n_5}{N_{5.d4.top}} = 6 \cdot 10^{-302}$$

$$D_{d4.top} := D_{1.d4.top} + D_{2.d4.top} + D_{3.d4.top} + D_{4.d4.top} + D_{5.d4.top} = 6 \cdot 10^{-301}$$

Detail 5 - Longitudinal weld (rat-hole)

EN 1993-1-9:

$\Delta\sigma_{C.5} := 112\ MPa$ — Detail category (detail 5)

$\Delta\sigma_{D.5} := 0.737 \cdot \Delta\sigma_{C.5} = 82.544\ MPa$ — CAFL

$\Delta\sigma_{L.5} := 0.549 \cdot \Delta\sigma_{D.5} = 45.317\ MPa$ — Cut-off limit

Sectional properties:

$e_{d5.bot} := h_{tot} - y_{tp} - t_{bf} = 1.732\ m$ — Dist. from GC to top of bottom flange (where the rat hole is located)

$e_{d5.top} := y_{tp} - t_{tf} = 0.131\ m$ — Dist. from GC to bot of top flange (where the rat hole is located)

$$I\_e_{d5.bot} := \frac{I_{tot}}{e_{d5.bot}} = 0.127\ m^3$$

$$I\_e_{d5.top} := \frac{I_{tot}}{e_{d5.top}} = 1.679\ m^3$$

Stress history:

Lorry 1:

$$\Delta\sigma_{1.d5.bot} := \frac{\Delta M_1}{I\_e_{d5.bot}} = 11.54\ MPa$$

$$\Delta\sigma_{1.d5.top} := \frac{\Delta M_1}{I\_e_{d5.top}} = 0.873\ MPa$$

Lorry 2:

$$\Delta\sigma_{2.d5.bot} := \frac{\Delta M_2}{I\_e_{d5.bot}} = 18.194\ MPa$$

$$\Delta\sigma_{2.d5.top} := \frac{\Delta M_2}{I\_e_{d5.top}} = 1.376\ MPa$$

Lorry 3:

$$\Delta\sigma_{3.d5.bot} := \frac{\Delta M_3}{I\_e_{d5.bot}} = 24.951\ MPa$$

$$\Delta\sigma_{3.d5.top} := \frac{\Delta M_3}{I\_e_{d5.top}} = 1.888\ MPa$$

Lorry 4:

$$\Delta\sigma_{4.d5.bot} := \frac{\Delta M_4}{I\_e_{d5.bot}} = 18.944\ MPa$$

$$\Delta\sigma_{4.d5.top} := \frac{\Delta M_4}{I\_e_{d5.top}} = 1.433\ MPa$$

Lorry 5:

$$\Delta\sigma_{5.d5.bot} := \frac{\Delta M_5}{I\_e_{d5.bot}} = 21.204\ MPa$$

$$\Delta\sigma_{5.d5.top} := \frac{\Delta M_5}{I\_e_{d5.top}} = 1.604\ MPa$$

Damage calculation (BOTTOM):

Lorry 1:

$$N_{1.d5.bot} := \begin{Vmatrix} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d5.bot} \geq \dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}} \\ \left\Vert 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}}}{\Delta\sigma_{1.d5.bot} \cdot \gamma_{Ff}} \right)^3 \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d5.bot} \geq \dfrac{\Delta\sigma_{L.5}}{\gamma_{Mf}} \\ \left\Vert 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}}}{\Delta\sigma_{1.d5.bot} \cdot \gamma_{Ff}} \right)^5 \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d5.bot} < \dfrac{\Delta\sigma_{L.5}}{\gamma_{Mf}} \\ \left\Vert \infty \right. \end{Vmatrix} = 1 \cdot 10^{307}$$

$$D_{1.d5.bot} := \frac{n_1}{N_{1.d5.bot}} = 1.2 \cdot 10^{-301}$$

Lorry 2:

$$N_{2.d5.bot} := \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d5.bot} \geq \dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}}}{\Delta\sigma_{1.d5.bot} \cdot \gamma_{Ff}} \right)^{3} \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d5.bot} \geq \dfrac{\Delta\sigma_{L.5}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}}}{\Delta\sigma_{2.d5.bot} \cdot \gamma_{Ff}} \right)^{5} \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d5.bot} < \dfrac{\Delta\sigma_{L.5}}{\gamma_{Mf}} \\ \quad \| \; \infty \end{array} = 1 \cdot 10^{307} \quad D_{2.d5.bot} := \frac{n_2}{N_{2.d5.bot}} = 3 \cdot 10^{-302}$$

Lorry 3:

$$N_{3.d5.bot} := \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d5.bot} \geq \dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}}}{\Delta\sigma_{3.d5.bot} \cdot \gamma_{Ff}} \right)^{3} \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d5.bot} \geq \dfrac{\Delta\sigma_{L.5}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}}}{\Delta\sigma_{3.d5.bot} \cdot \gamma_{Ff}} \right)^{5} \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d5.bot} < \dfrac{\Delta\sigma_{L.5}}{\gamma_{Mf}} \\ \quad \| \; \infty \end{array} = 1 \cdot 10^{307}$$

$$D_{3.d5.bot} := \frac{n_3}{N_{3.d5.bot}} = 3 \cdot 10^{-301}$$

Lorry 4:

$$N_{4.d5.bot} := \begin{cases} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d5.bot} \ge \dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}} \\ \quad 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}}}{\Delta\sigma_{4.d5.bot} \cdot \gamma_{Ff}} \right)^{3} \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d5.bot} \ge \dfrac{\Delta\sigma_{L.5}}{\gamma_{Mf}} \\ \quad 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}}}{\Delta\sigma_{4.d5.bot} \cdot \gamma_{Ff}} \right)^{5} \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d5.bot} < \dfrac{\Delta\sigma_{L.5}}{\gamma_{Mf}} \\ \quad \infty \end{cases} = 1 \cdot 10^{307}$$

$$D_{4.d5.bot} := \frac{n_4}{N_{4.d5.bot}} = 9 \cdot 10^{-302}$$

Lorry 5:

$$N_{5.d5.bot} := \begin{cases} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d5.bot} \ge \dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}} \\ \quad 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}}}{\Delta\sigma_{5.d5.bot} \cdot \gamma_{Ff}} \right)^{3} \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d4.bot} \ge \dfrac{\Delta\sigma_{L.5}}{\gamma_{Mf}} \\ \quad 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}}}{\Delta\sigma_{5.d5.bot} \cdot \gamma_{Ff}} \right)^{5} \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d5.bot} < \dfrac{\Delta\sigma_{L.5}}{\gamma_{Mf}} \\ \quad \infty \end{cases} = 1 \cdot 10^{307}$$

$$D_{5.d5.bot} := \frac{n_5}{N_{5.d5.bot}} = 6 \cdot 10^{-302}$$

$$D_{d5.bot} := D_{1.d5.bot} + D_{2.d5.bot} + D_{3.d5.bot} + D_{4.d5.bot} + D_{5.d5.bot} = 6 \cdot 10^{-301}$$

Damage calculation (TOP):

Lorry 1:

$$N_{1.d5.top} := \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d5.top} \geq \dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}} \\ \quad 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}}}{\Delta\sigma_{1.d5.top} \cdot \gamma_{Ff}} \right)^3 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d5.top} \geq \dfrac{\Delta\sigma_{L.5}}{\gamma_{Mf}} \\ \quad 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}}}{\Delta\sigma_{1.d5.top} \cdot \gamma_{Ff}} \right)^5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d5.top} < \dfrac{\Delta\sigma_{L.5}}{\gamma_{Mf}} \\ \quad \infty \end{array} = 1 \cdot 10^{307} \qquad D_{1.d5.top} := \frac{n_1}{N_{1.d5.top}} = 1.2 \cdot 10^{-301}$$

Lorry 2:

$$N_{2.d5.top} := \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d5.top} \geq \dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}} \\ \quad 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}}}{\Delta\sigma_{1.d5.top} \cdot \gamma_{Ff}} \right)^3 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d5.top} \geq \dfrac{\Delta\sigma_{L.5}}{\gamma_{Mf}} \\ \quad 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}}}{\Delta\sigma_{2.d5.top} \cdot \gamma_{Ff}} \right)^5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d5.top} < \dfrac{\Delta\sigma_{L.5}}{\gamma_{Mf}} \\ \quad \infty \end{array} = 1 \cdot 10^{307} \quad D_{2.d5.top} := \frac{n_2}{N_{2.d5.top}} = 3 \cdot 10^{-302}$$

Lorry 3:

$$N_{3.d5.top} := \begin{cases} 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}}}{\Delta\sigma_{3.d5.top} \cdot \gamma_{Ff}} \right)^{3} & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d5.top} \geq \dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}} \\ 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}}}{\Delta\sigma_{3.d5.top} \cdot \gamma_{Ff}} \right)^{5} & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d5.top} \geq \dfrac{\Delta\sigma_{L.5}}{\gamma_{Mf}} \\ \infty & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d5.top} < \dfrac{\Delta\sigma_{L.5}}{\gamma_{Mf}} \end{cases} = 1 \cdot 10^{307}$$

$$D_{3.d5.top} := \frac{n_3}{N_{3.d5.top}} = 3 \cdot 10^{-301}$$

Lorry 4:

$$N_{4.d5.top} := \begin{cases} 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}}}{\Delta\sigma_{4.d5.top} \cdot \gamma_{Ff}} \right)^{3} & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d5.top} \geq \dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}} \\ 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}}}{\Delta\sigma_{4.d5.top} \cdot \gamma_{Ff}} \right)^{5} & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d5.top} \geq \dfrac{\Delta\sigma_{L.5}}{\gamma_{Mf}} \\ \infty & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d5.top} < \dfrac{\Delta\sigma_{L.5}}{\gamma_{Mf}} \end{cases} = 1 \cdot 10^{307}$$

$$D_{4.d5.top} := \frac{n_4}{N_{4.d5.top}} = 9 \cdot 10^{-302}$$

Lorry 5:

$$N_{5.d5.top} := \begin{cases} 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}}}{\Delta\sigma_{5.d5.top} \cdot \gamma_{Ff}} \right)^3 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d5.top} \geq \dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}} \\ 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}}}{\Delta\sigma_{5.d5.top} \cdot \gamma_{Ff}} \right)^5 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d5.top} \geq \dfrac{\Delta\sigma_{L.5}}{\gamma_{Mf}} \\ \infty & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d5.top} < \dfrac{\Delta\sigma_{L.5}}{\gamma_{Mf}} \end{cases} = 1 \cdot 10^{307}$$

$$D_{5.d5.top} := \frac{n_5}{N_{5.d5.top}} = 6 \cdot 10^{-302}$$

$$D_{d5.top} := D_{1.d5.top} + D_{2.d5.top} + D_{3.d5.top} + D_{4.d5.top} + D_{5.d5.top} = 6 \cdot 10^{-301}$$

Detail 6 - Base metal

EN 1993-1-9:

$\Delta\sigma_{C.6} := 160\ MPa$ Detail category (detail 6)

$\Delta\sigma_{D.6} := 0.737 \cdot \Delta\sigma_{C.6} = 117.92\ MPa$ CAFL

$\Delta\sigma_{L.6} := 0.549 \cdot \Delta\sigma_{D.6} = 64.738\ MPa$ Cut-off limit

Sectional properties:

$e_{d6.bot} := h_{tot} - y_{tp} - t_{bf} = 1.732\ m$ Dist. from GC to outer most fibre of bottom flange

$e_{d6.top} := y_{tp} - t_{tf} = 0.131\ m$ Dist. from GC to the outer most fibre of top flange

$$I\_e_{d6.bot} := \frac{I_{tot}}{e_{d6.bot}} = 0.127\ m^3$$

$$I\_e_{d6.top} := \frac{I_{tot}}{e_{d6.top}} = 1.679\ m^3$$

Stress history:

Lorry 1:

$$\Delta\sigma_{1.d6.bot} := \frac{\Delta M_1}{I\_e_{d6.bot}} = 11.54\ MPa$$

$$\Delta\sigma_{1.d6.top} := \frac{\Delta M_1}{I\_e_{d6.top}} = 0.873\ MPa$$

Lorry 2:

$$\Delta\sigma_{2.d6.bot} := \frac{\Delta M_2}{I\_e_{d6.bot}} = 18.194\ MPa$$

$$\Delta\sigma_{2.d6.top} := \frac{\Delta M_2}{I\_e_{d6.top}} = 1.376\ MPa$$

Lorry 3:

$$\Delta\sigma_{3.d6.bot} := \frac{\Delta M_3}{I\_e_{d6.bot}} = 24.951\ MPa$$

$$\Delta\sigma_{3.d6.top} := \frac{\Delta M_3}{I\_e_{d6.top}} = 1.888\ MPa$$

Lorry 4:

$$\Delta\sigma_{4.d6.bot} := \frac{\Delta M_4}{I\_e_{d6.bot}} = 18.944\ MPa$$

$$\Delta\sigma_{4.d6.top} := \frac{\Delta M_4}{I\_e_{d6.top}} = 1.433\ MPa$$

Lorry 5:

$$\Delta\sigma_{5.d6.bot} := \frac{\Delta M_5}{I\_e_{d6.bot}} = 21.204\ MPa$$

$$\Delta\sigma_{5.d6.top} := \frac{\Delta M_5}{I\_e_{d6.top}} = 1.604\ MPa$$

Damage calculation (BOTTOM):

Lorry 1:

$$N_{1.d6.bot} := \begin{cases} 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}}}{\Delta\sigma_{1.d6.bot} \cdot \gamma_{Ff}}\right)^3 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d6.bot} \ge \dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}} \\ 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}}}{\Delta\sigma_{1.d6.bot} \cdot \gamma_{Ff}}\right)^5 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d6.bot} \ge \dfrac{\Delta\sigma_{L.6}}{\gamma_{Mf}} \\ \infty & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d6.bot} < \dfrac{\Delta\sigma_{L.6}}{\gamma_{Mf}} \end{cases} = 1 \cdot 10^{307}$$

$$D_{1.d6.bot} := \frac{n_1}{N_{1.d6.bot}} = 1.2 \cdot 10^{-301}$$

Lorry 2:

$$N_{2.d6.bot} := \begin{cases} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d6.bot} \geq \dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}} \\ \quad 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}}}{\Delta\sigma_{1.d6.bot} \cdot \gamma_{Ff}} \right)^{3} \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d6.bot} \geq \dfrac{\Delta\sigma_{L.6}}{\gamma_{Mf}} \\ \quad 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}}}{\Delta\sigma_{2.d6.bot} \cdot \gamma_{Ff}} \right)^{5} \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d6.bot} < \dfrac{\Delta\sigma_{L.6}}{\gamma_{Mf}} \\ \quad \infty \end{cases} = 1 \cdot 10^{307}$$

$$D_{2.d6.bot} := \frac{n_2}{N_{2.d6.bot}} = 3 \cdot 10^{-302}$$

Lorry 3:

$$N_{3.d6.bot} := \begin{cases} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d6.bot} \geq \dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}} \\ \quad 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}}}{\Delta\sigma_{3.d6.bot} \cdot \gamma_{Ff}} \right)^{3} \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d6.bot} \geq \dfrac{\Delta\sigma_{L.6}}{\gamma_{Mf}} \\ \quad 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}}}{\Delta\sigma_{3.d6.bot} \cdot \gamma_{Ff}} \right)^{5} \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d6.bot} < \dfrac{\Delta\sigma_{L.6}}{\gamma_{Mf}} \\ \quad \infty \end{cases} = 1 \cdot 10^{307}$$

$$D_{3.d6.bot} := \frac{n_3}{N_{3.d6.bot}} = 3 \cdot 10^{-301}$$

Lorry 4:

$$N_{4.d6.bot} := \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d6.bot} \geq \dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}}}{\Delta\sigma_{4.d6.bot} \cdot \gamma_{Ff}} \right)^{3} \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d6.bot} \geq \dfrac{\Delta\sigma_{L.6}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}}}{\Delta\sigma_{4.d6.bot} \cdot \gamma_{Ff}} \right)^{5} \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d6.bot} < \dfrac{\Delta\sigma_{L.6}}{\gamma_{Mf}} \\ \quad \| \; \infty \end{array} = 1 \cdot 10^{307}$$

$$D_{4.d6.bot} := \frac{n_4}{N_{4.d6.bot}} = 9 \cdot 10^{-302}$$

Lorry 5:

$$N_{5.d6.bot} := \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d5.bot} \geq \dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}}}{\Delta\sigma_{5.d6.bot} \cdot \gamma_{Ff}} \right)^{3} \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d4.bot} \geq \dfrac{\Delta\sigma_{L.6}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}}}{\Delta\sigma_{5.d6.bot} \cdot \gamma_{Ff}} \right)^{5} \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d6.bot} < \dfrac{\Delta\sigma_{L.6}}{\gamma_{Mf}} \\ \quad \| \; \infty \end{array} = 1 \cdot 10^{307}$$

$$D_{5.d6.bot} := \frac{n_5}{N_{5.d6.bot}} = 6 \cdot 10^{-302}$$

$$D_{d6.bot} := D_{1.d6.bot} + D_{2.d6.bot} + D_{3.d6.bot} + D_{4.d6.bot} + D_{5.d6.bot} = 6 \cdot 10^{-301}$$

Damage calculation (TOP):

Lorry 1:

$$N_{1.d6.top} := \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d6.top} \ge \dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}} \\ \quad 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}}}{\Delta\sigma_{1.d6.top} \cdot \gamma_{Ff}} \right)^{3} \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d6.top} \ge \dfrac{\Delta\sigma_{L.6}}{\gamma_{Mf}} \\ \quad 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}}}{\Delta\sigma_{1.d6.top} \cdot \gamma_{Ff}} \right)^{5} \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d6.top} < \dfrac{\Delta\sigma_{L.6}}{\gamma_{Mf}} \\ \quad \infty \end{array} = 1 \cdot 10^{307} \qquad D_{1.d6.top} := \frac{n_1}{N_{1.d6.top}} = 1.2 \cdot 10^{-301}$$

Lorry 2:

$$N_{2.d6.top} := \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d6.top} \ge \dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}} \\ \quad 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}}}{\Delta\sigma_{1.d6.top} \cdot \gamma_{Ff}} \right)^{3} \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d6.top} \ge \dfrac{\Delta\sigma_{L.6}}{\gamma_{Mf}} \\ \quad 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}}}{\Delta\sigma_{2.d6.top} \cdot \gamma_{Ff}} \right)^{5} \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d6.top} < \dfrac{\Delta\sigma_{L.6}}{\gamma_{Mf}} \\ \quad \infty \end{array} = 1 \cdot 10^{307} \quad D_{2.d6.top} := \frac{n_2}{N_{2.d6.top}} = 3 \cdot 10^{-302}$$

Lorry 3:

$$N_{3.d6.top} := \begin{array}{|l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d6.top} \ge \dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}}}{\Delta\sigma_{3.d6.top} \cdot \gamma_{Ff}} \right)^{3} \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d6.top} \ge \dfrac{\Delta\sigma_{L.6}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}}}{\Delta\sigma_{3.d6.top} \cdot \gamma_{Ff}} \right)^{5} \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d6.top} < \dfrac{\Delta\sigma_{L.6}}{\gamma_{Mf}} \\ \quad \| \; \infty \end{array} = 1 \cdot 10^{307}$$

$$D_{3.d6.top} := \frac{n_3}{N_{3.d6.top}} = 3 \cdot 10^{-301}$$

Lorry 4:

$$N_{4.d6.top} := \begin{array}{|l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d6.top} \ge \dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}}}{\Delta\sigma_{4.d6.top} \cdot \gamma_{Ff}} \right)^{3} \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d6.top} \ge \dfrac{\Delta\sigma_{L.6}}{\gamma_{Mf}} \\ \quad \left\| \; 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}}}{\Delta\sigma_{4.d6.top} \cdot \gamma_{Ff}} \right)^{5} \right. \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d6.top} < \dfrac{\Delta\sigma_{L.6}}{\gamma_{Mf}} \\ \quad \| \; \infty \end{array} = 1 \cdot 10^{307}$$

$$D_{4.d6.top} := \frac{n_4}{N_{4.d6.top}} = 9 \cdot 10^{-302}$$

Lorry 5:

$$N_{5.d6.top} := \begin{cases} 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.5}}{\gamma_{Mf}}}{\Delta\sigma_{5.d6.top} \cdot \gamma_{Ff}} \right)^{3} & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d6.top} \geq \dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}} \\ 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\sigma_{D.6}}{\gamma_{Mf}}}{\Delta\sigma_{5.d6.top} \cdot \gamma_{Ff}} \right)^{5} & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d6.top} \geq \dfrac{\Delta\sigma_{L.6}}{\gamma_{Mf}} \\ \infty & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{5.d6.top} < \dfrac{\Delta\sigma_{L.6}}{\gamma_{Mf}} \end{cases} = 1 \cdot 10^{307}$$

$$D_{5.d6.top} := \frac{n_5}{N_{5.d6.top}} = 6 \cdot 10^{-302}$$

$$D_{d6.top} := D_{1.d6.top} + D_{2.d6.top} + D_{3.d6.top} + D_{4.d6.top} + D_{5.d6.top} = 6 \cdot 10^{-301}$$

Detail 3 - Shear stud

EN 1993-1-9:

$\Delta\tau_C := 90\ MPa$ Detail category (detail 3)

$\Delta\tau_L := 0.457 \cdot \Delta\tau_C = 41.13\ MPa$ Cut-off limit

Sectional properties:

$A_{btg} := 349714.3\ mm^2$ $e_{btg} := -150\ mm$ $y_{tp} = 0.166\ m$

$n_0 = 6.176$ $\phi_{stud} := 22\ mm$

$$S_c := \frac{A_{btg} \cdot \left(y_{tp} - e_{btg}\right)}{n_0} = 0.018\ m^3$$

Stress history:

Lorry 1:

$V_{1.min} := -47.66\ kN$ $V_{1.max} := 119.42\ kN$

$$\Delta V_1 := \text{abs}\left(V_{1.min}\right) + \text{abs}\left(V_{1.max}\right) = \left(1.671 \cdot 10^5\right)\ N$$

$$\Delta\tau_1 := \frac{\Delta V_1 \cdot S_c}{I_{tot} \cdot \phi_{stud} \cdot 2} = 0.309\ MPa$$

Lorry 2:

$V_{2.min} := -69.84\ kN$ $V_{2.max} := 186.00\ kN$

$$\Delta V_2 := \text{abs}\left(V_{2.min}\right) + \text{abs}\left(V_{2.max}\right) = \left(2.558 \cdot 10^5\right)\ N$$

$$\Delta\tau_2 := \frac{\Delta V_2 \cdot S_c}{I_{tot} \cdot \phi_{stud} \cdot 2} = 0.473\ MPa$$

Lorry 3:

$V_{3.min} := -80.98\ kN$ $V_{3.max} := 241.54\ kN$

$\Delta V_3 := \text{abs}\left(V_{3.min}\right) + \text{abs}\left(V_{3.max}\right) = \left(3.225 \cdot 10^5\right)\ N$

$$\Delta\tau_3 := \frac{\Delta V_3 \cdot S_c}{I_{tot} \cdot \phi_{stud} \cdot 2} = 0.596\ MPa$$

Lorry 4:

$V_{4.min} := -67.37\ kN$ $V_{4.max} := 184.28\ kN$

$\Delta V_4 := \text{abs}\left(V_{4.min}\right) + \text{abs}\left(V_{4.max}\right) = \left(2.517 \cdot 10^5\right)\ N$

$$\Delta\tau_4 := \frac{\Delta V_4 \cdot S_c}{I_{tot} \cdot \phi_{stud} \cdot 2} = 0.465\ MPa$$

Lorry 5:

$V_{5.min} := -60.70\ kN$ $V_{5.max} := 199.58\ kN$

$\Delta V_5 := \text{abs}\left(V_{5.min}\right) + \text{abs}\left(V_{5.max}\right) = \left(2.603 \cdot 10^5\right)\ N$

$$\Delta\tau_5 := \frac{\Delta V_5 \cdot S_c}{I_{tot} \cdot \phi_{stud} \cdot 2} = 0.481\ MPa$$

Damage calculation (TOP):

The slope m=8 according to 1994-2:2005 Section 6.8.6.2 (4)

Lorry 1:

$$N_{1.d3} := \begin{cases} 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\tau_L}{\gamma_{Mf}}}{\Delta\tau_1 \cdot \gamma_{Ff}} \right)^8 & \text{if } \gamma_{Ff} \cdot \Delta\tau_1 \geq \dfrac{\Delta\tau_L}{\gamma_{Mf}} \\ \infty & \text{if } \gamma_{Ff} \cdot \Delta\tau_1 < \dfrac{\Delta\tau_L}{\gamma_{Mf}} \end{cases} = 1 \cdot 10^{307}$$

$$D_{1.d3} := \frac{n_1}{N_{1.d3}} = 1.2 \cdot 10^{-301}$$

Lorry 2:

$$N_{2.d3} := \begin{cases} 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\tau_L}{\gamma_{Mf}}}{\Delta\tau_2 \cdot \gamma_{Ff}} \right)^8 & \text{if } \gamma_{Ff} \cdot \Delta\tau_2 \geq \dfrac{\Delta\tau_L}{\gamma_{Mf}} \\ \infty & \text{if } \gamma_{Ff} \cdot \Delta\tau_2 < \dfrac{\Delta\tau_L}{\gamma_{Mf}} \end{cases} = 1 \cdot 10^{307}$$

$$D_{2.d3} := \frac{n_2}{N_{2.d3}} = 3 \cdot 10^{-302}$$

Lorry 3:

$$N_{3.d3} := \begin{cases} 5 \cdot 10^6 \cdot \left(\dfrac{\dfrac{\Delta\tau_L}{\gamma_{Mf}}}{\Delta\tau_3 \cdot \gamma_{Ff}} \right)^8 & \text{if } \gamma_{Ff} \cdot \Delta\tau_3 \geq \dfrac{\Delta\tau_L}{\gamma_{Mf}} \\ \infty & \text{if } \gamma_{Ff} \cdot \Delta\tau_3 < \dfrac{\Delta\tau_L}{\gamma_{Mf}} \end{cases} = 1 \cdot 10^{307}$$

$$D_{3.d3} := \frac{n_3}{N_{3.d3}} = 3 \cdot 10^{-301}$$

Lorry 4:

$$N_{4.d3} := \begin{cases} 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\tau_L}{\gamma_{Mf}}}{\Delta\tau_4 \cdot \gamma_{Ff}} \right)^{8} & \text{if } \gamma_{Ff} \cdot \Delta\tau_4 \geq \dfrac{\Delta\tau_L}{\gamma_{Mf}} \\ \infty & \text{if } \gamma_{Ff} \cdot \Delta\tau_4 < \dfrac{\Delta\tau_L}{\gamma_{Mf}} \end{cases} = 1 \cdot 10^{307}$$

$$D_{4.d3} := \frac{n_4}{N_{4.d3}} = 9 \cdot 10^{-302}$$

Lorry 5:

$$N_{5.d3} := \begin{cases} 5 \cdot 10^{6} \cdot \left(\dfrac{\dfrac{\Delta\tau_L}{\gamma_{Mf}}}{\Delta\tau_5 \cdot \gamma_{Ff}} \right)^{8} & \text{if } \gamma_{Ff} \cdot \Delta\tau_5 \geq \dfrac{\Delta\tau_L}{\gamma_{Mf}} \\ \infty & \text{if } \gamma_{Ff} \cdot \Delta\tau_5 < \dfrac{\Delta\tau_L}{\gamma_{Mf}} \end{cases} = 1 \cdot 10^{307}$$

$$D_{5.d3} := \frac{n_5}{N_{5.d3}} = 6 \cdot 10^{-302}$$

$$D_{d3} := D_{1.d3} + D_{2.d3} + D_{3.d3} + D_{4.d3} + D_{5.d3} = 6 \cdot 10^{-301}$$

Maximum damage:

$$D_{max.bot} := \max\left(D_{d1.bot}, D_{d2.bot}, D_{d4.bot}, D_{d5.bot}, D_{d6.bot}\right) = 0.041$$

$$D_{max.top} := \max\left(D_{d1.top}, D_{d2.top}, D_{d4.top}, D_{d5.top}, D_{d6.top}, D_{d3}\right) = 6 \cdot 10^{-301}$$

A.17 Overloads (characterisitc combination)

Overloads
Maximum stress limitations
Verification for x=50.25m

Reference:
Verification of the Maximum Stresses in Enhanced Welded Details via High-Frequency Mechanical Impact in Road Bridges (Al-Emrani et al, 2023). Equation (2) for transversal and Equation (3) for butt-weld

Detail type	Maximum stress limitations
Longitudinal attachment	$-0.5f_y < \sigma_{max} < f_y$
Transversal attachment	$-0.7f_y < \sigma_{max} < f_y$
Butt weld attachment	$-0.9f_y < \sigma_{max} < f_y$

$f_y := 355\ MPa$

Detail 1 Transversal attachment

Maximum characteristic stresses obtained from Sofistik

$\sigma_{1.bot} := 139.1\ MPa$

$\sigma_{1.top} := 10.5\ MPa$

if $-0.7 \cdot f_y < \sigma_{1.bot} < f_y$ = "OK"
‖ "OK"
else
‖ "NOT OK"

if $-0.7 \cdot f_y < \sigma_{1.top} < f_y$ = "OK"
‖ "OK"
else
‖ "NOT OK"

Detail 2 butt-weld

Maximum characteristic stresses obtained from Sofistik

$\sigma_{2.bot} := 142.3\ MPa$

$\sigma_{2.top} := 13.4\ MPa$

$$\text{if } -0.9 \cdot f_y < \sigma_{1.bot} < f_y \;\; \| \text{"OK"} \;\; \text{else} \;\; \| \text{"NOT OK"} \quad = \text{"OK"}$$

$$\text{if } -0.9 \cdot f_y < \sigma_{2.top} < f_y \;\; \| \text{"OK"} \;\; \text{else} \;\; \| \text{"NOT OK"} \quad = \text{"OK"}$$

A.18 FLS verification with HFMI (FLM3)

HFMI - calculations, similar procedure for all details
High Frequecy Mechanical Impact -
Recommendations for the design of welded details in
road and railway bridges from Chalmers.

Self-weight moment from Sofistik
$M_{sw} := 6288.3\ kN \cdot m$

Maximum FLM3 stress for
investigated details:

$\sigma_{max.1.bot} := 35.4\ MPa$

$\sigma_{max.1.top} := 15.6\ MPa$

$\sigma_{max.2.bot} := 36.2\ MPa$

$\sigma_{max.2.top} := 16.6\ MPa$

$\sigma_{max.5.bot} := 22.9\ MPa$

$\sigma_{max.5.top} := 15.6\ MPa$

FLM3 EN 1993-1-9 : 2005 (E)

$\boxed{\phi_2} := 1.0$ Dynamic amplification factor (already included in FLM3)

$\boxed{H} := 1937.5\ mm$

$\boxed{t_{top.flange}} := 35\ mm$

$\boxed{\Delta M} := 3109.24\ kN \cdot m$

$\boxed{GC} := 166.27\ mm$

$I_{tot} := 2.2 \cdot 10^{11}\ mm^4$

Detail 1: Transversal stiffeners

$e_{1.bot} := H - GC = 1.771\ m$

$e_{1.top} := GC - t_{top.flange} = 0.131\ m$

$$\sigma_{1.bot.sw} := \frac{M_{sw}}{\frac{I_{tot}}{e_{1.bot}}} = 50.627\ MPa$$

$$\sigma_{1.top.sw} := \frac{M_{sw}}{\frac{I_{tot}}{e_{1.top}}} = 3.752\ MPa$$

$$\sigma_{1.bot} := \frac{\Delta M}{\frac{I_{tot}}{e_{1.bot}}} = 25.033\ MPa$$

$$\sigma_{1.top} := \frac{\Delta M}{\frac{I_{tot}}{e_{1.top}}} = 1.855\ MPa$$

HFMI

$$\phi_{1.bot} := \frac{\sigma_{1.bot.sw}}{2 \cdot \sigma_{max.1.bot}} = 0.715$$ eq (19)

$$\phi_{1.top} := \frac{\sigma_{1.top.sw}}{2 \cdot \sigma_{max.1.top}} = 0.12$$ eq (19)

$$\lambda_{HFMI.1.bot} := \frac{2.38 \cdot \phi_{1.bot} + 0.64}{\phi_{1.bot} + 0.66} = 1.703$$ eq (17)

$$\lambda_{HFMI.1.top} := \frac{2.38 \cdot \phi_{1.top} + 0.64}{\phi_{1.top} + 0.66} = 1.187$$ eq (17)

$f_{y.bot} := 355\ MPa$

$\Delta\sigma_{HFMI.ref.1} := 140\ MPa$ Table 1

$$f_1 := 1 + \frac{0.1 \cdot (f_{y.bot} - 355\ MPa)}{\Delta\sigma_{HFMI.ref.1}} = 1$$ eq (6)

$\Delta\sigma_{c1.HFMI} := \Delta\sigma_{HFMI.ref.1} \cdot f_1 = 140\ MPa$ eq (5)

Bottom flange: EN 1993-2: 2006 Section 9.4

$\sigma_{E.1.bot.HFMI} := \sigma_{1.bot} \cdot \lambda_{span22} \cdot \lambda_{HFMI.1.bot} = 61.586\ MPa$

Verification: EN 1993-1-9 : 2005 Section 8

$\gamma_{Ff} := 1$
$\gamma_{Mf} := 1.35$

$$\frac{\sigma_{E.1.bot.HFMI} \cdot \gamma_{Ff}}{\frac{\Delta\sigma_{c1.HFMI}}{\gamma_{Mf}}} = 0.594$$ < 1 OK!

Top flange:

$\sigma_{E.1.top.HFMI} := \sigma_{1.top} \cdot \lambda_{span22} \cdot \lambda_{HFMI.1.top} = 3.181\ MPa$

Verification:

$$\frac{\sigma_{E.1.top.HFMI} \cdot \gamma_{Ff}}{\frac{\Delta\sigma_{c1.HFMI}}{\gamma_{Mf}}} = 0.031$$ < 1 OK!

Detail 2: Butt-weld

$\Delta\sigma_{c2} := 112\ MPa$

$e_{2.bot} := H - GC = 1.771\ m$
$e_{2.top} := GC = 0.166\ m$

$$\sigma_{2.bot.sw} := \frac{M_{sw}}{\frac{I_{tot}}{e_{2.bot}}} = 50.627\ MPa$$

$$\sigma_{2.top.sw} := \frac{M_{sw}}{\frac{I_{tot}}{e_{2.top}}} = 4.753\ MPa$$

HFMI

$$\phi_{2.bot} := \frac{\sigma_{2.bot.sw}}{2 \cdot \sigma_{max.2.bot}} = 0.699$$ eq (19)

$$\phi_{2.top} := \frac{\sigma_{2.top.sw}}{2 \cdot \sigma_{max.2.top}} = 0.143$$ eq (19)

$$\lambda_{HFMI.2.bot} := \frac{2.38 \cdot \phi_{2.bot} + 0.64}{\phi_{2.bot} + 0.66} = 1.695$$ eq (17)

$$\lambda_{HFMI.2.top} := \frac{2.38 \cdot \phi_{2.top} + 0.64}{\phi_{2.top} + 0.66} = 1.221$$ eq (17)

$$\Delta\sigma_{HFMI.ref.2} := 160\ MPa$$ Table 1

$$f_{1.d2} := 1 + \frac{0.1 \cdot \left(f_{y.bot} - 355\ MPa\right)}{\Delta\sigma_{HFMI.ref.2}} = 1$$ eq (6)

$$\Delta\sigma_{c2.HFMI} := \Delta\sigma_{HFMI.ref.1} \cdot f_1 = 140\ MPa$$ eq (5)

Bottom flange:

$$\boxed{\sigma_{2.bot}} := \frac{\Delta M}{\left(\frac{I_{tot}}{e_{2.bot}}\right)} = 25.033\ MPa$$

$$\sigma_{E.2.bot.HFMI} := \sigma_{2.bot} \cdot \lambda_{span22} \cdot \lambda_{HFMI.2.bot} = 61.301\ MPa$$

Verification:

$$\frac{\sigma_{E.2.bot.HFMI} \cdot \gamma_{Ff}}{\frac{\Delta\sigma_{c2}}{\gamma_{Mf}}} = 0.739$$ < 1 OK!

Top flange:

$$\sigma_{2.top} := \frac{\Delta M}{\left(\frac{I_{tot}}{e_{2.top}}\right)} = 2.35\ MPa$$

$$\sigma_{E.2.top.HFMI} := \sigma_{2.top} \cdot \lambda_{span22} \cdot \lambda_{HFMI.2.top} = 4.145\ MPa$$

Verification:

$$\frac{\sigma_{E.2.top.HFMI} \cdot \gamma_{Ff}}{\frac{\Delta\sigma_{c2}}{\gamma_{Mf}}} = 0.05$$ < 1 OK!

Detail 5: Rat-hole (notch)

$$\Delta\sigma_{c5} := 71\ MPa$$

$$e_{5.bot} := H - GC = 1.771\ m$$
$$e_{5.top} := GC - t_{top.flange} = 0.131\ m$$

$$\sigma_{5.bot.sw} := \frac{M_{sw}}{\frac{I_{tot}}{e_{1.bot}}} = 50.627\ MPa$$

$$\sigma_{5.top.sw} := \frac{M_{sw}}{\frac{I_{tot}}{e_{1.top}}} = 3.752\ MPa$$

HFMI

$$\phi_{5.bot} := \frac{\sigma_{5.bot.sw}}{2 \cdot \sigma_{max.5.bot}} = 1.105$$ eq (19)

$$\phi_{5.top} := \frac{\sigma_{5.top.sw}}{2 \cdot \sigma_{max.5.top}} = 0.12$$ eq (19)

$$\lambda_{HFMI.5.bot} := \frac{2.38 \cdot \phi_{5.bot} + 0.64}{\phi_{5.bot} + 0.66} = 1.853$$ eq (17)

$$\lambda_{HFMI.5.top} := \frac{2.38 \cdot \phi_{5.top} + 0.64}{\phi_{5.top} + 0.66} = 1.187$$ eq (17)

$$\Delta\sigma_{HFMI.ref.5} := 100\ MPa$$ Table 1

$$f_{1.d5} := 1 + \frac{0.1 \cdot \left(f_{y.bot} - 355\ MPa\right)}{\Delta\sigma_{HFMI.ref.5}} = 1$$ eq (6)

$$\Delta\sigma_{c5.HFMI} := \Delta\sigma_{HFMI.ref.5} \cdot f_{1.d5} = 100\ MPa$$ eq (5)

Bottom flange:

$$\boxed{\sigma_{5.bot}} := \frac{\Delta M}{\left(\frac{I_{tot}}{e_{5.bot}}\right)} = 25.033\ MPa$$

$$\sigma_{E.5.bot.HFMI} := \sigma_{5.bot} \cdot \lambda_{span22} \cdot \lambda_{HFMI.5.bot} = 66.997\ MPa$$

Verification:

$$\frac{\sigma_{E.5.bot.HFMI} \cdot \gamma_{Ff}}{\frac{\Delta\sigma_{c5}}{\gamma_{Mf}}} = 1.274$$ < 1 OK!

Top flange:

$$\boxed{\sigma_{5.top}} := \frac{\Delta M}{\left(\frac{I_{tot}}{e_{5.top}}\right)} = 1.855\ MPa$$

$$\sigma_{E.5.top.HFMI} := \sigma_{5.top} \cdot \lambda_{span22} \cdot \lambda_{HFMI.5.top} = 3.181\ MPa$$

Verification:

$$\frac{\sigma_{E.5.top.HFMI} \cdot \gamma_{Ff}}{\frac{\Delta\sigma_{c5}}{\gamma_{Mf}}} = 0.06$$ < 1 OK!

A.19 FLS verification with HFMI (FLM4)

Damage accumulation method FLM4 INCLUDING HFMI

EN 1991-2:2003, 4.6.5

For road bridges: FLM4 should be uses to calculate total fatigue damage accumulated trough the design service life of the bridge

$\gamma_{Ff} := 1.0$ $\gamma_{Mf} := 1.35$ EN 1993-1-9:2005

$\gamma_{Mf.s} := 1.0$ For shear studs - EN 1994-2 2.4.1.2 (6)

Safe life method - TRVFS 2011:12 Design life 120 years

$c := 8000\ mm$ $e := 3200\ mm$

$LDF := 0.5 + \frac{e}{c} = 0.9$ Load distribution factor (Fatigue design of steel bridges)

EN 1991-2:2003 Indicative nr of heavy veichles expected per year and per slow lane - Table 4.5

$N_{obs} := 0.05 \cdot 10^6$ Roads and motorways with medium flow rates of lorries

EN 1993-2:2006 - Section 9.5.2

$Q_0 := 480\ kN$

$N_0 := 0.5 \cdot 10^6$

EN 1991-2 - Table 4.7 - Set of equivalent lorries

Lorry:		n/year	n in 120 years
Lorrie 1 20%	$p_1 := 0.2$	$n_{11} := p_1 \cdot N_{obs} = 1 \cdot 10^4$	$n_1 := n_{11} \cdot 120 = 1.2 \cdot 10^6$
Lorrie 2 5%	$p_2 := 0.05$	$n_{22} := p_2 \cdot N_{obs} = 2.5 \cdot 10^3$	$n_2 := n_{22} \cdot 120 = 3 \cdot 10^5$

Lorrie 3 50%	$p_3 := 0.5$	$n_{33} := p_3 \cdot N_{obs} = 2.5 \cdot 10^4$	$n_3 := n_{33} \cdot 120 = 3 \cdot 10^6$
Lorrie 4 15%	$p_4 := 0.15$	$n_{44} := p_4 \cdot N_{obs} = 7.5 \cdot 10^3$	$n_4 := n_{44} \cdot 120 = 9 \cdot 10^5$
Lorrie 5 10%	$p_5 := 0.1$	$n_{55} := p_5 \cdot N_{obs} = 5 \cdot 10^3$	$n_5 := n_{55} \cdot 120 = 6 \cdot 10^5$

Weight of each veichles:

$$Q_1 := (70 + 130)\ kN = 200\ kN$$

$$Q_2 := (70 + 120 + 120)\ kN = 310\ kN$$

$$Q_3 := (70 + 150 + 90 + 90 + 90)\ kN = 490\ kN$$

$$Q_4 := (70 + 140 + 90 + 90)\ kN = 390\ kN$$

$$Q_5 := (70 + 130 + 90 + 80 + 80)\ kN = 450\ kN$$

$$Q_{M1} := \left(\frac{n_{11} \cdot Q_1^{\ 5} + n_{22} \cdot Q_2^{\ 5} + n_{33} \cdot Q_3^{\ 5} + n_{44} \cdot Q_4^{\ 5} + n_{55} \cdot Q_5^{\ 5}}{\left(n_{11} + n_{22} + n_{33} + n_{44} + n_{55}\right)}\right)^{\left(\frac{1}{5}\right)} = 445.404\ kN$$

The average gross weight of the lorries in the slow lane (källa
FAT design composite bridge)

Assuming 1 veichle = 1 cycle

The following calculations are for section x=50.25 m and fo steel strength S355

$h_{tot} = 1.938\ m$ $\qquad$ $I_{tot} := 0.22\ m^4$

$y_{tp} := 0.166\ m$ $\qquad$ (Short term calculations of GC)

$f_y = 355\ MPa$

All calculations and equations for HFMI-treated details is picked from the report: "High Frequency Mechanical Impact Treatment - Recommendations for the design of welded details in road and railway bridges (Al-Emrani, Shams-Hakimi, Al-Karawi, 2024)

Detail 1 - Transverse attachment

$\Delta\sigma_{C.1.HFMI.ref} := 140\ MPa$ Detail category (detail 1) - Reference HFMI

Steel strength effect:

$$f_1 := 1 + \left(\frac{\left(0.1 \cdot \left(f_y - 355\ MPa\right)\right)}{\Delta\sigma_{C.1.HFMI.ref}}\right) = 1$$ Eq. (6)

$\Delta\sigma_{C.1.HFMI} := \Delta\sigma_{C.1.HFMI.ref} \cdot f_1 = 140\ MPa$ Eq. (5)

$\Delta\sigma_{D.1.HFMI} := 0.833 \cdot \Delta\sigma_{C.1.HFMI} = 116.62\ MPa$ Eq. (1)

$\Delta\sigma_{L.1.HFMI} := 0.717 \cdot \Delta\sigma_{D.1.HFMI} = 83.617\ MPa$ Eq. (2)

Sectional properties:

$e_{d1.bot} := h_{tot} - y_{tp} - t_{bf} = 1.732\ m$ Dist. from GC to top of bottom flange (where the transverse stiffener is attached)

$e_{d1.top} := y_{tp} - t_{tf} = 0.131\ m$ Dist. from GC to bot of top flange (where the transverse stiffener is attached)

$$I\_e_{d1.bot} := \frac{I_{tot}}{e_{d1.bot}} = 0.127\ m^3$$

$$I\_e_{d1.top} := \frac{I_{tot}}{e_{d1.top}} = 1.679\ m^3$$

Selfweight stress:

$M_{sw} := 6288.3\ kN \cdot m$

$$\sigma_{sw.1.bot} := \frac{M_{sw}}{I\_e_{d1.bot}} = 49.492\ MPa$$

$$\sigma_{sw.1.top} := \frac{M_{sw}}{I\_e_{d1.top}} = 3.744\ MPa$$

$\sigma_{max.FLM3.bot} := 35.43\ MPa$ Max stress range generated by FLM3

$\sigma_{max.FLM3.top} := 15.61\ MPa$

$\phi_{HFMI.1.bot} := \dfrac{\sigma_{sw.1.bot}}{\left(2 \cdot \sigma_{max.FLM3.bot}\right)} = 0.698$ Eq. (19)

$\phi_{HFMI.1.top} := \dfrac{\sigma_{sw.1.top}}{\left(2 \cdot \sigma_{max.FLM3.top}\right)} = 0.12$

$\lambda_{1.HFMI.bot} := \dfrac{2.38 \cdot \phi_{HFMI.1.bot} + 0.64}{\phi_{HFMI.1.bot} + 0.64} = 1.72$ ≥ 1 Eq. (17) Span section

$\lambda_{1.HFMI.top} := \dfrac{2.38 \cdot \phi_{HFMI.1.top} + 0.64}{\phi_{HFMI.1.top} + 0.64} = 1.218$ ≥ 1 Span section

Stress history:

Lorry 1:

$M_{1.max} := 1327.68\ kN \cdot m$ From Sofisitk (FLM4)

$M_{1.min} := -138.54\ kN \cdot m$

$\Delta M_1 := \text{abs}\left(M_{1.max}\right) + \text{abs}\left(M_{1.min}\right) = \left(1.466 \cdot 10^3\right)\ kN \cdot m$

$\Delta\sigma_{1.d1.bot} := \dfrac{\Delta M_1}{I\_e_{d1.bot}} = 11.54\ MPa$

$\Delta\sigma_{1.d1.top} := \dfrac{\Delta M_1}{I\_e_{d1.top}} = 0.873\ MPa$

Lorry 2:

$M_{2.max} := 2096.80\ kN \cdot m$ From Sofisitk (FLM4)

$M_{2.min} := -214.82\ kN \cdot m$

$\Delta M_2 := \text{abs}\left(M_{2.max}\right) + \text{abs}\left(M_{2.min}\right) = \left(2.312 \cdot 10^3\right)\ kN \cdot m$

$$\Delta\sigma_{2.d1.bot} := \frac{\Delta M_2}{I\_e_{d1.bot}} = 18.194\ MPa$$

$$\Delta\sigma_{2.d1.top} := \frac{\Delta M_2}{I\_e_{d1.top}} = 1.376\ MPa$$

Lorry 3:

$M_{3.max} := 2853.87\ kN \cdot m$ From Sofisitk (FLM4)

$M_{3.min} := -316.38\ kN \cdot m$

$$\Delta M_3 := \text{abs}\left(M_{3.max}\right) + \text{abs}\left(M_{3.min}\right) = \left(3.17 \cdot 10^3\right)\ kN \cdot m$$

$$\Delta\sigma_{3.d1.bot} := \frac{\Delta M_3}{I\_e_{d1.bot}} = 24.951\ MPa$$

$$\Delta\sigma_{3.d1.top} := \frac{\Delta M_3}{I\_e_{d1.top}} = 1.888\ MPa$$

Lorry 4:

$M_{4.max} := 2158.08\ kN \cdot m$ From Sofisitk (FLM4)

$M_{4.min} := -248.88\ kN \cdot m$

$$\Delta M_4 := \text{abs}\left(M_{4.max}\right) + \text{abs}\left(M_{4.min}\right) = \left(2.407 \cdot 10^3\right)\ kN \cdot m$$

$$\Delta\sigma_{4.d1.bot} := \frac{\Delta M_4}{I\_e_{d1.bot}} = 18.944\ MPa$$

$$\Delta\sigma_{4.d1.top} := \frac{\Delta M_4}{I\_e_{d1.top}} = 1.433\ MPa$$

Lorry 5:

$M_{5.max} := 2418.59\ kN \cdot m$ From Sofisitk (FLM4)

$M_{5.min} := -275.53\ kN \cdot m$

$$\Delta M_5 := \text{abs}\left(M_{5.max}\right) + \text{abs}\left(M_{5.min}\right) = \left(2.694 \cdot 10^3\right)\ kN \cdot m$$

$$\Delta\sigma_{5.d1.bot} := \frac{\Delta M_5}{I\_e_{d1.bot}} = 21.204\ MPa$$

$$\Delta\sigma_{5.d1.top} := \frac{\Delta M_5}{I\_e_{d1.top}} = 1.604\ MPa$$

CALCULATING $\Delta\sigma_{eq}$ **in steps:**

Damage calculation (BOTTOM):

Lorry 1:

Claculating the new slope of the curve for a HFMI-treated detail:

$$m_{1.d1.bot} := \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d1.bot} \geq \dfrac{\Delta\sigma_{D.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \ 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d1.bot} \geq \dfrac{\Delta\sigma_{L.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \ 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d1.bot} < \dfrac{\Delta\sigma_{L.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \ 0 \end{array} = 0$$

Lorry 2:

Claculating the new slope of the curve for a HFMI-treated detail:

$$m_{2.d1.bot} := \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d1.bot} \geq \dfrac{\Delta\sigma_{D.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \ 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d1.bot} \geq \dfrac{\Delta\sigma_{L.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \ 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d1.bot} < \dfrac{\Delta\sigma_{L.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \ 0 \end{array} = 0$$

Lorry 3:

Claculating the new slope of the curve for a HFMI-treated detail:

$$m_{3.d1.bot} := \left\| \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d1.bot} \geq \dfrac{\Delta\sigma_{D.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d1.bot} \geq \dfrac{\Delta\sigma_{L.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d1.bot} < \dfrac{\Delta\sigma_{L.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 0 \end{array} \right. = 0$$

Lorry 4:

Claculating the new slope of the curve for a HFMI-treated detail:

$$m_{4.d1.bot} := \left\| \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d1.bot} \geq \dfrac{\Delta\sigma_{D.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d1.bot} \geq \dfrac{\Delta\sigma_{L.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d1.bot} < \dfrac{\Delta\sigma_{L.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 0 \end{array} \right. = 0$$

Lorry 5:

Claculating the new slope of the curve for a HFMI-treated detail:

$$m_{5.d1.bot} := \left\| \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d1.bot} \geq \dfrac{\Delta\sigma_{D.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d1.bot} \geq \dfrac{\Delta\sigma_{L.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d1.bot} < \dfrac{\Delta\sigma_{L.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 0 \end{array} \right. = 0$$

$$n\_\Delta\sigma_{bot.1.d1} := \begin{array}{l} \text{if } m_{1.d1.bot} = 5 \\ \quad \| \; n_1 \cdot \Delta\sigma_{1.d1.bot}{}^{m_{1.d1.bot}} \\ \text{else if } m_{1.d1.bot} = 9 \\ \quad \| \; n_1 \cdot \Delta\sigma_{1.d1.bot}{}^{m_{1.d1.bot}} \\ \text{else if } m_{1.d1.bot} = 0 \\ \quad \| \; 0 \end{array} = 0$$

Lorrie 1

$$n\_\Delta\sigma_{bot.2.d1} := \begin{array}{l} \text{if } m_{2.d1.bot} = 5 \\ \quad \| \; n_2 \cdot \Delta\sigma_{2.d1.bot}{}^{m_{2.d1.bot}} \\ \text{else if } m_{2.d1.bot} = 9 \\ \quad \| \; n_2 \cdot \Delta\sigma_{2.d1.bot}{}^{m_{2.d1.bot}} \\ \text{else if } m_{2.d1.bot} = 0 \\ \quad \| \; 0 \end{array} = 0$$

Lorrie 2

$$n\_\Delta\sigma_{bot.3.d1} := \begin{array}{l} \text{if } m_{3.d1.bot} = 5 \\ \quad \| \; n_3 \cdot \Delta\sigma_{3.d1.bot}{}^{m_{3.d1.bot}} \\ \text{else if } m_{3.d1.bot} = 9 \\ \quad \| \; n_3 \cdot \Delta\sigma_{3.d1.bot}{}^{m_{3.d1.bot}} \\ \text{else if } m_{3.d1.bot} = 0 \\ \quad \| \; 0 \end{array} = 0$$

Lorrie 3

$$n\_\Delta\sigma_{bot.4.d1} := \begin{array}{l} \text{if } m_{4.d1.bot} = 5 \\ \quad \| \; n_4 \cdot \Delta\sigma_{4.d1.bot}{}^{m_{4.d1.bot}} \\ \text{else if } m_{4.d1.bot} = 9 \\ \quad \| \; n_4 \cdot \Delta\sigma_{4.d1.bot}{}^{m_{4.d1.bot}} \\ \text{else if } m_{4.d1.bot} = 0 \\ \quad \| \; 0 \end{array} = 0$$

Lorrie 4

$$n\_\Delta\sigma_{bot.5.d1} := \begin{array}{l} \text{if } m_{5.d1.bot} = 5 \\ \quad \| \; n_5 \cdot \Delta\sigma_{5.d1.bot}{}^{m_{5.d1.bot}} \\ \text{else if } m_{5.d1.bot} = 9 \\ \quad \| \; n_5 \cdot \Delta\sigma_{5.d1.bot}{}^{m_{5.d1.bot}} \\ \text{else if } m_{5.d1.bot} = 0 \\ \quad \| \; 0 \end{array} = 0$$

Lorrie 5

$$n\_\Delta\sigma_{bot.d1.sum} := \left(n\_\Delta\sigma_{bot.1.d1} + n\_\Delta\sigma_{bot.2.d1} + n\_\Delta\sigma_{bot.3.d1} + n\_\Delta\sigma_{bot.4.d1} + n\_\Delta\sigma_{bot.5.d1}\right) = 0$$

$$\Delta\sigma_{eq.bot.d1.A} := \left(\frac{n\_\Delta\sigma_{bot.d1.sum} + \boxed{\left(\frac{\Delta\sigma_{D.1.HFMI}}{\gamma_{Mf}}\right)^{(5-9)} \cdot n\_\Delta\sigma_{bot.d1.sum}}}{n_1 + n_2 + n_3 + n_4 + n_5}\right)^{\left(\frac{1}{5}\right)}$$

Error due to that the numerator is zero

$$\Delta\sigma_{eq.bot.d1.A} := 0$$

$$\Delta\sigma_{eq.bot.d1.B} := \left(\frac{n\_\Delta\sigma_{bot.d1.sum} \cdot \left(\frac{\frac{\Delta\sigma_{D.1.HFMI}}{\gamma_{Mf}}}{} \right)^{(9-5)} + \boxed{n\_\Delta\sigma_{bot.d1.sum}}}{n_1 + n_2 + n_3 + n_4 + n_5} \right)^{\left(\frac{1}{9}\right)}$$

Error due to that the numerator is zero

$$\Delta\sigma_{eq.bot.d1.B} := 0$$

$$\frac{\Delta\sigma_{D.HFMI}}{\gamma_{Mf}} > \Delta\sigma_{eq} \quad -> \quad \Delta\sigma_{eq.bot.d1} := \Delta\sigma_{eq.bot.d1.B} = 0$$

Eq. (13)

$$N_{eq.bot.d1.A} := 5 \cdot 10^{6} \cdot \left(\frac{\frac{\Delta\sigma_{D.1.HFMI}}{\gamma_{Mf}}}{\boxed{\lambda_{1.HFMI.bot} \cdot \Delta\sigma_{eq.bot.d1} \cdot \gamma_{Ff}}} \right)^{5}$$

Error due to that the denominator is zero

$$N_{eq.bot.d1.A} := \infty$$

$$N_{eq.bot.d1.B} := 5 \cdot 10^{6} \cdot \left(\frac{\frac{\Delta\sigma_{D.1.HFMI}}{\gamma_{Mf}}}{\boxed{\lambda_{1.HFMI.bot} \cdot \Delta\sigma_{eq.bot.d1} \cdot \gamma_{Ff}}} \right)^{9}$$

Error due to that the denominator is zero

$$N_{eq.bot.d1.B} := \infty$$

$$\frac{\Delta\sigma_{D.HFMI}}{\gamma_{Mf}} > \Delta\sigma_{eq} \cdot \lambda_{HFMI} \quad -> \quad N_{eq.bot.d1} := N_{eq.bot.d1.B} = 1 \cdot 10^{307}$$

Eq. (14)

$$D_{eq.bot.d1} := \left(\frac{n_1 + n_2 + n_3 + n_4 + n_5}{N_{eq.bot.d1}} \right) = 6 \cdot 10^{-301}$$

Damage calculation (TOP):

Lorry 1:

$$m_{1.d1.top} := \left\| \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d1.top} \geq \dfrac{\Delta\sigma_{D.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \ 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d1.top} \geq \dfrac{\Delta\sigma_{L.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \ 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d1.top} < \dfrac{\Delta\sigma_{L.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \ 0 \end{array} \right\| = 0$$

Lorry 2:

$$m_{2.d1.top} := \left\| \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d1.top} \geq \dfrac{\Delta\sigma_{D.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \ 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d1.top} \geq \dfrac{\Delta\sigma_{L.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \ 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d1.top} < \dfrac{\Delta\sigma_{L.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \ 0 \end{array} \right\| = 0$$

Lorry 3:

$$m_{3.d1.top} := \left\| \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d1.top} \geq \dfrac{\Delta\sigma_{D.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \ 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d1.top} \geq \dfrac{\Delta\sigma_{L.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \ 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d1.top} < \dfrac{\Delta\sigma_{L.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \ 0 \end{array} \right\| = 0$$

Lorry 4:

$$m_{4.d1.top} := \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d1.top} \geq \dfrac{\Delta\sigma_{D.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d1.top} \geq \dfrac{\Delta\sigma_{L.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d1.top} < \dfrac{\Delta\sigma_{L.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 0 \end{array} = 0$$

Lorry 5:

$$m_{5.d1.top} := \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d1.top} \geq \dfrac{\Delta\sigma_{D.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d1.top} \geq \dfrac{\Delta\sigma_{L.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d1.top} < \dfrac{\Delta\sigma_{L.1.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 0 \end{array} = 0$$

$$n\_\Delta\sigma_{top.1.d1} := \begin{array}{l} \text{if } m_{1.d1.top} = 5 \\ \quad \| \; n_1 \cdot \Delta\sigma_{1.d1.top}{}^{m_{1.d1.top}} \\ \text{else if } m_{1.d1.top} = 9 \\ \quad \| \; n_1 \cdot \Delta\sigma_{1.d1.top}{}^{m_{1.d1.top}} \\ \text{else if } m_{1.d1.top} = 0 \\ \quad \| \; 0 \end{array} = 0$$

Lorrie 1

$$n\_\Delta\sigma_{top.2.d1} := \begin{array}{l} \text{if } m_{2.d1.top} = 5 \\ \quad \| \; n_2 \cdot \Delta\sigma_{2.d1.top}{}^{m_{2.d1.top}} \\ \text{else if } m_{2.d1.top} = 9 \\ \quad \| \; n_2 \cdot \Delta\sigma_{2.d1.top}{}^{m_{2.d1.top}} \\ \text{else if } m_{2.d1.top} = 0 \\ \quad \| \; 0 \end{array} = 0$$

Lorrie 2

$$n\_\Delta\sigma_{top.3.d1} := \begin{array}{l} \text{if } m_{3.d1.top} = 5 \\ \quad \| \; n_3 \cdot \Delta\sigma_{3.d1.top}{}^{m_{3.d1.top}} \\ \text{else if } m_{3.d1.top} = 9 \\ \quad \| \; n_3 \cdot \Delta\sigma_{3.d1.top}{}^{m_{3.d1.top}} \\ \text{else if } m_{3.d1.top} = 0 \\ \quad \| \; 0 \end{array} = 0$$

Lorrie 3

$$n\_\Delta\sigma_{top.4.d1} := \begin{array}{l} \text{if } m_{4.d1.top} = 5 \\ \quad \| \; n_4 \cdot \Delta\sigma_{4.d1.top}{}^{m_{4.d1.top}} \\ \text{else if } m_{4.d1.top} = 9 \\ \quad \| \; n_4 \cdot \Delta\sigma_{4.d1.top}{}^{m_{4.d1.top}} \\ \text{else if } m_{4.d1.top} = 0 \\ \quad \| \; 0 \end{array} = 0$$

Lorrie 4

$$n\_\Delta\sigma_{top.5.d1} := \begin{array}{l} \text{if } m_{5.d1.top} = 5 \\ \quad \| \; n_5 \cdot \Delta\sigma_{5.d1.top}{}^{m_{5.d1.top}} \\ \text{else if } m_{5.d1.top} = 9 \\ \quad \| \; n_5 \cdot \Delta\sigma_{5.d1.top}{}^{m_{5.d1.top}} \\ \text{else if } m_{5.d1.top} = 0 \\ \quad \| \; 0 \end{array} = 0$$

Lorrie 5

$$n\_\Delta\sigma_{top.d1.sum} := \left(n\_\Delta\sigma_{top.1.d1} + n\_\Delta\sigma_{top.2.d1} + n\_\Delta\sigma_{top.3.d1} + n\_\Delta\sigma_{top.4.d1} + n\_\Delta\sigma_{top.5.d1}\right) = 0$$

$$\Delta\sigma_{eq.top.d1.A} := \left(\frac{n\_\Delta\sigma_{top.d1.sum} + \boxed{\left(\frac{\Delta\sigma_{D.1.HFMI}}{\gamma_{Mf}} \right)^{(5-9)} \cdot n\_\Delta\sigma_{top.d1.sum}}}{n_1 + n_2 + n_3 + n_4 + n_5} \right)^{\left(\frac{1}{5}\right)}$$ Error due to that the numerator is zero

$$\Delta\sigma_{eq.top.d1.A} := 0$$

$$\Delta\sigma_{eq.top.d1.B} := \left(\frac{n\_\Delta\sigma_{top.d1.sum} \cdot \left(\frac{\Delta\sigma_{D.1.HFMI}}{\gamma_{Mf}} \right)^{(9-5)} + \boxed{n\_\Delta\sigma_{top.d1.sum}}}{n_1 + n_2 + n_3 + n_4 + n_5} \right)^{\left(\frac{1}{9}\right)}$$ Error due to that the numerator is zero

$$\Delta\sigma_{eq.top.d1.B} := 0$$

$$\frac{\Delta\sigma_{D.HFMI}}{\gamma_{Mf}} > \Delta\sigma_{eq}$$ -> $$\Delta\sigma_{eq.top.d1} := \Delta\sigma_{eq.top.d1.B} = 0$$

$$N_{eq.top.d1.A} := 5 \cdot 10^6 \cdot \left(\frac{\frac{\Delta\sigma_{D.1.HFMI}}{\gamma_{Mf}}}{\boxed{\lambda_{1.HFMI.top} \cdot \Delta\sigma_{eq.top.d1} \cdot \gamma_{Ff}}} \right)^5$$ Error due to that the denominator is zero

$$N_{eq.top.d1.A} := \infty$$

$$N_{eq.top.d1.B} := 5 \cdot 10^6 \cdot \left(\frac{\frac{\Delta\sigma_{D.1.HFMI}}{\gamma_{Mf}}}{\boxed{\lambda_{1.HFMI.top} \cdot \Delta\sigma_{eq.top.d1} \cdot \gamma_{Ff}}} \right)^9$$ Error due to that the denominator is zero

$$N_{eq.top.d1.B} := \infty$$

$$\frac{\Delta\sigma_{D.HFMI}}{\gamma_{Mf}} > \Delta\sigma_{eq} \cdot \lambda_{HFMI}$$ -> $$N_{eq.top.d1} := N_{eq.top.d1.B} = 1 \cdot 10^{307}$$

$$D_{eq.top.d1} := \left(\frac{n_1 + n_2 + n_3 + n_4 + n_5}{N_{eq.top.d1}} \right) = 6 \cdot 10^{-301}$$

Detail 2 - Butt weld

$t_{bf} = 0.04\ m$ $t_{tf} = 0.035\ m$

$k_{s.bot} := \left(\dfrac{25\ mm}{t_{bf}}\right)^{0.2} = 0.91$ $k_{s.top} := \left(\dfrac{25\ mm}{t_{tf}}\right)^{0.2} = 0.935$

Table 1: 1) Thickness correction factor for when plate thickness exceed 25 mm

$\Delta\sigma_{C.2.HFMI.ref.bot} := 160\ MPa \cdot k_{s.bot} = 145.645\ MPa$

Detail category (detail 1) - Reference HFMI

$\Delta\sigma_{C.2.HFMI.ref.top} := 160\ MPa \cdot k_{s.bot} = 145.645\ MPa$

$\Delta\sigma_{C.2.HFMI.bot} := \Delta\sigma_{C.2.HFMI.ref.bot} \cdot f_1 = 145.645\ MPa$ Eq. (5)

$\Delta\sigma_{D.2.HFMI.bot} := 0.833 \cdot \Delta\sigma_{C.2.HFMI.bot} = 121.322\ MPa$ Eq. (1)

$\Delta\sigma_{L.2.HFMI.bot} := 0.717 \cdot \Delta\sigma_{D.2.HFMI.bot} = 86.988\ MPa$ Eq. (2)

$\Delta\sigma_{C.2.HFMI.top} := \Delta\sigma_{C.2.HFMI.ref.top} \cdot f_1 = 145.645\ MPa$ Eq. (5)

$\Delta\sigma_{D.2.HFMI.top} := 0.833 \cdot \Delta\sigma_{C.2.HFMI.top} = 121.322\ MPa$ Eq. (1)

$\Delta\sigma_{L.2.HFMI.top} := 0.717 \cdot \Delta\sigma_{D.2.HFMI.top} = 86.988\ MPa$ Eq. (2)

Sectional properties:

$e_{d2.bot} := h_{tot} - y_{tp} = 1.772\ m$

Dist. from GC to outer most fiber in bot flange (where the transverse stiffener is attached)

$e_{d2.top} := y_{tp} = 0.166\ m$

Dist. from GC to outer most fiber in top flange (where the transverse stiffener is attached)

$I\_e_{d2.bot} := \dfrac{I_{tot}}{e_{d2.bot}} = 0.124\ m^3$

$I\_e_{d2.top} := \dfrac{I_{tot}}{e_{d2.top}} = 1.325\ m^3$

Selfweight stress:

$M_{sw} := 6288.3\ kN \cdot m$

$\sigma_{sw.2.bot} := \dfrac{M_{sw}}{I\_e_{d2.bot}} = 50.635\ MPa$

$\sigma_{sw.2.top} := \dfrac{M_{sw}}{I\_e_{d2.top}} = 4.745\ MPa$

$\sigma_{max.FLM3.bot} := 35.43\ MPa$ Max stress range generated by FLM3

$\sigma_{max.FLM3.top} := 15.61\ MPa$

$\phi_{HFMI.2.bot} := \dfrac{\sigma_{sw.2.bot}}{\left(2 \cdot \sigma_{max.FLM3.bot}\right)} = 0.715$ Eq. (19)

$\phi_{HFMI.2.top} := \dfrac{\sigma_{sw.2.top}}{\left(2 \cdot \sigma_{max.FLM3.top}\right)} = 0.152$

$\lambda_{2.HFMI.bot} := \dfrac{2.38 \cdot \phi_{HFMI.2.bot} + 0.64}{\phi_{HFMI.2.bot} + 0.64} = 1.728$ ≥ 1 Eq. (17) Span section

$\lambda_{2.HFMI.top} := \dfrac{2.38 \cdot \phi_{HFMI.2.top} + 0.64}{\phi_{HFMI.2.top} + 0.64} = 1.265$ ≥ 1 Span section

Stress history:

Lorry 1:

$\Delta\sigma_{1.d2.bot} := \dfrac{\Delta M_1}{I\_e_{d2.bot}} = 11.806\ MPa$

$\Delta\sigma_{1.d2.top} := \dfrac{\Delta M_1}{I\_e_{d2.top}} = 1.106\ MPa$

Lorry 2:

$\Delta\sigma_{2.d2.bot} := \dfrac{\Delta M_2}{I\_e_{d2.bot}} = 18.614\ MPa$

$\Delta\sigma_{2.d2.top} := \dfrac{\Delta M_2}{I\_e_{d2.top}} = 1.744\ MPa$

Lorry 3:

$$\Delta\sigma_{3.d2.bot} := \frac{\Delta M_3}{I\_e_{d2.bot}} = 25.528\ MPa$$

$$\Delta\sigma_{3.d2.top} := \frac{\Delta M_3}{I\_e_{d2.top}} = 2.392\ MPa$$

Lorry 4:

$$\Delta\sigma_{4.d2.bot} := \frac{\Delta M_4}{I\_e_{d2.bot}} = 19.381\ MPa$$

$$\Delta\sigma_{4.d2.top} := \frac{\Delta M_4}{I\_e_{d2.top}} = 1.816\ MPa$$

Lorry 5:

$$\Delta\sigma_{5.d2.bot} := \frac{\Delta M_5}{I\_e_{d2.bot}} = 21.694\ MPa$$

$$\Delta\sigma_{5.d2.top} := \frac{\Delta M_5}{I\_e_{d2.top}} = 2.033\ MPa$$

Damage calculation (BOTTOM):

Lorry 1:

Claculating the new slope of the curve for a HFMI-treated detail:

$$m_{1.d2.bot} := \begin{array}{|l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d2.bot} \geq \dfrac{\Delta\sigma_{D.2.HFMI.bot}}{\gamma_{Mf}} \\ \quad 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d2.bot} \geq \dfrac{\Delta\sigma_{L.2.HFMI.bot}}{\gamma_{Mf}} \\ \quad 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d2.bot} < \dfrac{\Delta\sigma_{L.2.HFMI.bot}}{\gamma_{Mf}} \\ \quad 0 \end{array} = 0$$

Lorry 2:

Claculating the new slope of the curve for a HFMI-treated detail:

$$m_{2.d2.bot} := \begin{cases} 5 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d2.bot} \geq \dfrac{\Delta\sigma_{D.2.HFMI.bot}}{\gamma_{Mf}} \\ 9 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d2.bot} \geq \dfrac{\Delta\sigma_{L.2.HFMI.bot}}{\gamma_{Mf}} \\ 0 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d2.bot} < \dfrac{\Delta\sigma_{L.2.HFMI.bot}}{\gamma_{Mf}} \end{cases} = 0$$

Lorry 3:

Claculating the new slope of the curve for a HFMI-treated detail:

$$m_{3.d2.bot} := \begin{cases} 5 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d2.bot} \geq \dfrac{\Delta\sigma_{D.2.HFMI.bot}}{\gamma_{Mf}} \\ 9 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d2.bot} \geq \dfrac{\Delta\sigma_{L.2.HFMI.bot}}{\gamma_{Mf}} \\ 0 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d2.bot} < \dfrac{\Delta\sigma_{L.2.HFMI.bot}}{\gamma_{Mf}} \end{cases} = 0$$

Lorry 4:

Claculating the new slope of the curve for a HFMI-treated detail:

$$m_{4.d2.bot} := \begin{cases} 5 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d2.bot} \geq \dfrac{\Delta\sigma_{D.2.HFMI.bot}}{\gamma_{Mf}} \\ 9 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d2.bot} \geq \dfrac{\Delta\sigma_{L.2.HFMI.bot}}{\gamma_{Mf}} \\ 0 & \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d2.bot} < \dfrac{\Delta\sigma_{L.2.HFMI.bot}}{\gamma_{Mf}} \end{cases} = 0$$

Lorry 5:

Claculating the new slope of the curve for a HFMI-treated detail:

$$m_{5.d2.bot} := \begin{array}{|l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d2.bot} \ge \dfrac{\Delta\sigma_{D.2.HFMI.bot}}{\gamma_{Mf}} \\ \quad \| \; 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d2.bot} \ge \dfrac{\Delta\sigma_{L.2.HFMI.bot}}{\gamma_{Mf}} \\ \quad \| \; 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d2.bot} < \dfrac{\Delta\sigma_{L.2.HFMI.bot}}{\gamma_{Mf}} \\ \quad \| \; 0 \end{array} = 0$$

$$n\_\Delta\sigma_{bot.1.d2} := \begin{array}{l} \text{if } m_{1.d2.bot} = 5 \\ \quad \| \; n_1 \cdot \Delta\sigma_{1.d2.bot}{}^{m_{1.d2.bot}} \\ \text{else if } m_{1.d2.bot} = 9 \\ \quad \| \; n_1 \cdot \Delta\sigma_{1.d2.bot}{}^{m_{1.d2.bot}} \\ \text{else if } m_{1.d2.bot} = 0 \\ \quad \| \; 0 \end{array} = 0$$

Lorrie 1

$$n\_\Delta\sigma_{bot.2.d2} := \begin{array}{l} \text{if } m_{2.d2.bot} = 5 \\ \quad \| \; n_2 \cdot \Delta\sigma_{2.d2.bot}{}^{m_{2.d2.bot}} \\ \text{else if } m_{2.d2.bot} = 9 \\ \quad \| \; n_2 \cdot \Delta\sigma_{2.d2.bot}{}^{m_{2.d2.bot}} \\ \text{else if } m_{2.d2.bot} = 0 \\ \quad \| \; 0 \end{array} = 0$$

Lorrie 2

$$n\_\Delta\sigma_{bot.3.d2} := \begin{array}{l} \text{if } m_{3.d2.bot} = 5 \\ \quad \| \; n_3 \cdot \Delta\sigma_{3.d2.bot}{}^{m_{3.d2.bot}} \\ \text{else if } m_{3.d2.bot} = 9 \\ \quad \| \; n_3 \cdot \Delta\sigma_{3.d2.bot}{}^{m_{3.d2.bot}} \\ \text{else if } m_{3.d2.bot} = 0 \\ \quad \| \; 0 \end{array} = 0$$

Lorrie 3

$$n\_\Delta\sigma_{bot.4.d2} := \begin{array}{l} \text{if } m_{4.d2.bot} = 5 \\ \quad \| \; n_4 \cdot \Delta\sigma_{4.d2.bot}{}^{m_{4.d2.bot}} \\ \text{else if } m_{4.d2.bot} = 9 \\ \quad \| \; n_4 \cdot \Delta\sigma_{4.d2.bot}{}^{m_{4.d2.bot}} \\ \text{else if } m_{4.d2.bot} = 0 \\ \quad \| \; 0 \end{array} = 0$$

Lorrie 4

$$n\_\Delta\sigma_{bot.5.d2} := \begin{array}{l} \text{if } m_{5.d2.bot} = 5 \\ \quad \| \; n_5 \cdot \Delta\sigma_{5.d2.bot}{}^{m_{5.d2.bot}} \\ \text{else if } m_{5.d2.bot} = 9 \\ \quad \| \; n_5 \cdot \Delta\sigma_{5.d2.bot}{}^{m_{5.d2.bot}} \\ \text{else if } m_{5.d2.bot} = 0 \\ \quad \| \; 0 \end{array} = 0$$

Lorrie 5

$$n\_\Delta\sigma_{bot.d2.sum} := \left(n\_\Delta\sigma_{bot.1.d2} + n\_\Delta\sigma_{bot.2.d2} + n\_\Delta\sigma_{bot.3.d2} + n\_\Delta\sigma_{bot.4.d2} + n\_\Delta\sigma_{bot.5.d2}\right) = 0$$

$$\Delta\sigma_{eq.bot.d2.A} := \left(\frac{n\_\Delta\sigma_{bot.d2.sum} + \boxed{\left(\frac{\Delta\sigma_{D.2.HFMI.bot}}{\gamma_{Mf}}\right)^{(5-9)} \cdot n\_\Delta\sigma_{bot.d2.sum}}}{n_1 + n_2 + n_3 + n_4 + n_5} \right)^{\left(\frac{1}{5}\right)}$$

Error due to that the numerator is zero

$$\Delta\sigma_{eq.bot.d2.A} := 0$$

$$\Delta\sigma_{eq.bot.d2.B} := \left(\frac{n\_\Delta\sigma_{bot.d2.sum} \cdot \left(\frac{\Delta\sigma_{D.2.HFMI.bot}}{\gamma_{Mf}}\right)^{(9-5)} + \boxed{n\_\Delta\sigma_{bot.d2.sum}}}{n_1 + n_2 + n_3 + n_4 + n_5} \right)^{\left(\frac{1}{9}\right)}$$

Error due to that the numerator is zero

$$\Delta\sigma_{eq.bot.d2.B} := 0$$

$\dfrac{\Delta\sigma_{D.HFMI.bot}}{\gamma_{Mf}} > \Delta\sigma_{eq}$-> $\Delta\sigma_{eq.bot.d2} := \Delta\sigma_{eq.bot.d2.B} = 0$ Eq. (13)

$$N_{eq.bot.d2.A} := 5 \cdot 10^{6} \cdot \left(\frac{\frac{\boxed{\Delta\sigma_{D.1.HFMI.bot}}}{\gamma_{Mf}}}{\lambda_{2.HFMI.bot} \cdot \Delta\sigma_{eq.bot.d2} \cdot \gamma_{Ff}} \right)^{5}$$

Error due to that the denominator is zero

$$N_{eq.bot.d2.A} := \infty$$

$$N_{eq.bot.d2.B} := 5 \cdot 10^{6} \cdot \left(\frac{\frac{\boxed{\Delta\sigma_{D.1.HFMI.bot}}}{\gamma_{Mf}}}{\lambda_{2.HFMI.bot} \cdot \Delta\sigma_{eq.bot.d2} \cdot \gamma_{Ff}} \right)^{9}$$

Error due to that the denominator is zero

$$N_{eq.bot.d2.B} := \infty$$

$$\frac{\Delta\sigma_{D.HFMI.bot}}{\gamma_{Mf}} > \Delta\sigma_{eq} \cdot \lambda_{HFMI} \quad \text{->} \qquad N_{eq.bot.d2} := N_{eq.bot.d2.B} = 1 \cdot 10^{307}$$

Eq. (14)

$$D_{eq.bot.d2} := \left(\frac{n_1 + n_2 + n_3 + n_4 + n_5}{N_{eq.bot.d2}} \right) = 6 \cdot 10^{-301}$$

Damange calculation top:

Lorry 1:

$$m_{1.d2.top} := \left\| \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d2.top} \geq \frac{\Delta\sigma_{D.2.HFMI.top}}{\gamma_{Mf}} \\ \quad \| \, 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d2.top} \geq \frac{\Delta\sigma_{L.2.HFMI.top}}{\gamma_{Mf}} \\ \quad \| \, 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d2.top} < \frac{\Delta\sigma_{L.2.HFMI.top}}{\gamma_{Mf}} \\ \quad \| \, 0 \end{array} \right| = 0$$

Lorry 2:

$$m_{2.d2.top} := \begin{Vmatrix} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d2.top} \geq \dfrac{\Delta\sigma_{D.2.HFMI.top}}{\gamma_{Mf}} \\ \quad \| 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d2.top} \geq \dfrac{\Delta\sigma_{L.2.HFMI.top}}{\gamma_{Mf}} \\ \quad \| 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d2.top} < \dfrac{\Delta\sigma_{L.2.HFMI.top}}{\gamma_{Mf}} \\ \quad \| 0 \end{Vmatrix} = 0$$

Lorry 3:

$$m_{3.d2.top} := \begin{Vmatrix} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d2.top} \geq \dfrac{\Delta\sigma_{D.2.HFMI.top}}{\gamma_{Mf}} \\ \quad \| 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d2.top} \geq \dfrac{\Delta\sigma_{L.2.HFMI.top}}{\gamma_{Mf}} \\ \quad \| 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d2.top} < \dfrac{\Delta\sigma_{L.2.HFMI.top}}{\gamma_{Mf}} \\ \quad \| 0 \end{Vmatrix} = 0$$

Lorry 4:

$$m_{4.d2.top} := \begin{Vmatrix} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d2.top} \geq \dfrac{\Delta\sigma_{D.2.HFMI.top}}{\gamma_{Mf}} \\ \quad \| 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d2.top} \geq \dfrac{\Delta\sigma_{L.2.HFMI.top}}{\gamma_{Mf}} \\ \quad \| 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d2.top} < \dfrac{\Delta\sigma_{L.2.HFMI.top}}{\gamma_{Mf}} \\ \quad \| 0 \end{Vmatrix} = 0$$

Lorry 5:

$$m_{5.d2.top} := \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d2.top} \geq \dfrac{\Delta\sigma_{D.2.HFMI.top}}{\gamma_{Mf}} \\ \quad 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d2.top} \geq \dfrac{\Delta\sigma_{L.2.HFMI.top}}{\gamma_{Mf}} \\ \quad 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d2.top} < \dfrac{\Delta\sigma_{L.2.HFMI.top}}{\gamma_{Mf}} \\ \quad 0 \end{array} = 0$$

$$n\_\Delta\sigma_{top.1.d2} := \begin{array}{l} \text{if } m_{1.d2.top} = 5 \\ \quad n_1 \cdot \Delta\sigma_{1.d2.top}{}^{m_{1.d2.top}} \\ \text{else if } m_{1.d2.top} = 9 \\ \quad n_1 \cdot \Delta\sigma_{1.d2.top}{}^{m_{1.d2.top}} \\ \text{else if } m_{1.d2.top} = 0 \\ \quad 0 \end{array} = 0$$

Lorrie 1

$$n\_\Delta\sigma_{top.2.d2} := \begin{array}{l} \text{if } m_{2.d2.top} = 5 \\ \quad n_2 \cdot \Delta\sigma_{2.d2.top}{}^{m_{2.d2.top}} \\ \text{else if } m_{2.d2.top} = 9 \\ \quad n_2 \cdot \Delta\sigma_{2.d2.top}{}^{m_{2.d2.top}} \\ \text{else if } m_{2.d2.top} = 0 \\ \quad 0 \end{array} = 0$$

Lorrie 2

$$n\_\Delta\sigma_{top.3.d2} := \begin{array}{l} \text{if } m_{3.d2.top} = 5 \\ \quad n_3 \cdot \Delta\sigma_{3.d2.top}{}^{m_{3.d2.top}} \\ \text{else if } m_{3.d2.top} = 9 \\ \quad n_3 \cdot \Delta\sigma_{3.d2.top}{}^{m_{3.d2.top}} \\ \text{else if } m_{3.d2.top} = 0 \\ \quad 0 \end{array} = 0$$

Lorrie 3

$$n\_\Delta\sigma_{top.4.d2} := \begin{array}{l} \text{if } m_{4.d2.top} = 5 \\ \quad \| \; n_4 \cdot \Delta\sigma_{4.d2.top}{}^{m_{4.d2.top}} \\ \text{else if } m_{4.d2.top} = 9 \\ \quad \| \; n_4 \cdot \Delta\sigma_{4.d2.top}{}^{m_{4.d2.top}} \\ \text{else if } m_{4.d2.top} = 0 \\ \quad \| \; 0 \end{array} = 0$$

Lorrie 4

$$n\_\Delta\sigma_{top.5.d2} := \begin{array}{l} \text{if } m_{5.d2.top} = 5 \\ \quad \| \; n_5 \cdot \Delta\sigma_{5.d2.top}{}^{m_{5.d2.top}} \\ \text{else if } m_{5.d2.top} = 9 \\ \quad \| \; n_5 \cdot \Delta\sigma_{5.d2.top}{}^{m_{5.d2.top}} \\ \text{else if } m_{5.d2.top} = 0 \\ \quad \| \; 0 \end{array} = 0$$

Lorrie 5

$$n\_\Delta\sigma_{top.d2.sum} := \left(n\_\Delta\sigma_{top.1.d2} + n\_\Delta\sigma_{top.2.d2} + n\_\Delta\sigma_{top.3.d2} + n\_\Delta\sigma_{top.4.d2} + n\_\Delta\sigma_{top.5.d2}\right) = 0$$

$$\Delta\sigma_{eq.top.d2.A} := \left(\frac{n\_\Delta\sigma_{top.d2.sum} + \boxed{\left(\frac{\Delta\sigma_{D.2.HFMI.top}}{\gamma_{Mf}}\right)^{(5-9)} \cdot n\_\Delta\sigma_{top.d2.sum}}}{n_1 + n_2 + n_3 + n_4 + n_5}\right)^{\left(\frac{1}{5}\right)}$$

Error due to that the numerator is zero

$$\Delta\sigma_{eq.top.d2.A} := 0$$

$$\Delta\sigma_{eq.top.d2.B} := \left(\frac{n\_\Delta\sigma_{top.d2.sum} \cdot \left(\frac{\Delta\sigma_{D.2.HFMI.top}}{\gamma_{Mf}}\right)^{(9-5)} + \boxed{n\_\Delta\sigma_{top.d2.sum}}}{n_1 + n_2 + n_3 + n_4 + n_5}\right)^{\left(\frac{1}{9}\right)}$$

Error due to that the numerator is zero

$$\Delta\sigma_{eq.top.d2.B} := 0$$

$$\frac{\Delta\sigma_{D.HFMI.top}}{\gamma_{Mf}} > \Delta\sigma_{eq} \text{->}$$

$$\Delta\sigma_{eq.top.d2} := \Delta\sigma_{eq.top.d2.B} = 0$$

$$N_{eq.top.d2.A} := 5 \cdot 10^6 \cdot \left(\frac{\frac{\Delta\sigma_{D.2.HFMI.top}}{\gamma_{Mf}}}{\boxed{\lambda_{2.HFMI.top} \cdot \Delta\sigma_{eq.top.d2} \cdot \gamma_{Ff}}} \right)^5$$

Error due to that the denominator is zero

$$N_{eq.top.d2.A} := \infty$$

$$N_{eq.top.d2.B} := 5 \cdot 10^6 \cdot \left(\frac{\frac{\Delta\sigma_{D.2.HFMI.top}}{\gamma_{Mf}}}{\boxed{\lambda_{2.HFMI.top} \cdot \Delta\sigma_{eq.top.d2} \cdot \gamma_{Ff}}} \right)^9$$

Error due to that the denominator is zero

$$N_{eq.top.d2.B} := \infty$$

$$\frac{\Delta\sigma_{D.HFMI}}{\gamma_{Mf}} > \Delta\sigma_{eq} \cdot \lambda_{HFMI}$$ -> $$N_{eq.top.d2} := N_{eq.top.d2.B} = 1 \cdot 10^{307}$$

$$D_{eq.top.d2} := \left(\frac{n_1 + n_2 + n_3 + n_4 + n_5}{N_{eq.top.d2}} \right) = 6 \cdot 10^{-301}$$

Detail 5 - Longitudinal weld (rat-hole)

$\Delta\sigma_{C.5.HFMI.ref} := 100\ MPa$ Detail category (detail 1) - Reference HFMI

$\Delta\sigma_{C.5.HFMI} := \Delta\sigma_{C.5.HFMI.ref} \cdot f_1 = 100\ MPa$ Eq. (5)

$\Delta\sigma_{D.5.HFMI} := 0.833 \cdot \Delta\sigma_{C.5.HFMI} = 83.3\ MPa$ Eq. (1)

$\Delta\sigma_{L.5.HFMI} := 0.717 \cdot \Delta\sigma_{D.5.HFMI} = 59.726\ MPa$ Eq. (2)

<u>Sectional properties:</u>

$e_{d5.bot} := h_{tot} - y_{tp} - t_{bf} = 1.732\ m$ Dist. from GC to top of bottom flange (where the rat hole is located)

$e_{d5.top} := y_{tp} - t_{tf} = 0.131\ m$ Dist. from GC to bot of top flange (where the rat hole is located)

$$I\_e_{d5.bot} := \frac{I_{tot}}{e_{d5.bot}} = 0.127\ m^3$$

$$I\_e_{d5.top} := \frac{I_{tot}}{e_{d5.top}} = 1.679\ m^3$$

Selfweight stress:

$$M_{sw} := 6288.3\ kN \cdot m$$

$$\sigma_{sw.5.bot} := \frac{M_{sw}}{I\_e_{d5.bot}} = 49.492\ MPa$$

$$\sigma_{sw.5.top} := \frac{M_{sw}}{I\_e_{d5.top}} = 3.744\ MPa$$

$\sigma_{max.FLM3.bot} := 35.43\ MPa$ Max stress range generated by FLM3

$$\sigma_{max.FLM3.top} := 15.61\ MPa$$

$\phi_{HFMI.5.bot} := \frac{\sigma_{sw.5.bot}}{\left(2 \cdot \sigma_{max.FLM3.bot}\right)} = 0.698$ Eq. (19)

$$\phi_{HFMI.5.top} := \frac{\sigma_{sw.5.top}}{\left(2 \cdot \sigma_{max.FLM3.top}\right)} = 0.12$$

$\lambda_{5.HFMI.bot} := \frac{2.38 \cdot \phi_{HFMI.5.bot} + 0.64}{\phi_{HFMI.1.bot} + 0.64} = 1.72$ ≥ 1 Eq. (17) Span section

$\lambda_{5.HFMI.top} := \frac{2.38 \cdot \phi_{HFMI.5.top} + 0.64}{\phi_{HFMI.1.top} + 0.64} = 1.218$ ≥ 1 Span section

Stress history:

Lorry 1:

$$\Delta\sigma_{1.d5.bot} := \frac{\Delta M_1}{I\_e_{d5.bot}} = 11.54\ MPa$$

$$\Delta\sigma_{1.d5.top} := \frac{\Delta M_1}{I\_e_{d5.top}} = 0.873\ MPa$$

Lorry 2:

$$\Delta\sigma_{2.d5.bot} := \frac{\Delta M_2}{I\_e_{d5.bot}} = 18.194 \ MPa$$

$$\Delta\sigma_{2.d5.top} := \frac{\Delta M_2}{I\_e_{d5.top}} = 1.376 \ MPa$$

Lorry 3:

$$\Delta\sigma_{3.d5.bot} := \frac{\Delta M_3}{I\_e_{d5.bot}} = 24.951 \ MPa$$

$$\Delta\sigma_{3.d5.top} := \frac{\Delta M_3}{I\_e_{d5.top}} = 1.888 \ MPa$$

Lorry 4:

$$\Delta\sigma_{4.d5.bot} := \frac{\Delta M_4}{I\_e_{d5.bot}} = 18.944 \ MPa$$

$$\Delta\sigma_{4.d5.top} := \frac{\Delta M_4}{I\_e_{d5.top}} = 1.433 \ MPa$$

Lorry 5:

$$\Delta\sigma_{5.d5.bot} := \frac{\Delta M_5}{I\_e_{d5.bot}} = 21.204 \ MPa$$

$$\Delta\sigma_{5.d5.top} := \frac{\Delta M_5}{I\_e_{d5.top}} = 1.604 \ MPa$$

CALCULATING $\Delta\sigma_{eq}$ in steps:

Damage calculation (BOTTOM):

Lorry 1:

Claculating the new slope of the curve for a HFMI-treated detail:

$$m_{1.d5.bot} := \left\| \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d5.bot} \geq \dfrac{\Delta\sigma_{D.5.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d5.bot} \geq \dfrac{\Delta\sigma_{L.5.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d5.bot} < \dfrac{\Delta\sigma_{L.5.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 0 \end{array} \right| = 0$$

Lorry 2:

Claculating the new slope of the curve for a HFMI-treated detail:

$$m_{2.d5.bot} := \left\| \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d5.bot} \geq \dfrac{\Delta\sigma_{D.5.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d5.bot} \geq \dfrac{\Delta\sigma_{L.5.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d5.bot} < \dfrac{\Delta\sigma_{L.5.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 0 \end{array} \right| = 0$$

Lorry 3:

Claculating the new slope of the curve for a HFMI-treated detail:

$$m_{3.d5.bot} := \left\| \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d5.bot} \geq \dfrac{\Delta\sigma_{D.5.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d5.bot} \geq \dfrac{\Delta\sigma_{L.5.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d5.bot} < \dfrac{\Delta\sigma_{L.5.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 0 \end{array} \right| = 0$$

Lorry 4:

Claculating the new slope of the curve for a HFMI-treated detail:

$$m_{4.d5.bot} := \begin{Vmatrix} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d5.bot} \geq \dfrac{\Delta\sigma_{D.5.HFMI}}{\gamma_{Mf}} \\ \quad \| 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d5.bot} \geq \dfrac{\Delta\sigma_{L.5.HFMI}}{\gamma_{Mf}} \\ \quad \| 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d5.bot} < \dfrac{\Delta\sigma_{L.5.HFMI}}{\gamma_{Mf}} \\ \quad \| 0 \end{Vmatrix} = 0$$

Lorry 5:

Claculating the new slope of the curve for a HFMI-treated detail:

$$m_{5.d5.bot} := \begin{Vmatrix} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d5.bot} \geq \dfrac{\Delta\sigma_{D.5.HFMI}}{\gamma_{Mf}} \\ \quad \| 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d5.bot} \geq \dfrac{\Delta\sigma_{L.5.HFMI}}{\gamma_{Mf}} \\ \quad \| 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d5.bot} < \dfrac{\Delta\sigma_{L.5.HFMI}}{\gamma_{Mf}} \\ \quad \| 0 \end{Vmatrix} = 0$$

$$n\_\Delta\sigma_{bot.1.d5} := \begin{vmatrix} \text{if } m_{1.d5.bot} = 5 \\ \quad \| n_1 \cdot \Delta\sigma_{1.d5.bot}{}^{m_{1.d5.bot}} \\ \text{else if } m_{1.d5.bot} = 9 \\ \quad \| n_1 \cdot \Delta\sigma_{1.d5.bot}{}^{m_{1.d5.bot}} \\ \text{else if } m_{1.d5.bot} = 0 \\ \quad \| 0 \end{vmatrix} = 0$$

Lorrie 1

$$n\_\Delta\sigma_{bot.2.d5} := \begin{array}{l} \text{if } m_{2.d5.bot} = 5 \\ \quad \| \; n_2 \cdot \Delta\sigma_{2.d5.bot}{}^{m_{2.d5.bot}} \\ \text{else if } m_{2.d5.bot} = 9 \\ \quad \| \; n_2 \cdot \Delta\sigma_{2.d5.bot}{}^{m_{2.d5.bot}} \\ \text{else if } m_{2.d5.bot} = 0 \\ \quad \| \; 0 \end{array} = 0$$

Lorrie 2

$$n\_\Delta\sigma_{bot.3.d5} := \begin{array}{l} \text{if } m_{3.d5.bot} = 5 \\ \quad \| \; n_3 \cdot \Delta\sigma_{3.d5.bot}{}^{m_{3.d5.bot}} \\ \text{else if } m_{3.d5.bot} = 9 \\ \quad \| \; n_3 \cdot \Delta\sigma_{3.d5.bot}{}^{m_{3.d5.bot}} \\ \text{else if } m_{3.d5.bot} = 0 \\ \quad \| \; 0 \end{array} = 0$$

Lorrie 3

$$n\_\Delta\sigma_{bot.4.d5} := \begin{array}{l} \text{if } m_{4.d5.bot} = 5 \\ \quad \| \; n_4 \cdot \Delta\sigma_{4.d5.bot}{}^{m_{4.d5.bot}} \\ \text{else if } m_{4.d5.bot} = 9 \\ \quad \| \; n_4 \cdot \Delta\sigma_{4.d5.bot}{}^{m_{4.d5.bot}} \\ \text{else if } m_{4.d5.bot} = 0 \\ \quad \| \; 0 \end{array} = 0$$

Lorrie 4

$$n\_\Delta\sigma_{bot.5.d5} := \begin{array}{l} \text{if } m_{5.d5.bot} = 5 \\ \quad \| \; n_5 \cdot \Delta\sigma_{5.d5.bot}{}^{m_{5.d5.bot}} \\ \text{else if } m_{5.d5.bot} = 9 \\ \quad \| \; n_5 \cdot \Delta\sigma_{5.d5.bot}{}^{m_{5.d5.bot}} \\ \text{else if } m_{5.d5.bot} = 0 \\ \quad \| \; 0 \end{array} = 0$$

Lorrie 5

$$n\_\Delta\sigma_{bot.d5.sum} := \left(n\_\Delta\sigma_{bot.1.d5} + n\_\Delta\sigma_{bot.2.d5} + n\_\Delta\sigma_{bot.3.d5} + n\_\Delta\sigma_{bot.4.d5} + n\_\Delta\sigma_{bot.5.d5}\right) = 0$$

$$\Delta\sigma_{eq.bot.d5.A} := \left(\frac{n\_\Delta\sigma_{bot.d5.sum} + \boxed{\left(\frac{\Delta\sigma_{D.5.HFMI}}{\gamma_{Mf}}\right)^{(5-9)} \cdot n\_\Delta\sigma_{bot.d5.sum}}}{n_1 + n_2 + n_3 + n_4 + n_5} \right)^{\left(\frac{1}{5}\right)}$$

Error due to that the numerator is zero

$$\Delta\sigma_{eq.bot.d5.A} := 0$$

$$\Delta\sigma_{eq.bot.d5.B} := \left(\frac{n\_\Delta\sigma_{bot.d5.sum} \cdot \left(\frac{\Delta\sigma_{D.5.HFMI}}{\gamma_{Mf}}\right)^{(9-5)} + \boxed{n\_\Delta\sigma_{bot.d5.sum}}}{n_1 + n_2 + n_3 + n_4 + n_5}\right)^{\left(\frac{1}{9}\right)}$$

Error due to that the numerator is zero

$$\Delta\sigma_{eq.bot.d5.B} := 0$$

$$\frac{\Delta\sigma_{D.HFMI}}{\gamma_{Mf}} > \Delta\sigma_{eq} \quad \text{->} \quad \Delta\sigma_{eq.bot.d5} := \Delta\sigma_{eq.bot.d5.B} = 0$$

Eq. (13)

$$N_{eq.bot.d5.A} := 5 \cdot 10^{6} \cdot \left(\frac{\frac{\Delta\sigma_{D.5.HFMI}}{\gamma_{Mf}}}{\boxed{\lambda_{5.HFMI.bot} \cdot \Delta\sigma_{eq.bot.d5} \cdot \gamma_{Ff}}}\right)^{5}$$

Error due to that the denominator is zero

$$N_{eq.bot.d5.A} := \infty$$

$$N_{eq.bot.d5.B} := 5 \cdot 10^{6} \cdot \left(\frac{\frac{\Delta\sigma_{D.5.HFMI}}{\gamma_{Mf}}}{\boxed{\lambda_{5.HFMI.bot} \cdot \Delta\sigma_{eq.bot.d5} \cdot \gamma_{Ff}}}\right)^{9}$$

Error due to that the denominator is zero

$$N_{eq.bot.d5.B} := \infty$$

$$\frac{\Delta\sigma_{D.HFMI}}{\gamma_{Mf}} > \Delta\sigma_{eq} \cdot \lambda_{HFMI} \quad \text{->} \quad N_{eq.bot.d5} := N_{eq.bot.d5.B} = 1 \cdot 10^{307}$$

Eq. (14)

$$D_{eq.bot.d5} := \left(\frac{n_1 + n_2 + n_3 + n_4 + n_5}{N_{eq.bot.d5}}\right) = 6 \cdot 10^{-301}$$

Damage calculation (TOP):

Lorry 1:

$$m_{1.d5.top} := \left\| \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d5.top} \geq \dfrac{\Delta\sigma_{D.5.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d5.top} \geq \dfrac{\Delta\sigma_{L.5.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{1.d5.top} < \dfrac{\Delta\sigma_{L.5.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 0 \end{array} \right| = 0$$

<u>Lorry 2:</u>

$$m_{2.d5.top} := \left\| \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d5.top} \geq \dfrac{\Delta\sigma_{D.5.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d5.top} \geq \dfrac{\Delta\sigma_{L.5.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{2.d5.top} < \dfrac{\Delta\sigma_{L.5.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 0 \end{array} \right| = 0$$

<u>Lorry 3:</u>

$$m_{3.d5.top} := \left\| \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d5.top} \geq \dfrac{\Delta\sigma_{D.5.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d5.top} \geq \dfrac{\Delta\sigma_{L.5.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{3.d5.top} < \dfrac{\Delta\sigma_{L.5.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 0 \end{array} \right| = 0$$

Lorry 4:

$$m_{4.d5.top} := \left\| \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d5.top} \geq \dfrac{\Delta\sigma_{D.5.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d5.top} \geq \dfrac{\Delta\sigma_{L.5.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d5.top} < \dfrac{\Delta\sigma_{L.5.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 0 \end{array} \right| = 0$$

Lorry 5:

$$m_{5.d5.top} := \left\| \begin{array}{l} \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d5.top} \geq \dfrac{\Delta\sigma_{D.5.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 5 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d5.top} \geq \dfrac{\Delta\sigma_{L.5.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 9 \\ \text{if } \gamma_{Ff} \cdot \Delta\sigma_{4.d5.top} < \dfrac{\Delta\sigma_{L.5.HFMI}}{\gamma_{Mf}} \\ \quad \| \; 0 \end{array} \right| = 0$$

$$n\_\Delta\sigma_{top.1.d5} := \left. \begin{array}{l} \text{if } m_{1.d5.top} = 5 \\ \quad \| \; n_1 \cdot \Delta\sigma_{1.d5.top}{}^{m_{1.d5.top}} \\ \text{else if } m_{1.d5.top} = 9 \\ \quad \| \; n_1 \cdot \Delta\sigma_{1.d5.top}{}^{m_{1.d5.top}} \\ \text{else if } m_{1.d5.top} = 0 \\ \quad \| \; 0 \end{array} \right| = 0$$

Lorrie 1

$$n\_\Delta\sigma_{top.2.d5} := \left. \begin{array}{l} \text{if } m_{2.d5.top} = 5 \\ \quad \| \; n_2 \cdot \Delta\sigma_{2.d5.top}{}^{m_{2.d5.top}} \\ \text{else if } m_{2.d5.top} = 9 \\ \quad \| \; n_2 \cdot \Delta\sigma_{2.d5.top}{}^{m_{2.d5.top}} \\ \text{else if } m_{2.d5.top} = 0 \\ \quad \| \; 0 \end{array} \right| = 0$$

Lorrie 2

$$n\_\Delta\sigma_{top.3.d5} := \begin{array}{|l} \text{if } m_{3.d5.top} = 5 \\ \quad \| \; n_3 \cdot \Delta\sigma_{3.d5.top}{}^{m_{3.d5.top}} \\ \text{else if } m_{3.d5.top} = 9 \\ \quad \| \; n_3 \cdot \Delta\sigma_{3.d5.top}{}^{m_{3.d5.top}} \\ \text{else if } m_{3.d5.top} = 0 \\ \quad \| \; 0 \end{array} = 0$$

Lorrie 3

$$n\_\Delta\sigma_{top.4.d5} := \begin{array}{|l} \text{if } m_{4.d5.top} = 5 \\ \quad \| \; n_4 \cdot \Delta\sigma_{4.d5.top}{}^{m_{4.d5.top}} \\ \text{else if } m_{4.d5.top} = 9 \\ \quad \| \; n_4 \cdot \Delta\sigma_{4.d5.top}{}^{m_{4.d5.top}} \\ \text{else if } m_{4.d5.top} = 0 \\ \quad \| \; 0 \end{array} = 0$$

Lorrie 4

$$n\_\Delta\sigma_{top.5.d5} := \begin{array}{|l} \text{if } m_{5.d5.top} = 5 \\ \quad \| \; n_5 \cdot \Delta\sigma_{5.d5.top}{}^{m_{5.d5.top}} \\ \text{else if } m_{5.d5.top} = 9 \\ \quad \| \; n_5 \cdot \Delta\sigma_{5.d5.top}{}^{m_{5.d5.top}} \\ \text{else if } m_{5.d5.top} = 0 \\ \quad \| \; 0 \end{array} = 0$$

Lorrie 5

$$n\_\Delta\sigma_{top.d5.sum} := \left(n\_\Delta\sigma_{top.1.d5} + n\_\Delta\sigma_{top.2.d5} + n\_\Delta\sigma_{top.3.d5} + n\_\Delta\sigma_{top.4.d5} + n\_\Delta\sigma_{top.5.d5}\right) = 0$$

$$\Delta\sigma_{eq.top.d5.A} := \left(\frac{n\_\Delta\sigma_{top.d5.sum} + \boxed{\left(\frac{\Delta\sigma_{D.5.HFMI}}{\gamma_{Mf}}\right)^{(5-9)} \cdot n\_\Delta\sigma_{top.d5.sum}}}{n_1 + n_2 + n_3 + n_4 + n_5}\right)^{\left(\frac{1}{5}\right)}$$

Error due to that the numerator is zero

$$\Delta\sigma_{eq.top.d5.A} := 0$$

$$\Delta\sigma_{eq.top.d5.B} := \left(\frac{n\_\Delta\sigma_{top.d5.sum} \cdot \left(\frac{\Delta\sigma_{D.5.HFMI}}{\gamma_{Mf}}\right)^{(9-5)} + \boxed{n\_\Delta\sigma_{top.d5.sum}}}{n_1 + n_2 + n_3 + n_4 + n_5}\right)^{\left(\frac{1}{9}\right)}$$

Error due to that the numerator is zero

$$\Delta\sigma_{eq.top.d5.B} := 0$$

$$\frac{\Delta\sigma_{D.HFMI}}{\gamma_{Mf}} > \Delta\sigma_{eq} \quad \text{->} \quad \Delta\sigma_{eq.top.d5} := \Delta\sigma_{eq.top.d5.B} = 0$$

$$N_{eq.top.d5.A} := 5 \cdot 10^6 \cdot \left(\frac{\frac{\Delta\sigma_{D.5.HFMI}}{\gamma_{Mf}}}{\boxed{\lambda_{5.HFMI.top} \cdot \Delta\sigma_{eq.top.d5} \cdot \gamma_{Ff}}}\right)^5$$

Error due to that the denominator is zero

$$N_{eq.top.d5.A} := \infty$$

$$N_{eq.top.d5.B} := 5 \cdot 10^6 \cdot \left(\frac{\frac{\Delta\sigma_{D.5.HFMI}}{\gamma_{Mf}}}{\boxed{\lambda_{5.HFMI.top} \cdot \Delta\sigma_{eq.top.d5} \cdot \gamma_{Ff}}}\right)^9$$

Error due to that the denominator is zero

$$N_{eq.top.d5.B} := \infty$$

$$\frac{\Delta\sigma_{D.HFMI}}{\gamma_{Mf}} > \Delta\sigma_{eq} \cdot \lambda_{HFMI} \quad \text{->} \quad N_{eq.top.d5} := N_{eq.top.d5.B} = 1 \cdot 10^{307}$$

$$D_{eq.top.d5} := \left(\frac{n_1 + n_2 + n_3 + n_4 + n_5}{N_{eq.top.d5}}\right) = 6 \cdot 10^{-301}$$

A.20 Cost calculations

Cost equation:

Nr. of details:

Assumptions:

$n_{transv} := 33 \cdot 2 \cdot 2 \cdot 2 = 264$ — 33 locations, one on each side of the web, top and bot, for two gider beams

$n_{butt} := 13 \cdot 2 \cdot 2 = 52$ — One girder is divided into 14 beams, one weld in top and one in bottom, for two girder beams

$n_{long} := 13 \cdot 2 \cdot 2 \cdot 2 = 104$ — Two rat-hole welds where every beam intersect, in top and in bottom, for two gider beams

Attachment widths (average values) h=L/20

$b_{transv} := 525\ mm$ — Half of average width of bot flange minus thickness of web

$t_{transv} := 12\ mm$

$b_{butt} := 867\ mm$ — Average width of flanges

$t_w := 18.8\ mm$ — Average web thickness

$a := 5\ mm$

Weld lengths:

$$l_{transv} := 2 \cdot b_{transv} + 2 \cdot t_{transv} + \sqrt{2} \cdot a \cdot \pi = 1.096\ m$$

$$l_{butt} := b_{butt} \cdot 2 = 1.734\ m$$

$$l_{long} := (1\ m + t_w) = 1.019\ m$$

Total lengths:

$$l_{tot.transv} := l_{transv} \cdot n_{transv} = 289.401\ m$$

$$l_{tot.butt} := l_{butt} \cdot n_{butt} = 90.168\ m$$

$$l_{tot.long} := l_{long} \cdot n_{long} = 105.955\ m$$

$l_{tot} := l_{tot.transv} + l_{tot.butt} + l_{tot.long} = 485.524\ m$

Treatment speed:

$S_{HFMI} := 250\ mm \cdot 60 = 15\ m$ per hour

250 mm/min (Table 2.1 - Chapter 2.4)

Time to HFMI-treat all welds:

$\gamma := 4$ (Estimating a safety factor of 4 due to inspection, quality check, moving from one place to another etc.)

$T_h := \frac{l_{tot}}{S_{HFMI}} \cdot \gamma = 129.473$ hours

Operator shift is typically 6 hours (HiFit)

$T_{days} := \frac{T_h}{6} = 21.579$ days

The time it takes to HFMI-treat all details

Labour costs: [SEK]

Labour cost: Assummption of labour cost of 500 SEK/hour

$C_{labour} := 500 \cdot T_h = 6.474 \cdot 10^4$ SEK

$\frac{6.474 \cdot 10^4}{10^6} = 0.065$

Leasing cost: 1200 SEK/day (HiFit)

$\frac{2.589 \cdot 10^4}{10^6} = 0.026$

$C_{leasing} := 1200 \cdot T_{days} = 2.589 \cdot 10^4$ SEK

Total cost of HFMI:

$C_{HFMI} := C_{labour} + C_{leasing} = 9.063 \cdot 10^4$ SEK

$C_{HFMI.MSEK} := \frac{C_{HFMI}}{10^6} = 0.091$ MSEK

<u>Steel cost per tone:</u>

$C_{S355} := 10 \cdot 1000 = 1 \cdot 10^{4}$ SEK/tone (SSAB SEK/kg price)

$C_{S460} := 10.83 \cdot 1000 = 1.083 \cdot 10^{4}$ SEK/tone

$C_{S690} := 19.24 \cdot 1000 = 1.924 \cdot 10^{4}$ SEK/tone

Steel cost for the different designs:

<u>HFMI before erection (in workshop):</u>

Original design h=**L/20** S355: Steel usage: 225.6 tone

$$C_{20.original} := \frac{225.6 \cdot C_{S355}}{10^{6}} = 2.256 \quad \text{MSEK}$$

Optimal design h=**L/20** S460: Steel usage: 126.1 tone

$$C_{20.460} := \frac{126.1 \cdot C_{S460}}{10^{6}} = 1.366 \quad \text{MSEK}$$

Optimal design h=**L/20** S690 Steel usage: 111.5 tone

$$C_{20.690} := \frac{111.5 \cdot C_{S690}}{10^{6}} = 2.145 \quad \text{MSEK}$$

Original design h=**L/30** S355: Steel usage: 239.7 tone

$$C_{30.original} := \frac{239.7 \cdot C_{S355}}{10^{6}} = 2.397 \quad \text{MSEK}$$

Optimal design h=**L/30** S460: Steel usage: 173.4 tone

$$C_{30.460} := \frac{173.4 \cdot C_{S460}}{10^{6}} = 1.878 \quad \text{MSEK}$$

Optimal design h=**L/30** S690 Steel usage: 136.8 tone

$$C_{30.690} := \frac{136.8 \cdot C_{S690}}{10^6} = 2.632$$ MSEK

HFMI after erection (on site):

Original design h=**L/20** S355: Steel usage: 225.6 tone

$$C_{A.20.original} := \frac{225.6 \cdot C_{S355}}{10^6} = 2.256$$ MSEK

Optimal design h=**L/20** S460: Steel usage: 118.5 tone

$$C_{A.20.460} := \frac{118.5 \cdot C_{S460}}{10^6} = 1.283$$ MSEK

Optimal design h=**L/20** S690 Steel usage: 111.5 tone

$$C_{A.20.690} := \frac{111.5 \cdot C_{S690}}{10^6} = 2.145$$ MSEK

Original design h=**L/30** S355: Steel usage: 239.7 tone

$$C_{A.30.original} := \frac{239.7 \cdot C_{S355}}{10^6} = 2.397$$ MSEK

Optimal design h=**L/30** S460: Steel usage: 167.4 tone

$$C_{A.30.460} := \frac{167.4 \cdot C_{S460}}{10^6} = 1.813$$ MSEK

Optimal design h=**L/30** S690 Steel usage: 112.0 tone

$$C_{A.30.690} := \frac{112.0 \cdot C_{S690}}{10^6} = 2.155$$ MSEK

Total cost:

Cost = Steel usage [tone] * unit price [SEK/tone] + (Operator cost (labour hour) [SEK/hour] + Rental cost HFMI-machine [SEK/hour]) * (Length to be HFMI-treated [m])/(Speed for HFMI-treatment [m/h]) + Operator traingn cost [SEK]

ORIGINAL DESIGNS (No HFMI-treatment)

h=L/20 S355:
$C_{20.original} = 2.256$ MSEK

h=L/30 S355:
$C_{30.original} = 2.397$ MSEK

OTIMISED DESIGNS (HFMI before erection - in workshop):

h=L/20 S460:
$C_{20.460} + C_{HFMI.MSEK} = 1.456$ MSEK

$Cost\_save_{20.460} := C_{20.original} - 1.456 = 0.8$

$$Cost_{diff.20.460} := \frac{0.8}{C_{20.original}} = 0.355$$

h=L/30 S460:
$C_{30.460} + C_{HFMI.MSEK} = 1.969$ MSEK

$Cost\_save_{30.460} := C_{30.original} - 1.969 = 0.428$

$$Cost_{diff.30460} := \frac{0.428}{C_{30.original}} = 0.179$$

h=L/20 S690:
$C_{20.690} + C_{HFMI.MSEK} = 2.236$ MSEK

$Cost\_save_{20.690} := C_{20.original} - 2.236 = 0.02$

$$Cost_{diff.20.690} := \frac{0.02}{C_{20.original}} = 0.009$$

h=L/30 S690:
$C_{30.690} + C_{HFMI.MSEK} = 2.723$ MSEK

$Cost\_save_{30.690} := C_{30.original} - 2.723 = -0.326$

$$Cost_{diff.3.690} := \frac{-0.326}{C_{30.original}} = -0.136$$

OTIMISED DESIGNS (<u>HFMI after erection - on site</u>):

h=L/20 S460:
$C_{A.20.460} + C_{HFMI.MSEK} = 1.374$ MSEK

$Cost\_save_{A.20.460} := C_{20.original} - 1.374 = 0.882$

$$Cost_{diff.A.20.460} := \frac{0.882}{C_{20.original}} = 0.391$$

h=L/30 S460:
$C_{A.30.460} + C_{HFMI.MSEK} = 1.904$ MSEK

$Cost\_save_{A.30.460} := C_{30.original} - 1.904 = 0.493$

$$Cost_{diffA.30.460} := \frac{0.493}{C_{30.original}} = 0.206$$

h=L/20 S690:
$C_{A.20.690} + C_{HFMI.MSEK} = 2.236$ MSEK

$Cost\_save_{A.20.690} := C_{20.original} - 2.236 = 0.02$

h=L/30 S690:
$C_{A.30.690} + C_{HFMI.MSEK} = 2.246$ MSEK

$Cost\_save_{A.30.690} := C_{30.original} - 2.246 = 0.151$

$$Cost_{diff.A.20.690} := \frac{0.02}{C_{20.original}} = 0.009 \qquad Cost_{diff.A.30.690} := \frac{0.151}{C_{30.original}} = 0.063$$