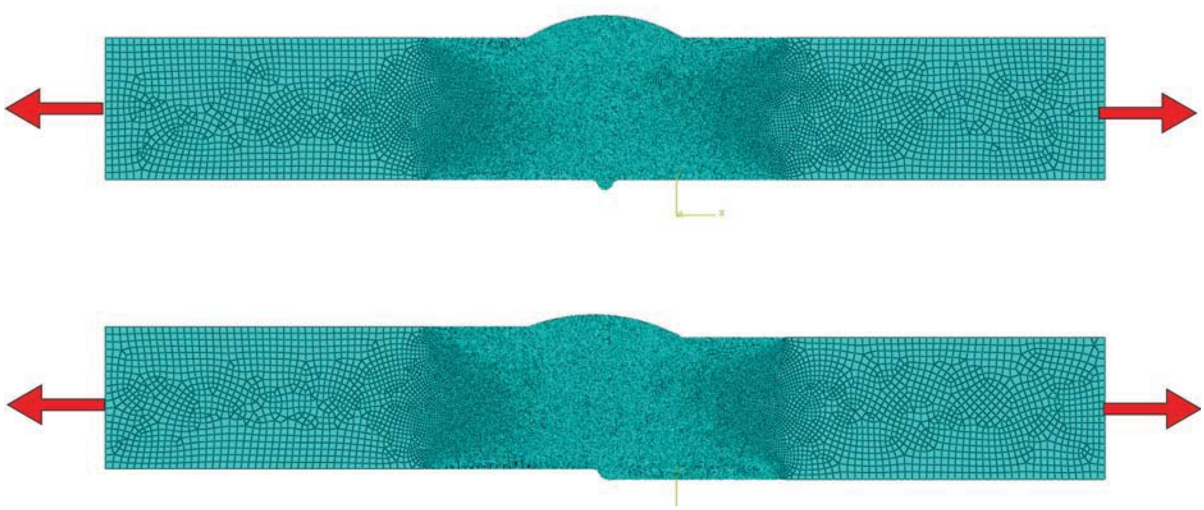
The effect of misalignment on the stress field and fatigue strength of welded joints



D-5-48/2014

Baltali Gürel
Institut für Stahlbau
Technische Universität Graz

Masterarbeiten/Dissertationen | Forschung | Skripten | Vorträge/Tagungen

The effect of misalignment on the stress field and fatigue strength of welded joints

A numerical case study

Master's Thesis in the Master's Programme
Civil Engineering and Structural Engineering

by

GÜREL BALTALI, BSc

Supervisor: Univ. Prof. Dipl.-Ing. Dr.techn. Harald Unterweger
Co-Supervisor: Ass. Prof. Dipl.-Ing. Dr.techn. Andreas Taras

Graz University of Technology
Faculty of Civil Engineering, Institute for Steel Structures

In Partial Fulfilment of the Requirements
for the title of "Diplom-Ingenieur"
in
Structural Engineering

SEPTEMBER 2014

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name: Gürel Baltalı

Signature:

ABSTRACT

THE EFFECT OF MISALIGNMENT ON THE STRESS FIELD AND FATIGUE STRENGTH OF WELDED JOINTS

In this thesis, the fatigue resistances and performances of common welded joints were numerically assessed based on different methods, such as the (modified) nominal stress method, the structural hot spot stress method and the effective notch stress method. The main aim of this project was to investigate the effect of misalignment on the predicted stresses and – consequently - the fatigue strength, by including weld imperfections, and to compare the results with the suggested stress magnification factors given by Eurocode 3 and the IIW Recommendations.

In case of transverse butt welded joints, the shape of the weld plays a significant role in the fatigue strength for cracks originating in the weld toes. Existing fatigue class catalogs, which were created as a result of experimental measurements, mostly contain information about X-joints, even though the numerical strength assessment can be performed for other weld shapes (Y-, U-, I- welds, for example). In this thesis, the numerical study was also conducted for Y-joints and inverse Y-joints. Additionally, fatigue class catalogs had quality level restrictions especially for the height of weld convexity. Since different weld reinforcements yielded separate fatigue strength, different qualities of welding were also modelled and compared to each other. In addition to butt welds, a cruciform joint with fillet welds was investigated as well.

The results show that the analytical stress magnification factors given by the IIW Recommendations are mostly applicable (with some exceptions) for transverse butt welded joints with equal thickness and cruciform joints with fillet welds. Nevertheless, the values are not precise enough to estimate the combined effect of misalignment and “planned” eccentricities in the case of transverse butt welded joints with eccentric thickness transition, and need a clearer specification of the considered boundary conditions of the plates adjacent to the welds in all cases.

During this work, the FEM discretization level for element sizes and element meshing was taken from the 2014 edition of the IIW Recommendation for the fatigue resistance of welded joints. However, in some cases the number of elements was not accurate enough for stress convergence. Because of this reason, a convergence study was also carried out to discuss the effects of mesh size on fatigue life prediction.

Keywords: nominal stress, structural hot spot stress, effective notch stress, fatigue assessment, welded joints, finite element method, fatigue life cycle, axial misalignment

KURZFASSUNG

DER EFFEKT VON EXZENTRIZITÄTEN AUF SPANNUNGEN UND ERMÜDUNGSFESTIGKEIT GESCHWEISZTER ANSCHLÜSSE

In dieser Arbeit wurde die Ermüdungsfestigkeit einiger üblicher Schweißdetails mittels verschiedener spannungsbasierter Methoden untersucht. Dabei wurden die Methode der nominellen, der Struktur- und der (effektiven) Kerbspannungen angewandt. Das Hauptziel dieser Studie war es, den Effekt von unvermeidbaren Kantenversätzen und Exzentritäten auf die Spannungen – und damit die Lebensdauer bei Ermüdung – im Schweißdetail zu quantifizieren. Dabei wurden die Methoden des Eurocodes und der Empfehlungen des IIW berücksichtigt und verglichen.

Beim zunächst untersuchten Grundfall der Stumpfstöße zwischen Blechen gleicher Dicke wurde festgestellt, dass die geometrische Form der Schweißnaht eine große Bedeutung für Ermüdungsrisse hat, welche von den Schweißnahtübergängen ausgehen können. Kerbfallkataloge aus der Literatur, welche auf Basis experimenteller Bauteilversuche erstellt wurden, berücksichtigen vorwiegend das Verhalten von Schweißstößen mit X-Nähten, obwohl die numerische/normative Beurteilung für alle Nahtformen erfolgen kann (auch für Y-, U-, I- Nähte). In der vorliegenden Arbeit wurden daher auch Y- und umgekehrte Y-Nähte berücksichtigt. Zusätzlich wurden auch die unterschiedlichen Anforderungen bezüglich Nahtüberhöhung berücksichtigt. Da unterschiedlich große Überhöhungen zu unterschiedlichen Spannungen führen, konnte der Zusammenhang zwischen Nahtform und Kerbfall quantifiziert werden.

Die Ergebnisse dieser Arbeit zeigten, dass die bestehenden IIW Empfehlungen bezüglich der Berücksichtigung der Effekte von Exzentrizitäten bei den Grundfällen des Stumpfstoßes mit Blechen gleicher Dicke und beim T-Stoß mit Kehlnähten grundsätzlich (aber nicht immer) sichere und sinnvolle Ergebnisse liefern. Bei anderen Konfigurationen, wie einem Gurtdickenübergang, sind die Empfehlungen in den Normen jedoch unklar oder nicht anwendbar. Prinzipiell zeigte sich zudem, dass die drei erwähnten spannungsbasierten Methoden auch bei den untersuchten Grundfällen zu häufig sehr unterschiedlichen Ergebnissen der rechnerischen Lebensdauer führen; diese Tatsache wird durch das Vorhandensein von Exzentrizitäten noch verstärkt.

Abschließend wurde in der Arbeit auch eine Konvergenzstudie des FEM-Netzes durchgeführt, welche zeigte, dass die in der Literatur empfohlene Netzteilung bei gewissen Kerbfällen und dem Strukturspannungskonzept noch nicht zur Konvergenz der Spannungsergebnisse führt.

.

ACKNOWLEDGEMENTS

First of all, I want to thank to my Co-Supervisor Ass. Prof. Dipl.-Ing Dr. techn. Andreas Taras. It would not be possible to construct this work without his motivation. He provided me all kinds of supports and help. The process would be unbearable without his priceless guidance.

I also want to thank to my supervisor Univ. Prof. Dipl.-Ing. Dr.techn. Harald Unterweger for his guidance and giving me the opportunity to work in this project.

Furthermore, I would like to express my sincere gratitude to Çağatay Ata, Ezgi Ünal, Senem Demircioğlu, Kristina Gril, Johannes Schwarz, Ilija Vuksanovic, Tolga Gürol, Murat Bayraktar, Alihan Günaydın and Onursal Önen for their support and friendship.

Finally, I present my deepest gratefulness to my father Serdar Kurtuluş Baltalı and my mother Günaç Baltalı for their endless love and compassion.

TABLE OF CONTENTS

1

Introduction

Fatigue strength verifications based on the so-called nominal stress approach are needed for the design of steel structures for many engineering applications. For this classical method, there exist numerous experimentally acquired fatigue classes (FATs) of different joint types, which can be used in fatigue life cycle calculations with this method, considering the classical beam-theoretical stresses only (without considering geometric discontinuities in the proximity of the weld).

Another method, which utilizes the experimental data but grouping locally similar joint types together, is the structural (or "hot spot") stress method. This method accounts for stress concentration effects due to local geometry, but excludes the local notch effect in the immediate proximity of the weld. However, there are limited FAT classes for fatigue verification based on this approach, many of which are generalizing the joint type.

Undoubtedly, testing of specimens often requires excessive effort; this led researchers to develop a more general, purely numerical method, the effective notch stress method. On top of other described methods, the effective notch stress method also includes the local notch stress raising effects in the numerical calculation of stresses, and then treats all (welded) joints of a certain material with one, single FAT class (in the case of steel structures, with FAT class 225). There are different approaches for the application of this method. One common recommendation for the rounding of notches can be seen in Fig 1.1. Assigning an **r=1mm** arch around the notch is said to give consistent results for steel, when combined with the above-mentioned FAT class of 225 [2].

The number of cycles to failure is affected from imperfections such as weld tolerances and misalignment in the joint geometry [3]. The International Institute of Welding (IIW) recommendation explains the effect of misalignment as: "Misalignment in axially loaded joints leads to an increase of stress in the welded joint due to the occurrence of secondary shell bending stresses" [2]. During the experimental tests, some misalignment was inevitably already included and the resulting reduction of fatigue life cycles is reflected in part in the relevant S-N curves [2]. However, in some methods of calculation, the amount of already covered misalignment needs further investigation. In some standards and recommendations (e.g. the Eurocode 3 [1] and IIW Recommendations [2]), additional misalignment is specifically treated with either stress magnification factors $\mathbf{k_m}$ (in IIW) or resistance reduction factors $\mathbf{k_s}$ (in EC3). These factors and their applicability were verified in this study.

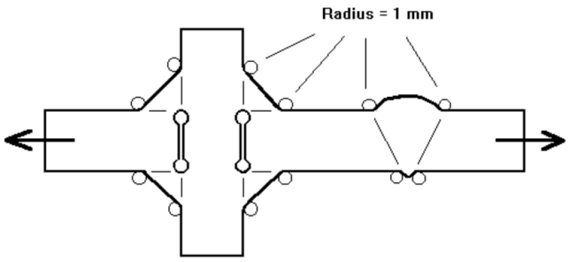


Fig 1.1 Fictitious rounding of weld notches for effective notch stress method [2].

1.1. Aim and Scope

In this study, both local and global approaches, namely the (modified) nominal stress, structural hot spot stress and effective notch stress methods, are used for the fatigue life assessment of different welded steel joints. The effects of imperfections on fatigue life cycles are also investigated.

This thesis is composed of six chapters. This very first one is the introduction and it includes motivation, methodology and terminology.

In Chapter 2, the resulting stresses of butt welds in plates of equal thickness according to the different stress calculation methods for fatigue design are presented. The cases with linear misalignment and without misalignment are discussed separately and the fatigue life cycles according to different approaches are calculated. Additionally, the recommended stress modification factor $\mathbf{k_m}$ is plotted against normalized numerical stress calculation results (ratio "stress with / without misalignment"). Fatigue life cycles are also calculated and shown in table format.

There is no specific information about fatigue classes for the structural hot spot stress method for butt welded joints in plates with thickness transition (found when a thicker plate is eccentrically joined with a thinner one), and the information given for the nominal stress approach appears ambiguous: no difference is made between flush butt welds and welds at (eccentric) thickness transitions, in spite of the presence of a "planned" eccentricity in the latter case. To investigate these points, some typical butt welded joints in thickness transitions are analysed in Chapter 3. After an assessment of these joints in the "ideal" configuration, i.e. without additional misalignment, the influence of a linear misalignment is also included and the results are discussed. Like in the previous chapter, stress modification factors are discussed here. Fatigue life cycles are also calculated and shown in table format.

In Chapter 4, a typical cruciform joint is investigated. The weld toe stresses are calculated with each of the three different methods. However, weld root stresses are only calculated by using nominal and effective notch stress method, since the numerical methods for the estimation of structural stresses at weld root are still under research and not yet included in international design standards.

During the analyses, a few possible sources of error or misinterpretation of the standard were encountered, particularly concerning the meshing for the effective notch stress method; they are presented in Chapter 5. Furthermore, a mesh convergence study was performed and the recommended mesh sizes and element numbers given by IIW Recommendations are compared here.

The final Chapter 6 includes a brief summary of the results and the conclusions drawn from of the results in this thesis.

1.2. Methodology

The finite element analyses in this thesis are performed with the Abaqus/CAE 6.10-1 software package. Since all the three previously mentioned fatigue assessment methods are taking into account linear elastic material behaviour, a single step linear elastic analysis was performed in all numerical calculations.

Due to the nature of the welding process, the welded material is somewhat inhomogeneous in reality [3]. However, in this thesis, isotropic and homogeneous material characteristics are assumed and mechanical properties of construction steel (E=210GPa and ν=0.28) are taken for both parent material (steel plates) and weld metal (weld reinforcement).

In all cases, loading is applied uniaxially, which can be seen in Fig 1.2. Furthermore, the studied joints are assumed to have a constant geometry in transversal ("out-of-plane") direction. Therefore, the models are able to be solved as part of a plane stress (or alternatively: plane strain) problem. The magnitude of the applied external stress is chosen depending on the nominal fatigue strength of the related joint type. For example, for assessment of transverse butt welded joints with "Weld Quality B" (according to ISO 5817), a tensile loading of 80N/mm^2 is selected deliberately, because the fatigue class based on the nominal stress approach of this joint type is FAT80.

Thus, the finite element method was used in this thesis to calculate the stresses for the structural (hot spot) stresses and the effective notch stresses; the (unmodified) nominal stresses did not need to be calculated, as they were equal to the applied load of the model according to the above definition.

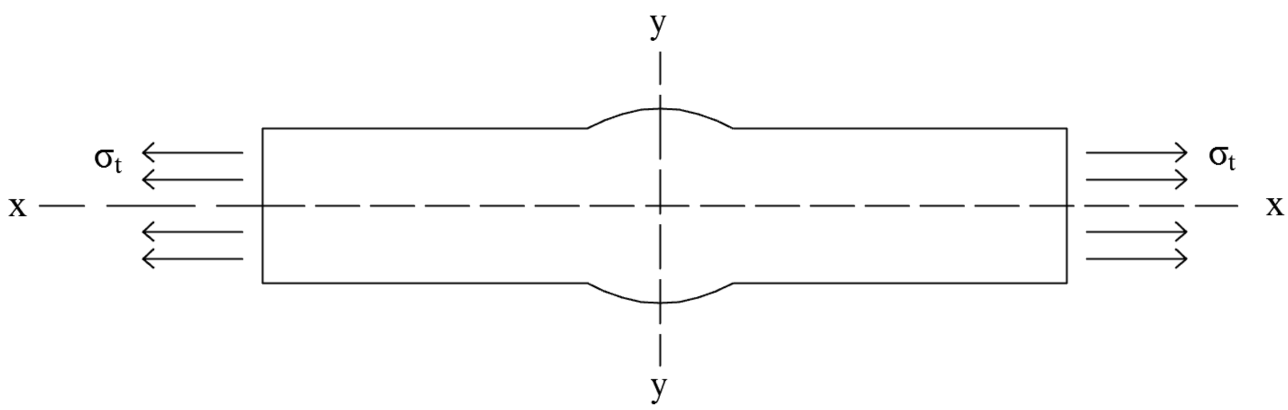


Fig 1.2 External loading is applied axially and remotely from weld.

Thus, the fatigue class of the joint according to the nominal stress method always corresponds to the resistance (in terms of stress amplitudes Δσ) that lead to a fatigue life of $2x10^6$ life cycle.

Note that, in calculations of *fatigue life*, throughout this thesis it was assumed that the loads will be applied with constant amplitude, starting from zero load. Thus, *the calculated stresses σ always were considered to also correspond to the applied stress amplitudes Δσ in the fatigue life calculations*.

1.2.1. Finite Element Method – Meshing and Stress Calculation

In this thesis, 4-node linear shell elements were used. Element mesh sizes and numbers were chosen according to recommendations given by IIW, shown in Fig 1.3, Fig 1.4 and Fig 1.5.

Type of model and weld toe		Relatively coarse models		Relatively fine models	
		Type a	Type b	Type a	Type b
Element size	Shells	t x t max t x w/2*)	10 x 10 mm	≤0.4 t x t or ≤0.4 t x w/2	≤ 4 x 4 mm

Fig 1.3 Recommended element sizes at the surface for the assessment based on structural stress method (IIW Recommendations, 2014 Table 2.2.-2).

Element type	relative size	absolute size [mm]	No. of elements in 45° arc	No. of elements in 360° arc
quadratic with mid-side nodes	≤ r/4	≤ 0.25	≥ 3	≥ 24
linear	≤ r/6	≤ 0.15	≥ 5	≥ 40

Fig 1.4 Recommended element sizes at the surface for the assessment based on effective notch stress method (IIW Recommendations, 2014 Table 2.2.-3).

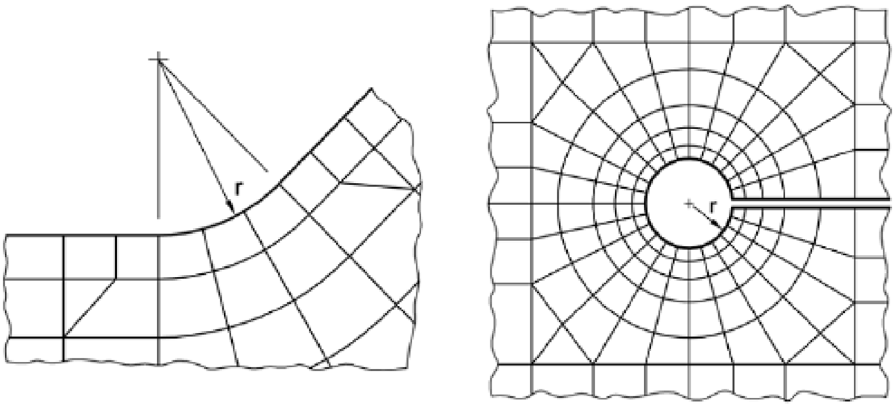


Fig 1.5 Mesh generation recommendations based on effective notch stress method (IIW Recommendations, 2014 Figure (2.2)-17).

An example for a generated mesh around a weld toe notch of a transverse butt welded joint can be seen in Fig 1.6. In general, the minimum recommended number of elements is taken as basis during modelling. For instance, only five elements around the weld toe notch are generated, which is the minimum suggested by the recommendations (see Fig 1.4). However, in some cases the number of elements around the notch is increased up to seven elements (in cases where the notch length was significantly increased) and decreased up to three elements (in cases where the notch length was significantly decreased).

The straight region just before the notch and the curved region around the weld imperfection should also be observed during modelling [2]. Thus, the fine meshing around the notch is also kept around the weld region and in the straight part as well (see Fig 1.7).

In Fig 1.8, the number of elements around the weld root and toes of a cruciform joint is shown. 40 elements per weld root (internal notch with 1mm radius) are used, according to suggestions shown in Fig 1.4 and Fig 1.5. The region with relatively fine mesh is also shown in Fig 1.9.

For the fictitious rounding of weld toes and roots, an effective notch radius of **r=1mm** is chosen. This value is said to give consisting results for steel material [2].

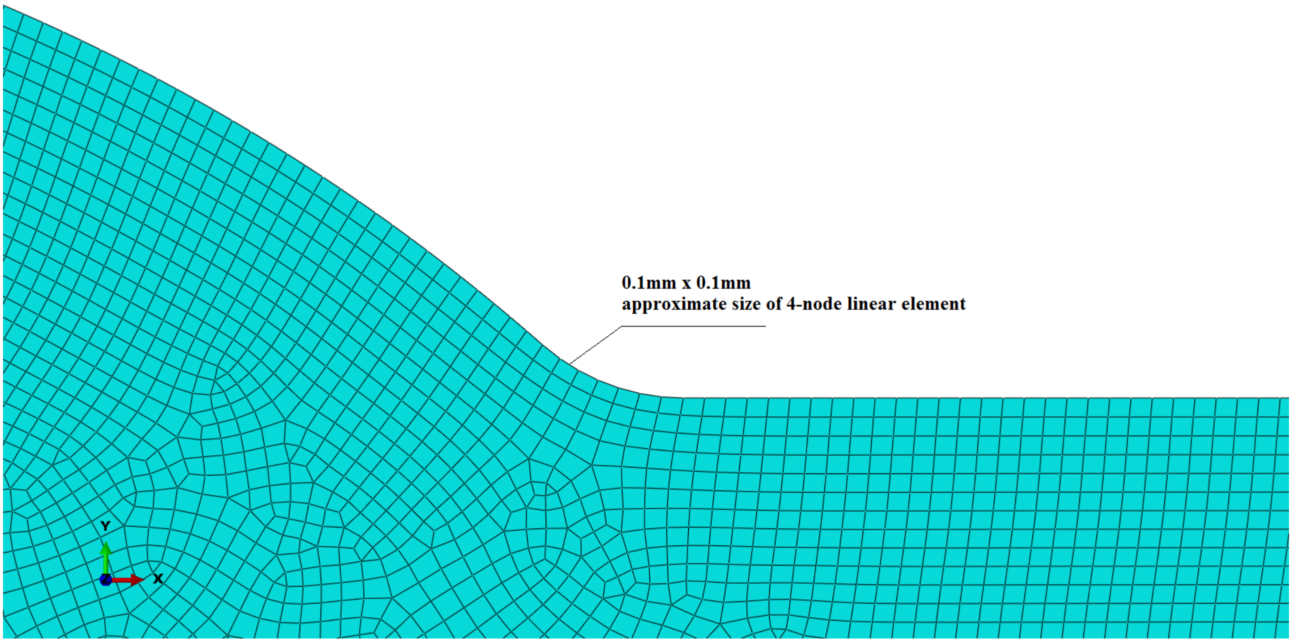


Fig 1.6 Element meshing at around weld notch in transverse butt welded double-vee joint. (Screenshot from Abaqus model).

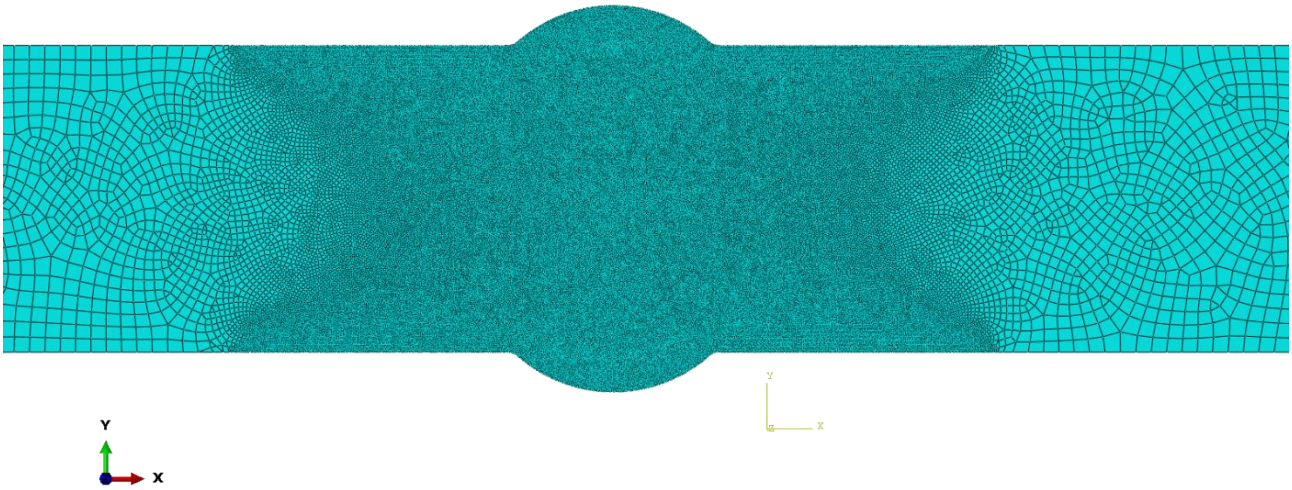


Fig 1.7 Element fine meshing region in transverse butt welded double-vee joint (Screenshot from Abaqus model).

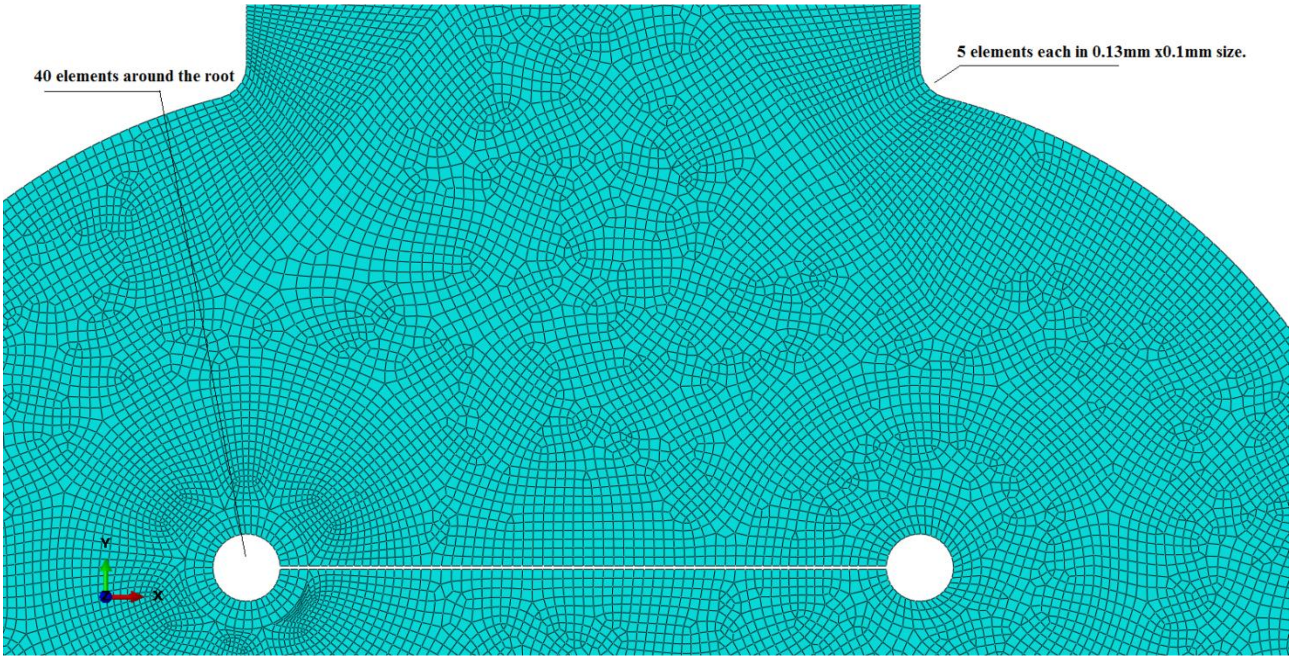


Fig 1.8 Element meshing at weld roots and weld toes in the cruciform joint.

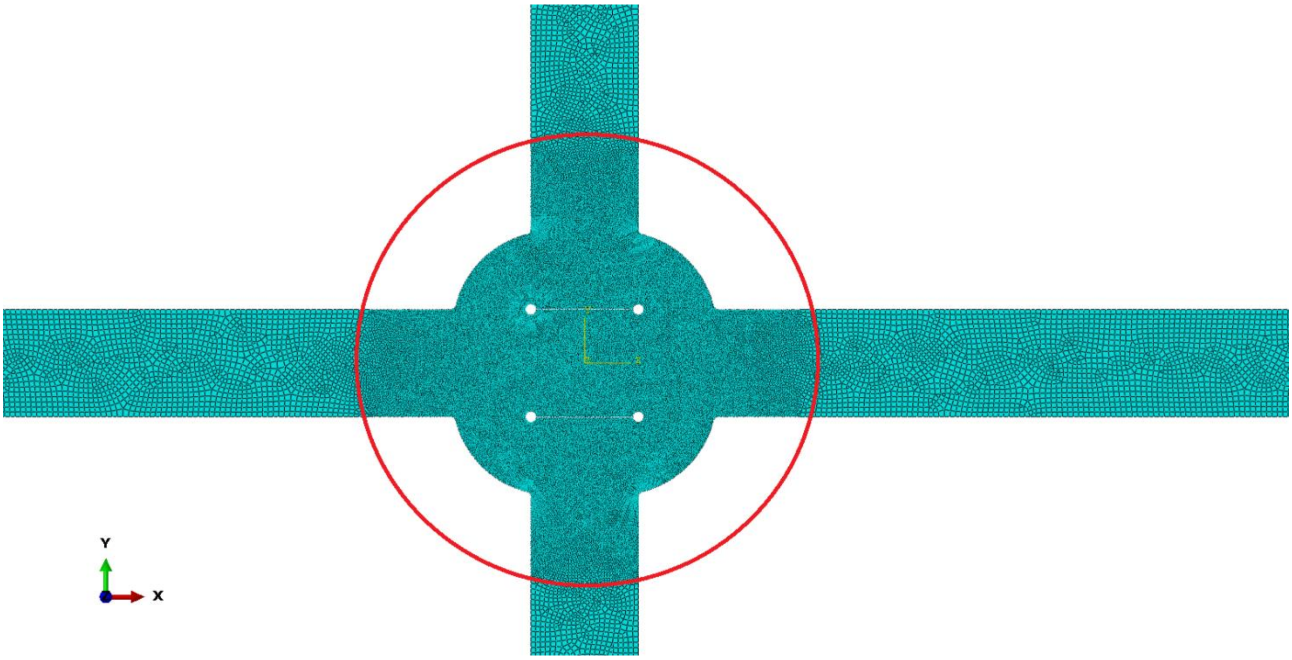


Fig 1.9 Region of relatively fine meshing in cruciform joint (Screenshot from Abaqus model).

The structural hot spot stress $\boldsymbol{\sigma_{hs}}$ was evaluated by surface extrapolation from the corner nodes of two different elements. The type of hot spot stress is type "a" for both studied elements (meaning a hot spot stress calculated at the toe of welds in a section perpendicular to the width of the plate, as opposed to type "b" for a section parallel to the width of the plate) and the resulting structural hot spot stress is calculated with Eq.1.1 (IIW Recommendations [2], pg.24).

$$\sigma_{\mathrm{hs}} = 1.67 * \sigma_{0.4*\mathrm{t}} - 0.67 * \sigma_{1.0*\mathrm{t}} \quad (1.1)$$

An example surface extrapolation is shown in Fig 1.10. In all configurations, the selected reference plate thickness is equal to 20mm. However, in transverse butt welds with thickness transition, two different plates with thickness 40mm and 20mm are welded, with a transition slope in the thicker plate; nevertheless "t" in the above formula was considered to be 20mm on both sides of the weld even in the thickness transition

1.2.2. Life Cycle Calculation

Fatigue lifes are estimated by using so called "S-N curves", which are dependent on the applied calculation method and the studied welded detail. (*Note*: in the following, "S" and "Δσ" are used equivalently, both representing stress amplitudes; the former is more common in English language literature, while the latter is used e.g. in the Eurocodes). Since the S-N curves of design recommendation and codes such as Eurocode 3 and the IIW recommendation are represented by (segmentally) straight lines when plotted on a log-log scale, the curves are described by using Eq.1.2.

$$N_1 = N_2 \cdot \left(\frac{S_2}{S_1} \right)^m \quad (1.2)$$

where m is the slope of the line, S_i is the stress amplitude and N_i is the corresponding reachable number of fatigue loading cycles. An idealized example S-N curve is shown in Fig 1.11.

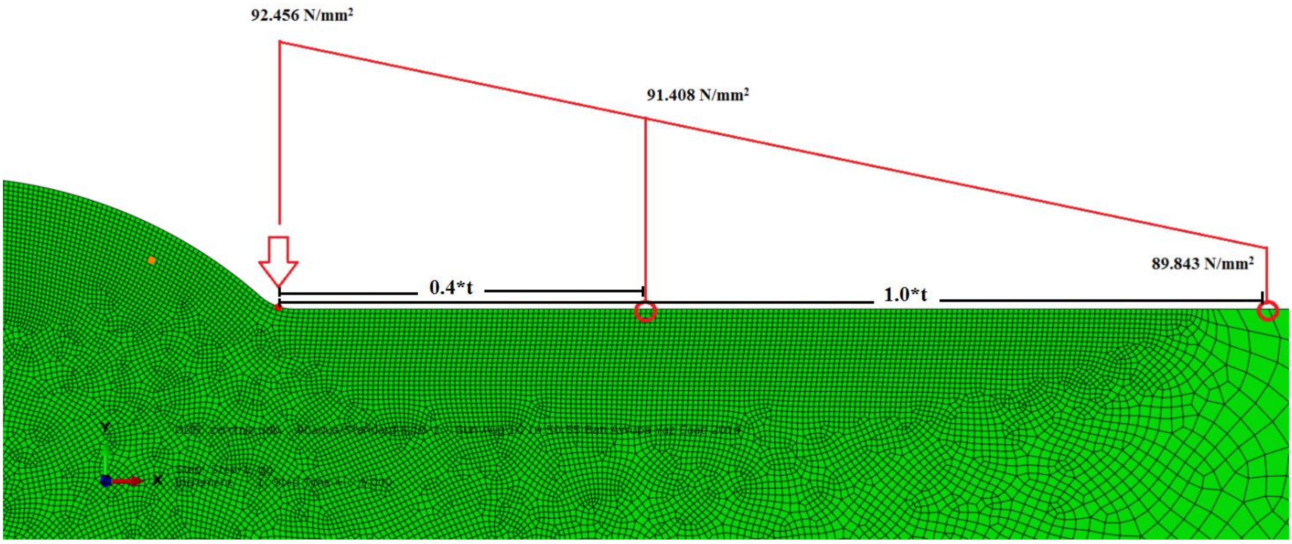


Fig 1.10 Determination of structural hot spot stress at weld toe of a transverse butt welded joint.

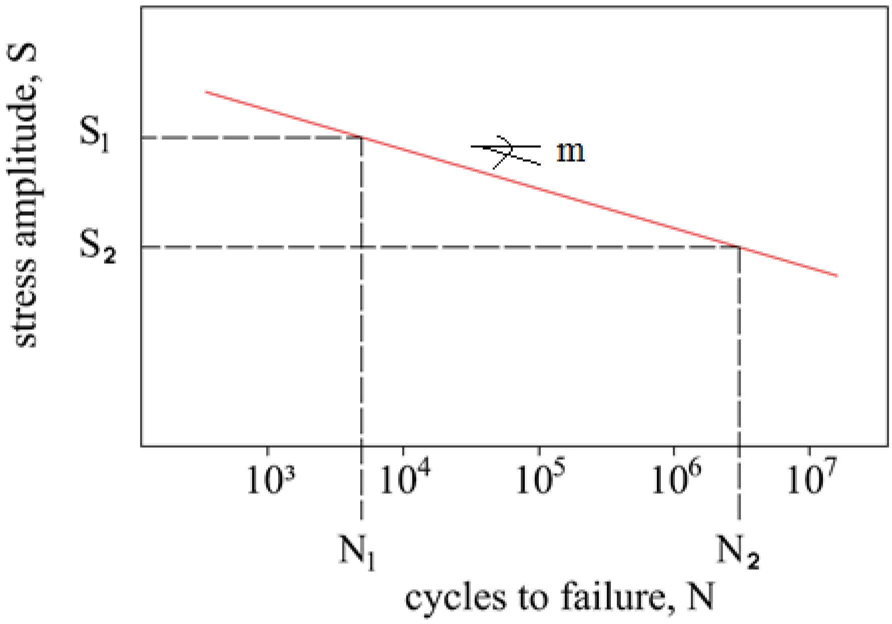


Fig 1.11 Idealized S-N curve example.

In Eurocode 3, the fatigue strength for nominal stress ranges is represented by a series of curves; each corresponding to different fatigue classes. As mentioned earlier, those fatigue classes are designated by a number which represents the resistance that leads to a fatigue life of $2x10^6$ life cycles. In Fig 1.12, the fatigue strength curves for direct stress ranges $\Delta\sigma$ given by Eurocode 3 are shown. As can be seen in this graph, the constant amplitude fatigue limit (CAFL) begins at $5x10^6$ life cycles. Below this value no fatigue damage occurred during the tests under constant amplitude stress conditions [1]. In this thesis, the load is applied with constant amplitude. For this reason, the fatigue life for stresses below the CAFL is assumed to be infinite.

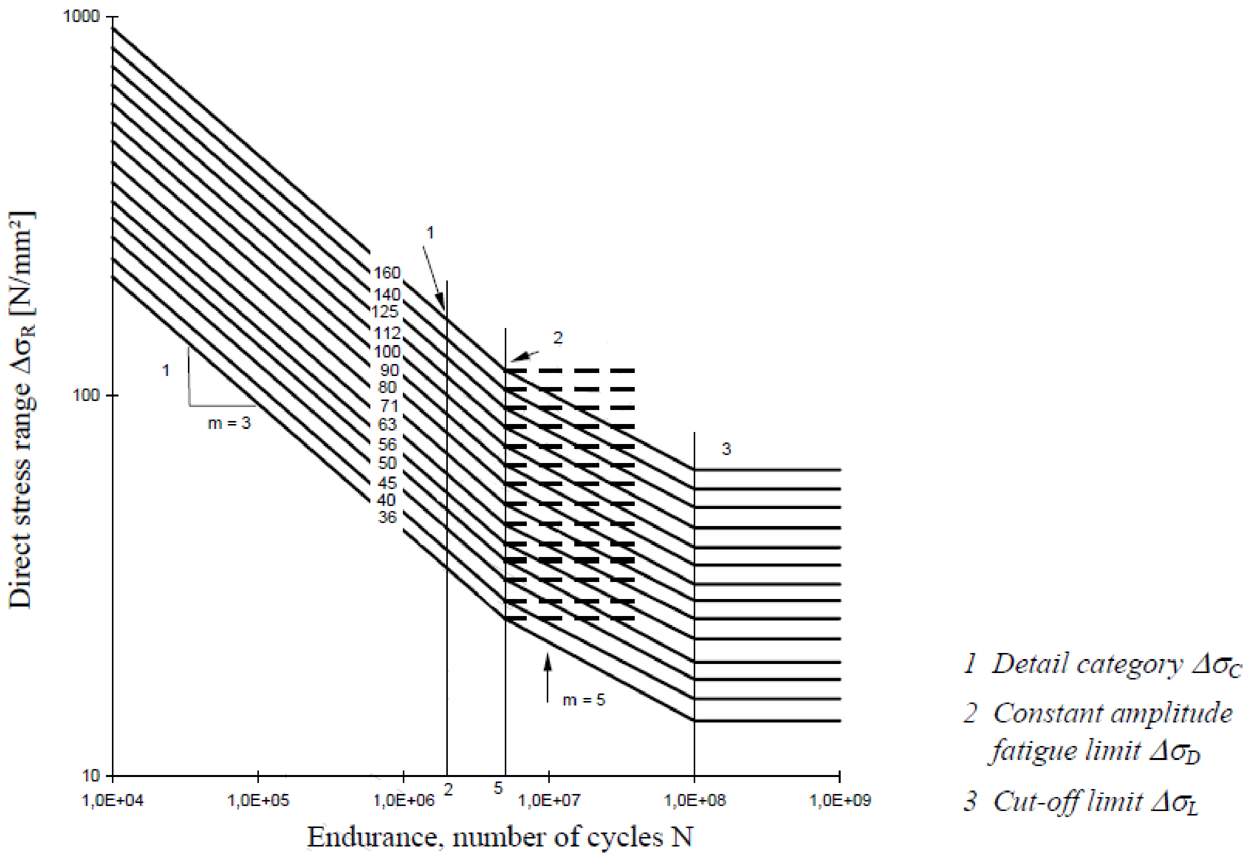


Fig 1.12 Fatigue strength curves for direct stress ranges (EN 1993-1-9:2005 Figure 7.1).

Furthermore, as stated previously, in this thesis only loading from "zero" (unloaded state) to the applied load was considered whenever fatigue lives were calculated. This means that all stresses σ calculated in this thesis can directly be regarded as equivalent to a (fatigue relevant) stress amplitude Δσ.

1.3. Definitions (taken from [2])

Classified or standard structural detail	A structural detail containing a structural discontinuity including a weld or welds, for which the nominal stress approach is applicable, and which appear in the tables of these fatigue design recommendations. Also referred to as standard structural detail.
Effective notch stress	Notch stress calculated for a notch with a certain assumed notch radius.
Fatigue	Deterioration of a component caused by the crack initiation and/or by the growth of a crack.
Fatigue action	Load effect causing fatigue, i.e. fluctuating load.
Fatigue life	Number of stress cycles of a particular magnitude required to cause fatigue failure of the component.
Fatigue limit	Fatigue strength under constant amplitude loading corresponding to a high number of cycles large enough to be considered as infinite.
Fatigue resistance	Structural detail's resistance to fatigue actions expressed in terms of a S-N curve or crack propagation properties.
Fatigue strength	Magnitude of stress range leading to a particular fatigue life.
Fusion zone	The weld volume forming after the welding process.
Heat affected zone	The area which is not welded but affected by welding operation.
Hot spot	A point in a structure where a fatigue crack may initiate due to the combined effect of structural stress fluctuation and the weld geometry or a similar notch.
Local or modified nominal stress	Nominal stress including macro-geometric effects, concentrated load effects and

	misalignments, disregarding the stress raising effects of the welded joint itself.
Modified nominal stress	See 'Local nominal stress'.
Nominal stress	A stress in a component, resolved using general theories, e.g. beam theory. See also local nominal stress.
Nonlinear stress peak	The stress component of a notch stress which exceeds the linearly distributed structural stress at a local notch.
Notch stress	Total stress at the root of a notch taking into account the stress concentration caused by the local notch, consisting of the sum of structural stress and nonlinear stress peak.
Shell bending stress	Bending stress in a shell or plate-like part of a component, linearly distributed across the thickness as assumed in the theory of shells.
S-N curve	Graph of the dependence of fatigue life **N** on applied stress range **S** ($\Delta\sigma_R$ or $\Delta\tau_R$), also known as Wöhler curve.
Stress cycle	A part of a stress history containing a stress maximum and a stress minimum, usually determined by cycle counting.
Stress range	The difference between the maximum and minimum stresses in a cycle.
Stress intensity factor ratio	Ratio of minimum to maximum algebraic value of the stress intensity factor of a particular load cycle.
Structural discontinuity	A geometric discontinuity due to the type of welded joint, usually to be found in the tables of classified structural details. The effects of a structural discontinuity are (I) concentration of the membrane stress and (ii) formation of secondary shell bending stresses

Structural or geometric stress	A stress in a component, resolved to take into account the effects of a structural discontinuity, and consisting of membrane and shell bending stress components.
Structural hot spot stress	The value of structural stress on the surface at a hot spot.
Weld metal	The melted and solidified material after welding operation.
Weld reinforcement	The height of excess concavity in welds.

1.4. Symbols

e	eccentricity, amount of offset misalignment
k_m	stress magnification factor due to misalignment
$k_{m,eff}$	effective stress magnification factor due to misalignment
m	exponent of S-N curve
t	plate thickness, thickness parameter
σ_t	normal tensile stress
σ_b	shell bending stress
σ_{nom}	(modified) nominal stress
σ_{hs}	structural hot spot stress
$\sigma_{hs,0}$	structural hot spot stress without misalignment effects
σ_{en}	effective notch stress
$\sigma_{en,0}$	effective notch stress without misalignment effects
$\Delta\sigma$	stress amplitude
N.C	not calculated
-	geometrically not available

2

Butt Welds in Plates of Equal Thickness

In this chapter, as stated in the introduction, stresses, fatigue life predictions and the effect of misalignment are studied for the basic case of butt welds in plates of equal thickness.

2.1. Considered Geometries and Misalignment

Several methods of edge preparations before welding are applied in practice, depending on the different factors. These heavily influence the final geometry of the weld. In this chapter, two different common edge preparations for welding are considered, which are marked in Fig 2-1.

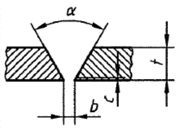
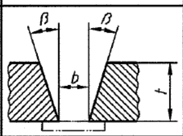
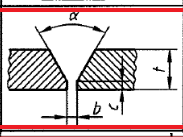
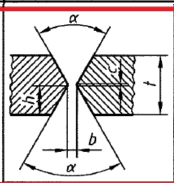
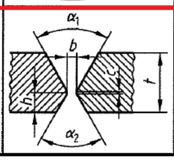
Kenn-zahl Nr	Werkstück-dicke t mm	Art der Schweiß-nahtvorbe-reitung	Symbol (nach ISO 2553)	Schnitt	Maße: Winkel[a] α, β	Spalt[b] b mm	Steg-höhe c mm	Flanken-höhe h mm	Empfohlener Schweiß-prozess[c] (nach ISO 4063)
1.3	$3 < t \leq 10$	V- Fuge	V		$40° \leq \alpha \leq 60°$	≤ 4	≤ 2	–	3 111 13 141
	$8 < t \leq 12$				$6° \leq \alpha \leq 8°$	–			52[d]
1.4	> 16	Steilflanken-V-Fuge	\/		$5° \leq \beta \leq 20°$	$5 \leq b \leq 15$	–	–	111 13
1.5	$5 \leq t \leq 40$	Y-Fuge	Y		$\alpha \approx 60°$	$1 \leq b \leq 4$	$2 \leq c \leq 4$	–	111 13 141
2.5.1	> 10	D(oppel)-V-Fuge	X		$\alpha \approx 60°$	$1 \leq b \leq 3$	≤ 2	$\approx \frac{t}{2}$	111 141
					$40° \leq \alpha \leq 60°$				13
2.5.2		Unsymme-trische D(oppel)-V-Fuge			$\alpha_1 \approx 60°$ $\alpha_2 \approx 60°$			$\approx \frac{t}{3}$	111 141
					$40° \leq \alpha_1 \leq 60°$ $40° \leq \alpha_2 \leq 60°$				13

Fig 2-1 Selected Y-joint and X-joint (ÖNORM EN ISO 9692-1:2004, Tables 1 and 2).

The edge preparation parameters such as the root gap “b”, root face depth “c” and included angle “α” are chosen on the basis of the recommendations given in ÖNORM EN ISO 9692-1. The final chosen geometries prior to welding are shown in Fig 2-2 and Fig 2-3. Note that a plate thickness of t=20mm was considered in all cases.

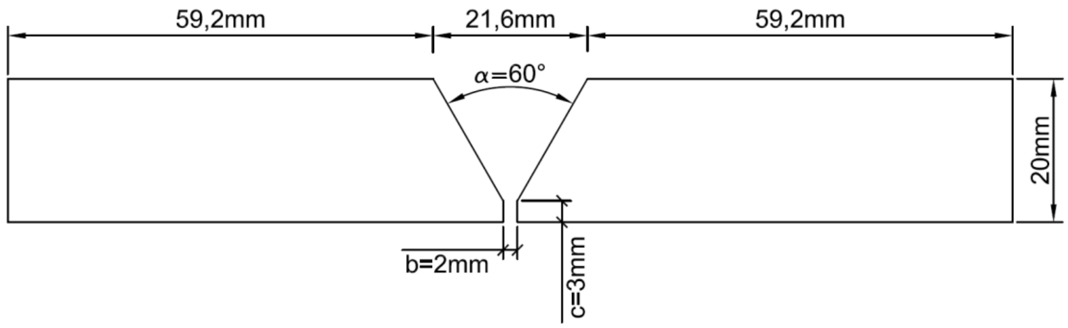


Fig 2-2 Y-joint (or “single-vee”) edge preparation.

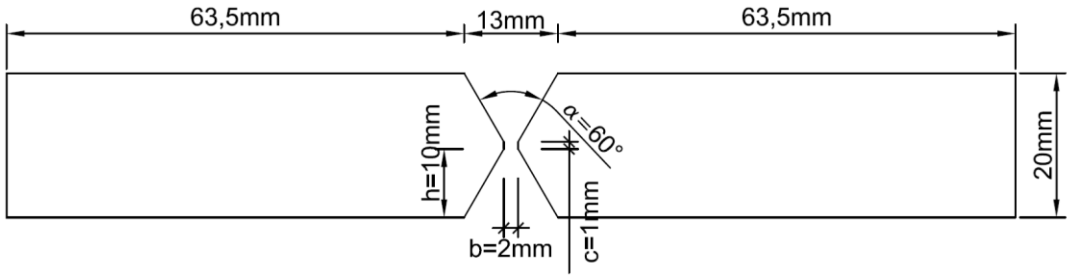


Fig 2-3 X-joint (or “double-vee”) edge preparation.

At first, the case without misalignment is considered in calculations. Following that, a linear misalignment of up to 2mm (10% of the plate thickness) is applied and the results of the structural hot spot and effective notch stresses are recorded in every step increase of 0.5mm. In order to compare the results to other sources, different boundary conditions have to be considered. Additionally, the applied tensile load is expected to change the sign of bending moments depending on the direction of misalignment. Because of this reason, in some cases the direction of the misalignment is applied in both positive and negative directions. In Fig 2-4, the different boundary conditions, the applied tensile load vector and direction of misalignments can be seen.

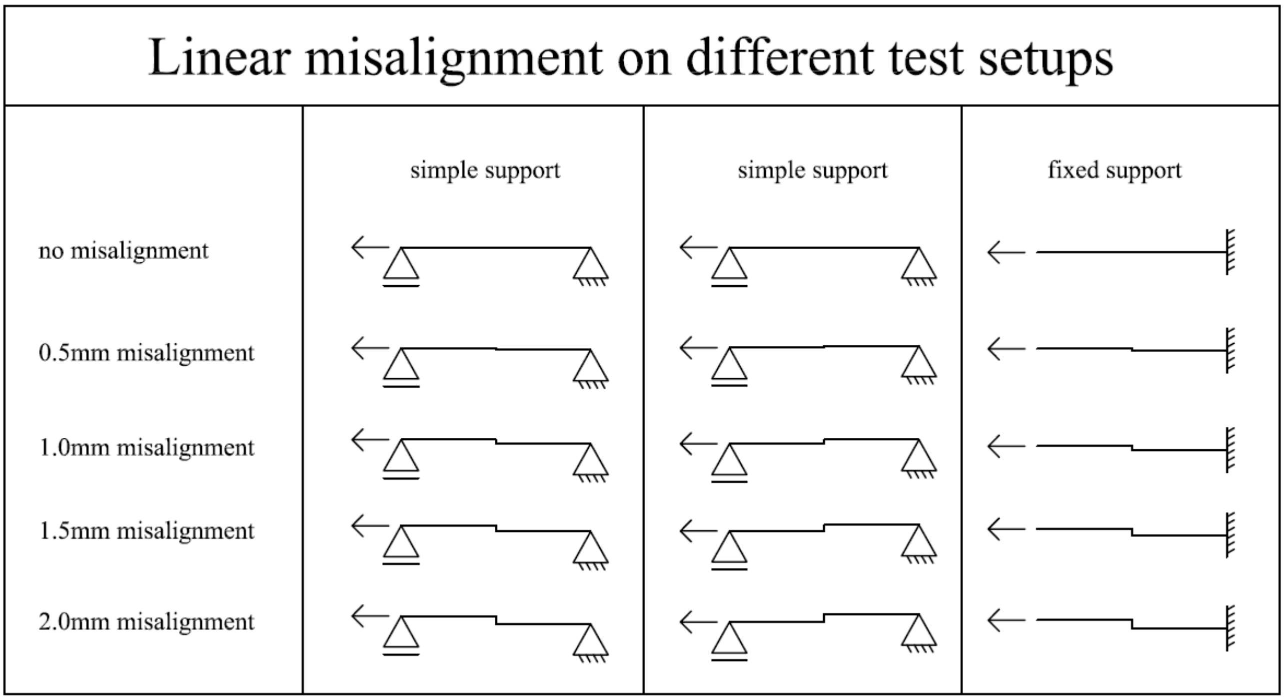


Fig 2-4 Considered linear misalignments and static systems.

2.2. Weld Shapes and Imperfections

In this chapter, a fully penetrated butt weld is considered. Furthermore, the mechanical properties of the weld metal, fusion zone and the heat affected zone are assumed to be equal to the parent metal. Hence, the weld and parent metal are modelled as a single part.

In weld manufacturing, allowance for some imperfections in the weld geometry must necessarily be made. Limitations such as the requirement for a smooth transition at the edges, or the heights of excess weld penetration and weld metal are given in EN ISO 5817:2007. In this standard, three different "quality classes" for weld imperfections and tolerances are given: class D, C and B, with B representing the highest quality.

In EN 1090-2:2008 [6], the fabrication standard for structural steel components used in combination with the Eurocodes' for the design, fabrication and erection of steel structures, the quality level "B" complies with "Execution class 3" (EXC3). For fatigue design of structures or parts, quality level "B" is the most common choice [3]. Consequently, quality B is selected as the main considered quality level for calculations. Nevertheless, another class - called quality level "B-Fatigue" in this thesis -, which has higher quality standards than "quality level B" to comply with fatigue-specific requirements of e.g. the Eurocode (EN 1993-1-9), is also checked during the fatigue verification (see for example Fig 2-12, blue rectangle for EC3 FAT class 90). The considered imperfection limitations for quality class "B" are depicted in Fig 2-5 and Fig 2-6.

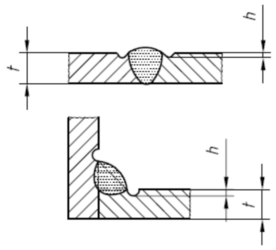
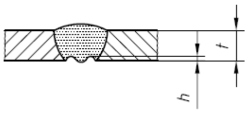
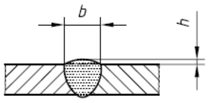
No.	Reference to ISO 6520-1:1998	Imperfection designation	Remarks	t mm	Limits for imperfections for quality levels D	C	B
1.7	5011 5012	Continuous undercut Intermittent undercut	Smooth transition is required. This is not regarded as a systematic imperfection. 	0,5 to 3	Short imperfections: $h \leqslant 0{,}2\ t$	Short imperfections: $h \leqslant 0{,}1\ t$	Not permitted
				> 3	$h \leqslant 0{,}2\ t$, but max. 1 mm	$h \leqslant 0{,}1\ t$, but max. 0,5 mm	$h \leqslant 0{,}05\ t$, but max. 0,5 mm
1.8	5013	Shrinkage groove	Smooth transition is required. 	0,5 to 3	$h \leqslant 0{,}2\ \text{mm} + 0{,}1\ t$	Short imperfections: $h \leqslant 0{,}1\ t$	Not permitted
				> 3	Short imperfections: $h \leqslant 0{,}2\ t$, but max. 2 mm	Short imperfections: $h \leqslant 0{,}1\ t$, but max.1 mm	Short imperfections: $h \leqslant 0{,}05\ t$, but max. 0,5 mm
1.9	502	Excess weld metal (butt weld)	Smooth transition is required. 	⩾ 0,5	$h \leqslant 1\ \text{mm} + 0{,}25\ b$, but max. 10 mm	$h \leqslant 1\ \text{mm} + 0{,}15\ b$, but max. 7 mm	$h \leqslant 1\ \text{mm} + 0{,}1\ b$, but max. 5 mm

Fig 2-5 Selected excess weld metal limitation (BS EN ISO 5817:2007, Table 1).

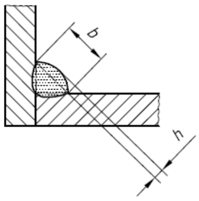
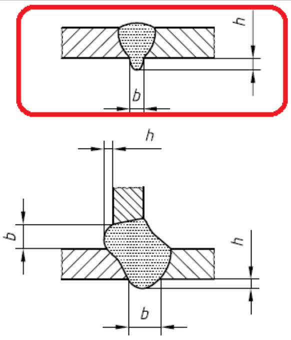
No.	Reference to ISO 6520-1:1998	Imperfection designation	Remarks	t mm	Limits for imperfections for quality levels D	C	B
1.10	503	Excessive convexity (fillet weld)		⩾ 0,5	$h \leqslant 1\ \text{mm} + 0{,}25\ b$, but max. 5 mm	$h \leqslant 1\ \text{mm} + 0{,}15\ b$, but max. 4 mm	$h \leqslant 1\ \text{mm} + 0{,}1\ b$, but max. 3 mm
1.11	504	Excess penetration		0,5 to 3	$h \leqslant 1\ \text{mm} + 0{,}6\ b$	$h \leqslant 1\ \text{mm} + 0{,}3\ b$	$h \leqslant 1\ \text{mm} + 0{,}1\ b$
				> 3	$h \leqslant 1\ \text{mm} + 1{,}0\ b$, but max. 5 mm	$h \leqslant 1\ \text{mm} + 0{,}6\ b$, but max. 4 mm	$h \leqslant 1\ \text{mm} + 0{,}2\ b$, but max. 3 mm

Fig 2-6 Selected excess weld penetration limitation (BS EN ISO 5817:2007, Table 1).

The maximum values of the weld shape imperfection limitations are selected and applied to the FEM model. The final weld shape dimensions including imperfections are shown in Fig 2-7, Fig 2-8, Fig 2-10 and Fig 2-9. During modelling -for the case of misaligned plates- some toe locations were almost vanished due to the misaligned geometry for upper values of misalignment, near the tolerance limits. A stress assessment was not always possible in these cases. An example can be seen in Fig 2-11 where the toe 4 is not visible anymore.

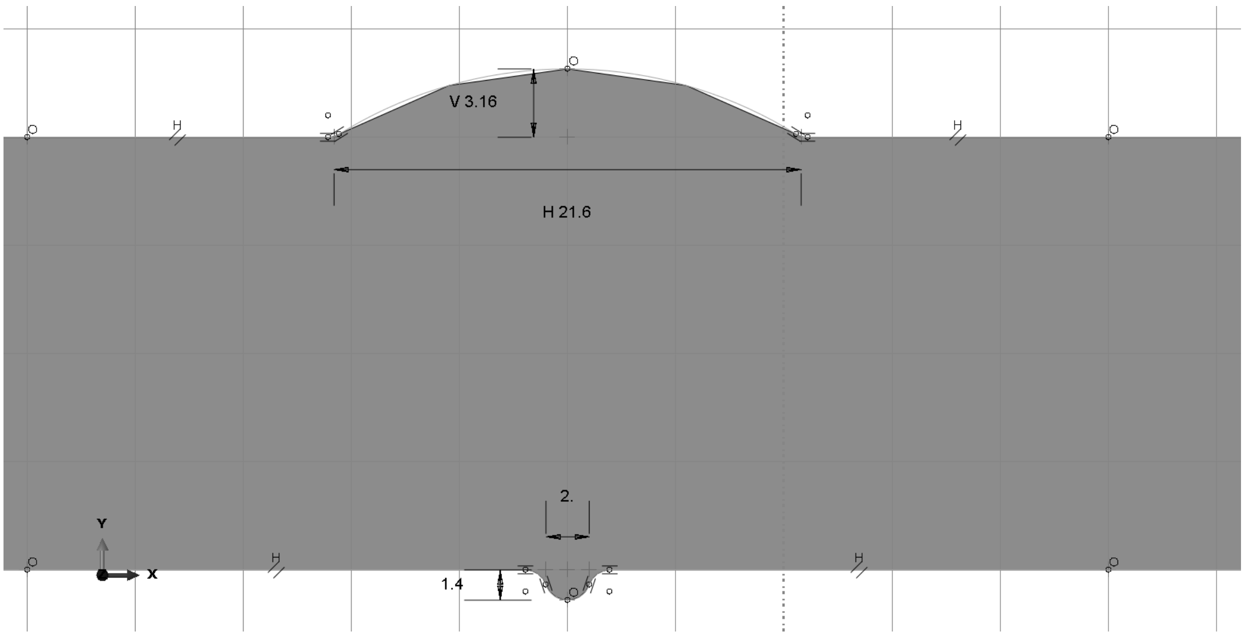


Fig 2-7 Quality level "B" single-vee joint. Weld imperfections in the Abaqus model. (all measures are in millimeters)

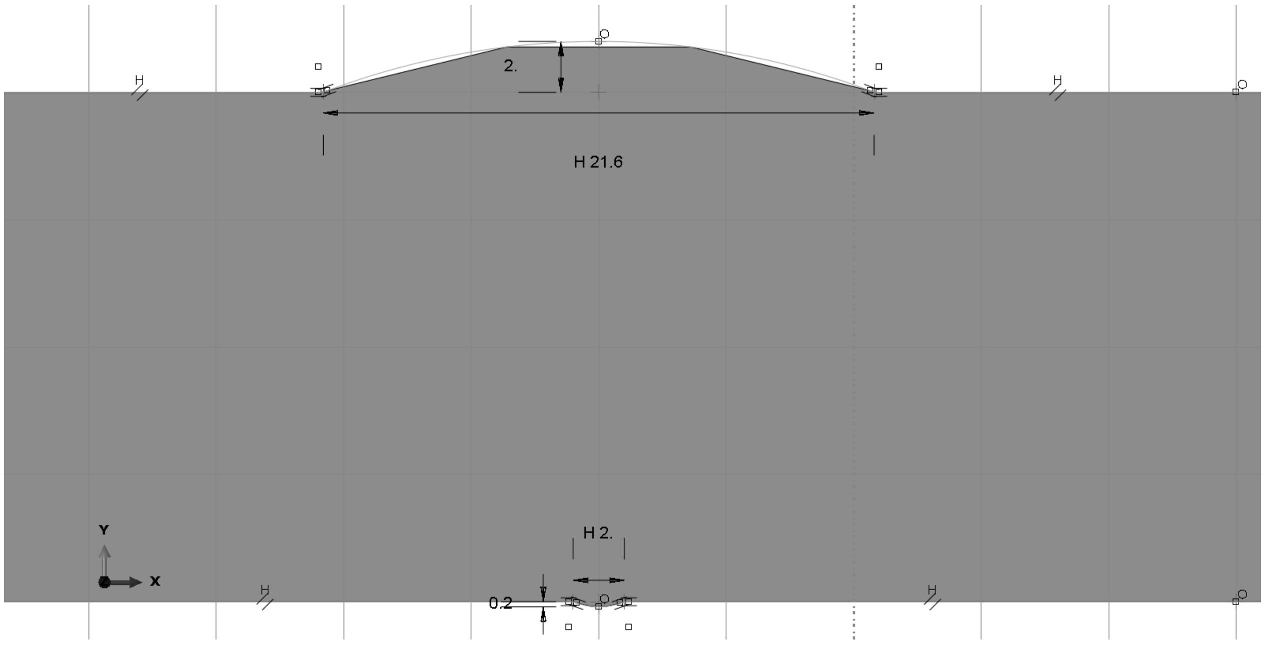


Fig 2-8 Quality level "B-Fatigue" single-vee joint. Weld imperfections in the Abaqus model. (all measures are in millimeters)

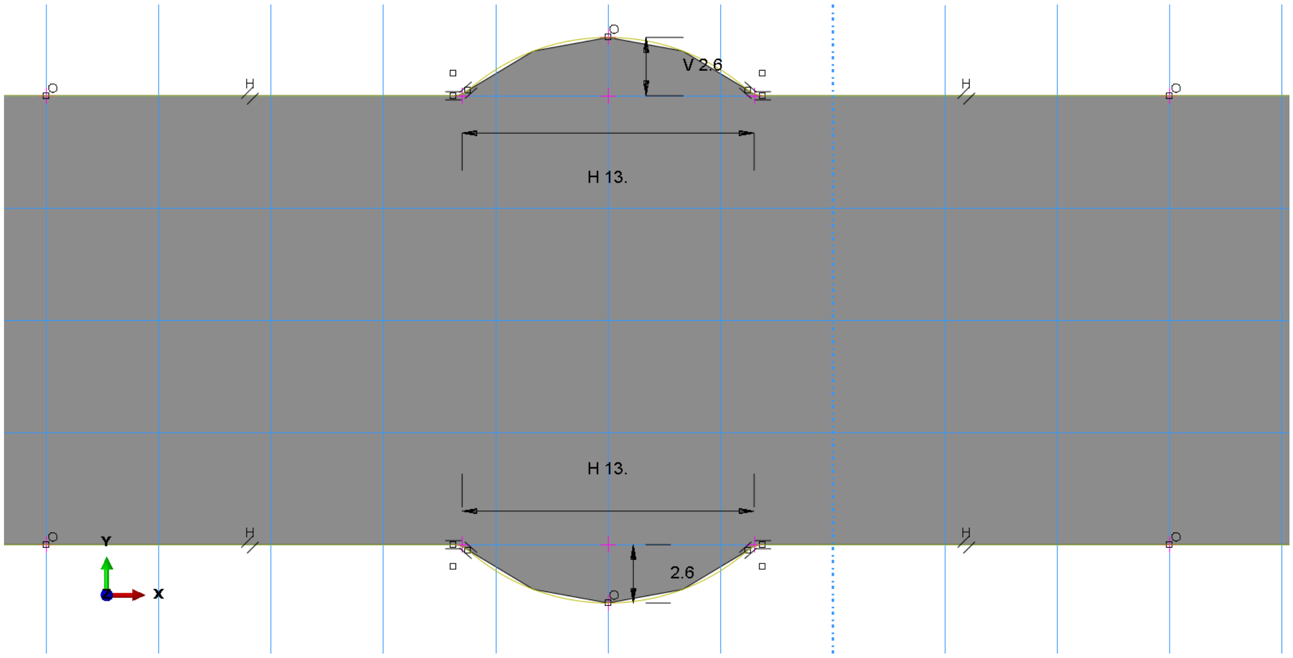


Fig 2-9 Quality level “B” double-vee joint. Weld imperfections in the Abaqus model. (all measures are in millimeters)

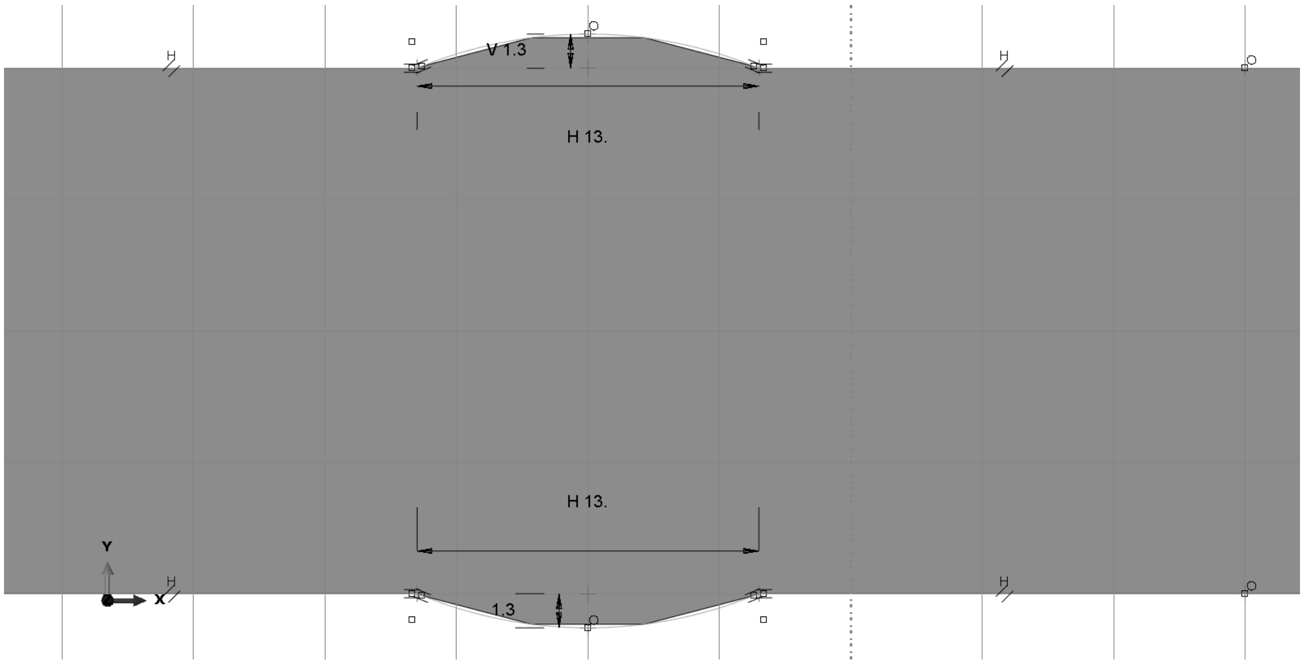


Fig 2-10 Quality level “B-Fatigue” double-vee joint. Weld imperfections in the Abaqus model. (all measures are in millimeters)

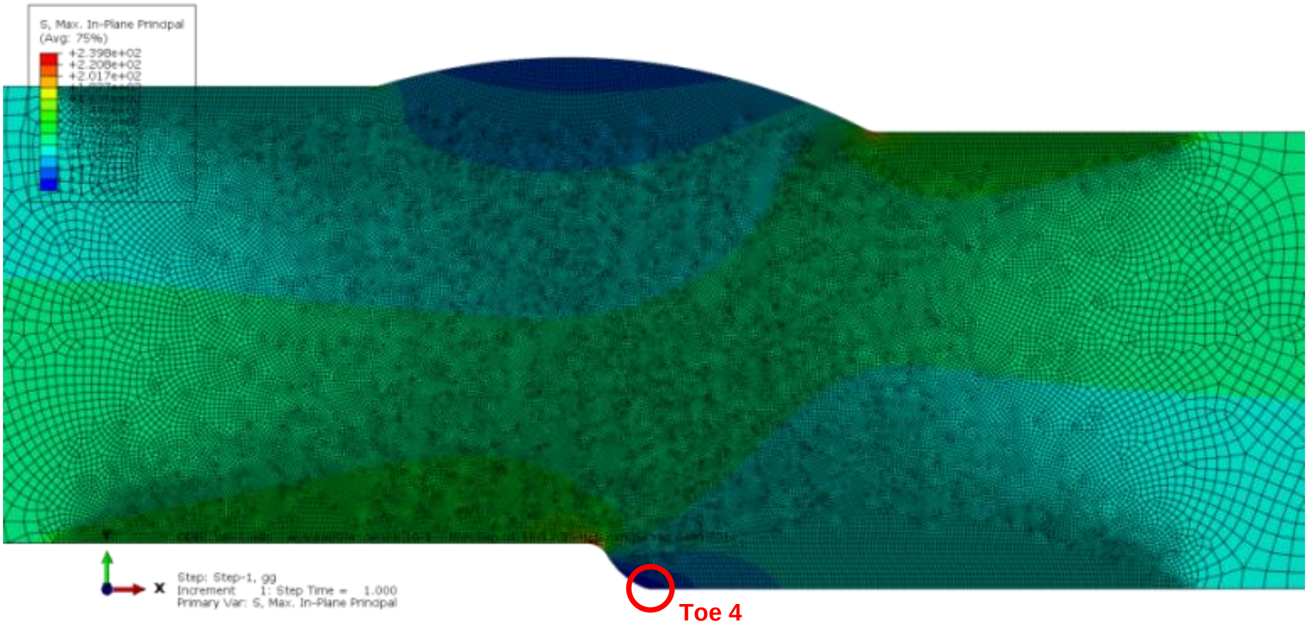


Fig 2-11 Representation of the geometry, mesh and maximum in-plane principal stress results of a single-vee joint with misalignment e=2.0mm. Toe 4 (at the root, on the bottom right side of the weld) vanishes due to the misaligned geometry.

2.3. Applicable Fatigue Classes

The following tables and figures, taken from either Eurocode 3 (part 1-9) or the IIW recommendation, show the applicable FAT classes considered for the details studied in this chapter.

2.3.1. Nominal Stress Approach

Both IIW Recommendations and EN 1993-1-9 show that the (nominal stress method) fatigue strength of transverse butt welded joints is also dependent upon the height of weld reinforcement. As can be seen in Fig 2-12, fatigue class 90 (FAT90) can be selected where the weld convexity is smaller than 10% of the weld thickness. In case of a weld convexity which is smaller than 20% of the weld thickness, a reduced strength, FAT80, is suggested (see Fig 2-13).

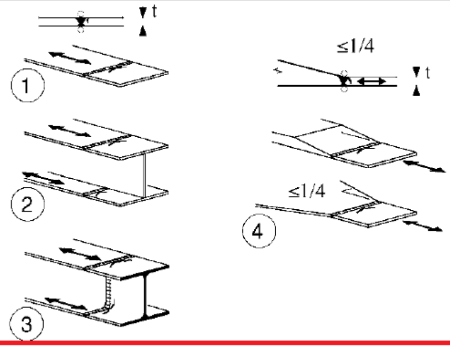
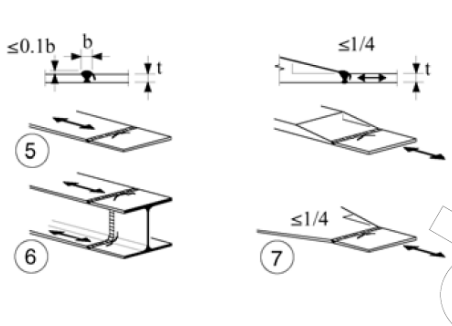
Detail category	Constructional detail		Description	Requirements
112	size effect for t>25mm: $k_s=(25/t)^{0,2}$		Without backing bar: 1) Transverse splices in plates and flats. 2) Flange and web splices in plate girders before assembly. 3) Full cross-section butt welds of rolled sections without cope holes. 4) Transverse splices in plates or flats tapered in width or in thickness, with a slope ≤ ¼.	- All welds ground flush to plate surface parallel to direction of the arrow. - Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress. - Welded from both sides; checked by NDT. Detail 3): Applies only to joints of rolled sections, cut and rewelded.
90	size effect for t>25mm: $k_s=(25/t)^{0,2}$		5) Transverse splices in plates or flats. 6) Full cross-section butt welds of rolled sections without cope holes. 7) Transverse splices in plates or flats tapered in width or in thickness with a slope ≤ ¼. Translation of welds to be machined notch free.	- The height of the weld convexity to be not greater than 10% of the weld width, with smooth transition to the plate surface. - Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress. - Welded from both sides; checked by NDT. Details 5 and 7: Welds made in flat position.

Fig 2-12 Selected detail category for transverse butt welds (EN 1993-1-9:2005 Table 8.3). Detail category to be used in assessments based on nominal stress approach. Quality level "B-Fatigue" due to additional geometric requirements, highlighted in small blue box.

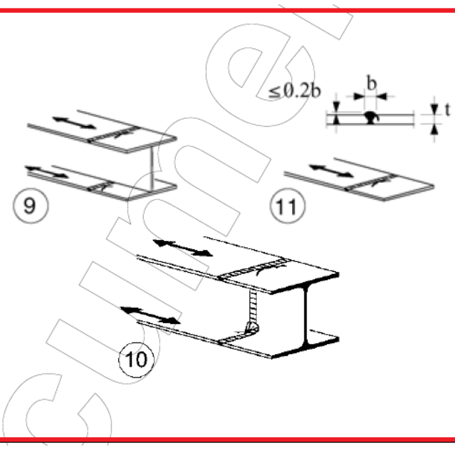
80	size effect for t>25mm: $k_s=(25/t)^{0,2}$		9) Transverse splices in welded plate girders without cope hole. 10) Full cross-section butt welds of rolled sections with cope holes. 11) Transverse splices in plates, flats, rolled sections or plate girders.	- The height of the weld convexity to be not greater than 20% of the weld width, with smooth transition to the plate surface. - Weld not ground flush - Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress. - Welded from both sides; checked by NDT. Detail 10: The height of the weld convexity to be not greater than 10% of the weld width, with smooth transition to the plate surface.

Fig 2-13 Selected detail category for transverse butt welds (EN 1993-1-9:2005 Table 8.3). Detail category to be used in assessments based on nominal stress approach. "Quality level B".

No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
200	Butt welds, transverse loaded				
211		Transverse loaded butt weld (X-groove or V-groove) ground flush to plate, 100% NDT	112	45	All welds ground flush to surface, grinding parallel to direction of stress. Weld run-on and run-off pieces to be used and subsequently removed. Plate edges ground flush in direction of stress. Welded from both sides. Misalignment < 5% of plate thickness. Proved free from significant defects by appropriate NDT
212		Transverse butt weld made in shop in flat position, NDT weld reinforcement < 0.1 · thickness	90	36	Weld run-on and run-off pieces to be used and subsequently removed. Plate edges ground flush in direction of stress. Welded from both sides. Misalignment <5% of plate thickness.
213		Transverse butt weld not satisfying conditions of 212, NDT Al.: Butt weld with toe angle ≤50° Butt welds with toe angle >50°	80	 32 25	Weld run-on and run-off pieces to be used and subsequently removed. Plate edges ground flush in direction of stress. Welded from both sides. Misalignment <10% of plate thickness.

Fig 2-14 Selected detail category for transverse butt welds (IIW Fatigue Recommendations, 2014). Detail category to be used in assessments based on nominal stress approach.

On the other hand, the IIW Recommendation relates this strength reduction to the thickness of the plate. In Fig 2-14, two different fatigue classes due to different weld reinforcements are shown. Where the convexity is smaller than 10% of the plate thickness, FAT90 is applicable. For cases when the conditions of No. 212 are not satisfied, FAT80 is suggested.

2.3.2. Structural Hot Spot Stress Approach

Unlike in the nominal stress method, fatigue class recommendations for this method do not give any information about the effects of weld reinforcement on fatigue strength. The fatigue class for all transverse butt welded joints according to both IIW Recommendations and EN 1993-1-9 are suggested to be taken as FAT100 (see Fig 2-15 and Fig 2-16).

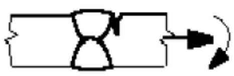
No.	Structural detail	Description	Requirements	FAT Steel	FAT Alu.
1		Butt joint	As welded, NDT	100	40

Fig 2-15 Selected detail category for transverse butt welds (IIW Fatigue Recommendations, 2014). Detail category to be used in assessments based on structural hot spot stress approach.

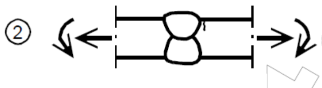
100		2) Full penetration butt joint.	2) - Weld not ground flush - Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress. - Welded from both sides. - For misalignment see NOTE 1.

Fig 2-16 Selected detail category for transverse butt welds (EN 1993-1-9:2005 Table B.1). Detail category to be used in assessments based on structural hot spot stress approach. “NOTE 1” in the standard additionally indicates that misalignment should explicitly be included in the calculations.

2.3.3. Effective Notch Stress Approach

The IIW Recommendation suggests a fatigue class of 225 (FAT225) for all transverse butt welded joints where a notch stress approach is used (see Fig 2-17). The Eurocode 3 does not mention the effective notch stress method.

No.	Quality of weld notch	Description	FAT
1	Effective notch radius equal to **1 mm** replacing weld toe and weld root notch	Notch as-welded, normal welding quality m=3	225

Fig 2-17 The only detail category (FAT225) for transverse butt welds based on effective notch stress approach (IIW Fatigue Recommendations, 2014).

2.4. Comparison of Nominal, Structural Hot Spot and Effective Notch Stress Methods – No Misalignment

By using the methods described in Chapter 1.3, stresses are calculated at four different weld toes, namely toe 1, toe 2, toe 3 and toe 4, which are marked in Fig 2-18.

As mentioned before, to compare the fatigue life cycles of different methods, a tensile load which creates $2x10^6$ life cycle based on the nominal stress method is selected. The load is applied to the free end of simple support in the Abaqus model.

As can be seen in Fig 2-19 and Fig 2-20 the static system (fixed or simple support) has (almost) no influence on the results for the case without misalignment (the small differences stem from different meshing in the models).

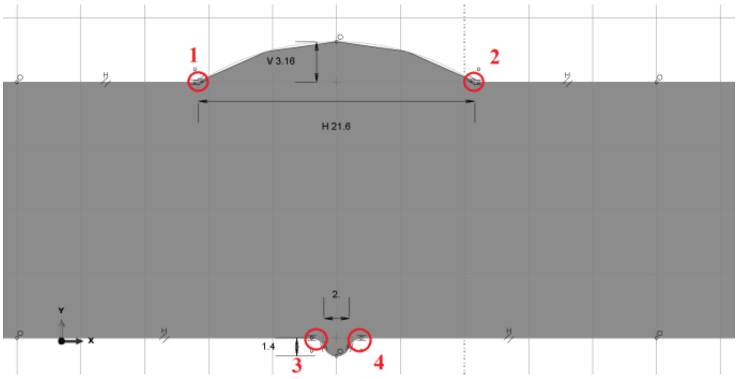
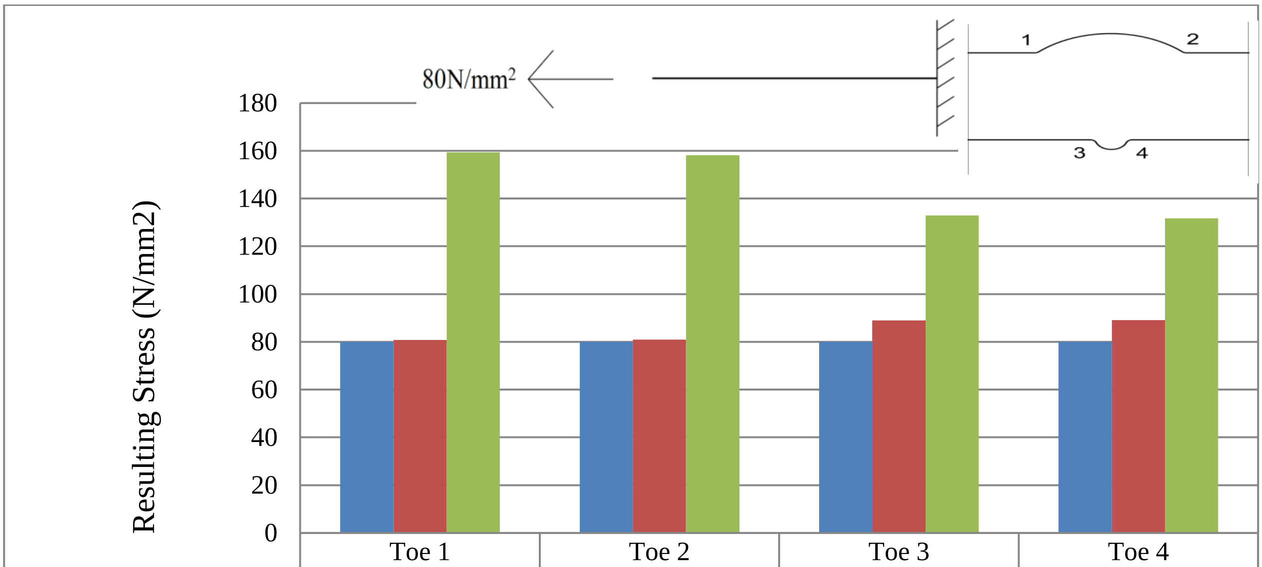
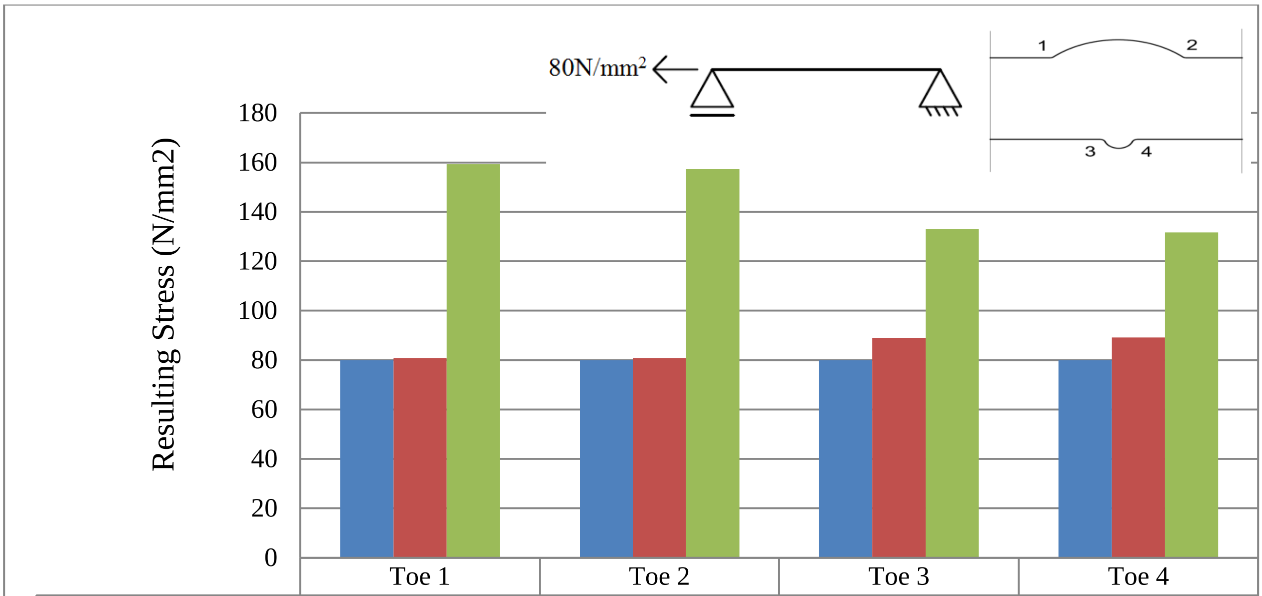


Fig 2-18 The locations of toe 1, toe 2, toe 3 and toe 4



	Toe 1	Toe 2	Toe 3	Toe 4
Nominal stress	80.000	80.000	80.000	80.000
Hot spot stress	80.763	80.869	88.981	89.113
Effective notch stress	159.275	158.048	132.961	131.730

Fig 2-19 Comparison of nominal, structural hot spot and effective notch stresses. Resultant maximum in-plane principal tensile stresses for transverse butt welded joint with no misalignment. Fixed supported, quality level "B" single-vee joint.

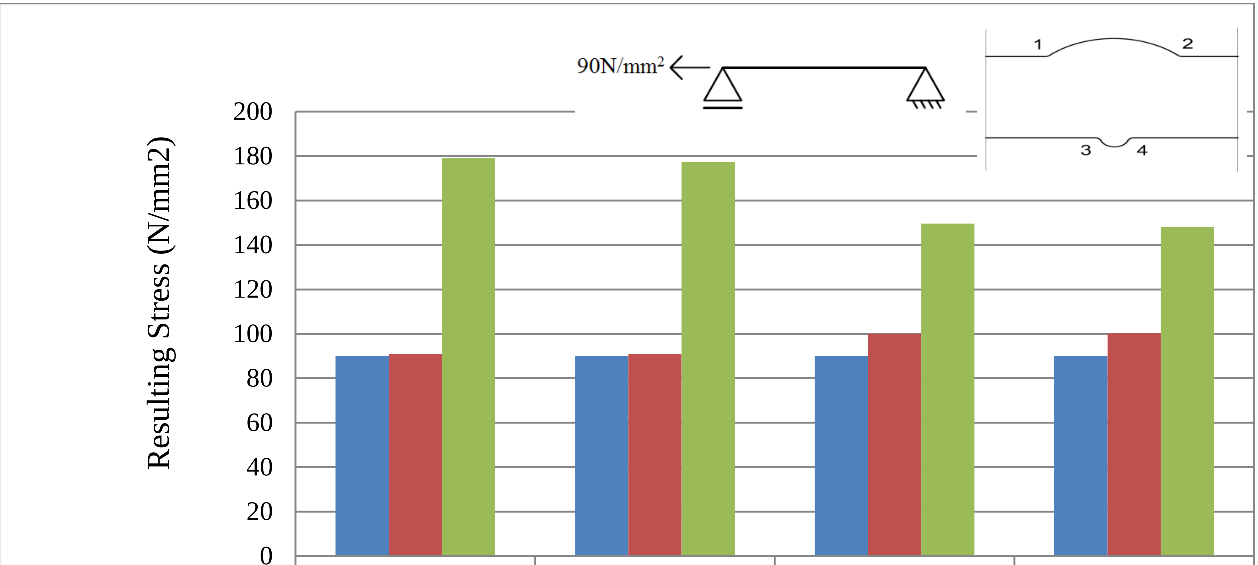


	Toe 1	Toe 2	Toe 3	Toe 4
Nominal stress	80.000	80.000	80.000	80.000
Hot spot stress	80.808	80.818	88.980	89.113
Effective notch stress	159.275	157.559	132.960	131.730

Fig 2-20 Comparison of nominal, structural hot spot and effective notch stresses. Resultant maximum in-plane principal tensile stresses for transverse butt welded joint with no misalignment. Simply supported, quality level “B” single-vee joint.

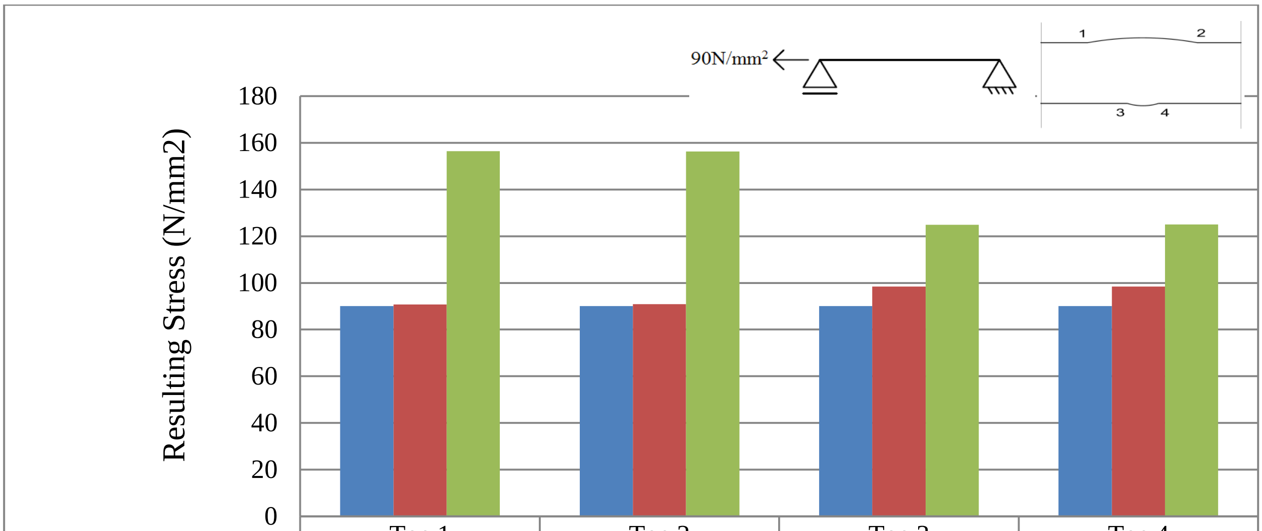
The drop of the local notch stress raising effect between joints with different weld “reinforcements” (i.e. the weld convexity, and thus the different geometric quality levels) can be observed in Fig 2-21 and Fig 2-22. In Fig 2-21, the same results of Fig 2-20 are used, but scaled to a reference load of 90 N/mm^2, for better direct comparability of the results for the different quality levels (“B” or “B-fatigue”). As can be seen in the comparison of the two figures, the effective notch stress at toe 1 with quality level “B” (Fig 2-21) is equal to 179.184N/mm^2. On the other hand, the effective notch stress at the same location and for the same external loading of 90N/mm^2 with quality level “B-Fatigue” is 155.762N/mm^2 (Fig 2-22). A very similar observation can be made for X-joints, see the comparison of Fig 2-24 and Fig 2-25. The structural stress values have almost the same value for all cases, which indicates that the method is very weld-geometry dependent.

When the same quality X-joints and Y-joints are compared to each other based on the effective notch stress (see Fig 2-20 vs. Fig 2-23 and Fig 2-22vs. Fig 2-25), it shows that the resulting stress at X-joints are better distributed to each weld toe. The stress at two weld toes (toe 3 and toe 4) of Y-joint are significantly lower, however the maximum stresses, which occur at toes 1 and 2, are only minimally lower in Y-joints than in X-joints. This indicates that – for the case without misalignment – no differences in fatigue life between Y- and X-joints of equal quality are to be expected.



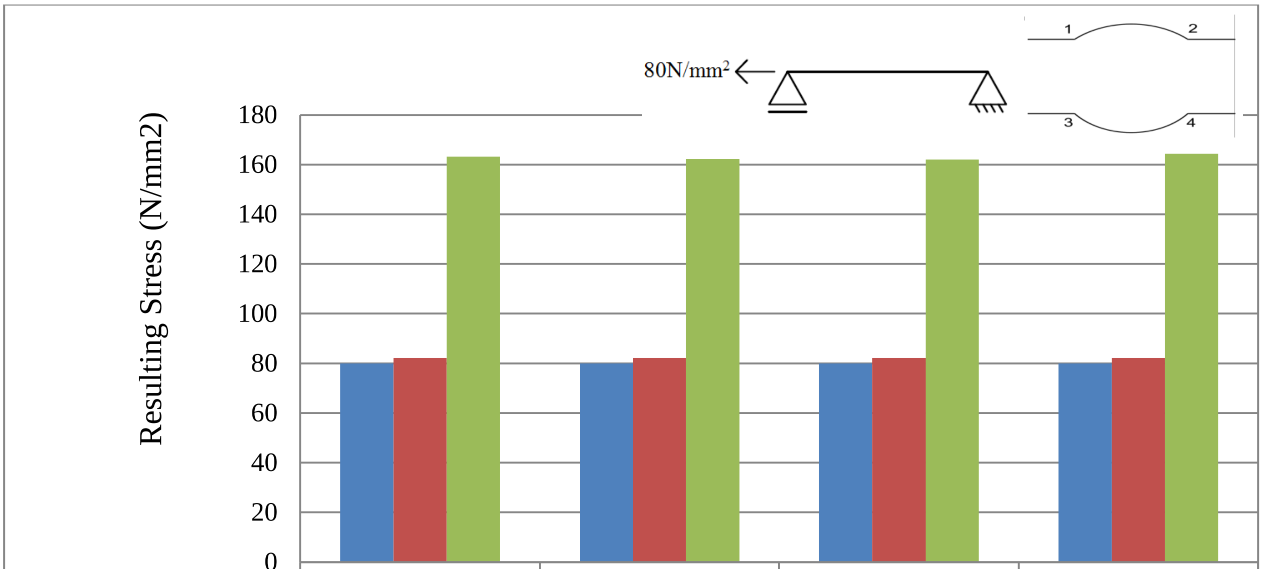
	Toe 1	Toe 2	Toe 3	Toe 4
Nominal stress	90.000	90.000	90.000	90.000
Hot spot stress	90.909	90.920	100.102	100.252
Effective notch stress	179.184	177.254	149.580	148.196

Fig 2-21 Comparison of nominal, structural hot spot and effective notch stresses. Resultant maximum in-plane principal tensile stresses for transverse butt welded joint with no misalignment. Simply supported quality level "B" single-vee joint, calculated here for a reference load of 90 N/mm² for better comparison with Fig 2-22



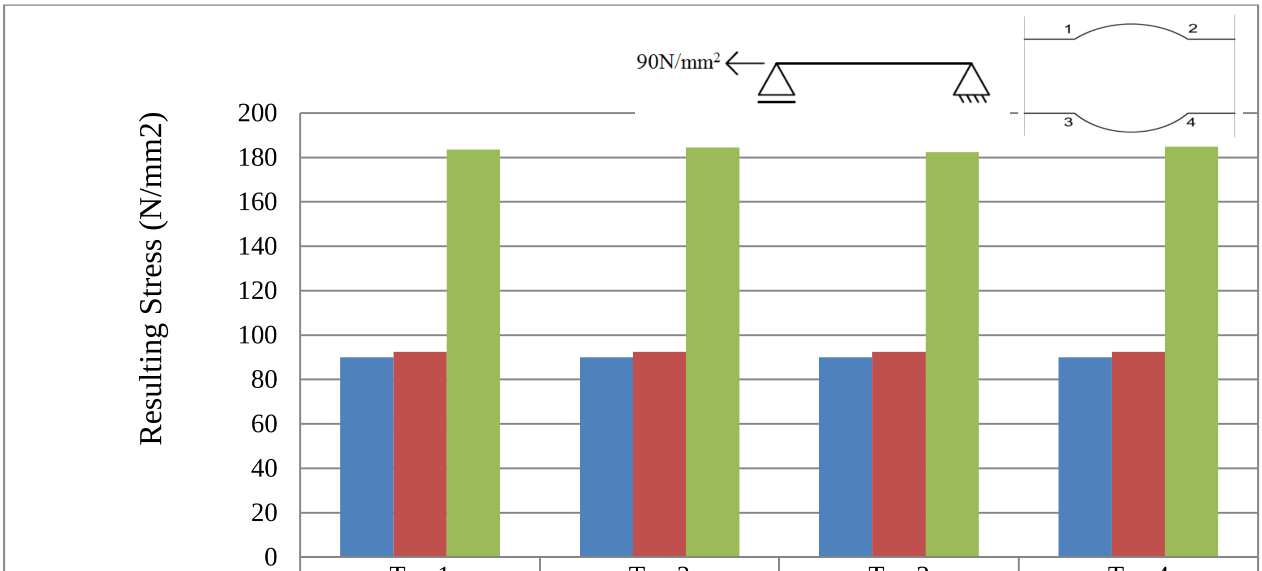
	Toe 1	Toe 2	Toe 3	Toe 4
Nominal stress	90.000	90.000	90.000	90.000
Hot spot stress	90.787	90.849	98.410	98.410
Effective notch stress	156.400	156.320	124.925	125.013

Fig 2-22 Comparison of nominal, structural hot spot and effective notch stresses. Resultant maximum in-plane principal tensile stresses for transverse butt welded joint with no misalignment. Simply supported quality level "B-Fatigue" single-vee joint.



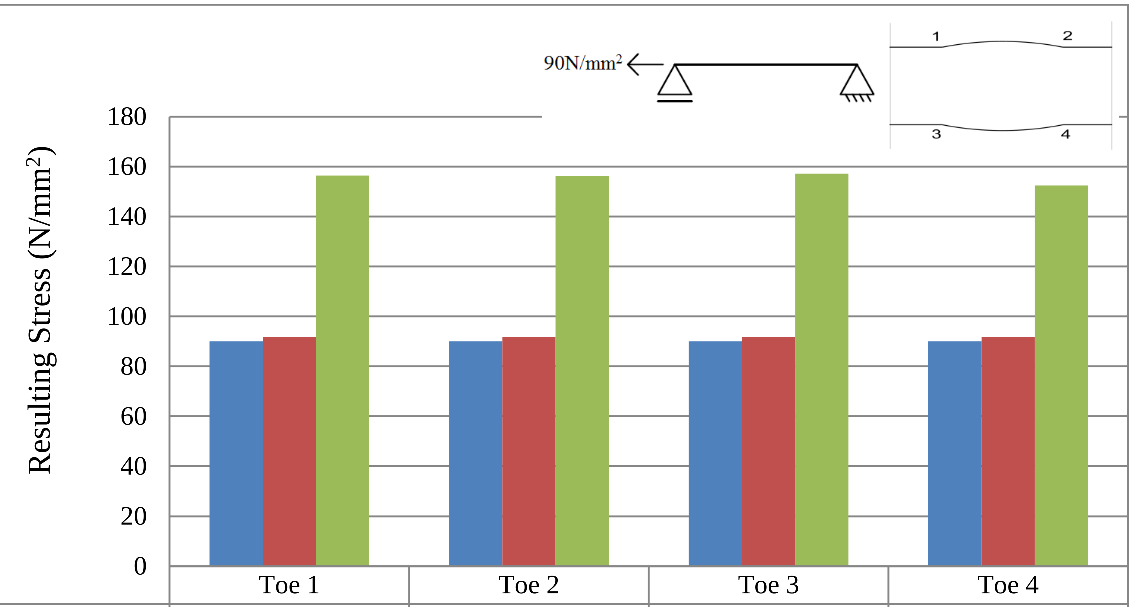
	Toe 1	Toe 2	Toe 3	Toe 4
Nominal stress	80.000	80.000	80.000	80.000
Hot spot stress	82.122	82.183	82.183	82.122
Effective notch stress	163.148	164.453	162.064	164.300

Fig 2-23 Comparison of nominal, structural hot spot and effective notch stresses. Resultant maximum in-plane principal tensile stresses for transverse butt welded joint with no misalignment. Simply supported quality level “B” double-vee joint.



	Toe 1	Toe 2	Toe 3	Toe 4
Nominal stress	90.000	90.000	90.000	90.000
Hot spot stress	92.387	92.456	92.456	92.387
Effective notch stress	183.541	185.010	182.322	184.838

Fig 2-24 Comparison of nominal, structural hot spot and effective notch stresses. Resultant maximum in-plane principal tensile stresses for transverse butt welded joint with no misalignment. Simply supported quality level “B” double-vee joint, calculated here for a reference load of 90 N/mm² for better comparison with Fig 2-25.



	Toe 1	Toe 2	Toe 3	Toe 4
Nominal stress	90.000	90.000	90.000	90.000
Hot spot stress	91.718	91.803	91.803	91.718
Effective notch stress	156.344	156.133	157.159	152.414

Fig 2-25 Comparison of nominal, structural hot spot and effective notch stresses. Resultant maximum in-plane principal tensile stresses for transverse butt welded joint with no misalignment. Simply supported quality level “B-Fatigue” double-vee joint.

Fatigue Life Calculation – No misalignment case

The following **Table 2-A** shows a comparison of fatigue life predictions for the studied details and quality classes according to the different calculation methods: nominal stress, structural hot spot stress and effective stress approach. Thereby, as stated above, the nominal stress was always chosen so that a fatigue life of 2 million load cycles is achieved.

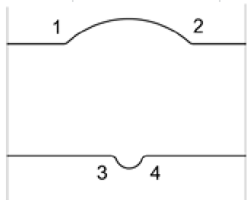
Note that in these calculations no misalignment is considered; this means that – at least for the cases of the effective notch stress and structural stress approach – the calculated fatigue life values are not (yet) valid, as for these methods misalignment must be taken into account directly; see the fatigue life calculations with misalignment case for this effect.

In all cases, the fatigue life is calculated using Eq. 1.2. The fatigue classes shown in section 2.3 are used: FAT 80 or 90 for the nominal stress case, FAT 100 for structural stresses, and FAT 225 for effective notch stresses. In all cases, the constant amplitude fatigue limit (CAFL) was assumed to be at $5*10^6$ load cycles and the slope of m=3 of the Eurocode 3 and IIW S-N curves was used.

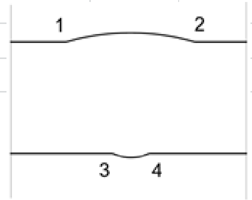
				Nominal	CALCULATED STRESSES [N/mm^2]											
				FAT-CLASS	Toe 1			Toe 2			Toe 3			Toe 4		
Welding	Joint type	Support Con.	Quality	≈Load(N/mm2)	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$
Transverse Butt	Y-Joint	Fixed	B	80	80.000	80.763	159.275	80.000	80.869	158.048	80.000	88.981	132.961	80.000	89.113	131.730
Transverse Butt	Y-Joint	Simple	B	80	80.000	80.808	159.275	80.000	80.818	157.559	80.000	88.980	132.960	80.000	89.113	131.730
Transverse Butt	Y-Joint	Simple	B-Fatigue	90	90.000	90.787	156.400	90.000	90.849	156.320	90.000	98.410	124.925	90.000	98.410	125.013
Transverse Butt	X-Joint	Simple	B	80	80.000	82.122	163.148	80.000	82.183	164.453	80.000	82.183	162.064	80.000	82.122	164.300
Transverse Butt	X-Joint	Simple	B-Fatigue	90	90.000	91.718	156.344	90.000	91.803	156.133	90.000	91.803	157.159	90.000	91.718	152.414

				Nominal	FATIGUE LIFE CYCLES											
				FAT-CLASS	Toe 1			Toe 2			Toe 3			Toe 4		
Welding	Joint type	Support Con.	Quality	≈Load(N/mm2)	nom.	hot spot	eff. not.	nom.	hot spot	eff. not.	nom.	hot spot	eff. not.	nom.	hot spot	eff. not.
Transverse Butt	Y-Joint	Fixed	B	80		3.80E+06			3.78E+06			2.84E+06			2.83E+06	
Transverse Butt	Y-Joint	Simple	B	80	2	3.79E+06	∞	2	3.79E+06	∞	2	2.84E+06	∞	2	2.83E+06	∞
Transverse Butt	Y-Joint	Simple	B-Fatigue	90	million	2.67E+06	(infinite	million	2.67E+06	(infinite	million	2.10E+06	(infinite	million	2.10E+06	(infinite
Transverse Butt	X-Joint	Simple	B	80	cycles	3.61E+06	cycles)	cycles	3.60E+06	cycles)	cycles	3.60E+06	cycles)	cycles	3.61E+06	cycles)
Transverse Butt	X-Joint	Simple	B-Fatigue	90		2.59E+06			2.58E+06			2.58E+06			2.59E+06	

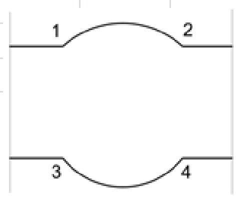
Quality	B	B-Fatigue
$CAFL_{nom}$	58.96 MPa	66.33 Mpa
$CAFL_{hs}$	73.70 MPa	73.70 MPa
$CAFL_{en}$	165.825 MPa	165.825 MPa



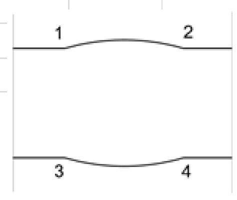
Y-Joint quality "B"



Y-Joint quality "B-Fatigue"



X-Joint quality "B"



X-Joint quality "B-Fatigue"

Tab 2-A Calculated stresses and fatigue life cycle calculations. No misalignment case.

The following observations can be made about the above results:

i. When misalignment is not explicitly included, the fatigue lives accordinging the structural hot-spot and effective notch stress methods are higher than the nominal stress fatigue life cycles; in the latter case, they are even "infinite" (because they are below the CAFL) in all cases.
ii. In the structural hot-spot stress case, this is due to the fact that the FAT class is higher than for the nominal stress case (FAT 100 vs. 80 or 90), while the stresses are (almost) the same for both methods.
iii. In the effective notch stress method, the assumption that the CAFL is at $5*10^6$ load cycles for the used FAT class 225 means that all stress amplitudes below 0.74*225=164 N/mm² lead to infinite life predictions

2.5. Effect of Misalignment

All butt-welded joints of plates of equal thickness will inevitably feature some degree of misalignment of the individual plate surfaces, which leads to an undesired eccentricity in the joints and thus to some additional bending, which in turn increases the stresses in the joints. Part of these effects will be included in the (nominal) FAT classes, as misalignment was also present in tests, but the degree to which this is the case is not quite made clear in the literature. While the Eurocode is not very explicit regarding the consideration of misalignment effects (it is stated that it must be explicitly considered, but not how), the IIW Recommendation contains a formula for the direct, analytical calculation of misalignment effects for transverse butt welded joints with equal plate thickness. This recommended $\mathbf{k_m}$ factor is used as a multiplier to the stresses calculated without any explicit consideration of misalignment and is calculated according to the following Eq.2.1 (IIW Recommendations:2014 Table 6.3-1):

$$k_m = 1 + \lambda * \frac{e * l_1}{t * (l_1 + l_2)} \tag{2.1}$$

where λ =6 for unrestrained joints and l is the length of each welded plate.

In the following, this formula will be compared with the equivalent results of the numerical stress calculations carried out in this thesis. The results of the latter are presented as follows for both the structural hot spot ("**hs**") and the effective notch ("**en**") approaches:

- For the different notches (toes of the weld), first the hot spot or effective notch stress is calculated for the case without misalignment (see section 2.4), leading to $\sigma_{hs,0}$ and $\sigma_{en,0}$, respectively.
- Then, the hot spot and effective notch stresses are calculated for different levels of misalignment in the numerical model, progressing step-wise from zero to the maximum

tolerance of 10% of the plate thickness in this case (valid for FAT class 80, i.e. weld quality level “B”, while 5% are permissible for FAT 90 / weld quality level “B-Fatigue”). This leads, for the individual cases, to the stresses σ_{hs} and σ_{en}.

- Finally, the ratio of $\sigma_{hs}/\sigma_{hs,0}$ respectively $\sigma_{en}/\sigma_{en,0}$ is calculated and compared with the k_m factor of the recommendation; effectively, these ratios represent the “real” values of k_m as retrieved from the numerical calculations.

2.5.1. Structural Hot Spot Stress Changes Due to Misalignment

The results are presented in form of graphs and tables; the cases are description in the corresponding captions.

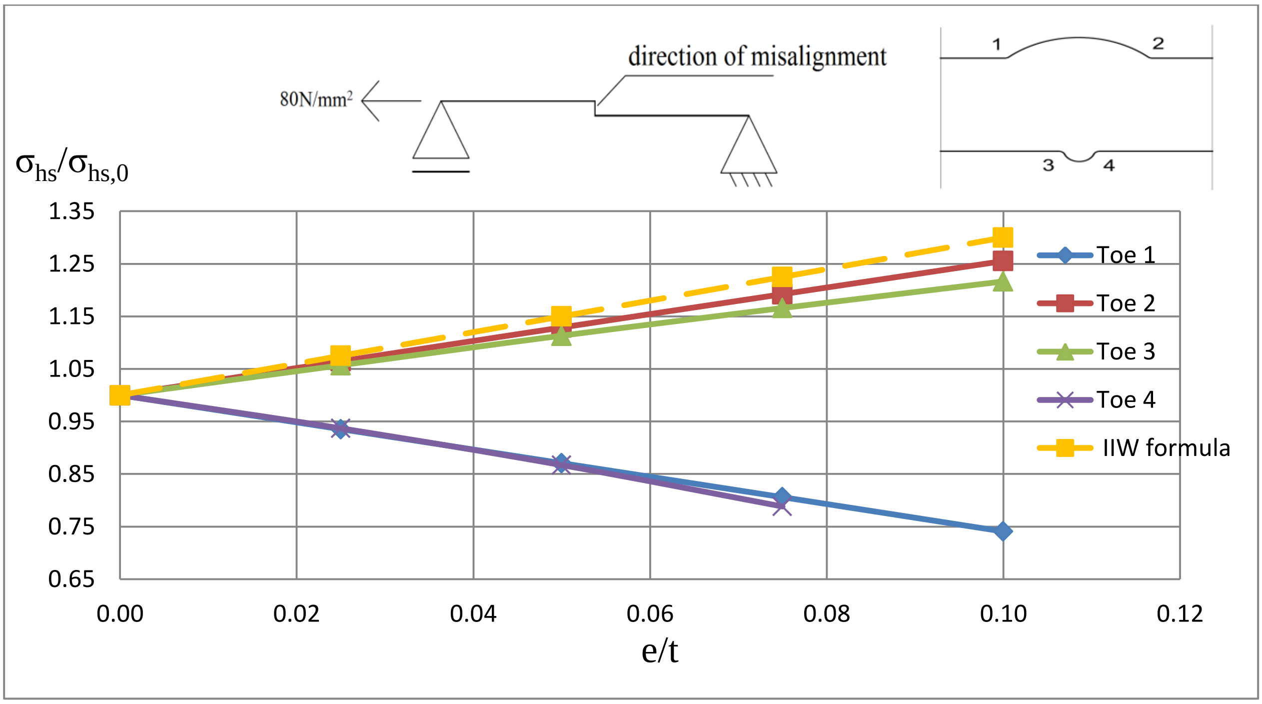


Fig 2-26 Effect of increasing misalignment (upwards) on structural stress. Stress magnification factor (k_m) according to [2] is also shown as “IIW formula”. Simply supported, quality level “B”, single-vee joint.

				Toe 1	Toe 2	Toe 3	Toe 4
				Hot spot stress ($\sigma_{hs,0}$ in N/mm^2)			
				80.808	80.818	88.980	89.113
P (N/mm^2)	e (mm)	t (mm)	e/t	Normalized stress ratio ($\sigma_{hs}/\sigma_{hs,0}$)			
80	0.0	20	0.000	1.000	1.000	1.000	1.000
80	0.5	20	0.025	0.935	1.065	1.057	0.937
80	1.0	20	0.050	0.871	1.129	1.113	0.867
80	1.5	20	0.075	0.806	1.192	1.166	0.788
80	2.0	20	0.100	0.741	1.255	1.216	-

Tab 2-1 Normalized structural stress results. Values are depicted in Fig 2-26.

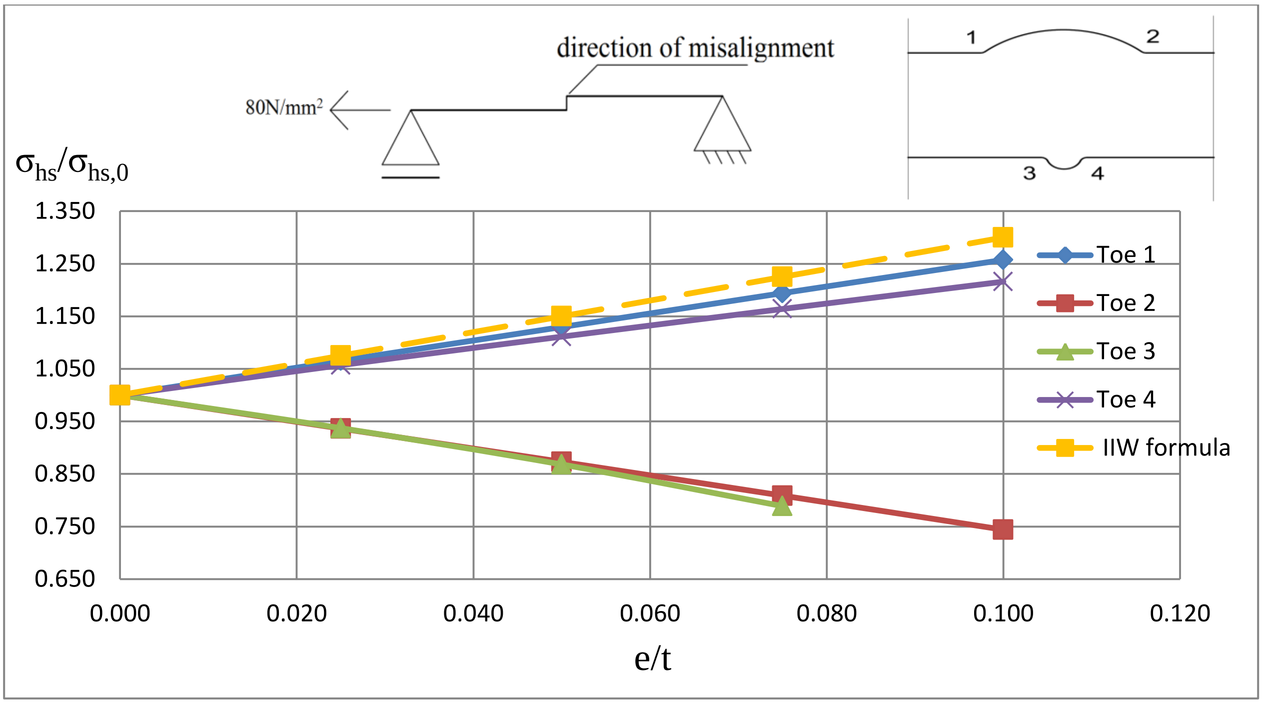


Fig 2-27 Effect of increasing misalignment (downwards) on structural stress. Stress magnification factor (k_m) according to [2] is also shown as "IIW formula". Simply supported quality level "B" single-vee joint.

				Toe 1	Toe 2	Toe 3	Toe 4
				Hot spot stress $\sigma_{hs,0}$ (N/mm^2)			
				80.759	80.817	88.980	89.113
P (N/mm^2)	e (mm)	t (mm)	e/t	Normalized stress ($\sigma_{hs}/\sigma_{hs,0}$) ratio			
80	0	20	0.000	1.000	1.000	1.000	1.000
80	0.5	20	0.025	1.065	0.936	0.937	1.057
80	1	20	0.050	1.130	0.873	0.868	1.111
80	1.5	20	0.075	1.194	0.809	0.789	1.164
80	2	20	0.100	1.257	0.744	-	1.216

Tab 2-2 Normalized structural stress results. Values are depicted in Fig 2-27.

Depending on the direction of misalignment, the critical weld toe has changed as expected. As can be seen in Fig 2-26, the critical weld toe is toe 2, while in Fig 2-27 the critical weld toe is toe 1. The reason for the slight change in normalized stress ratios between the two models (compare the value of 1.255 in Tab 2-1 with the value of 1.257 in Tab 2-2; they theoretically should be equal) is due to a slightly unsymmetrical automatic meshing. However, this small error is negligible. Secondly, the stress change curves are under the "IIW formula" curve, which means the given $\mathbf{k_m}$ formula in Eq.2.1 can be safely applied to practical calculations.

In Fig 2-28, the normalized structural stress results of quality level "B" single-vee joint with *fixed support condition* (one-sided encastre) is shown. It is interesting to note that, in this case, the recommended $\mathbf{k_m}$ formula leads to values that are only half as large as the normalized stress ratio at toe 2, which shows that the λ=6 value in Eq.2.1 should be replaced with λ=12 in fixed support conditions. Note that this difference due to boundary conditions is not clearly mentioned in the IIW recommendation.

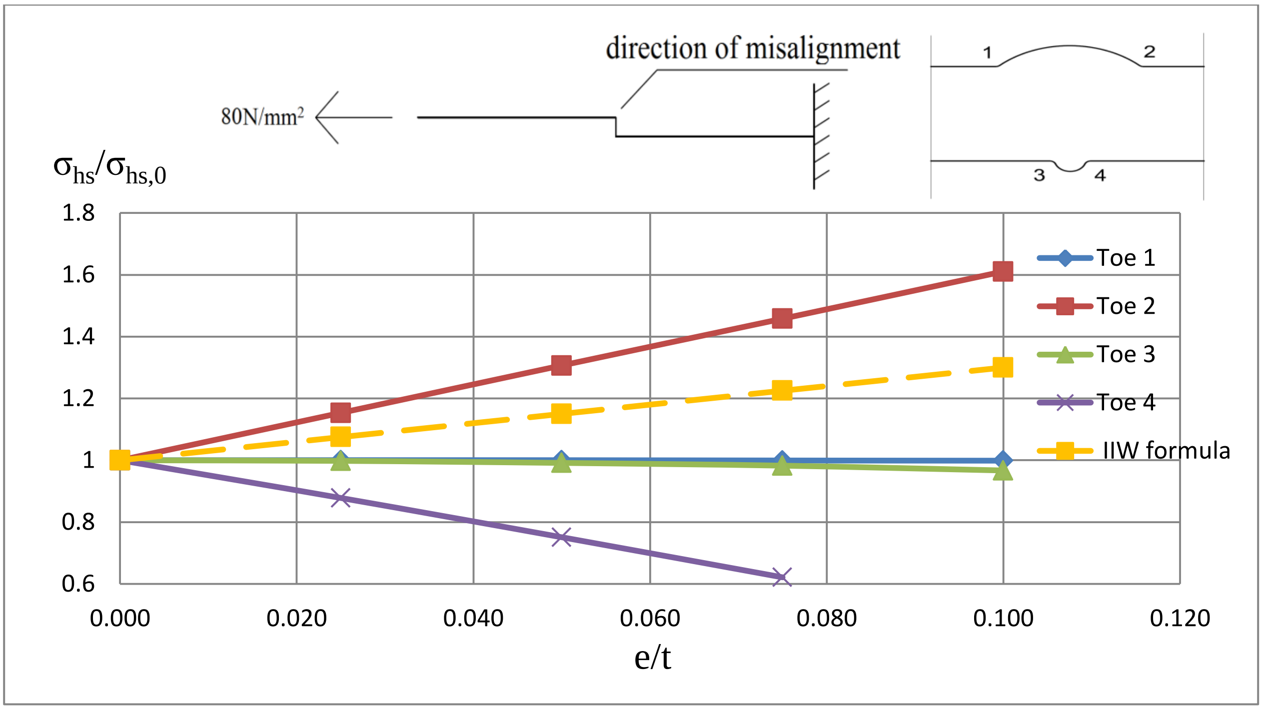


Fig 2-28 Effect of increasing misalignment (upwards) on structural stress. Stress magnification factor (k_m) according to [2] is also shown as "IIW formula". Fixed supported quality level "B" single-vee joint.

				Toe 1	Toe 2	Toe 3	Toe 4
				Hot spot stress $\sigma_{hs,0}$ (N/mm^2)			
				80.763	80.869	88.981	89.113
P (N/mm^2)	e (mm)	t (mm)	e/t	Normalized stress ratio ($\sigma_{hs}/\sigma_{hs,0}$)			
80	0	20	0.000	1	1	1	1
80	0.5	20	0.025	1.000313	1.153398	0.998076	0.877957
80	1	20	0.050	1.000258	1.306674	0.991491	0.751027
80	1.5	20	0.075	0.999344	1.45799	0.982598	0.621274
80	2	20	0.100	0.998673	1.610712	0.967015	-

Tab 2-3 Normalized structural stress results. Values are depicted in Fig 2-28.

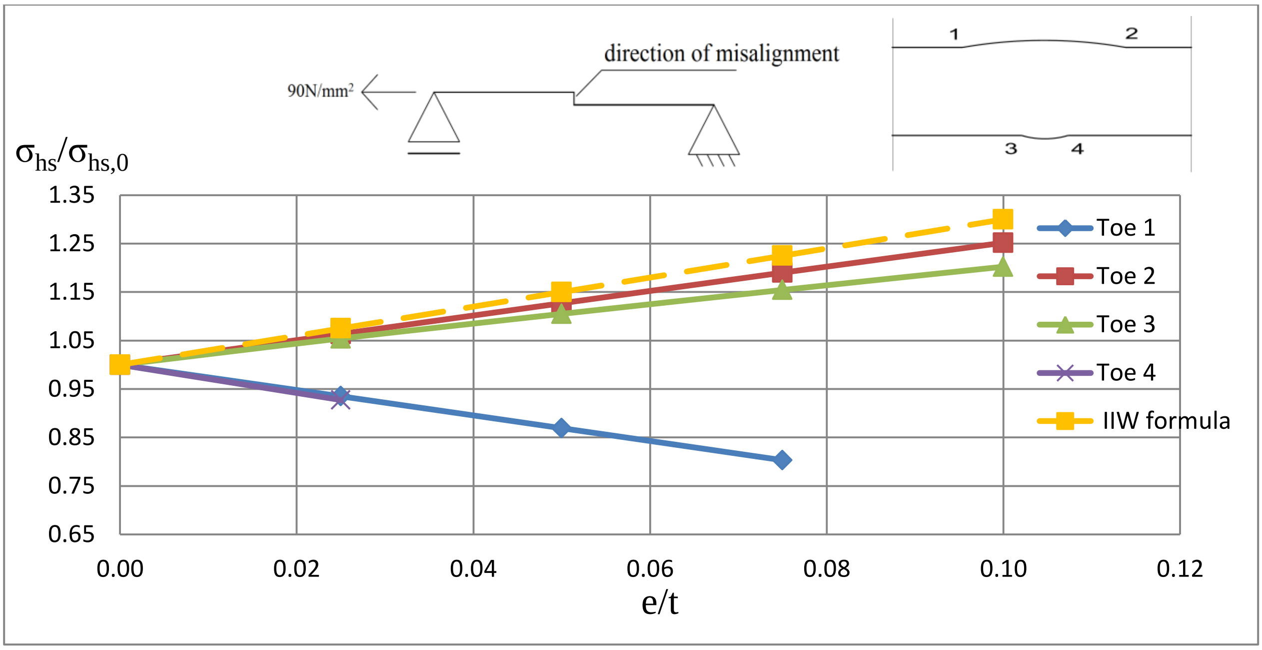


Fig 2-29 Effect of increasing misalignment (upwards) on structural stress. Stress magnification factor (k_m) according to [2] is also shown as "IIW formula". Simply supported quality level "B-Fatigue" single-vee joint.

				Toe 1	Toe 2	Toe 3	Toe 4
				Hot spot stress $\sigma_{hs,0}$ (N/mm^2)			
				90.787	90.849	98.410	98.410
P (N/mm^2)	e (mm)	t (mm)	e/t	Nominalized stress ratio ($\sigma_{hs}/\sigma_{hs,0}$)			
80	0.0	20	0.000	1.000	1.000	1.000	1.000
80	0.5	20	0.025	0.935	1.064	1.054	0.927
80	1.0	20	0.050	0.869	1.127	1.105	N.C
80	1.5	20	0.075	0.803	1.190	1.154	N.C
80	2.0	20	0.100	N.C	1.252	1.202	N.C

Tab 2-4 Normalized structural stress results. Values are depicted in Fig 2-29.

In Fig 2-30, the normalized structural stress results of a quality level "B" double-vee joint is shown. The toes, which are now symmetric about the diagonal axes of the weld (toe 1 and 4, toe 2 and 3 are equal), show the same results as expected.

Additionally, both X-joint and Y-joint with different qualities result in very similar stress increases with the increasing misalignment, which also confirms that the structural stress does not include local effects of the weld geometry. This can be seen for example by comparing Fig 2-30 and Fig 2-31, where the resulting normalized ratios are very similar.

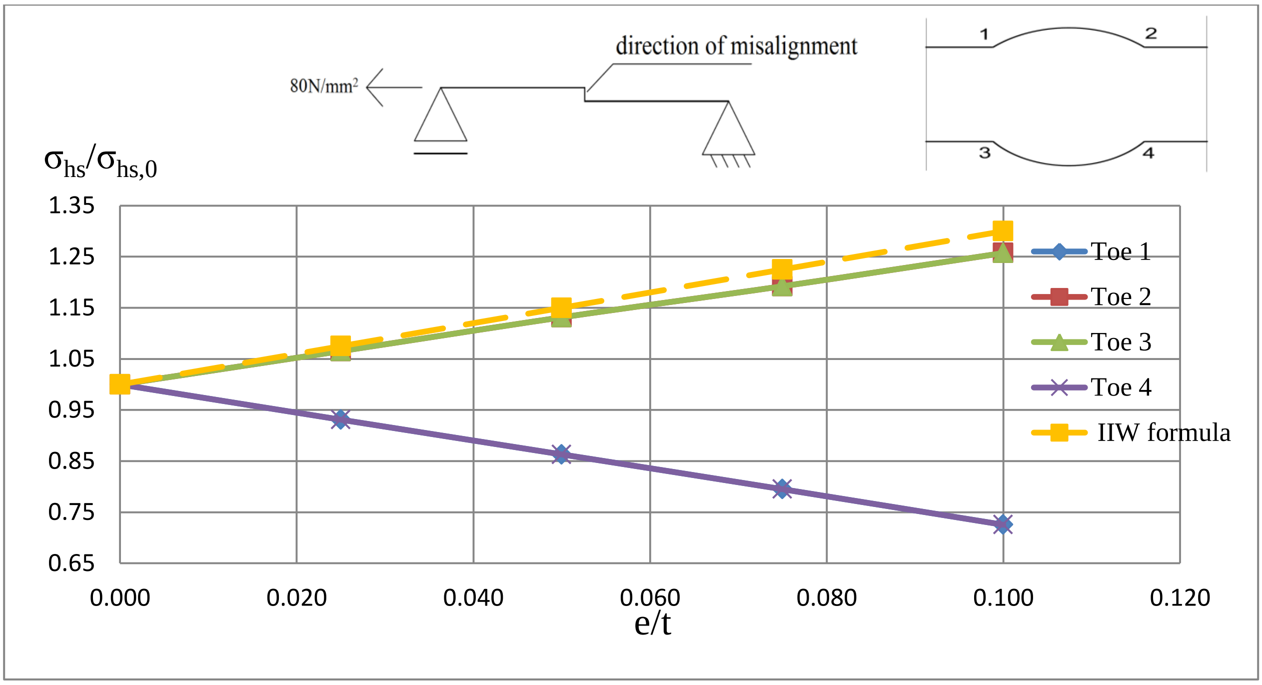


Fig 2-30 Effect of increasing misalignment (upwards) on structural stress. Stress magnification factor (k_m) according to [2] is also shown as "IIW formula". Simply supported quality level "B" double-vee joint.

				Toe 1	Toe 2	Toe 3	Toe 4
				Hot spot stress $\sigma_{hs,0}$ (N/mm^2)			
				82.122	82.183	82.183	82.122
P (N/mm^2)	e (mm)	t (mm)	e/t	Normalized stress ratio ($\sigma_{hs}/\sigma_{hs,0}$)			
80	0	20	0.000	1	1	1	1
80	0.5	20	0.025	0.9311267	1.06535	1.06535	0.931127
80	1	20	0.050	0.8631734	1.131317	1.131317	0.863173
80	1.5	20	0.075	0.7950577	1.192286	1.192286	0.795058
80	2	20	0.100	0.7254917	1.257149	1.257149	0.725492

Tab 2-5 Normalized structural stress results. Values are depicted in Fig 2-30.

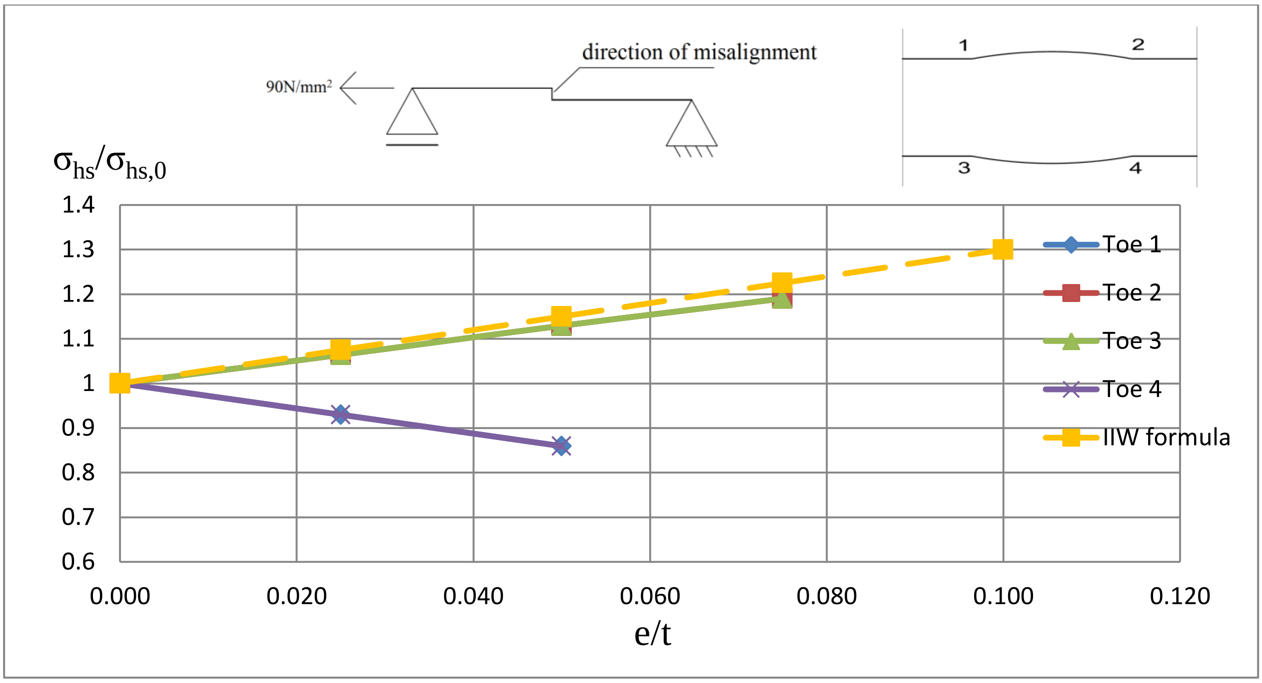


Fig 2-31 Effect of increasing misalignment (upwards) on structural stress. Stress magnification factor (k_m) according to [2] is also shown as "IIW formula". Simply supported quality level "B-Fatigue" double-vee joint.

P (N/mm^2)	e (mm)	t (mm)	e/t	Toe 1	Toe 2	Toe 3	Toe 4
				Hot spot stress $\sigma_{hs,0}$ (N/mm^2)			
				91.718	91.803	91.803	91.718
				Normalized stress ratio ($\sigma_{hs}/\sigma_{hs,0}$)			
90	0	20	0.000	1	1	1	1
90	0.5	20	0.025	0.929839	1.064159	1.064159	0.929839
90	1	20	0.050	0.859373	1.129331	1.129331	0.859373
90	1.5	20	0.075	-	1.190288	1.190288	-
90	2	20	0.100	-	-	-	-

Tab 2-6 Normalized structural stress results. Values are depicted in Fig 2-31.

2.5.2. Effective Notch Stress Changes Due to Misalignment

The effects of misalignment on stresses based on effective notch stress are shown in figures from Fig 2-32 to Fig 2-38.

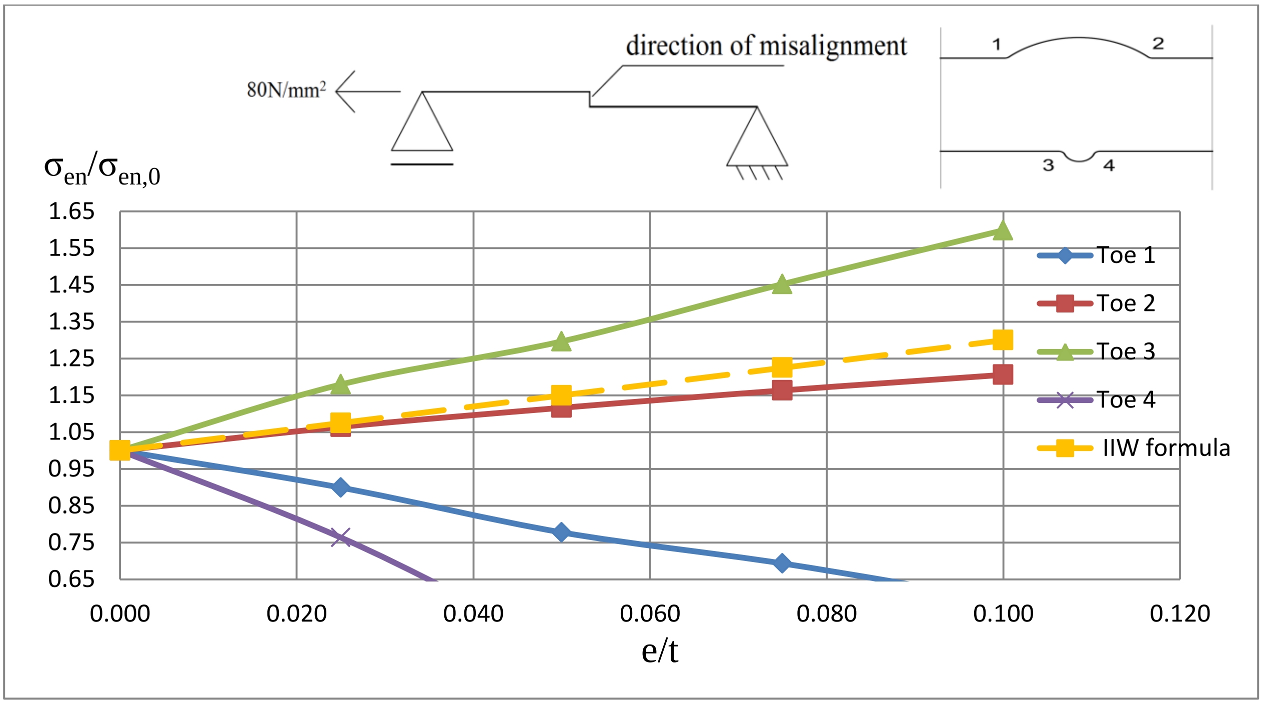


Fig 2-32 Effect of increasing misalignment (upwards) on effective notch stresses. The stress magnification factor according to [2] is also shown as "IIW formula". Simply supported, quality level "B" single-vee joint.

				Toe 1	Toe 2	Toe 3	Toe 4
				Eff. notch stress $\sigma_{en,0}$ (N/mm^2)			
				159.274	157.559	132.960	131.729
P (N/mm^2)	e (mm)	t (mm)	e/t	Normalized stress ratio ($\sigma_{en}/\sigma_{en,0}$)			
80	0	20	0.000	1	1	1	1
80	0.5	20	0.025	0.89926	1.06448	1.179725	0.763509
80	1	20	0.050	0.777603	1.116286	1.296791	0.471531
80	1.5	20	0.075	0.693142	1.163584	1.452567	0.223204
80	2	20	0.100	0.593066	1.205887	1.598925	-

Tab 2-7 Normalized effective notch stress results. Values are depicted in Fig 2-32.

Fig 2-32, Fig 2-33 and Fig 2-34 show that the recommended "IIW formula" is not fitting well for the estimation of misalignment effects for the effective notch stress approach for single-vee ("Y-") joints of quality level "B". However, as can be seen in Fig 2-36 and Fig 2-38, the formula is above the resulting normalized stresses for a double-vee joint, where all toes have equal geometry. As a result, one can conclude that the $\mathbf{k_m}$ formula is valid only for double-vee joints in calculations based on the effective notch stress.

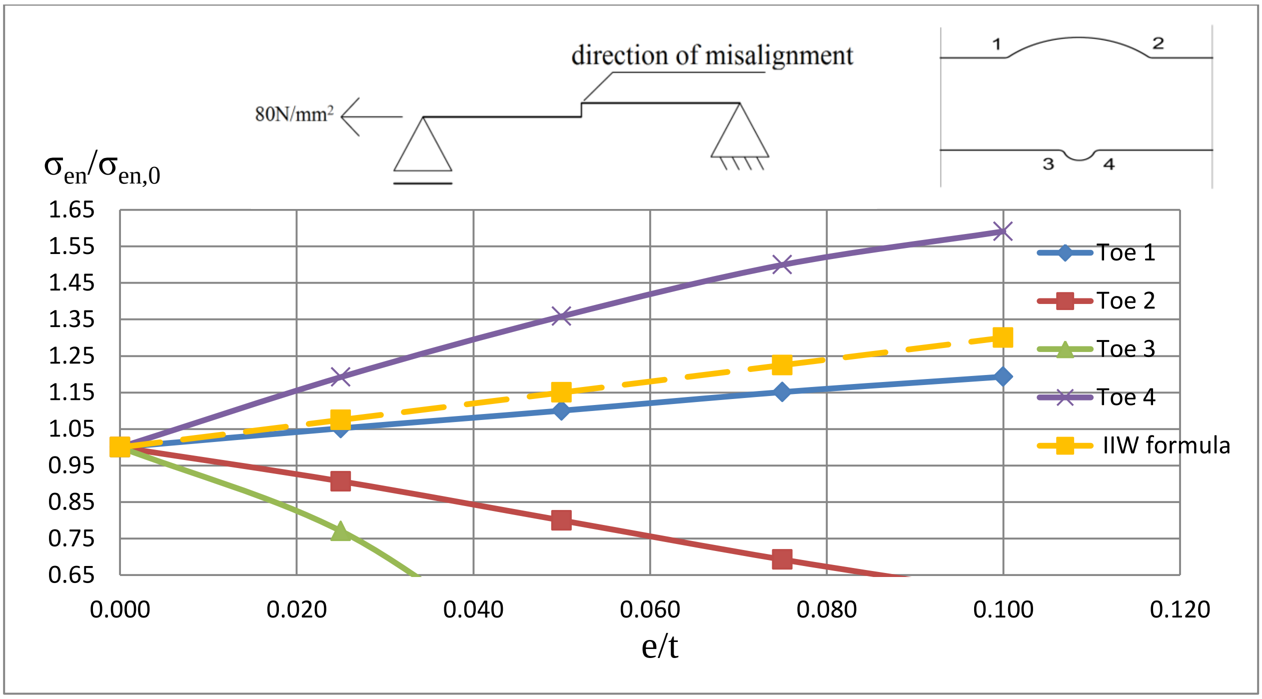


Fig 2-33 Effect of increasing misalignment (downwards) on effective notch stresses. A stress magnification factor according to [2] is also shown as "IIW formula". Simply supported quality level "B" single-vee joint.

				Toe 1	Toe 2	Toe 3	Toe 4
				Eff. notch stress $\sigma_{en,0}$ (N/mm^2)			
				159.274	158.048	132.961	131.729
P (N/mm^2)	e (mm)	t (mm)	e/t	Normalized stress ratio ($\sigma_{en}/\sigma_{en,0}$)			
80	0	20	0.000	1	1	1	1
80	0.5	20	0.025	1.05203	0.906886	0.770773	1.192236
80	1	20	0.050	1.100315	0.799864	0.395986	1.358482
80	1.5	20	0.075	1.151133	0.69265	0.221586	1.499479
80	2	20	0.100	1.193266	0.598462	-	1.590924

Tab 2-8 Normalized effective notch stress results. Values are depicted in Fig 2-33.

Note that there is steep stress increase at weld toes 3 and 4 of Y-Joints (see Fig 2-32 and Fig 2-33). Recall that in Fig 2-11 it has already been shown that due to increasing misalignment, the opposite weld toes (depending on the direction of misalignment; toe 3 or toe4) tend to vanish. The reason of this steep stress increase could thus be that the structural discontinuity only remained at one side of the weld, and is very "sharp" there now. In Fig 2-37, the remaining structural discontinuity at weld toe 3 is shown.

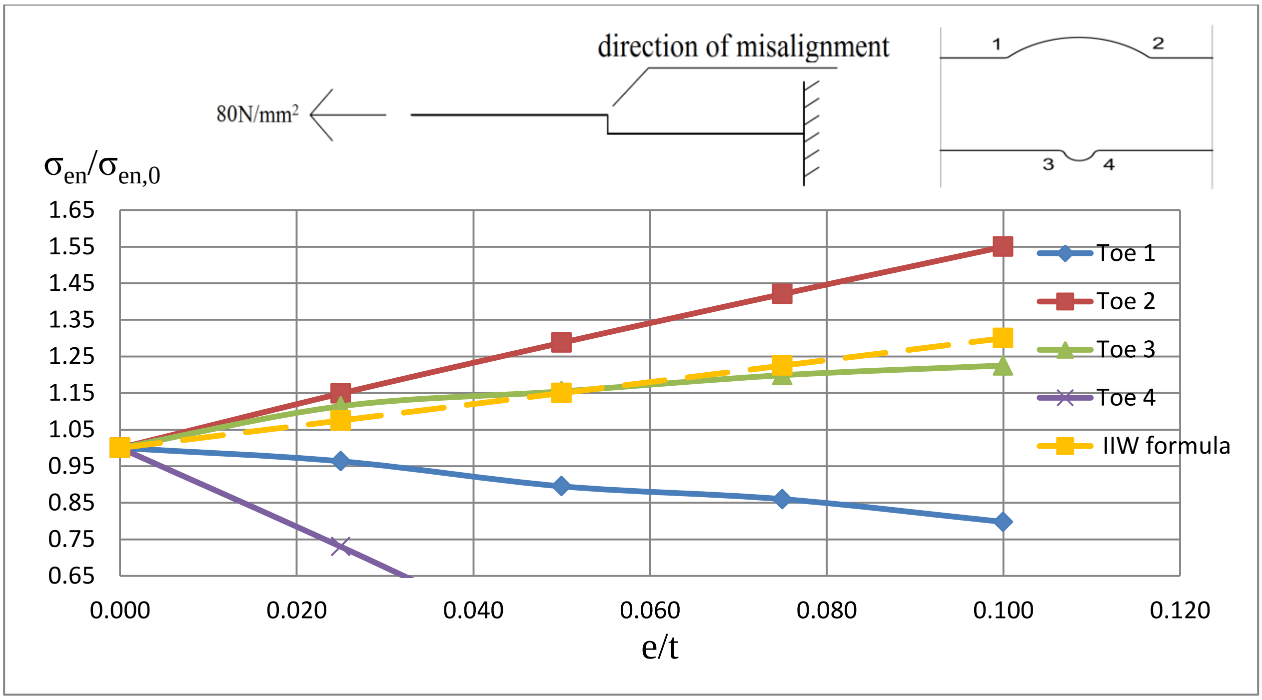


Fig 2-34 Effect of increasing misalignment (upwards) on effective notch stresses. A stress magnification factor according to [2] is also shown as "IIW formula". Fixed supported, quality level "B" single-vee joint.

				Toe 1	Toe 2	Toe 3	Toe 4
				Eff. notch stress $\sigma_{en,0}$ (N/mm^2)			
				159.275	158.048	132.960	131.729
P (N/mm^2)	e (mm)	t (mm)	e/t	Normalized stress ratio ($\sigma_{en}/\sigma_{en,0}$)			
80	0	20	0.000	1	1	1	1
80	0.5	20	0.025	0.963376	1.148805	1.113961	0.729839
80	1	20	0.050	0.89502	1.287463	1.154594	0.447015
80	1.5	20	0.075	0.859958	1.420662	1.198781	0.174215
80	2	20	0.100	0.797687	1.549741	1.225306	-

Tab 2-9 Normalized effective notch stress results. Values are depicted in Fig 2-34.

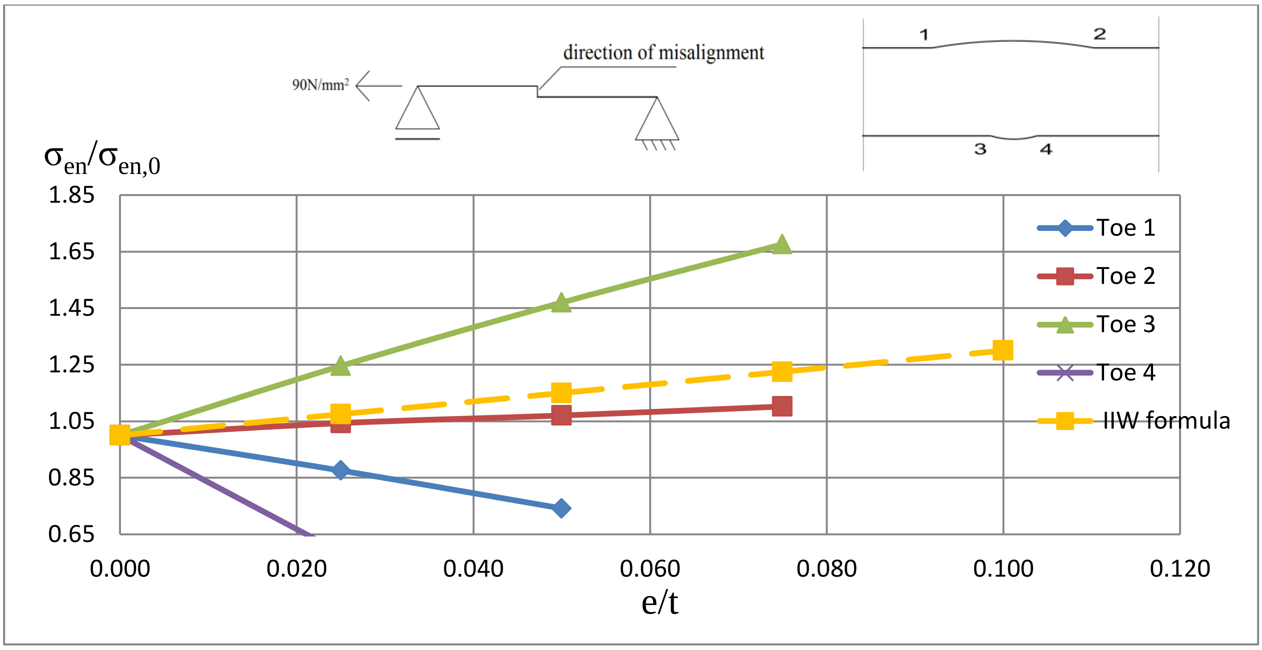


Fig 2-35 Effect of increasing misalignment (upwards) on effective notch stresses. A stress magnification factor according to [2] is also shown as "IIW formula". Simply supported, quality level "B-Fatigue" single-vee joint.

				Toe 1	Toe 2	Toe 3	Toe 4
				Eff. notch stress $\sigma_{en,0}$ (N/mm^2)			
				156.400	156.320	124.925	125.013
P (N/mm^2)	e (mm)	t (mm)	e/t	Normalized stress ratio ($\sigma_{en}/\sigma_{en,0}$)			
90	0	20	0.000	1	1	1	1
90	0.5	20	0.025	0.875614	1.043532	1.245635	0.5851551
90	1	20	0.050	0.741771	1.070439	1.469898	N.C
90	1.5	20	0.075	N.C	1.10229	1.676182	N.C
90	2	20	0.100	N.C	1.115551	1.764907	N.C

Tab 2-10 Normalized effective notch stress results. Values are depicted in Fig 2-35.

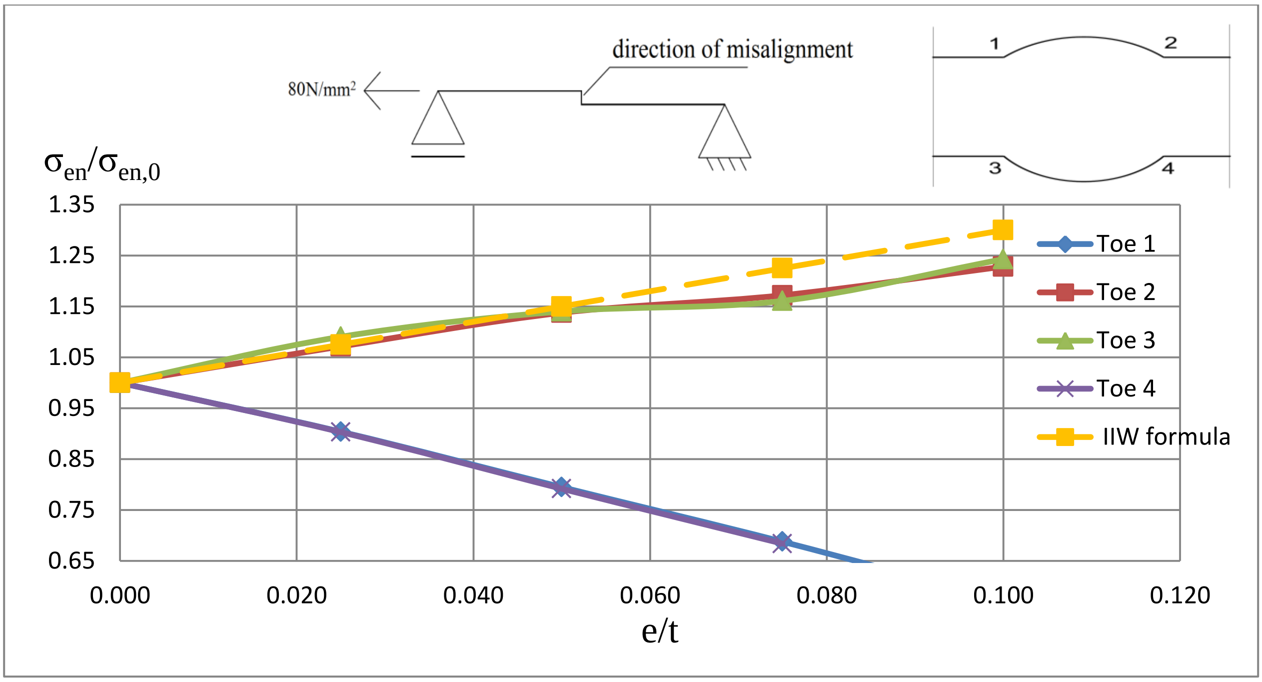


Fig 2-36 Effect of increasing misalignment (upwards) on effective notch stresses. A stress magnification factor according to [2] is also shown as "IIW formula". Simply supported quality level "B" double-vee joint.

				Toe 1	Toe 2	Toe 3	Toe 4
				Eff. notch stress $\sigma_{en,0}$ (N/mm^2)			
				163.147	164.453	162.064	164.300
P (N/mm^2)	e (mm)	t (mm)	e/t	Normalized stress ratio ($\sigma_{en}/\sigma_{en,0}$)			
80	0	20	0.000	1	1	1	1
80	0.5	20	0.025	0.903858	1.071493	1.090488	0.903158
80	1	20	0.050	0.795032	1.137701	1.140192	0.791866
80	1.5	20	0.075	0.687884	1.172018	1.16099	0.683994
80	2	20	0.100	0.571938	1.228453	1.24296	0.568422

Tab 2-11 Normalized effective notch stress results. Values are depicted in Fig 2-36.

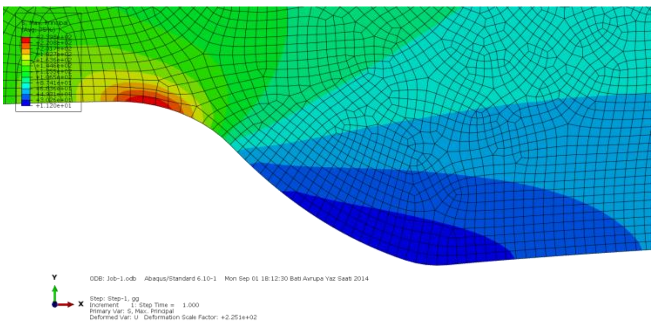


Fig 2-37 Zoomed view to weld toes 3 and toe 4 of Y-Joint with 2.0mm misalignment.

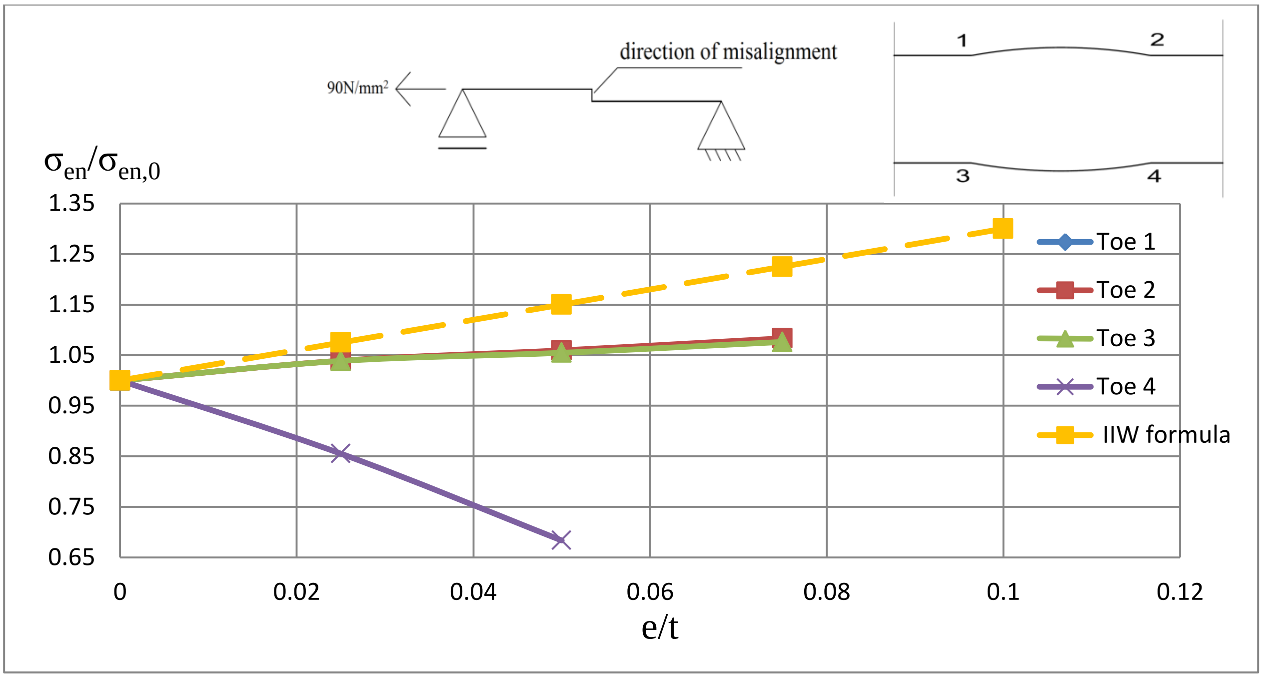


Fig 2-38 Effect of increasing misalignment (upwards) on effective notch stresses. Stress magnification factors according to [2] are also shown as "IIW formula". Simply supported quality level "B-Fatigue" double-vee joint.

P (N/mm^2)	e (mm)	t (mm)	e/t	Toe 1	Toe 2	Toe 3	Toe 4
				Eff. notch stress $\sigma_{en,0}$ (N/mm^2)			
				156.344	156.133	157.159	152.414
				Normalized stress ratio ($\sigma_{en}/\sigma_{en,0}$)			
90	0	20	0.000	1	1	1	1
90	0.5	20	0.025	0.833502	1.039088	1.0387	0.855302
90	1	20	0.050	0.663275	1.059545	1.054753	0.683704
90	1.5	20	0.075	-	1.083339	1.076209	-
90	2	20	0.100	-	-	-	-

Tab 2-12 Normalized effective notch stress results. Values are depicted in Fig 2-38.

Fatigue Life Calculations – Case with misalignment

The **Table 2-B** shows a comparison of fatigue life predictions for the studied details and quality classes according to the different calculation methods: nominal stress, structural hot spot stress and effective notch stress approach. Thereby, as stated above, again the nominal stress was always chosen so that a fatigue life of 2 million load cycles is achieved. Note that in these calculations the misalignment effect is considered, in the following way:

According to IIW Recommendations, in cases where the stress magnification factor $\mathbf{k_m}$ is calculated directly (meaning: it is included in the numerical model, instead of using formulae), the misalignment effect should be calculated (or modified) with an *effective* stress magnification factor called $\mathbf{k_{m,eff}}$ [2]. Note that $\mathbf{k_{m,eff}}$ is calculated by dividing the numerically calculated $\mathbf{k_m}$ by 1.05 (the amount of misalignment which is already covered in the structural hot-spot and effective notch stress S-N curves) [2], see the following table.

Type of k_m analysis	Nominal stress approach	Structural hot spot, effective notch and fracture mechanics appoach	
Type of welded joint	k_m already covered in FAT class	k_m already covered in SN curves	Default value of effective k_m to be considered in stress
Butt joint made in shop in flat position	1.15	1.05	1.10*
Other butt joints	1.30	1.05	1.25*
cruciform joints	1.45	1.05	1.40*
Fillet welds on one plate surface	1.25	1.05	1.20**
Fillet welds on both plate surfaces	1.25	1.05	1.10***

*) but not more than $(1 + 2.5 \cdot e_{max}/t)$, where e_{max} = permissible misalignment and t = wall thickness of loaded plate
**) but not more than $(1 + 0.2 \cdot t_{ref}/t)$, where t_{ref} = reference wall thickness of fatigue resistance curves
***) but not more than $(1 + 0.1 \cdot t_{ref}/t)$, where t_{ref} = reference wall thickness of fatigue resistance curves

Fig 2-39 Consideration of stress magnification factors due to misalignment (IIW Fatigue Recommendations:2014, Table 3.8-2).

In Fig 2-39, the stress magnification factors **($\mathbf{k_m}$)** which are already covered in verification methods and effective stress magnification factor **($\mathbf{k_{m,eff}}$)** which should be considered in calculations, are shown. The following procedure thus explains the calculation of fatigue life cycles in the case with misalignment:

- The allowable misalignment is given by IIW Recommendations in fatigue class tables for nominal stress approach (see Fig 2-14). Based on these restrictions, two different misalignment values (e= 1.0mm for quality level “B-Fatigue” and e= 2.0mm for quality level “B”) have been selected for different joint types (see Table 2-B “considered misalignment” column).
- The quality level “B-Fatigue” joints are assumed to be welded in flat position. However, quality level “B” joints are calculated according to “other butt joints” classification given in Fig 2-39.
- For the structural and the effective notch stress methods, the “calculated” k_m factor is equivalent to the ratio $\Delta\sigma_{hs}/\Delta\sigma_{hs,0}$ (respectively $\Delta\sigma_{en}/\Delta\sigma_{en,0}$) calculated as farther above, i.e.

by comparing the results of a model with the considered amount of mislaignment with a model without any misalignment.

- The “effective” value of $k_{m,eff}$ to be finally used in the fatigue life calculations is however needed, to calculate the “effective” value of the stress amplitude $\Delta\sigma_{eff}$.
- All fatigue life cycles are thus calculated with $\Delta\sigma_{eff}$, where the factor is calculated with the expressions given in Eq.2.2 and Eq.2.3. Note that $\Delta\sigma_{eff} = \sigma_{eff}$ because the load is applied with constant amplitude and with a single load step.

For quality level “B” joints;

$$\begin{aligned} & if \quad \frac{\Delta\sigma_{\mathrm{hs(en)}}}{\Delta\sigma_{\mathrm{hs(en),0}} * 1.05} \leq 1.25 \ , \ \Delta\sigma_{eff} = 1.25 * \Delta\sigma_{\mathrm{hs(en),0}} \\ & \text{else} \quad \Delta\sigma_{eff} = \frac{\Delta\sigma_{\mathrm{hs(en)}}}{1.05} \end{aligned} \tag{2.2}$$

For quality level “B-Fatigue” joints;

$$\begin{aligned} & if \quad \frac{\Delta\sigma_{\mathrm{hs(en)}}}{\Delta\sigma_{\mathrm{hs(en),0}} * 1.05} \leq 1.10 \ , \ \Delta\sigma_{eff} = 1.10 * \Delta\sigma_{\mathrm{hs(en),0}} \\ & \text{else} \quad \Delta\sigma_{eff} = \frac{\Delta\sigma_{\mathrm{hs(en)}}}{1.05} \end{aligned} \tag{2.3}$$

where the $\Delta\sigma_{hs(en)}$ / $\Delta\sigma_{hs(en),0}$ ratios and $\Delta\sigma_{hs(en),0}$ values are already available in tables from Tab 2-1 to Tab 2-12.

Note that the fatigue life cycles are only calculated for those weld toes where increasing misalignment led to an increase in stress (see tables from Tab 2-1 to Tab 2-12). The calculations are carried out for the configuration with the “maximum” amount of misalignment according to tolerances (1mm or 2mm acc. to [2], depending on the FAT class).

Furthermore, note that in the following table values of $\Delta\sigma_{hs}$ or $\Delta\sigma_{en}$ are given, which were calculated numerically, but not plotted directly in the tables further above (Tab 2-1 to Tab 2-11). These values can be retrieved, however, from $\Delta\sigma_{hs,0}$ times the ratio ($\Delta\sigma_{hs}/\Delta\sigma_{hs,0}$) in those tables. For example, the value of effective notch stress of $\Delta\sigma_{en}$ =189,998 N/mm² at Toe 2, Transverse Butt Weld, Y-Joint, e=2mm, Simple support conditions, Quality Class “B”, can be found from the values in Tab 2-7: $\Delta\sigma_{hs,0}$=157,559 times ($\Delta\sigma_{hs}/\Delta\sigma_{hs,0}$)=1,205887 =189,998 N/mm².

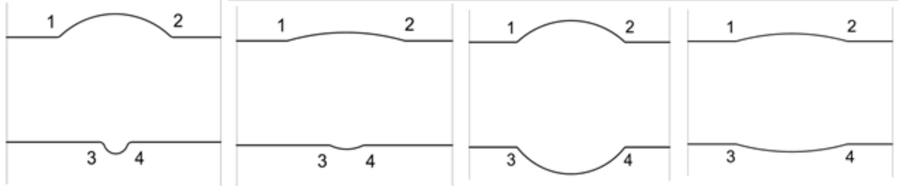
		Considered			Nominal FAT-CLASS	CALCULATED STRESSES - Case with misalignment [N/mm^2]											
						Toe 1			Toe 2			Toe 3			Toe 4		
Welding	Joint type	Misalignment	Support Con.	Quality	≈Load(N/mm2)	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$
Transverse Butt	Y-Joint	e=2mm	Fixed	B	80	80.000	80.656	127.052	80.000	130.256	244.933	80.000	86.046	162.917	80.000	N.C	N.C
Transverse Butt	Y-Joint	e=2mm	Simple	B	80	80.000	59.852	94.460	80.000	101.450	189.998	80.000	108.240	212.594	80.000	N.C	N.C
Transverse Butt	Y-Joint	e=1mm	Simple	B-Fatigue	90	90.000	78.911	116.013	90.000	102.389	167.331	90.000	108.748	183.627	90.000	N.C	N.C
Transverse Butt	X-Joint	e=2mm	Simple	B	80	80.000	59.579	93.310	80.000	103.316	202.023	80.000	103.316	201.439	80.000	59.579	93.392
Transverse Butt	X-Joint	e=1mm	Simple	B-Fatigue	90	90.000	78.820	103.699	90.000	103.676	165.430	90.000	103.676	165.764	90.000	78.820	104.206

		Considered			Nominal FAT-CLASS	EFFECTIVE STRESSES ($\Delta\sigma_{i,eff}$) - Case with misalignment [N/mm^2]											
						Toe 1			Toe 2			Toe 3			Toe 4		
Welding	Joint type	Misalignment	Support Con.	Quality	≈Load(N/mm2)	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs,eff}$	$\Delta\sigma_{en,eff}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs,eff}$	$\Delta\sigma_{en,eff}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$
Transverse Butt	Y-Joint	e=2mm	Fixed	B	80	80.000	not relavant		80.000	124.054	233.270	80.000	111.226	166.200	80.000	not relavant	
Transverse Butt	Y-Joint	e=2mm	Simple	B	80	80.000			80.000	101.022	196.949	80.000	111.225	202.470	80.000		
Transverse Butt	Y-Joint	e=1mm	Simple	B-Fatigue	90	90.000			90.000	99.934	171.952	90.000	108.251	174.883	90.000		
Transverse Butt	X-Joint	e=2mm	Simple	B	80	80.000			80.000	102.729	205.566	80.000	102.729	202.580	80.000		
Transverse Butt	X-Joint	e=1mm	Simple	B-Fatigue	90	90.000			90.000	100.983	171.746	90.000	100.983	172.875	90.000		

		Considered			Nominal FAT-CLASS	FATIGUE LIFE CYCLES - Case with Misalignment											
						Toe 1			Toe 2			Toe 3			Toe 4		
Welding	Joint type	Misalignment	Support Con.	Quality	≈Load(N/mm2)	nom.	hot spot	eff. not.	nom.	hot spot	eff. not.	nom.	hot spot	eff. not.	nom.	hot spot	eff. not.
Transverse Butt	Y-Joint	e=2mm	Fixed	B	80		not relavant			1.05E+06	1.79E+06		1.45E+06	4.96E+06		not relevant	
Transverse Butt	Y-Joint	e=2mm	Simple	B	80	2			2	1.94E+06	2.98E+06	2	1.45E+06	2.74E+06	2		
Transverse Butt	Y-Joint	e=1mm	Simple	B-Fatigue	90	million			million	2.00E+06	4.48E+06	million	1.58E+06	4.26E+06	million		
Transverse Butt	X-Joint	e=2mm	Simple	B	80	cycles			cycles	1.84E+06	2.62E+06	cycles	1.84E+06	2.74E+06	cycles		
Transverse Butt	X-Joint	e=1mm	Simple	B-Fatigue	90					1.94E+06	4.50E+06		1.94E+06	4.41E+06			

Quality	Effective stress formula
B	$if\ \frac{\Delta\sigma_{hs(en)}}{\Delta\sigma_{hs(en),0}*1.05} \le 1.25\ ,\ \Delta\sigma_{eff} = 1.25*\Delta\sigma_{hs(en),0}$ $else\ \ \Delta\sigma_{eff} = \frac{\Delta\sigma_{hs(en)}}{1.05}$
B-Fatigue	$if\ \frac{\Delta\sigma_{hs(en)}}{\Delta\sigma_{hs(en),0}*1.05} \le 1.10\ ,\ \Delta\sigma_{eff} = 1.10*\Delta\sigma_{hs(en),0}$ $else\ \ \Delta\sigma_{eff} = \frac{\Delta\sigma_{hs(en)}}{1.05}$

$CAFL_{nom}$	58.96 MPa
$CAFL_{hs}$	73.70 MPa
$CAFL_{en}$	165.825 MPa



Y-Joint quality "B" | Y-Joint quality "B-Fatigue" | X-Joint quality "B" | X-Joint quality "B-Fatigue"

Tab 2-B Calculated stresses, effective stresses and fatigue life cycle calculations.Effect of misalignment is included

The following observations can be made about the above results:

i. When misalignment is explicitly included, the fatigue lives at the critical toes according to the structural hot-spot and effective notch stress methods are quite different, sometimes lower and sometimes larger, than the nominal stress fatigue life cycles. In the case of the structural hot-spot stress, the differences are small expect for the case with “fixed” boundary condition, where it was already discussed that higher additional bending moments occur. The effective notch stresses lead to fairly similar, but mostly higher life predictions at the relevant toe.

ii. In the structural hot-spot stress case, the fact that the stresses of the “non-misaligned” case have to be increased by a factor of at least 1,25 (over-)compensates for the difference in fatigue classes (FAT 100 vs. 80 or 90).

3

Butt Welds at Thickness Transitions

3.1. Considered Geometries and Misalignment

In bridge girders, another common application where misalignment may play a role is butt welding of plates with different thicknesses, with one surface of the joint (nominally) flush. In this type of joint, relatively large eccentricities are present even in the "perfect" configuration. After considering a slope value of 1:4, the edge preparations prior to welding are prepared as seen in Fig 3-1, Fig 3-2 and Fig 3-3., depending on whether a single-vee, inverse single-vee or double-vee ("X") joint is fabricated.

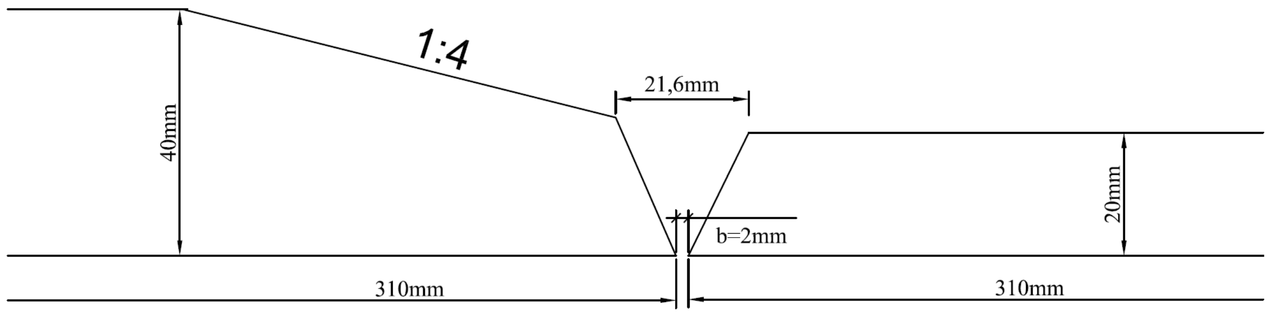


Fig 3-1 Edge preparation of V-joint.

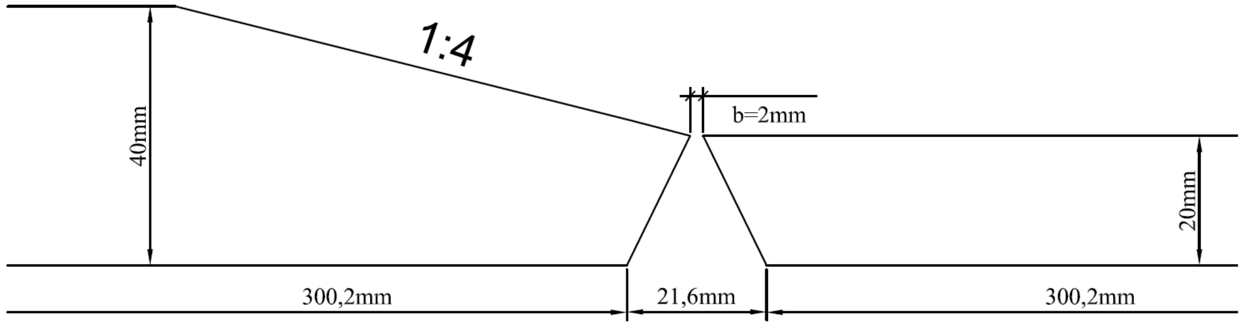


Fig 3-2 Edge preparation of reverse V-joint.

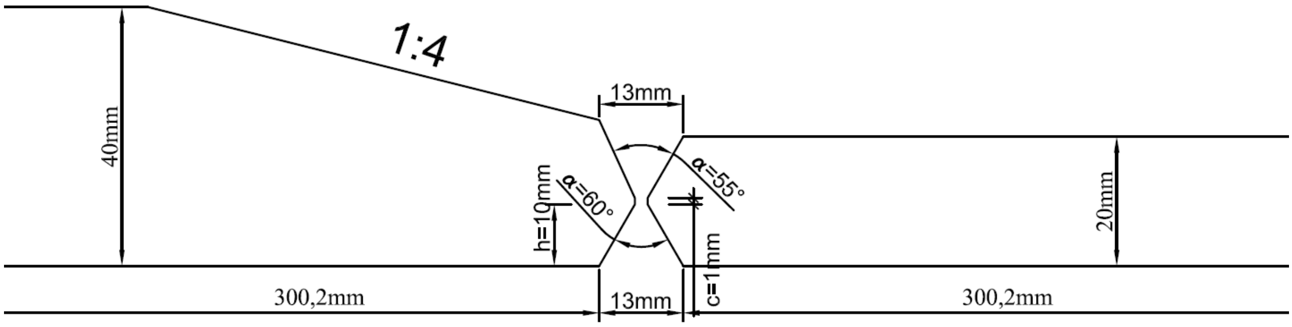


Fig 3-3 Edge preparation of double-vee (“X”) joint.

Similarly to Chapter 2, at first a case without (additional) misalignment is considered in calculations. Note that in this joint geometry, there is a (large!) eccentricity of the plates even without additional, “undesired” misalignment. Following that, a linear misalignment up to 2mm is applied and the results are recorded in every step increase of 0.5mm. However, only a simple supported static system is considered in this chapter (omitting the case of encastre) and the misalignment is applied in one direction (upwards) only (see Fig 3-4), i.e. the direction which further reinforces the always-present eccentricity of the two plates. Note that for these boundary conditions, the plates are fully “free” to deform transversally to their plane, except at the supports; in real configurations, this type of joint is often used in flanges, were additional restraint to this deformation is given by the girder web. However, since mostly relative effects are looked at here (nominal vs. structural vs. effective notch stress; effect of misalignment vs. no misalignment), the results remain general enough.

A tensile uniform loading of 90N/mm^2 is applied in the thin plate (20mm plate) side.

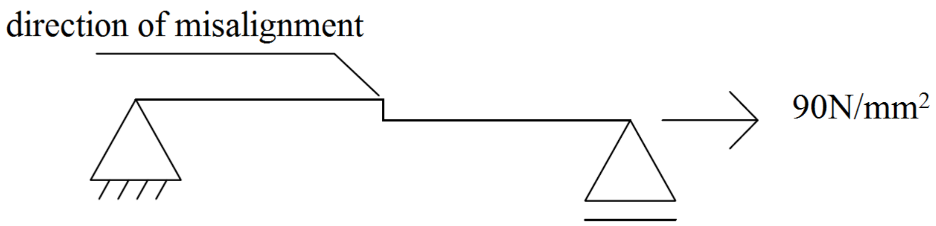


Fig 3-4 Considered static system and direction of misalignment (upwards).

3.2. Weld Shapes and Imperfections

In this chapter, a fully penetrated butt welding is considered. Furthermore, the mechanical properties of the weld metal, fusion zone and the heat affected zone are again assumed to be equal to the parent metal. Hence, the weld and parent metal are modelled as a whole part.

Unfortunately, the EN ISO 5817:2007 does not suggest clear weld imperfection tolerances for precisely this type of configuration, since it is not clear what plate thickness should be used as reference. For this reason, imperfections such as requirement for smooth transition, the heights of excess penetration and weld metal are selected in a way that is similar (but not perfectly equal) to the case with plates of equal thickness.

The considered geometries including the imperfections can be seen in Fig 3-5, Fig 3-6 and Fig 3-7, which show "zoom-in" views of the weld area (the thickness transition is to the left).

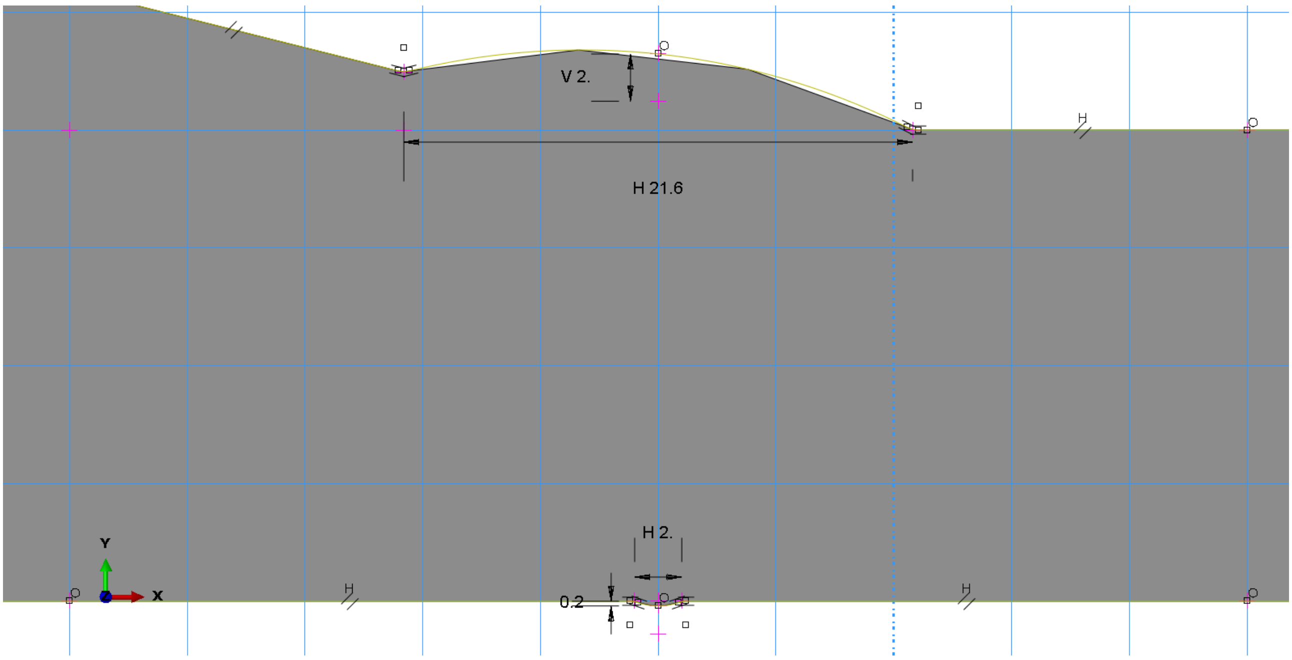


Fig 3-5 Quality level "B-Fatigue" V-joint between plates of different thicknesses. Weld imperfections in the Abaqus model (all measures are in millimeters).

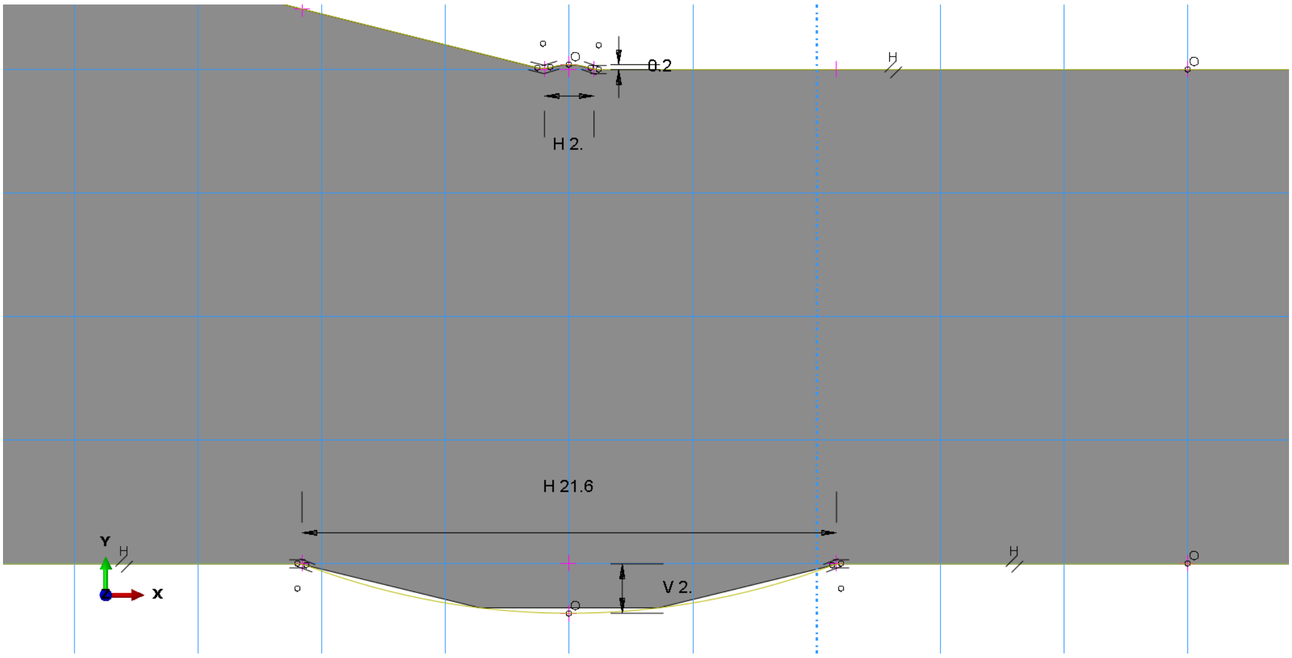


Fig 3-6 Quality level "B-Fatigue" inverse V-joint between plates of different thicknesses. Weld imperfections in the Abaqus model (all measures are in millimeters).

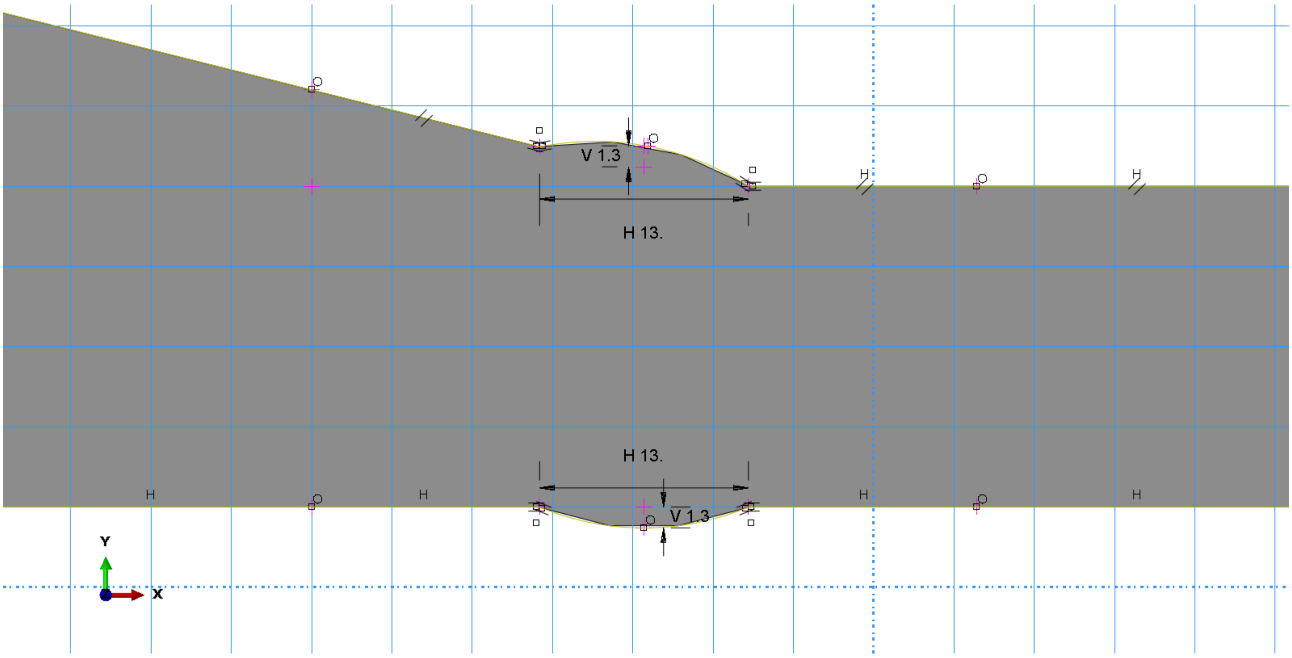


Fig 3-7 Quality level "B-Fatigue" double-vee joint between plates of different thicknesses. Weld imperfections in the Abaqus model (all measures are in millimeters).

3.3. Applicable Fatigue Classes

The fatigue classes of these types of joints in EN 1993-1-9:2005 for the nominal stress approach were already shown in Fig 2-12. The recommended class was FAT90 for all cases considered in this chapter. However, IIW Recommendations suggest different classes depending on the slope of transition (see Fig 3-8). In this thesis, FAT90 is uniformly selected as basis for fatigue strength verifications based on the nominal stress approach, following the Eurocode value.

For fatigue assessment based on structural stress, there is no available specific fatigue class for this type of joints yet. A comparison can be made with the classes already shown in Fig 2-15 and Fig 2-16 (FAT 100), because there is no information about the thickness transition. Correspondingly, the FAT 225 is again considered for the effective notch stress approach.

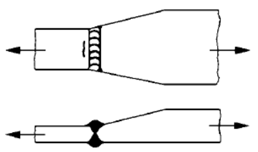
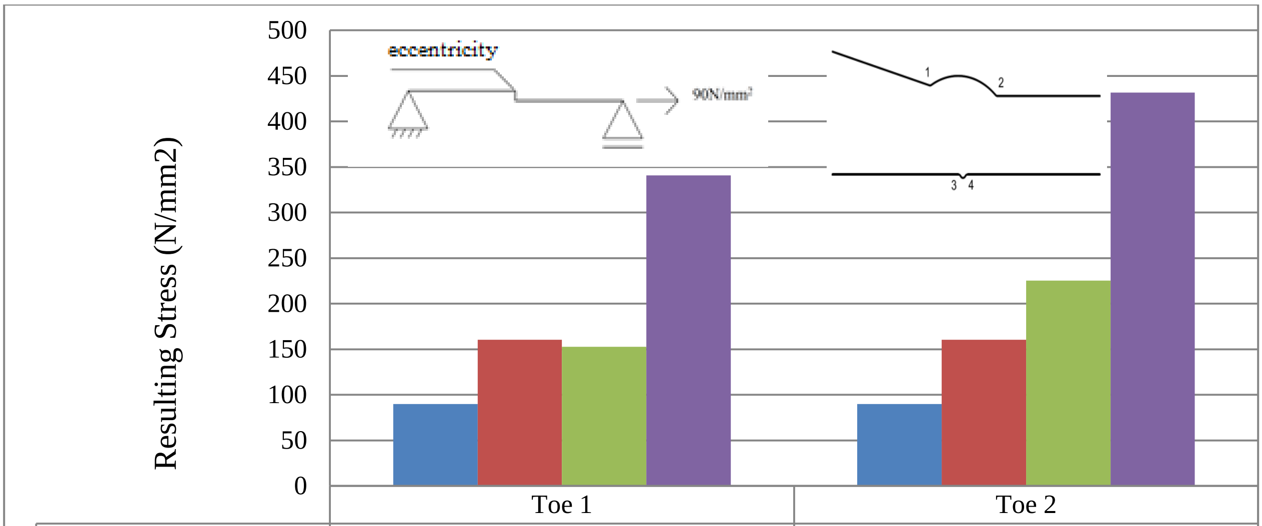
222		Transverse butt weld made in shop, welded in flat position, weld profile controlled, NDT, with transition in thickness and width: slope 1:5 slope 1:3 slope 1:2	90 80 72	32 28 25	Weld run-on and run-off pieces to be used and subsequently removed. Plate edges ground flush in direction of stress. Misalignment due to deliberate thickness step to be considered, see Section 3.8.2. Additional misalignment due to fabrication imperfection < 5% of plate thickness.

Fig 3-8 Selected detail category for transverse butt welds with thickness transition (IIW Fatigue Recommendations, 2014). Detail category to be used in assessments based on nominal stress approach.

3.4. Comparison of Nominal, Structural Hot Spot and Notch Stress Methods –No Misalignment

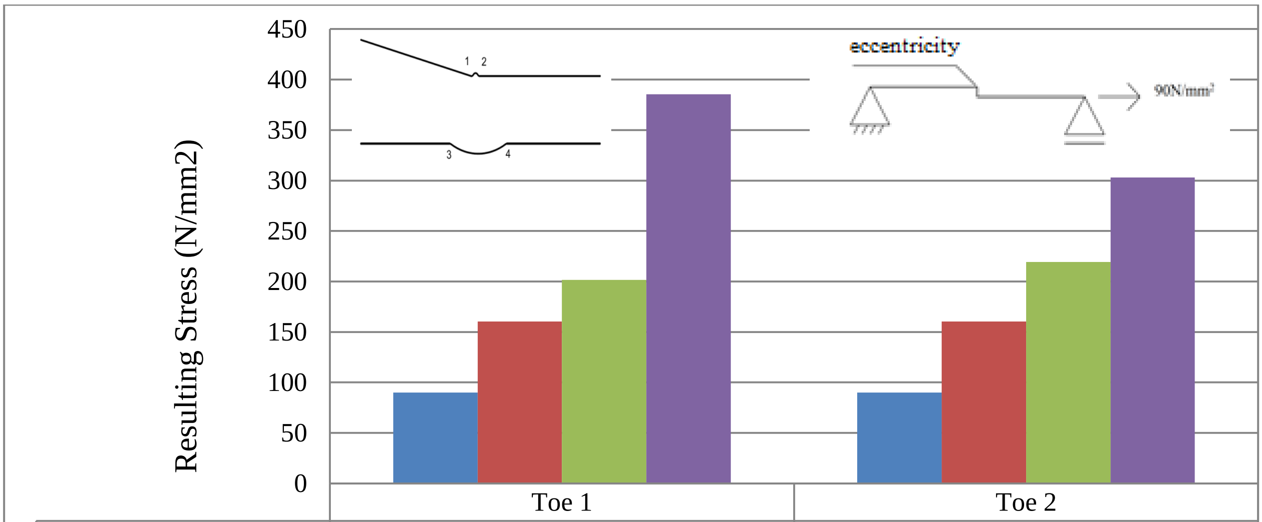
In order to easily compare the fatigue life cycles of different methods, a tensile load of 90N/mm^2 which (when considered as a stress amplitude $\Delta\sigma$) leads to a fatigue life (95% survival probability) of 2x10^6 life cycle based on the nominal stress method for FAT class 90, is selected deliberately. The load is applied to the free end of the simply supported case in the Abaqus model.

In case of butt welds at thickness transition, there is however already a planned misalignment (or rather: eccentricity) due to geometry (e= (40-20)/2= 10mm). This effect, while not clearly stated in the Eurocode, must be included in order to make the nominal stresses meaningful. Thus, “modified” nominal stresses are also reported in the following. These can be calculated by multiplying the applied 90N/mm² with a factor k_m, obtained with Eq.3.1 (see further below) by using the “planned eccentricity” of e=10mm; the resulting $\mathbf{k_m=1.783}$, which is a constant for the studied joints, can be multiplied with nominal stress values as a constant in order to find modified nominal stress values. The results of the four stress calculation methods are shown in the following figures.



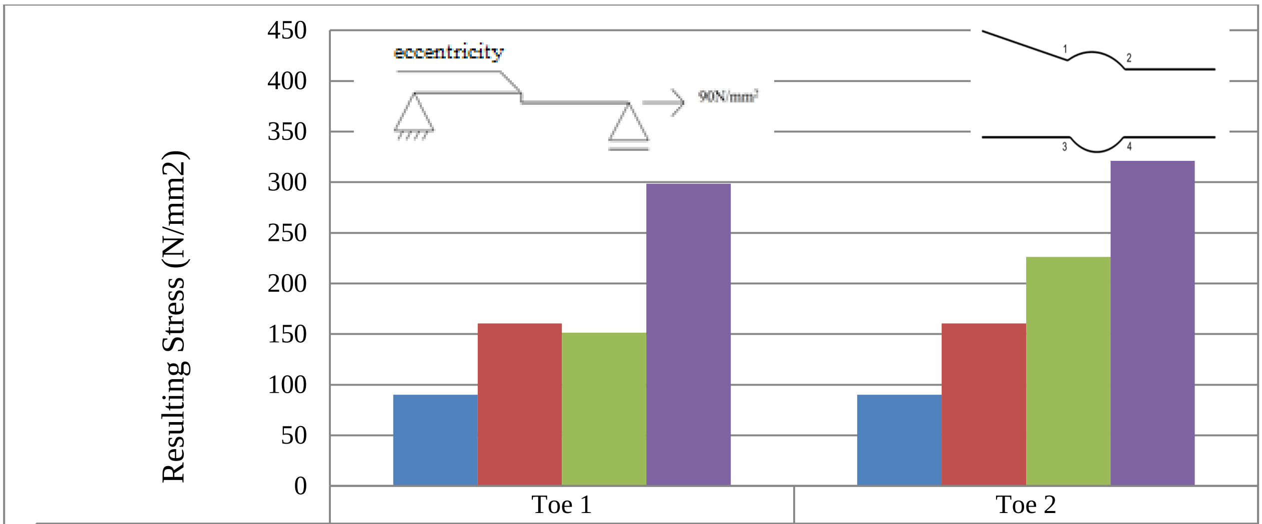
	Toe 1	Toe 2
Nominal stress	90.000	90.000
Modified nominal stress	160.470	160.470
Hot spot stress	152.720	225.550
Effective notch Stress	340.781	431.754

Fig 3-9 Comparison of nominal, modified nominal, structural hot spot and effective notch stresses. Resultant maximum in-plane principal tensile stresses for transverse butt welded joint with no misalignment. Simply supported quality level “B-Fatigue” single-vee joint with thickness transition.



	Toe 1	Toe 2
Nominal stress	90.000	90.000
Modified nominal stress	160.470	160.470
Hotspot stress	201.543	219.397
Effective notch stress	385.559	302.985

Fig 3-10 Comparison of nominal, modified nominal, structural hot spot and effective notch stresses. Resultant maximum in-plane principal tensile stresses for transverse butt welded joint with no misalignment. Simply supported quality level “B-Fatigue” inverse single-vee joint with thickness transition.



	Toe 1	Toe 2
Nominal stress	90.000	90.000
Modified nominal stress	160.470	160.470
Hotspot Stress	151.324	226.355
Effective Notch Stress	298.437	415.111

Fig 3-11 Comparison of nominal, modified nominal, structural hot spot and effective notch stresses. Resultant maximum in-plane principal tensile stresses for transverse butt welded joint with no misalignment. Simply supported quality level “B-Fatigue” double-vee joint with thickness transition.

Fatigue Life Calculation – No misalignment case

The following **Table 3-A** shows a comparison of fatigue life predictions for the studied details and quality classes according to the different calculation methods: nominal stress, modified nominal stress, structural hot spot stress and effective stress approach. Thereby, as stated above, the nominal stress was always chosen so that a fatigue life of 2 million load cycles is achieved.

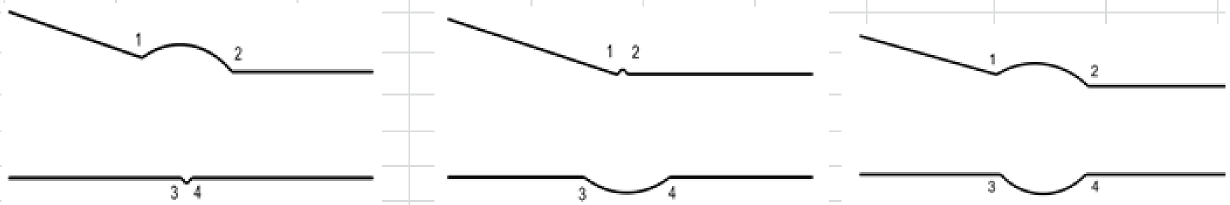
Note that in these calculations no misalignment is considered; this means that – at least for the cases of the effective notch stress and structural stress approach – the calculated fatigue life values are not (yet) valid, as for these methods misalignment must be taken into account directly; see the fatigue life calculations with misalignment case for this effect.

Additional explanations to the variables and methods used for the calculations in this table were already given in chapter 2 of this thesis, for the analogous case. The only new variable is $\Delta\sigma_{m,nom}$, symbolizing the modified nominal stress.

				Nominal	CALCULATED STRESSES [N/mm²]							
				FAT-CLASS	Toe 1				Toe 2			
Welding	Joint type	Support Con.	Quality	≈Load(N/mm2)	$\Delta\sigma_{nom}$	$\Delta\sigma_{m.nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{m.nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$
Butt Weld w. Tran.	Y-Joint	Simple	B-Fatigue	90	90.000	160.470	152.720	340.781	90.000	160.470	225.550	431.754
Butt Weld w. Tran.	inv. Y-Joint	Simple	B-Fatigue	90	90.000	160.470	201.543	385.559	90.000	160.470	219.397	302.985
Butt Weld w. Tran.	X-Joint	Simple	B-Fatigue	90	90.000	160.470	151.324	298.437	90.000	160.470	226.355	415.111

				Nominal	FATIGUE LIFE CYCLES							
				FAT-CLASS	Toe 1				Toe 2			
Welding	Joint type	Support Con.	Quality	≈Load(N/mm2)	nom.	mod. nom	hot spot	eff. not.	nom.	mod. nom	hot spot	eff. not.
Butt Weld w. Tran.	Y-Joint	Simple	B-Fatigue	90			5.61E+05	5.76E+05			1.74E+05	2.83E+05
Butt Weld w. Tran.	inv. Y-Joint	Simple	B-Fatigue	90	2.00E+06	3.53E+05	2.44E+05	3.97E+05	2.00E+06	3.53E+05	1.89E+05	8.19E+05
Butt Weld w. Tran.	X-Joint	Simple	B-Fatigue	90			5.77E+05	8.57E+05			1.72E+05	3.18E+05

$CAFL_{nom}$	66.33 MPa
$CAFL_{hs}$	73.70 MPa
$CAFL_{en}$	165.825 MPa



Y-Joint quality "B-Fatigue" | Inverse Y-Joint quality "B-Fatigue" | X-Joint quality "B-Fatigue"

Tab 3-A Calculated stresses and fatigue life cycle calculations of butt welds at thickness transition. No misalignment case.

The following observations can be made about the above results:

i. The most obvious observation is the the "pure", unmodified nominal stress would lead to far too high fatigue life predictions in this case. Obviously, it is not possible to neglect the presence of the (very large) "planned" eccentricity in this type of joint.

ii. When the modified (by k_m) nominal stresses are used as basis of the comparisons, one can see that the structural and effective notch stress methods lead to fatigue life predictions that are quite different from the (modified) nominal case. Mostly, at the critical toe, these life predictions can be very significantly lower than according to the modified nominal method, even in the case studied up to now, which completely neglects any additional misalignment effects.

3.5. Effect of Misalignment

For the case of butt-welded plates of unequal thickness (to which the studied configuration can be counted, even though the formula is valid also for butt welds with plates of different thickness, but without any thickness transition), a formula for the consideration of misalignment is given in the IIW Recommendations. This recommended $\mathbf{k_m}$ value is calculated according to the following Eq.3.1 (IIW Recommendations:2014 Table 6.3-1):

$$k_m = 1 + \frac{6e}{t_1} * \frac{t_1^{\,n}}{(t_1^{\,n} + t_2^{\,n})} \tag{3.1}$$

where n=1.5 and $t_2 \geq t_1$.

In the following comparisons, this formula is applied only for the "unplanned", i.e. truly "misaligned" portion of the total eccentricity. This is possible in the comparisons, because the numerical results (for the structural hot-spot and effective notch stresses) are also normalized against the stresses in the "perfect" configuration, which has an eccentricity of (40-20)/2=10mm, but no misalignment. Thus, the effect of this eccentricity is already included in the calculation of the basic stresses $\sigma_{hs,0}$ respectively $\sigma_{en,0}$.

3.5.1. Structural Stress Changes Due to Misalignment

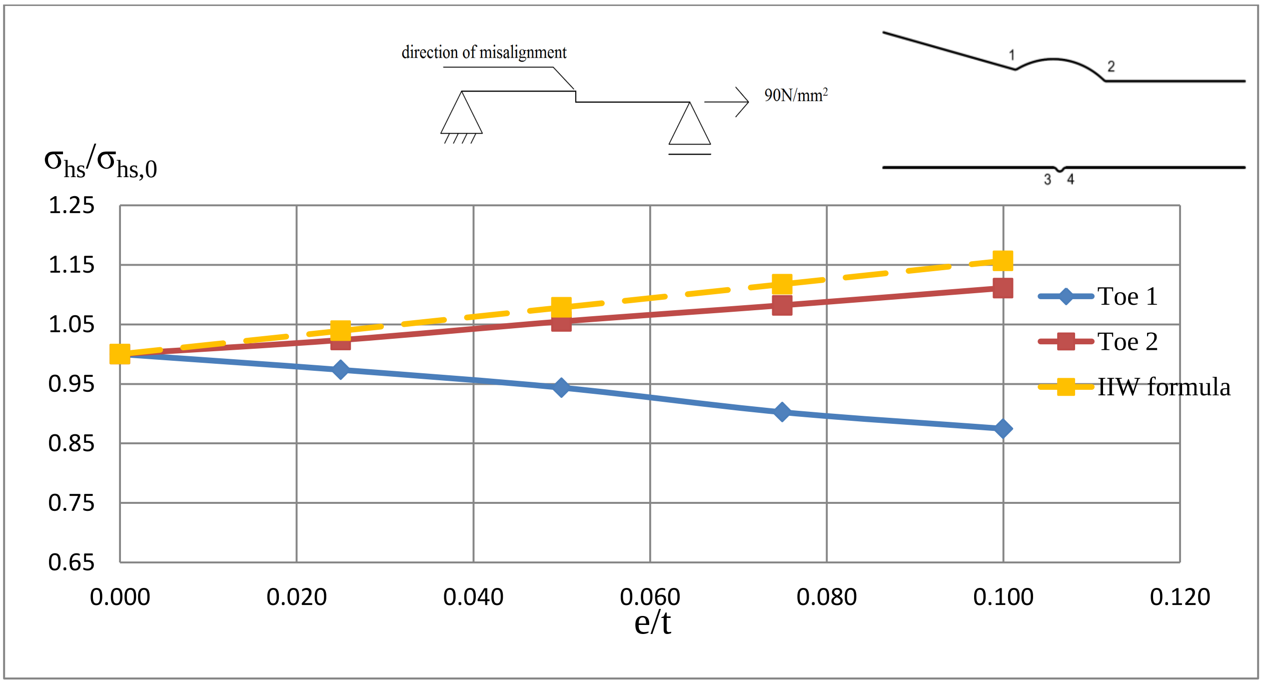


Fig 3-12 Effect of increasing misalignment (upwards) on structural stress. Stress magnification factor (k_m) according to [2] is also shown as "IIW formula". Simply supported quality level "B-Fatigue" V- joint with thickness transition.

				Toe 1	Toe 2	Toe 3	Toe 4
				Hot spot stress $\sigma_{hs,0}$ (N/mm^2)			
				152.720	225.550	N.C	N.C
P (N/mm^2)	e (mm)	t (mm)	e/t	Normalized stress ($\sigma_{hs}/\sigma_{hs,0}$)			
90	0	20	0.000	1	1	N.C	N.C
90	0.5	20	0.025	0.973559	1.023738	N.C	N.C
90	1	20	0.050	0.943576	1.054853	N.C	N.C
90	1.5	20	0.075	0.90239	1.082075	N.C	N.C
90	2	20	0.100	0.874666	1.111049	N.C	N.C

Tab 3-1 Normalized structural stress results. Values are depicted in Fig 3-12.

Note that in the above results, the stresses for toes 3 and 4 are not plotted / printed because they become very small or even negative due to the bending moment due to eccentricity + misalignment, and are thus not relevant. This pattern is repeated in the following figures and tables whenever results become (clearly) not relevant - they are then "N.C." for "not calculated".

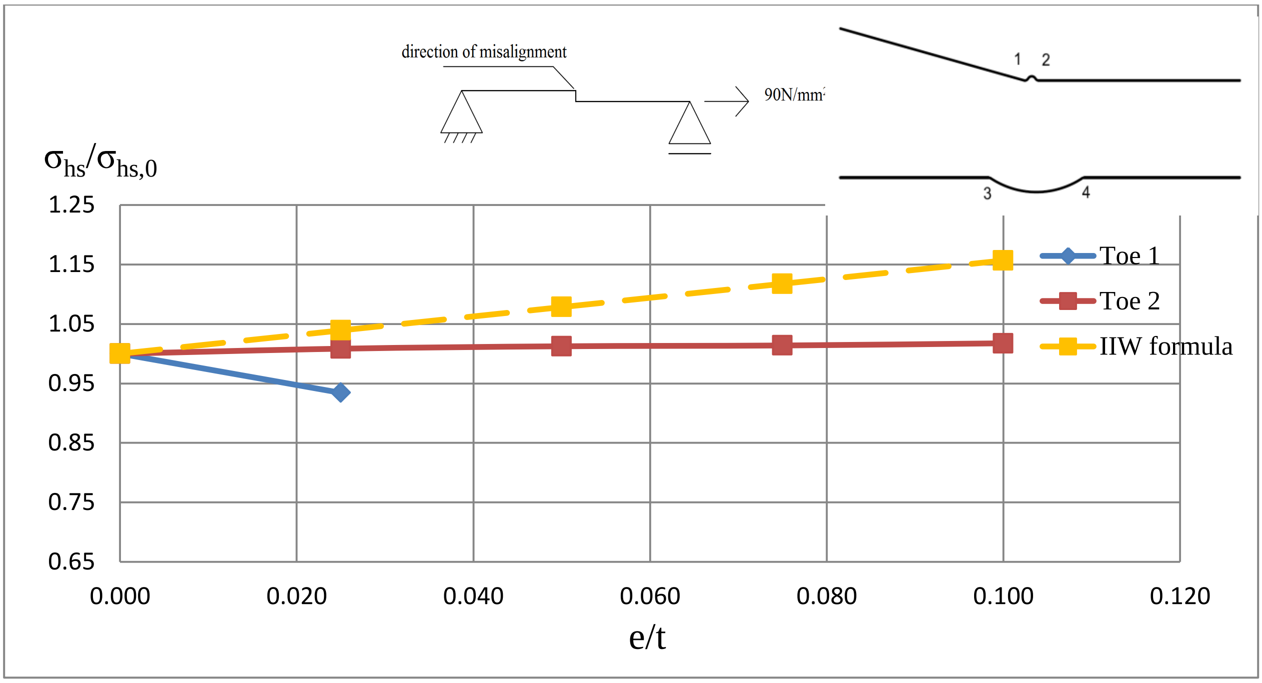


Fig 3-13 Effect of increasing misalignment (upwards) on structural stress. Stress magnification factor (k_m) according to [2] is also shown as "IIW formula". Simply supported quality level "B-Fatigue" inverse V- joint with thickness transition.

				Toe 1	Toe 2	Toe 3	Toe 4
				Hot spot stress $\sigma_{hs,0}$ (N/mm^2)			
				201.543	219.397	-4.312	-43.296
P (N/mm^2)	e (mm)	t (mm)	e/t	Normalized stress ($\sigma_{hs}/\sigma_{hs,0}$)			
90	0	20	0.000	1	1	1	1
90	0.5	20	0.025	0.934173	1.008419	-1.65005	1.001501
90	1	20	0.050	-	1.012461	-4.18112	1.001778
90	1.5	20	0.075	-	1.013815	-6.63984	1.012288
90	2	20	0.100	-	1.017489	-9.10181	1.014713

Tab 3-2 Normalized structural stress results. Values are depicted in Fig 3-13.

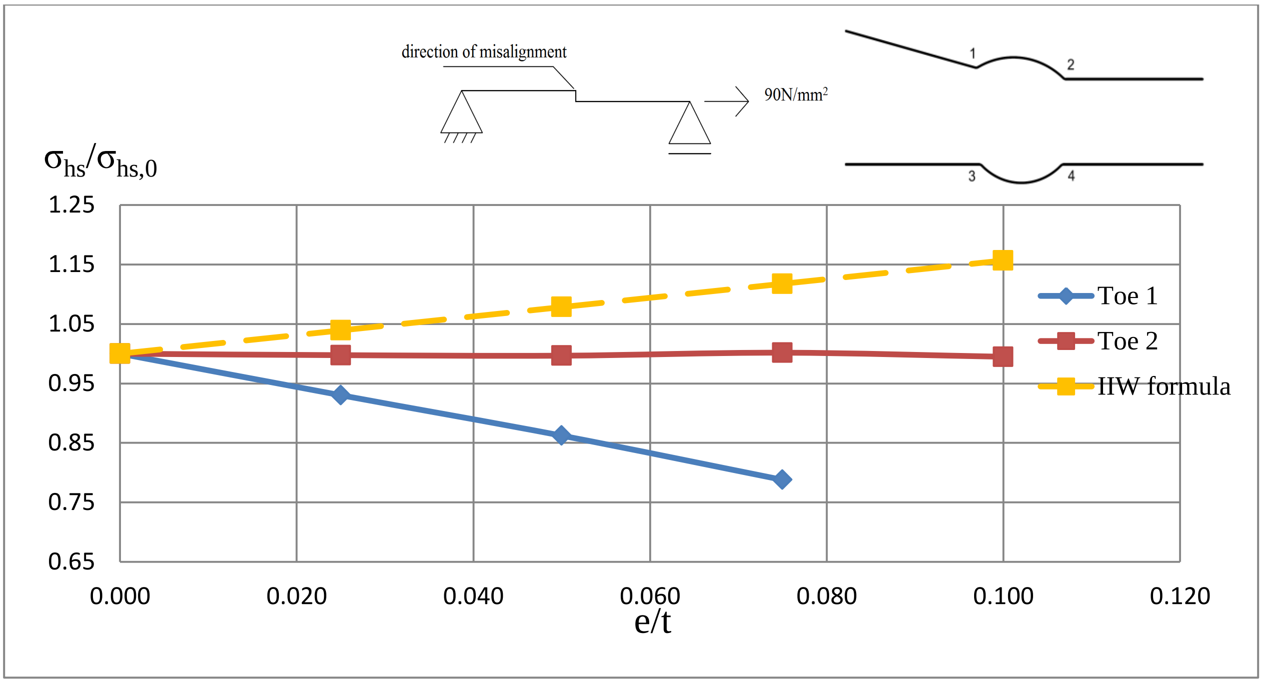


Fig 3-14 Effect of increasing misalignment (upwards) on structural stress. Stress magnification factor (k_m) according to [2] is also shown as "IIW formula". Simply supported quality level "B-Fatigue" double-vee joint with thickness transition.

				Toe 1	Toe 2	Toe 3	Toe 4
				Hot spot stress $\sigma_{hs,0}$ (N/mm^2)			
				151.324	226.355	1.962	N.C
P (N/mm^2)	e (mm)	t (mm)	e/t	Normalized stress ($\sigma_{hs}/\sigma_{hs,0}$)			
90	0	20	0.000	1	1	1	N.C
90	0.5	20	0.025	0.930163	0.997526	5.9862385	N.C
90	1	20	0.050	0.862216	0.996669	10.846075	N.C
90	1.5	20	0.075	0.787866	1.00167	16.001529	N.C
90	2	20	0.100	-	0.99484	20.53262	N.C

Tab 3-3 Normalized structural stress results. Values are depicted in Fig 3-14.

3.5.2. Effective Notch Stress Changes Due to Misalignment

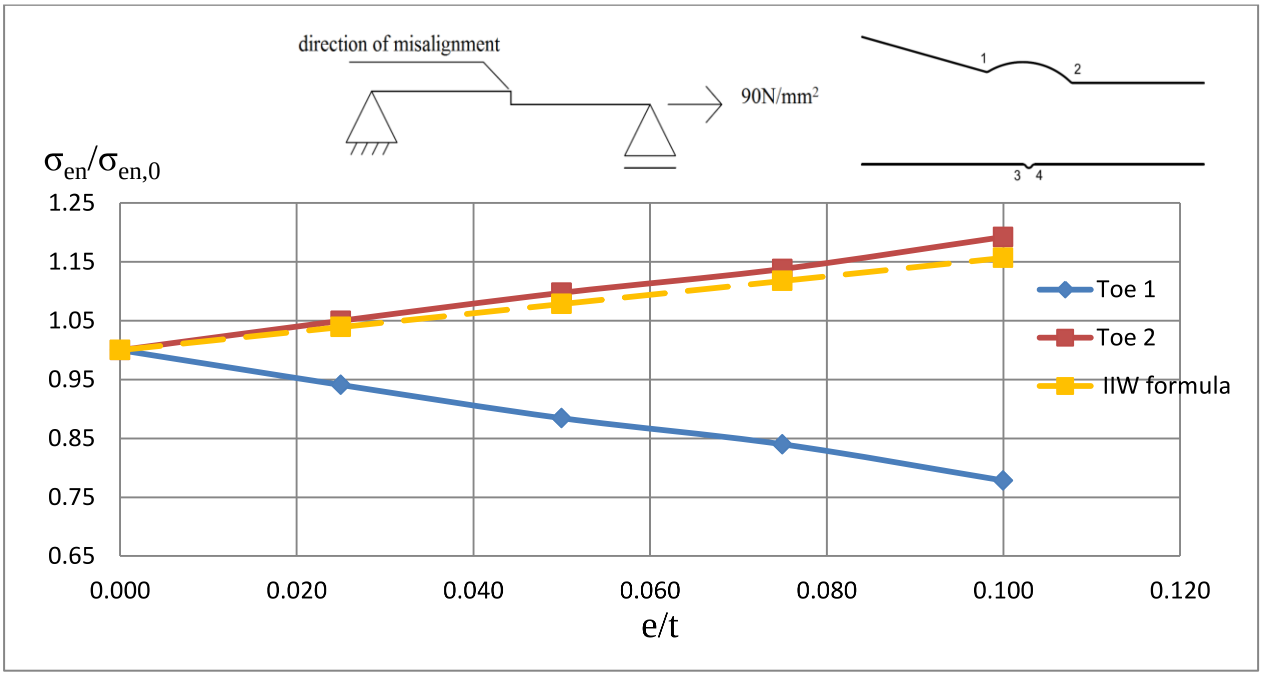


Fig 3-15 Effect of increasing misalignment (upwards) on effective notch stress. Stress magnification factor (k_m) according to [2] is also shown as "IIW formula". Simply supported quality level "B-Fatigue", V- joint with thickness transition.

				Toe 1	Toe 2	Toe 3	Toe 4
				Eff. notch stress $\sigma_{en,0}$ (N/mm^2)			
				340.781	431.754	-2.215	-5.614
P (N/mm^2)	e (mm)	t (mm)	e/t	Normalized stress ($\sigma_{en}/\sigma_{en,0}$)			
90	0	20	0.000	1	1	N.C	N.C
90	0.5	20	0.025	0.940795	1.049927	N.C	N.C
90	1	20	0.050	0.884374	1.097454	N.C	N.C
90	1.5	20	0.075	0.839932	1.137954	N.C	N.C
90	2	20	0.100	0.778344	1.192364	N.C	N.C

Tab 3-4 Normalized structural stress results. Values are depicted in Fig 3-15.

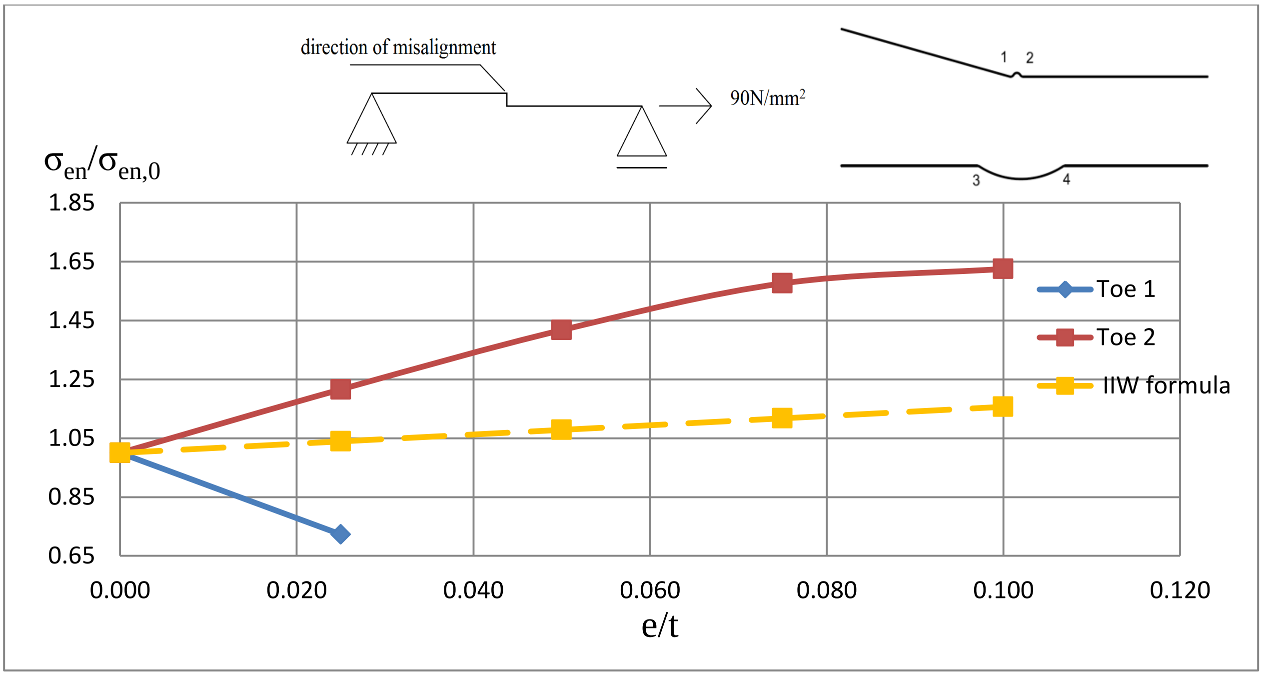


Fig 3-16 Effect of increasing misalignment (upwards) on effective notch stress. Stress magnification factor (k_m) according to [2] is also shown as "IIW formula". Simply supported quality level "B-Fatigue" inverse V- joint with thickness transition.

P (N/mm2)	e (mm)	t (mm)	e/t	Toe 1	Toe 2	Toe 3	Toe 4
				Eff. notch stress σen,0 (N/mm2)			
				385.559	302.985	-28.979	-74.107
				Normalized stress (σen/σen,0)			
90	0	20	0.000	1	1	N.C	N.C
90	0.5	20	0.025	0.722821	1.216011	N.C	N.C
90	1	20	0.050	-	1.417539	N.C	N.C
90	1.5	20	0.075	-	1.576309	N.C	N.C
90	2	20	0.100	-	1.625417	N.C	N.C

Tab 3-5 Normalized structural stress results. Values are depicted in Fig 3-16

Fig 3-16 and Tab 3-5 show that for this case –the configuration of an inverse single-vee joint, with the (small) root at the location where tension from bending overlaps with the global tension – the stresses at the critical toe (toe 2) can become much larger than for the "not-misaligned" case, much more so than predicted by the IIW recommendation formula. This may be explained by the fact that, for larger values of "unplanned" misalignment, the weld geometry becomes very irregular (increased discontinuity) at the (now critical) root: for example, there is no real "toe" anymore on the side of "toe 1" beginning at an eccentricity of 1mm, while "toe 2" looks very irregular (see Fig 3-17). This may explain the additional, high stresses which are observed.

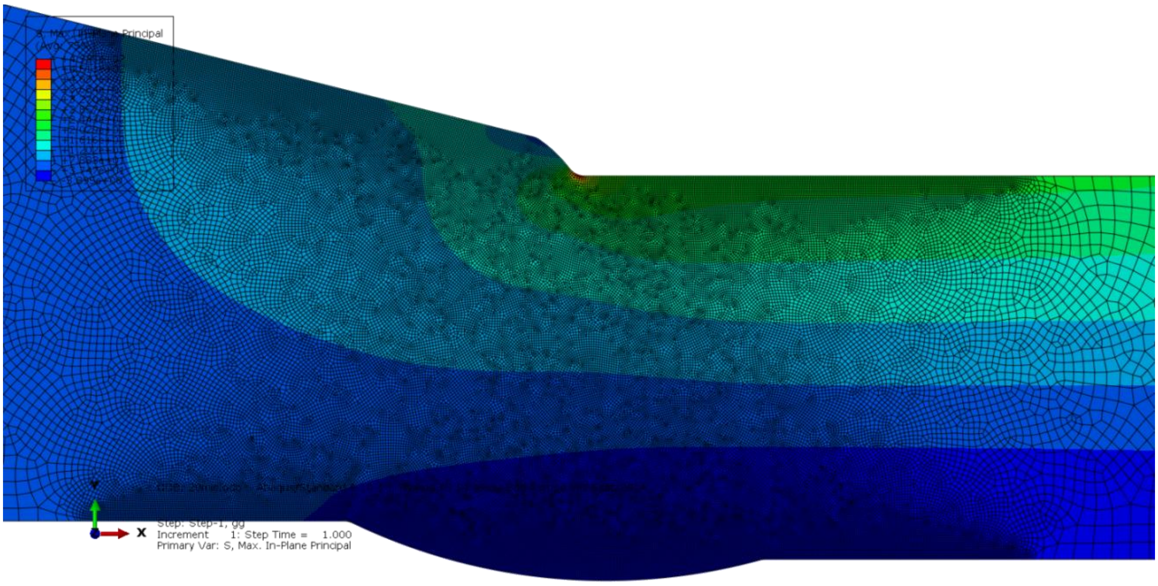


Fig 3-17 Unplanned misalignment e=2.0mm. Simply supported quality level "B-Fatigue" inverse single-vee joint with thickness transition. Toe 1 vanishes due to unplanned misalignment.

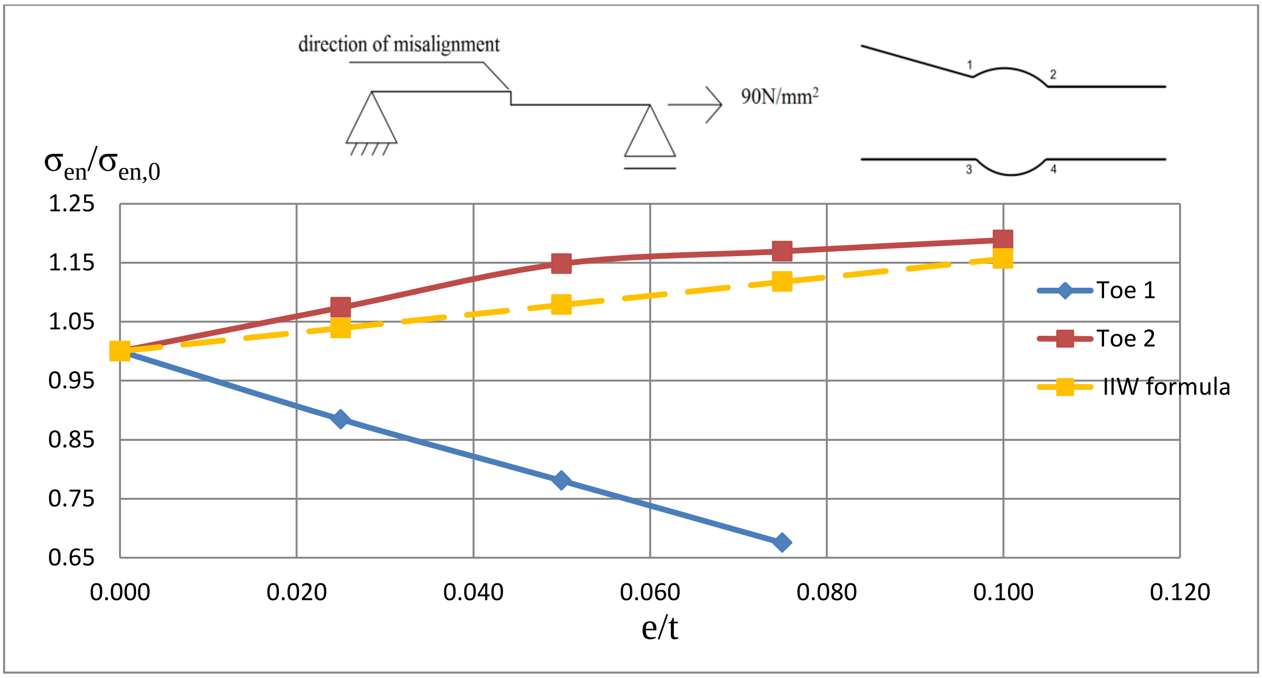


Fig 3-18 Effect of increasing misalignment (upwards) on effective notch stress. Stress magnification factor (k_m) according to [2] is also shown as "IIW formula". Simply supported quality level "B-Fatigue" double-vee joint with thickness transition.

P (N/mm^2)	e (mm)	t (mm)	e/t	Toe 1	Toe 2	Toe 3	Toe 4
				Eff. notch stress $\sigma_{en,0}$ (N/mm^2)			
				298.423	413.348	-5.352	-48.246
				Normalized stress ($\sigma_{en}/\sigma_{en,0}$)			
90	0	20	0.000	1	1	N.C	N.C
90	0.5	20	0.025	0.884543	1.074064	N.C	N.C
90	1	20	0.050	0.780453	1.148233	N.C	N.C
90	1.5	20	0.075	0.675059	1.169317	N.C	N.C
90	2	20	0.100	-	1.18841	N.C	N.C

Tab 3-6 Normalized structural stress results. Values are depicted in Fig 3-18.

Fatigue Life Calculations – With misalignment case

The **Table 3-B** shows a comparison of fatigue life predictions for the studied details and quality classes according to the different calculation methods: nominal stress, modified nominal stress, structural hot spot stress and effective notch stress approach. Thereby, as stated above, again the nominal stress was always chosen so that a fatigue life of 2 million load cycles is achieved. Note that in these calculations the misalignment effect is considered. As mentioned in chapter 2, according to IIW Recommendations, in cases where the stress magnification factor $\mathbf{k_m}$ is calculated directly, the misalignment effect should be calculated with an effective stress magnification factor called $\mathbf{k_{m,eff}}$ [2].

In Fig 2-39, the stress magnification factors ($\mathbf{k_m}$) which are already covered in verification methods and effective stress magnification factor ($\mathbf{k_{m,eff}}$) which should be considered in calculations, are shown. The following procedure explains the calculation of fatigue life cycles:

- The allowable misalignment is given by IIW Recommendations in fatigue class tables for nominal stress approach (see Fig 3-8). Based on this restriction, e=1.0mm (5% of the plate thickness) is taken as the considered unplanned misalignment in all cases. So, an additional 1mm of planned misalignment is to be added for the calculation of modified nominal stress (e=10mm+1mm= 11mm). The updated $\mathbf{k_m}$ factor is equal to 1.861.
- The quality level "B-Fatigue" joints are assumed to be welded in flat position so the $\mathbf{k_m}$ factors are selected accordingly (see Fig 2-39).
- All fatigue life cycles are calculated with $\Delta\sigma_{eff}$, where the value is calculated with the expressions given in Eq.2.3. According to Fig 2-39, the "default value of $k_{m,eff}$" is now 1,10 (quality class "B-Fatigue") , instead of 1,25 (which was valid for class "B").
- Due to high planned eccentricity, toe 3 and toe 4 are under compression and the minimum in-plane stresses are usually relatively low. The fatigue life cycles are not calculated at these points.
- Further, more generally valid explanations were already given in chapter 2.

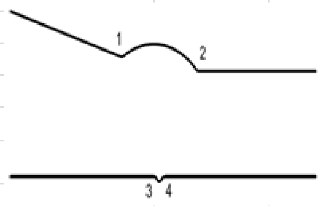
		Considered			Nominal	CALCULATED STRESSES - Case with misalignment [N/mm²]							
					FAT-CLASS	Toe 1				Toe 2			
Welding	Joint type	Misalignment	Support Con.	Quality	≈Load(N/mm2)	$\Delta\sigma_{nom}$	$\Delta\sigma_{m.nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{m.nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$
Butt Weld w. Tran.	Y-Joint	e=1mm	Simple	B-Fatigue	90	90.000	167.490	144.103	301.378	90.000	167.490	237.922	473.830
Butt Weld w. Tran.	rev. Y-Joint	e=1mm	Simple	B-Fatigue	90	90.000	167.490	N.A	N.A	90.000	167.490	222.131	429.493
Butt Weld w. Tran.	X-Joint	e=1mm	Simple	B-Fatigue	90	90.000	167.490	130.474	232.905	90.000	167.490	225.601	225.601

		Considered			Nominal	EFFECTIVE STRESSES ($\Delta\sigma_{i,eff}$) - Case with misalignment [N/mm²]							
					FAT-CLASS	Toe 1				Toe 2			
Welding	Joint type	Misalignment	Support Con.	Quality	≈Load(N/mm2)	$\Delta\sigma_{nom}$	$\Delta\sigma_{m.nom}$	$\Delta\sigma_{hs,eff}$	$\Delta\sigma_{en,eff}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{m.nom}$	$\Delta\sigma_{hs,eff}$	$\Delta\sigma_{en,eff}$
Butt Weld w. Tran.	Y-Joint	e=1mm	Simple	B-Fatigue	90	90.000	167.490	not relevant		90.000	167.490	248.105	474.929
Butt Weld w. Tran.	rev. Y-Joint	e=1mm	Simple	B-Fatigue	90	90.000	167.490			90.000	167.490	241.337	451.267
Butt Weld w. Tran.	X-Joint	e=1mm	Simple	B-Fatigue	90	90.000	167.490			90.000	167.490	248.991	454.683

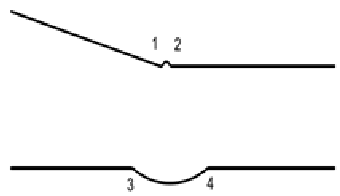
		Considered			Nominal	FATIGUE LIFE CYCLES - Case with Misalignment							
					FAT-CLASS	Toe 1				Toe 2			
Welding	Joint type	Misalignment	Support Con.	Quality	≈Load(N/mm2)	nom.	mod. nom	hot spot	eff. not.	nom.	mod. nom	hot spot	eff. not.
Butt Weld w. Tran.	Y-Joint	e=1mm	Simple	B-Fatigue	90			not relevant				1.31E+05	2.13E+05
Butt Weld w. Tran.	rev. Y-Joint	e=1mm	Simple	B-Fatigue	90	2.00E+06	3.10E+05			2.00E+06	3.10E+05	1.42E+05	2.48E+05
Butt Weld w. Tran.	X-Joint	e=1mm	Simple	B-Fatigue	90							1.30E+05	2.42E+05

Quality	Effective stress formula
B-Fatigue	if $\frac{\Delta\sigma_{hs(en)}}{\Delta\sigma_{hs(en),0} * 1.05} \leq 1.10$, $\Delta\sigma_{eff} = 1.10 * \Delta\sigma_{hs(en),0}$ else $\Delta\sigma_{eff} = \frac{\Delta\sigma_{hs(en)}}{1.05}$

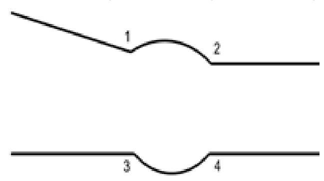
$CAFL_{nom}$	66.33 MPa
$CAFL_{hs}$	73.70 MPa
$CAFL_{en}$	165.825 MPa



Y-Joint quality "B-Fatigue"



Inverse Y-Joint quality "B-Fatigue"



X-Joint quality "B-Fatigue"

Tab 3-B Calculated stresses and fatigue life cycle calculations of butt welds at thickness transition. Misalignment is included.

Note that the fatigue life cycles are only calculated for the weld toe 2, where increasing misalignment led to an increase in stress (see tables from Tab 3-1 to Tab 3-6). Stress results are not available at toe 1 in case of inverse single-vee joint due to geometrically unavailability (toe disappears to increasing misalignment).

The following observations can be made about the above results:

i. Again, the most obvious observation is the the “pure”, unmodified nominal stress would lead to far too high fatigue life predictions in this case.
ii. Now that misalignment was explicitly included in accordance with the IIW recommendations, the structural hot-spot and effective notch stress methods always lead to significantly lower fatigue life predictions than even the modified nominal stress approach.

4

Cruciform Joints

In this chapter, one exemplary configuration for cruciform joints is studied as well. This is done in order to include joints with fillet welds into the study. This leads to the possibility (for the nominal and the effective notch approaches) of including cracking from the root in our considerations in this study.

4.1. Considered Geometries and Misalignment

The considered cruciform joint is formed by the joining (by welding) of three different 20mm thick steel plates as schematically shown in Fig 4-1. The plates are fillet welded without any edge preparation. The vertical plate is supported by a roller support at the top and a pin support at the bottom. The middle plate is continuous and is free to rotate and move. The static system is depicted in Fig 4-1.

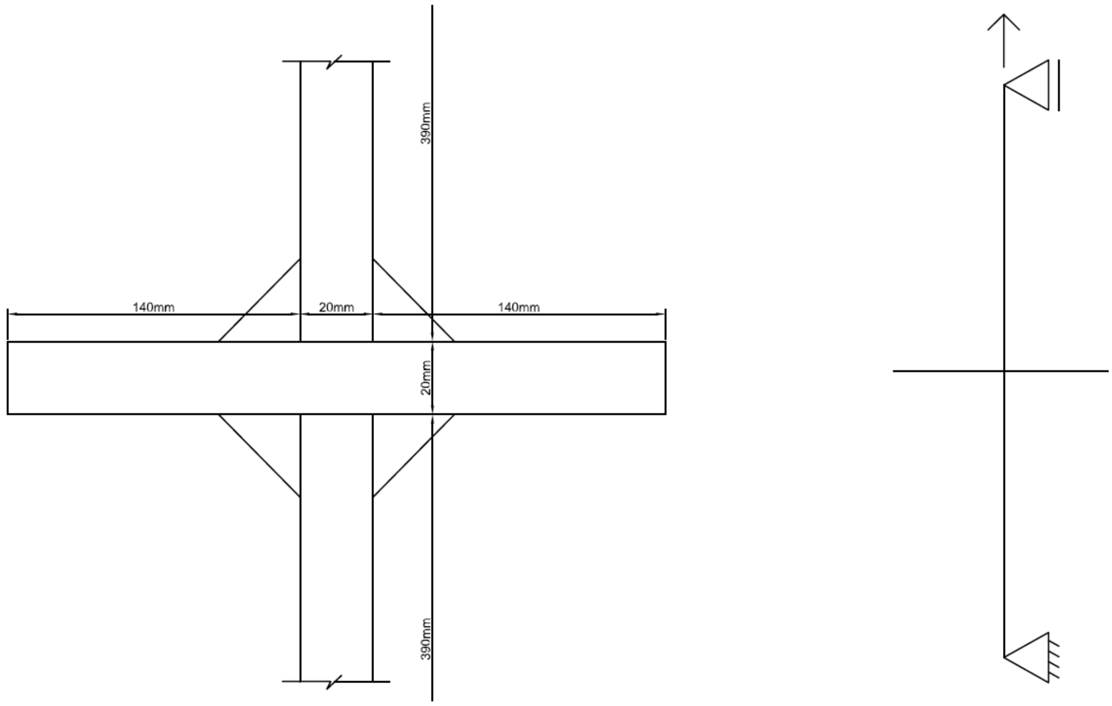


Fig 4-1 Considered dimensions and static system for cruciform joint.

In EN 1993-1-9:2005 table 8.5, it is stated that the maximum allowable misalignment is limited to 15% of the thickness of the intermediate plate. In spite of this, in this example, a linear misalignment of up to 2mm (10%) is explicitly applied to the structure (see Fig 4-4), and considered to be the upper limit of tolerance. The direction and applied misalignment step are shown in related tables and figures.

4.2. Weld Shapes and Imperfections

Excess weld convexity (weld reinforcement) is a source of “imperfection” in fillet welds, even though (for the fillet weld itself) it represents a “reinforcement” because the throat thickness increases. In this thesis, it was decided to take this additional weld thickness into account. The amount which is taken into account can be seen in Fig 4-2. With the contribution of additional weld reinforcement, the (actual) weld throat thickness $\mathbf{a_w}$ becomes 13mm. The weld reinforcement is a geometric imperfection which, in this case, actually “strengthens” the weld itself with regards to root cracking (for example, the “actual nominal” stress is thereby automatically decreased by a factor of 10/13), but makes the toe stresses worse.

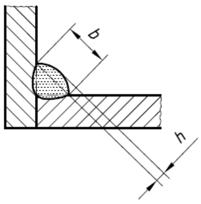
No.	Reference to ISO 6520-1:1998	Imperfection designation	Remarks	t mm	Limits for imperfections for quality levels		
					D	C	B
1.10	503	Excessive convexity (fillet weld)		⩾ 0,5	$h \leqslant$ 1 mm + 0,25 b, but max. 5 mm	$h \leqslant$ 1 mm + 0,15 b, but max. 4 mm	$h \leqslant$ 1 mm + 0,1 b, but max. 3 mm

Fig 4-2 Selected excess weld metal limitation for fillet weld (BS EN ISO 5847:2007, Table 1).

As previously mentioned in Chapter 2, in EN 1090-2:2008, the quality level “B” complies with “Execution class 3” (EXC3), which is a common choice for fatigue design of structures or parts. The height of weld imperfections can also be seen in the following figure taken from Abaqus model , Fig 4-3. Fig 4-4 shows a figure of a mesh (with contour plots of stresses) for a misaligned case, showing that the misalignment of 2mm alread leads to a “visually” observable, distorted shape (this is why the eccentricity tolerance of 3mm was considered excessive here).

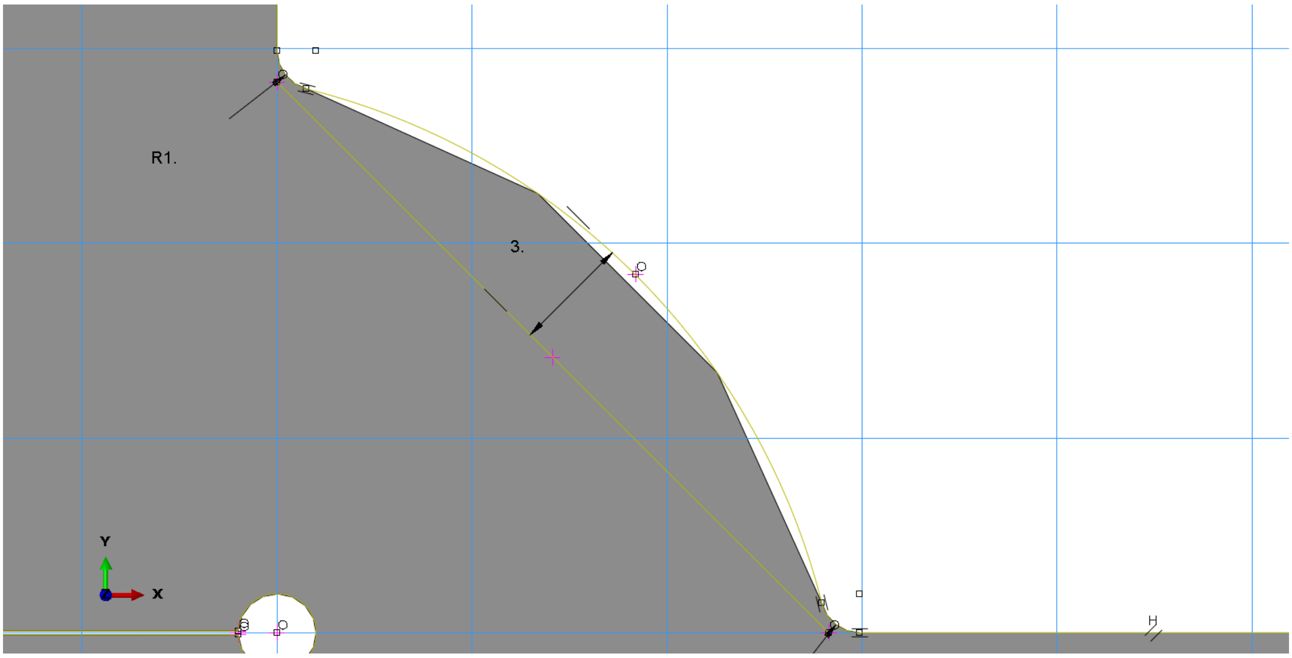


Fig 4-3 Imperfections at the fillet weld of quality level "B" cruciform joints. (all measures are in millimeters)

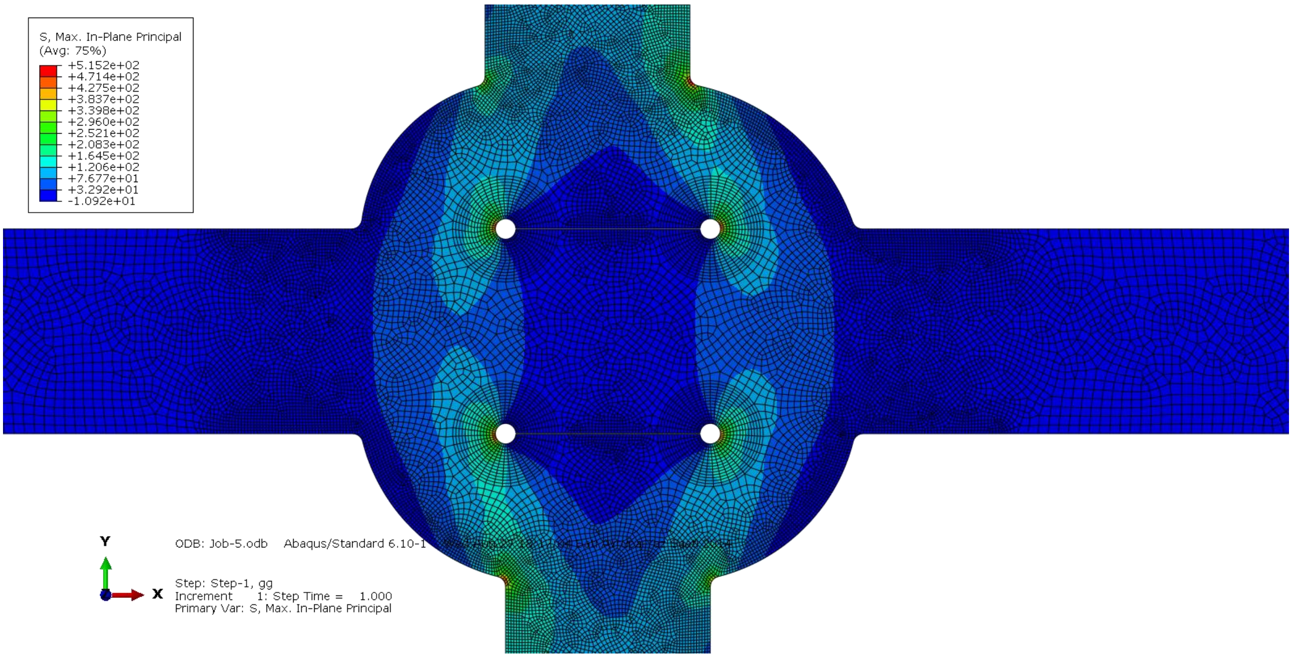


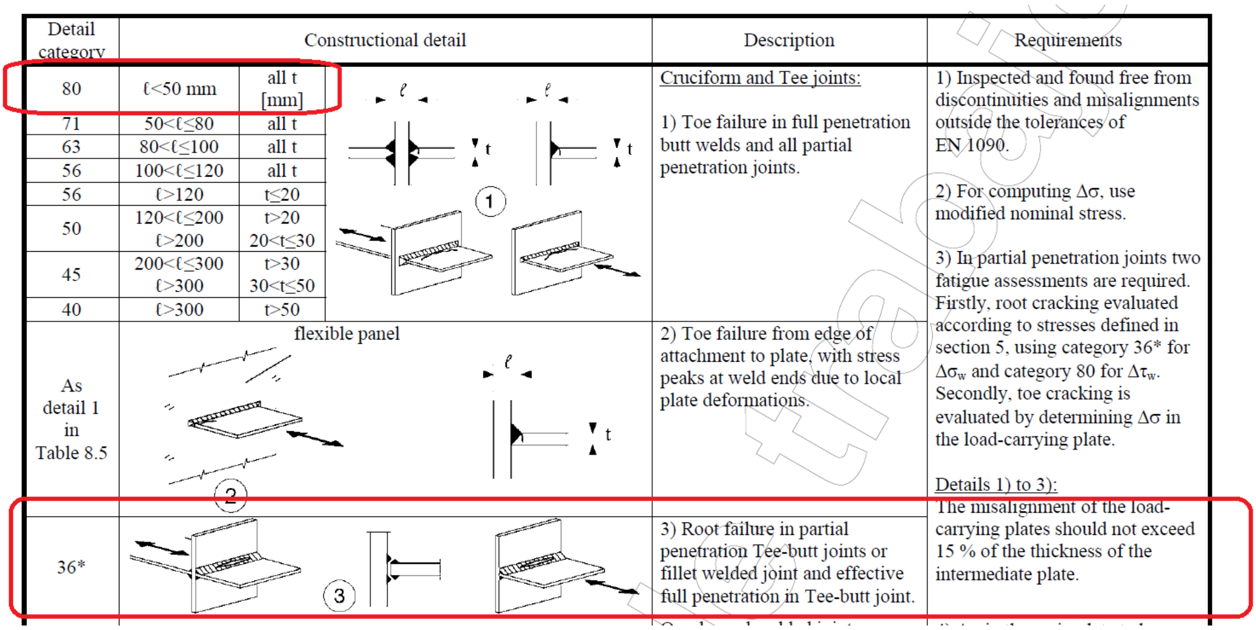
Fig 4-4 View of the mesh and maximum in-plane principal stresses at cruciform joint with e=2mm misalignment.

4.3. Applicable Fatigue Classes

In fillet welds, fatigue cracking usually – but not always – initiates from the root [1]. Therefore, verification at both weld root and weld toes is essential. As mentioned earlier in the thesis, the determination of hot spot stresses at weld root is not covered in this thesis, as it is not yet standardized and many (conflicting) methods are mentioned in the specialized literature. Nevertheless, the other assessment methods (nominal and effective notch stresses) can be used to determine stresses – and thus fatigue life - at the weld root.

4.3.1 Nominal Stress Approach

IIW Recommendations and EN 1993-1-9 recommend slightly different fatigue classes for cruciform joints with fillet welds. In Fig 4-5, the recommendations given by EN-1993-1-9 can be seen. Since, l = 48.284mm in the studied case (20mm + 2*(10^2 + 10^2)$^{1/2}$), the first detail category FAT80 is applicable for checks against toe failure. For the checks against root failure, FAT36 is applicable. Besides this, there is no restriction regarding the height of the weld reinforcement, which means that a “fatigue-appropriate” quality level without any “extra requirements” can be considered to apply, which normally means weld quality level “B”.



Detail category	Constructional detail		Description	Requirements
80	ℓ<50 mm	all t [mm]	Cruciform and Tee joints: 1) Toe failure in full penetration butt welds and all partial penetration joints.	1) Inspected and found free from discontinuities and misalignments outside the tolerances of EN 1090. 2) For computing Δσ, use modified nominal stress. 3) In partial penetration joints two fatigue assessments are required. Firstly, root cracking evaluated according to stresses defined in section 5, using category 36* for $\Delta\sigma_w$ and category 80 for $\Delta\tau_w$. Secondly, toe cracking is evaluated by determining Δσ in the load-carrying plate. Details 1) to 3): The misalignment of the load-carrying plates should not exceed 15 % of the thickness of the intermediate plate.
71	50<ℓ≤80	all t		
63	80<ℓ≤100	all t		
56	100<ℓ≤120	all t		
56	ℓ>120	t≤20		
50	120<ℓ≤200 ℓ>200	t>20 20<t≤30		
45	200<ℓ≤300 ℓ>300	t>30 30<t≤50		
40	ℓ>300	t>50		
As detail 1 in Table 8.5	flexible panel		2) Toe failure from edge of attachment to plate, with stress peaks at weld ends due to local plate deformations.	
36*			3) Root failure in partial penetration Tee-butt joints or fillet welded joint and effective full penetration in Tee-butt joint.	

Fig 4-5 Selected detail categories for cruciform joints with fillet weld (EN 1993-1-9:2005 Table 8.5). Detail category to be used in assessments based on nominal stress approach.

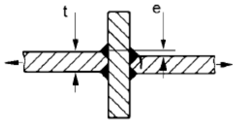
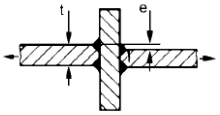
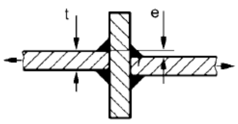
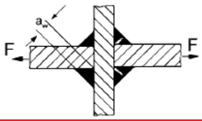
No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
400	**Cruciform joints and/or T-joints**				
411		Cruciform joint or T-joint, K-butt welds, full penetration, weld toes ground, potential failure from weld toe. Single sided T-joints	80 90	28 32	Advisable to ensure that intermediate plate was checked against susceptibility to lamellar tearing. Misalignment <15% of primary plate thickness in cruciform joints.
412		Cruciform joint or T-joint, K-butt welds, full penetration, potential failure from weld toe. Single sided T-joints	71 80	25 28	Advisable to ensure that intermediate plate was checked against susceptibility to lamellar tearing. Misalignment <15% of primary plate thickness in cruciform joints.
413		Cruciform joint or T-joint, fillet welds or partial penetration K-butt welds, potential failure from weld toe. Single sided T-joints	63 71	22 25	Advisable to ensure that intermediate plate was checked against susceptibility to lamellar tearing. Misalignment <15% of primary plate thickness in cruciform joints. Also to be assessed as 414
414		Cruciform joint or T-joint, fillet welds or partial penetration K-butt welds including toe ground joints, potential failure from weld root. For a/t<=1/3	36 40	12 14	Analysis based on stress in weld throat $\sigma_w = F / \sum (a_w \cdot l)$ l = length of weld, a_w = load carrying weld throat. Also to be assessed as 413.

Fig 4-6 Selected detail categories for cruciform joints with fillet weld (IIW Fatigue Recommendations, 2014). Detail category to be used in assessments based on nominal stress approach.

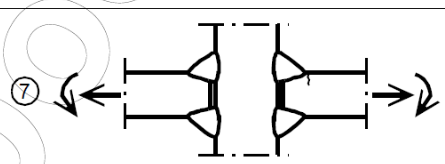
According to the IIW recommendation (Fig 4-6), a fatigue class of FAT63 is suitable for checks against toe cracking, which is lower than the value given by EN 1993-1-9. The IIW Recommendations here makes a distinction between fatigue classes for weld root failure depending on the ratio of weld throat thickness $\mathbf{a_w}$ to the plate thickness **t** (see Fig 4-6). In our case, where a= 13mm and t=20mm, FAT36 is applicable. This is also identical to the value given by EN 1993-1-9.

4.3.2 Structural Hot Spot Approach

As can be seen in Fig 4-7, a fatigue class of FAT90 against weld toe failure is given by EN 1993-1-9:2005. It is also noted in “NOTE 1” that misalignment should explicitly be included in the determination of stress. IIW Recommendations put forward the same fatigue class FAT90 against failure at weld toe (see Fig 4-8).

4.3.3 Effective Stress Approach

As seen and discussed previously, the IIW Recommendation suggest a fatigue class of 225 (FAT225) for all types of joints where a notch stress approach is used (see Fig 2-17).

90		7) Cruciform joints with load-carrying fillet welds.	7) - Weld toe angle ≤60°. - For misalignment see NOTE 1. - See also NOTE 2.

NOTE 1 Table B.1 does not cover effects of misalignment. They have to be considered explicitly in determination of stress.

NOTE 2 Table B.1 does not cover fatigue initiation from the root followed by propagation through the throat.

Fig 4-7 Selected detail category for cruciform joints with fillet welds (EN 1993-1-9:2005 Table B.1). Detail category to be used in assessments based on structural hot spot stress approach.

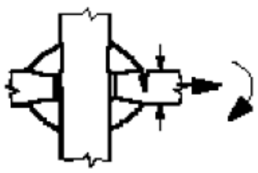
No.	Structural detail	Description	Requirements	FAT Steel	FAT Alu.
6		Cruciform joints with load-carrying fillet welds	Fillet welds, as welded	90	36

Fig 4-8 Selected detail category for cruciform joints with fillet welds (IIW Fatigue Recommendations, 2014). Detail category to be used in assessments based on structural hot spot stress approach.

4.4. Comparison of Nominal, Structural Hot Spot and Effective Notch Stress Methods – No Misalignment

By using the methods previously mentioned in Chapter 1.3, stresses are calculated at four different weld toes (toe 1, toe 2 , toe 7, toe 8) and four different weld roots (root 3, root 4, root 5, root 6) which are marked in Fig 4-9.

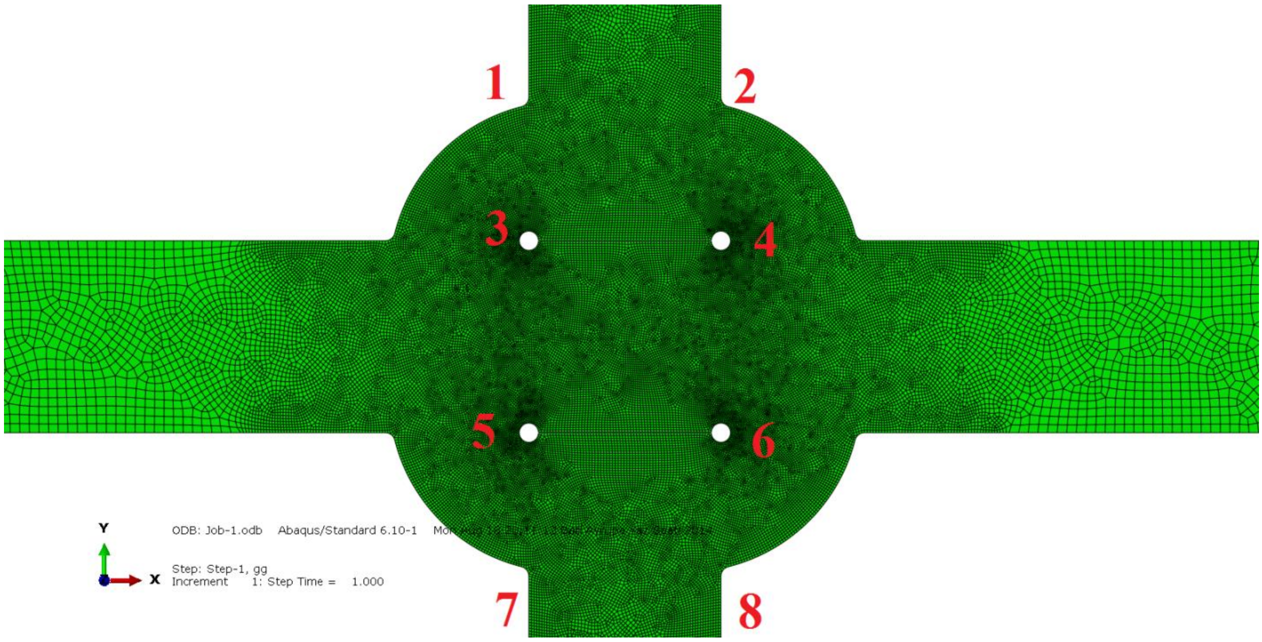
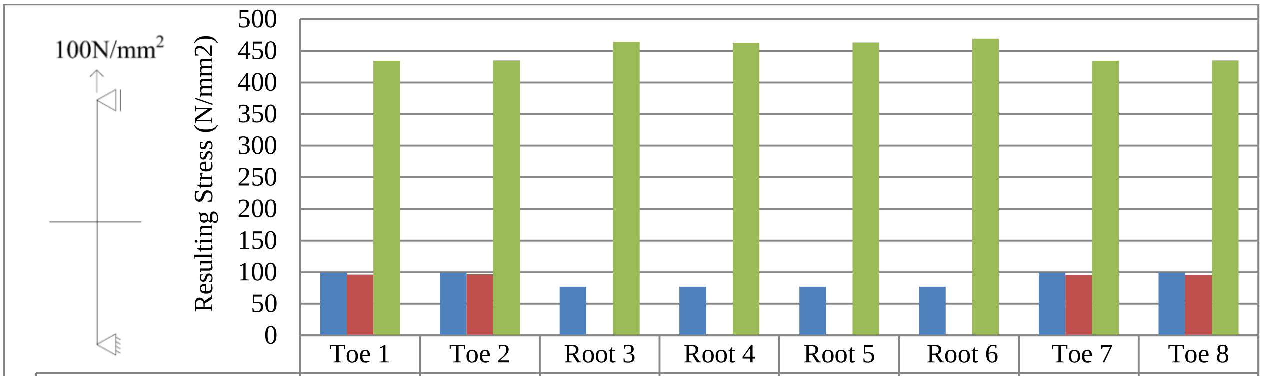


Fig 4-9 The locations of weld toes and roots.

Since two different sources of crack (toe or root) were studied simultaneously here, it was not sensible/possible to apply directly the "nominal" stress that leads to a calculated fatigue life of $2*10^6$ load cycles in this case. Instead, a uniform tensile stress of $\boldsymbol{\sigma_{nom}}$=100N/mm^2 is applied to the top end of the vertical plate. The loaded region can be seen in Fig 4-1 as well. Due to the "weld reinforcement" (i.e. larger actual weld throat thickness) considered, it was decided that – for better comparison – the nominal root stress will be calculated under consideration of this extra thickness in this thesis. This was considered necessary because otherwise the nominal stress approach could not benefit from the extra thickness, while the effective notch stress "automatically" would. The nominal stress at the weld root can be determined with the following Eq.4.1:

$$\sigma_{\text{nom,root}} = \frac{\sigma_{\text{nom}} * t}{2 * a} \tag{4.1}$$

where **t** is the plate thickness of the loaded plates and **a** is the weld throat thickness, including the reinforcement (imperfection) of 3mm when present.



	Toe 1	Toe 2	Root 3	Root 4	Root 5	Root 6	Toe 7	Toe 8
Nominal stress	100.000	100.000	76.923	76.923	76.923	76.923	100.000	100.000
Hot spot stress	96.260	96.746					95.907	95.829
Effective notch stress	434.389	434.555	463.999	462.476	463.205	468.960	434.516	434.794

Fig 4-10 Comparison of nominal, structural hot spot and effective notch stresses. Resultant maximum in-plane principal stresses for cruciform joints with fillet weld. Weld reinforcement of 3mm is included. No misalignment case.

The results of the comparison of stresses can be seen in Fig 4-10. As stated previously, the structural hot-spot stress could not be calculated in the weld root. The small differences in effective notch stresses between otherwise “symmetrical” weld toes or roots (e.g. root 3 and root 6) are due to slight asymmetries in the mesh geometry. The differences are, however, at or below 1%.

Fatigue Life Calculation – No misalignment case

The following **Table 4-A** shows a comparison of fatigue life predictions for the studied details and quality classes according to the different calculation methods: nominal stress, structural hot spot stress and effective stress approach. Since the fatigue classes are different in Eurocode 3 and IIW Recommendations for the weld toe strengths based on nominal stress, the life cycles for these points are calculated separately.

Note that in these calculations no misalignment is considered; this means that – at least for the cases of the effective notch stress and structural stress approach – the calculated fatigue life values are not (yet) valid, as for these methods misalignment must be taken into account directly; see the fatigue life calculations with misalignment further down for this effect.

	CALCULATED STRESSES [N/mm^2]											
	Toe 1			Toe 2			Toe 7			Toe 8		
Location	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$
Weld Toe	100.000	96.260	434.389	100.000	96.746	434.555	100.000	95.907	434.794	100.000	95.829	434.794
	Root 3			Root 4			Root 5			Root 6		
	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$
Weld Root	76.923	-	463.999	76.923	-	462.476	76.923	-	463.205	76.923	-	468.960

	EUROCODE 3												
	Nominal	FATIGUE LIFE CYCLES ACC. TO EUROCODE 3											
	FAT-CLASS	Toe 1			Toe 2			Toe 7			Toe 8		
Location	(N/mm2)	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$
Weld Toe	80	1.02E+06	1.63E+06	2.78E+05	1.02E+06	1.61E+06	2.78E+05	1.02E+06	1.65E+06	2.77E+05	1.02E+06	1.66E+06	2.77E+05
		Root 3			Root 4			Root 5			Root 6		
		$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$
Weld Root	36	2.05E+05	-	2.28E+05	2.05E+05	-	2.30E+05	2.05E+05	-	2.29E+05	2.05E+05	-	2.21E+05

	IIW												
	Nominal	FATIGUE LIFE CYCLES ACC. TO IIW RECOMMENDATIONS											
	FAT-CLASS	Toe 1			Toe 2			Toe 7			Toe 8		
Location	(N/mm2)	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$
Weld Toe	63	5.00E+05	1.96E+06	1.61E+06	5.00E+05	1.95E+06	1.61E+06	5.00E+05	1.96E+06	1.61E+06	5.00E+05	1.96E+06	1.61E+06
		Root 3			Root 4			Root 5			Root 6		
		$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$
Weld Root	36	2.05E+05	-	2.28E+05	2.05E+05	-	2.30E+05	2.05E+05	-	2.29E+05	2.05E+05	-	2.21E+05

Tab 4-A Calculated stresses and fatigue life cycle calculations of cruciform joints with filled welds. No misalignment case.

The following observations can be made about the above results:

i. When no misalignment is considered, for toe cracking the structural hot-spot method gives far higher fatigue e life predictions than the nominal stress approach. This is due to the higher FAT class (FAT 90 vs. 80 or even 63) combined with almost identical stresses (the structural stress is even lower due to some stress reorientation near the weld toe, approaching the weld).

ii. Again for toe cracking, the effective notch stress method, on the other hand, gives generally *lower* fatigue life predictions than the nominal stress approach. This is significantly so in the case of the Eurocode nominal FAT class (80), less so for the IIW FAT class (63).

iii. In the roots, the predictions of the nominal and effective notch stress methods are similar.

4.5. Effect of Misalignment

The effect of misalignment (linear misalignment between the loaded plates) is studied for this detail as well. A formula for the explicit, analytical consideration of stress magnification factor $\mathbf{k_m}$ is again given by the IIW Recommendation and is shown in Fig 4-11 and Fig 4-12. The Eurocode 3 has equivalent formulae, but on the resistance side (factors "k_s").

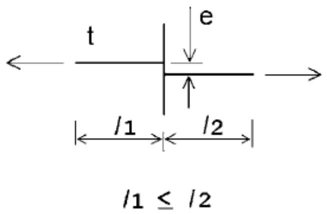
7	**Axial misalignment of cruciform joints (toe cracks)**	
		$k_m = 1+\lambda\cdot\frac{e\cdot l_1}{t(l_1+l_2)}$ λ is dependent on restraint
	λ varies from **λ=3** (fully restrained) to **λ=6** (unrestraint). For unrestrained remotely loaded joints assume: $\mathbf{l_1=l_2}$ and **λ=6**	

Fig 4-11 Stress magnification factor $\mathbf{k_m}$ for axially misaligned cruciform joints where toe cracking is expected (IIW Fatigue Recommendations:2014 Table 6.3-1)

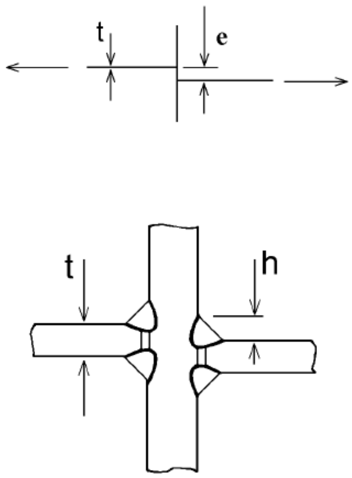
9	Axial misalignment in fillet welded cruciform joints (root cracks)	
		$k_m = 1 + \frac{e}{t+h}$

Fig 4-12 Stress magnification factor $\mathbf{k_m}$ for axially misaligned cruciform joints where root cracking is expected (IIW Fatigue Recommendations:2008 Table 6.3-1)

In the following subsections, these formulae will be compared to the stress raising effects of misalignment seen in the numerically calculated stresses, separate for structural hot spot stress σ_{hs} and the effective notch stress σ_{en}, and for the locations (toes and roots) depicted above (the roots only in the case of effective notch stresses). These stresses are again normalized by dividing them by the stresses calculated with the numerical model without misalignment at the same location.

4.5.1 Structural Hot Spot Stress σ_{hs} - Changes Due to Misalignment

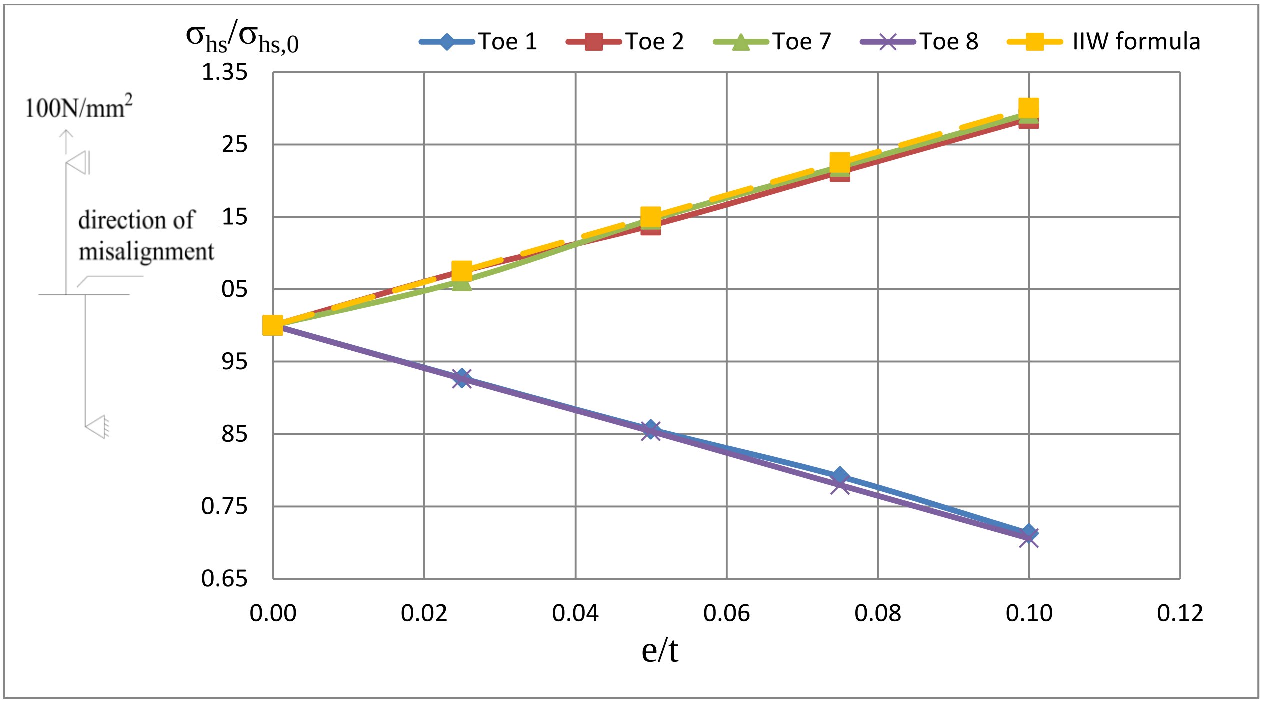


Fig 4-13 Effect of misalignment on structural stress. Stress magnification factor $\mathbf{k_m}$ according to [2] is also shown as "IIW Formula". Simply supported cruciform joint with fillet welds, case with weld reinforcement of 3mm.

				Toe 1	Toe 2	Toe 7	Toe 8
				Hot spot stress $\sigma_{hs,0}$ (N/mm^2)			
				96.260	96.746	95.907	95.829
P (N/mm^2)	e (mm)	t (mm)	e/t	Normalized stress ($\sigma_{hs}/\sigma_{hs,0}$)			
90	0.0	20	0.000	1.000	1.000	1.000	1.000
90	0.5	20	0.025	0.927	1.075	1.062	0.926
90	1.0	20	0.050	0.856	1.138	1.146	0.854
90	1.5	20	0.075	0.791	1.212	1.219	0.779
90	2.0	20	0.100	0.712	1.286	1.293	0.706

Tab 4-1 Normalized structural stress results. Values are depicted in Fig 4-13.

As can be seen in the above figure and table, the effect of misalignment on the toe stresses according to the structural hot spot stress approach is considerable, but well predicted by the IIW formula. The implications on the predicted fatigue life are discussed below.

4.5.2 Effective Notch Stress Changes Due to Misalignment

Two separate graphs and tables are reproduced, one dealing with the stresses in the weld toes, and one in the weld root. Of course, the appropriate IIW formula (see Fig 4-11 vs. Fig 4-12) was applied in each case.

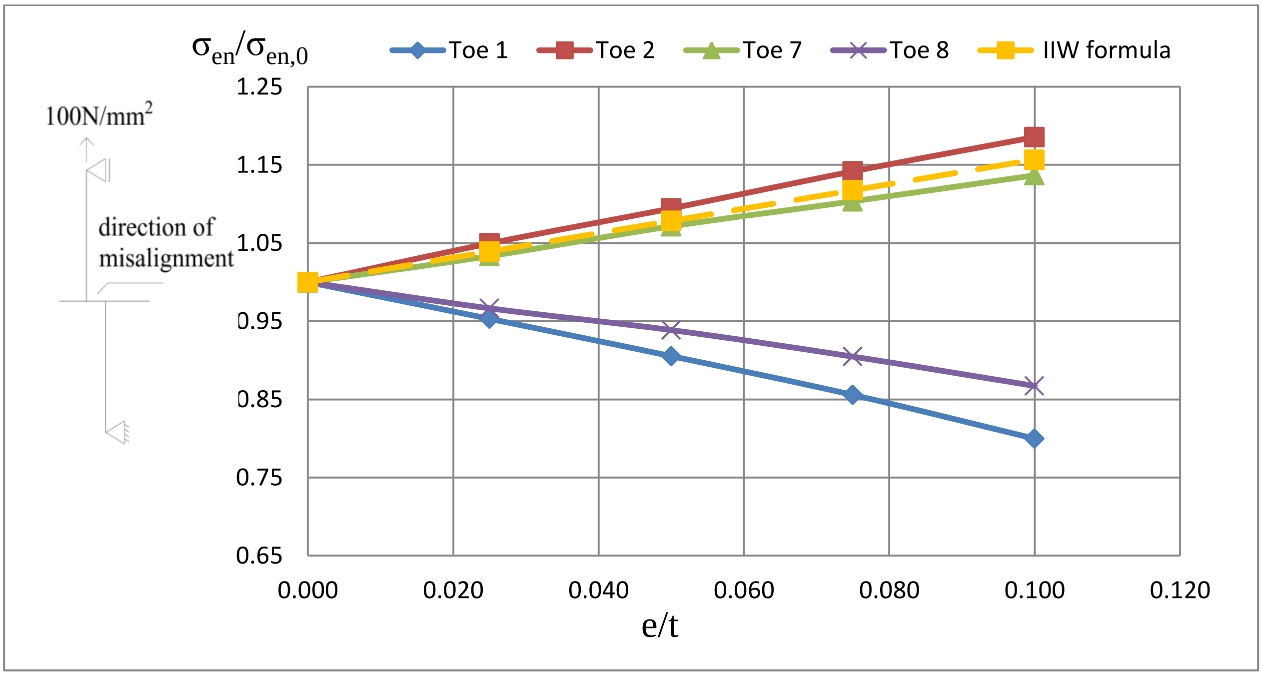


Fig 4-14 Effect of misalignment on effective notch stress in the weld toes. Stress magnification factor $\mathbf{k_m}$ according to [2] is also shown as "IIW Formula". Simply supported cruciform joint with fillet welds, case with weld "reinforcement" of 3mm.

				Toe 1	Toe 2	Toe 7	Toe 8
				Eff. notch stress $\sigma_{en,0}$ (N/mm^2)			
				434.389	434.555	434.516	434.794
P (N/mm^2)	e (mm)	t (mm)	e/t	Normalized stress ($\sigma_{en}/\sigma_{en,0}$)			
90	0	20	0.000	1	1	1	1
90	0.5	20	0.025	0.953054	1.049575	1.03332	0.966492
90	1	20	0.050	0.905297	1.094372	1.071445	0.938651
90	1.5	20	0.075	0.855659	1.141752	1.103469	0.904677
90	2	20	0.100	0.799756	1.185585	1.136718	0.867218

Tab 4-2 Normalized effective notch stress results. Values are depicted in Fig 4-14.

Again, the above figure and table show that – also for the case of the effective notch approach – the stress increases in the critical toes due to misalignment are significant, but predicted fairly well by the appropriate IIW formula for misalignment and toe cracking.

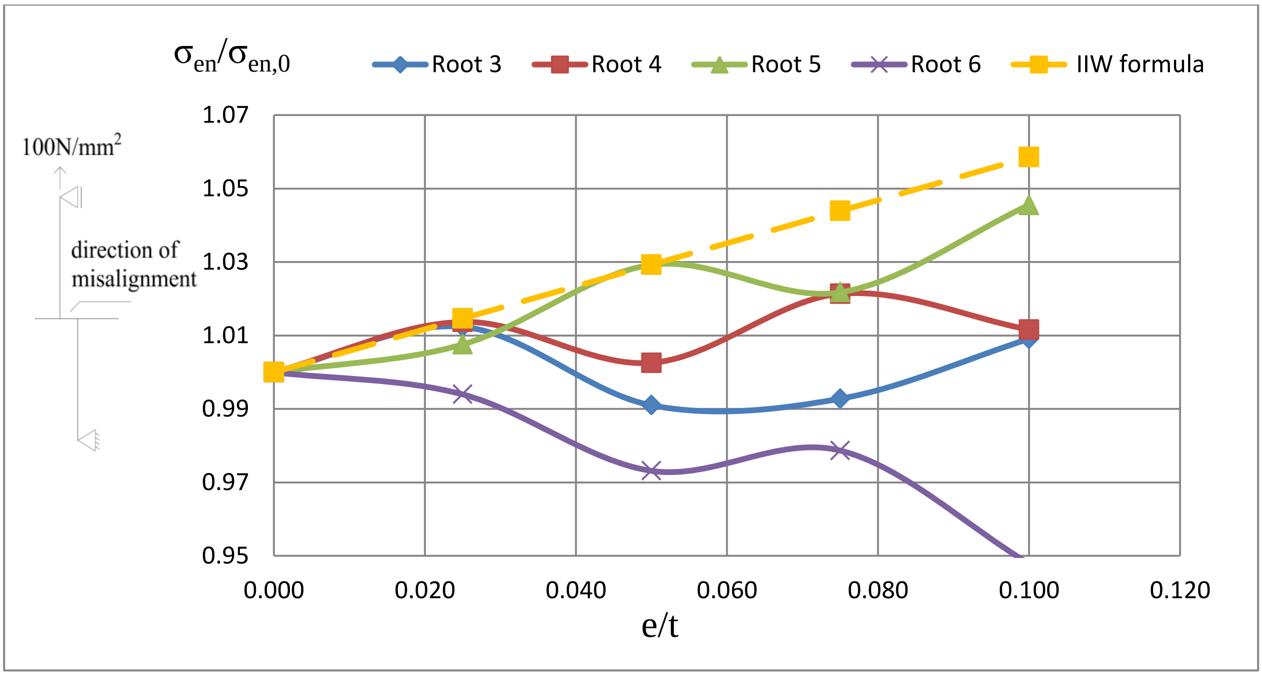


Fig 4-15 Effect of misalignment on effective notch stress in the weld roots. Stress magnification factor $\mathbf{k_m}$ according to [2] is also shown as “IIW Formula”. Simply supported cruciform joint with fillet welds, case with weld reinforcement of 3mm.

				Root 3	Root 4	Root 5	Root 6
				Eff. notch stress $\sigma_{en,0}$ (N/mm^2)			
				463.999	462.476	463.205	468.960
P (N/mm^2)	e (mm)	t (mm)	e/t	Normalized stress ($\sigma_{en}/\sigma_{en,0}$)			
90	0	20	0.000	1	1	1	1
90	0.5	20	0.025	1.012358	1.013715	1.007571	0.99398
90	1	20	0.050	0.991	1.00258	1.029255	0.973162
90	1.5	20	0.075	0.992791	1.021376	1.02177	0.978683
90	2	20	0.100	1.009101	1.011616	1.045548	0.947876

Tab 4-3 Normalized effective notch stress results. Values are depicted in Fig 4-15.

The above figure and table shows that the changes in root cracks (effective notch stresses) are less predictable in their pattern. This again could be due to the changing geometry with increasing misalignment, which makes the changes from one model to the next (with more misalignment) more “non-linear”. However, the IIW formula for this case represents an upper bound to the calculated stress increases in the relevant roots

Fatigue Life Calculations – With misalignment case

The **Table 4-B** shows a comparison of fatigue life predictions for the studied detail to the different calculation methods: nominal stress, modified nominal stress, structural hot spot stress and effective notch stress approach. Note that in these calculations the misalignment effect is considered. As mentioned in chapter 2, according to IIW Recommendations, in cases where the stress magnification factor $\mathbf{k_m}$ is calculated directly, the misalignment effect should be calculated with an effective stress magnification factor called $\mathbf{k_{m,eff}}$ [2].

In Fig 2-39, the stress magnification factors ($\mathbf{k_m}$) which are already covered in verification methods and effective stress magnification factor ($\mathbf{k_{m,eff}}$) which should be considered in calculations, are shown. The following procedure explains the calculation of fatigue life cycles:

- The allowable misalignment is given by IIW Recommendations in fatigue class tables for nominal stress approach (see Fig 4-6). Based on this restriction, the unplanned misalignment is possible up to e=3.0mm (15% of the intermediate plate thickness). In this thesis, the maximum unplanned misalignment is however taken as e= 2.0mm.
- $\mathbf{k_m}$ and $\mathbf{k_{m,eff}}$ factors are selected according to given values for cruciform joints (see Fig 2-39). However, due to additional limitations given on the footnote of the same figure, the default (minimum) value of $\mathbf{k_{m,eff}}$ factor is selected as 1+2.5*(2/20)=1.25.
- All fatigue life cycles are calculated with σ_{eff}, where the value is calculated with the expressions given in Eq.4.1. Note that $\Delta\sigma_{eff} = \sigma_{eff}$ because the load is applied with constant amplitude and with a single load step.
- Further, more generally valid explanations for the methodology used in the table were already given in chapter 2.

$$
\begin{aligned}
&if \quad \frac{\Delta\sigma_{\mathrm{hs(en)}}}{\Delta\sigma_{\mathrm{hs(en),0}} * 1.05} \le 1.25 \ , \ \Delta\sigma_{eff} = 1.25 * \Delta\sigma_{\mathrm{hs(en),0}} \\
&\text{else} \quad \Delta\sigma_{eff} = \frac{\Delta\sigma_{\mathrm{hs(en)}}}{1.05}
\end{aligned}
\qquad (4.1)
$$

	Considered	CALCULATED STRESSES [N/mm^2]											
		Toe 1			Toe 2			Toe 7			Toe 8		
Joint	Misalignment (mm)	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$
Weld Toe	e= 2mm	100.000	68.580	347.405	100.000	124.378	515.202	100.000	123.971	493.922	100.000	67.635	377.061
		Root 3			Root 4			Root 5			Root 6		
		$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$
Weld Root	e= 2mm	76.923	-	468.222	76.923	-	467.848	76.923	-	484.303	76.923	-	444.516

		EUROCODE 3													
		Nominal	FATIGUE LIFE CYCLES ACC. TO EUROCODE 3												
	Considered	FAT-CLASS	Toe 1			Toe 2			Toe 7			Toe 8			
Location	Misalignment (mm)	(N/mm2)	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	
Weld Toe	e= 2mm	80	1.02E+06	-	-	1.02E+06	8.24E+05	1.42E+05	1.02E+06	8.46E+05	1.42E+05	1.02E+06	-	-	
			Root 3			Root 4			Root 5			Root 6			
			$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	
Weld Root	e= 2mm	36	1.55E+06	-	1.17E+05	1.55E+06	-	1.18E+05	1.55E+06	-	1.17E+05	1.55E+06	-	1.13E+05	

		IIW												
		Nominal	FATIGUE LIFE CYCLES ACC. TO IIW RECOMMENDATIONS											
	Considered	FAT-CLASS	Toe 1			Toe 2			Toe 7			Toe 8		
Joint	Misalignment (mm)	(N/mm2)	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$
Weld Toe	e= 2mm	63	5.00E+05	-	-	5.00E+05	8.24E+05	1.42E+05	5.00E+05	8.46E+05	1.42E+05	5.00E+05	-	-
			Root 3			Root 4			Root 5			Root 6		
			$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$	$\Delta\sigma_{nom}$	$\Delta\sigma_{hs}$	$\Delta\sigma_{en}$
Weld Root	e= 2mm	36	1.55E+06	-	1.17E+05	1.55E+06	-	1.18E+05	1.55E+06	-	1.17E+05	1.55E+06	-	1.13E+05

Tab 4-B Calculated stresses and fatigue life cycle calculations of cruciform joints with fillet welds. Misalignment is included.

The following observations can be made about the above results:

i. The fatigue lives were only calculated for toes 2 and 7, as these become dominant due to the superposition with the bending stresses due to misalignment.
ii. In case of toe cracking the structural hot spot method gives higher fatigue life predictions than the nominal stress approach according to IIW FAT class 63. On the other hand, structural hot spot method gives lower fatigue life predictions than the nominal stress approach when Eurocode 3 FAT class 80 is considered.
iii. The effective notch stress method for toe cracking now leads to even lower fatigue life predictions than for the case without misalignment.
iv. In the roots, the predictions of the nominal and effective notch stress methods are still similar, but are now more conservative according to the effective notch stress method.

5

Sources of Error and Stress Sensitivity

5.1 Mesh Sensitivity

As mentioned earlier in Chapter 1.3, the element sizes and number of elements for the FEM modelling are selected according to suggestions given by IIW Recommendations (see Fig 1.4 and Fig 1.5). The minimum numbers of elements of the recommendation was taken as basis for the calculations, initially without a check of convergence. In some notch locations, while reading the results of effective notch stresses, a few illogical output values were examined. Increasing the number of elements had solved the problem; however this raised questions on the level of stress convergence in the models. For this reason, a mesh convergence test is conducted for an ***inverse single-vee ("Y") butt welded joint*** here (geometries from chapter 2, quality level "B"). The convergence error is shown in percentage and it is calculated by measuring the difference between current model and previous model [4].

The mesh refinement is only performed at one toe location (toe 2). The "current" element meshing (meaning the mesh used in this thesis) is shown in Fig 5-1 and the refined models are shown in Fig 5-2 and Fig 5-3.

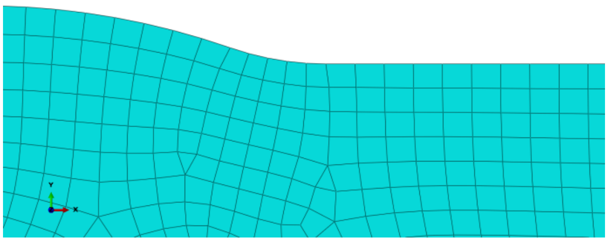


Fig 5-1 The current mesh generation with 5 equal size linear elements at the surface. Inverse Y-joint. The notch is located at toe 2.

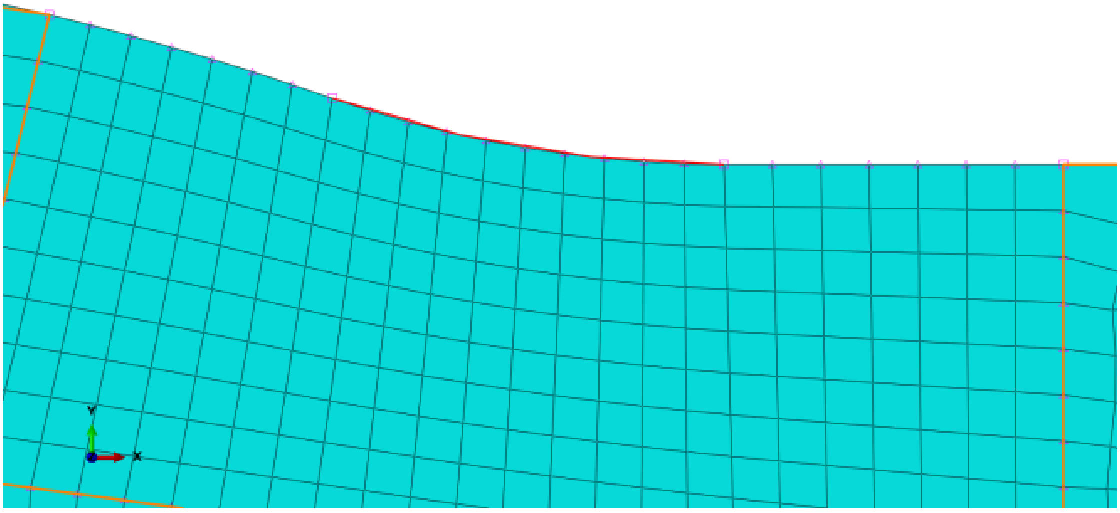


Fig 5-2 Updated mesh generation with 10 equal size linear elements at the surface. Inverse Y-joint. The notch is located at toe 2.

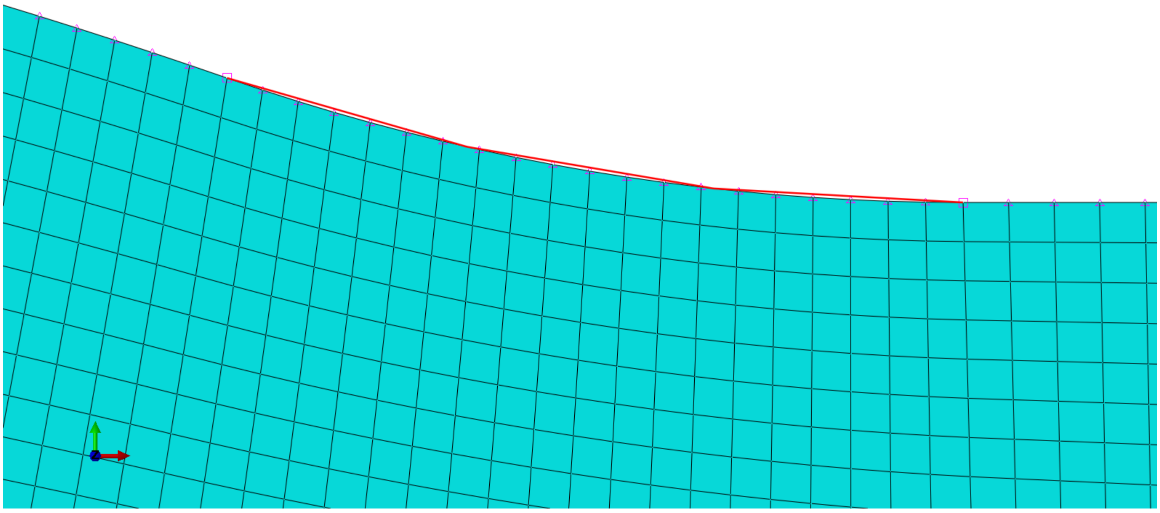


Fig 5-3 Updated mesh generation with 20 equal size linear elements at the surface. Inverse Y-joint. The notch is located at toe 2.

The results in Fig 5-4 and Tab 5-1 show that the stress convergence is satisfactory. The curve slope starts decreasing at around 10 elements case.

Another study is conducted for the ***weld root of cruciform joints***. The current generated mesh is shown in Fig 5-5. The number of elements is increased to 50 at first and 60 in the latter.

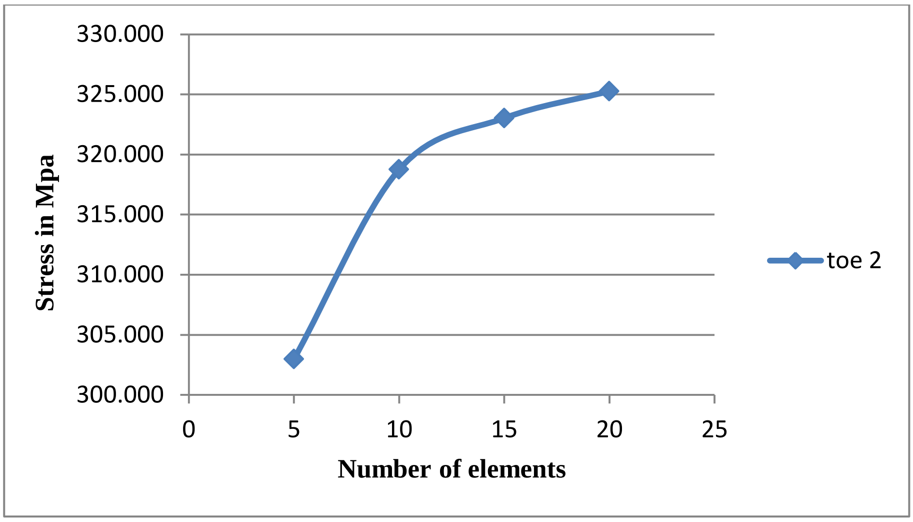


Fig 5-4 Stress convergence at toe 2 location.

Number of Elements	Maximum Principal Stress (in Mpa)	Convergence Error (% difference between one model and the previous)
5	302.985	N.C
10	318.747	4.944987718
15	323.028	1.325272113
20	325.267	0.688357565

Tab 5-1 Stress convergence test results at toe 2 location.

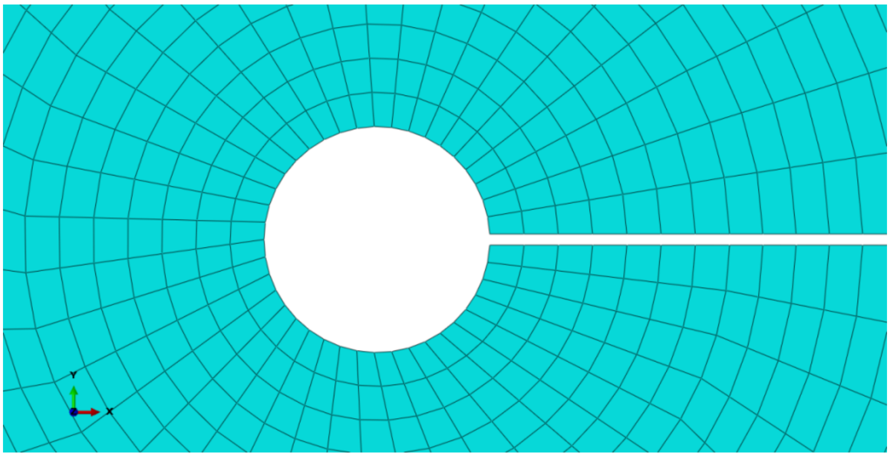


Fig 5-5 The current mesh generation with 40 equal size linear elements at the surface. Cruciform joint with fillet weld. The rounding is located at root 3.

The results of the convergence test are shown in Fig 5-6 and Tab 5-2. The stress starts converging at around 50 elements. Unlike in the previous example, this time the stress difference between the first and second model are quite high. This could create a significant error for the fatigue life cycle estimations with effective notch stress method.

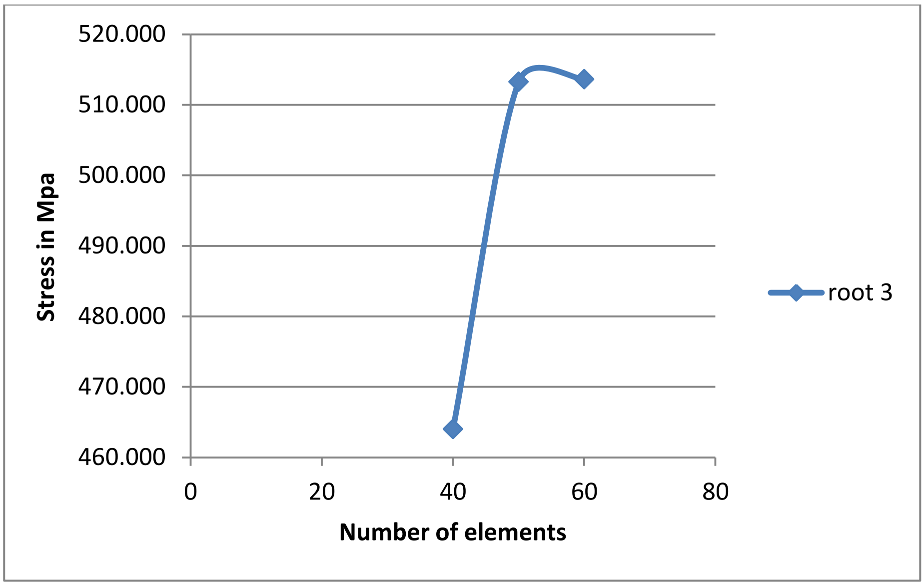


Fig 5-6 Stress convergence at root 3 location.

Number of Elements	Maximum Principal Stress (in Mpa)	Convergence Error (% difference between one model and the previous)
40	463.999	N.C
50	513.226	9.591680858
60	513.607	0.074181232

Tab 5-2 Stress convergence test results at root 3 location.

6

Summary

In this thesis, common welded joints were numerically assessed with different methods like (modified) nominal stress method, structural hot spot stress method and effective notch stress method. The aim of this project was to investigate the effect of misalignment by including weld imperfections and to compare the results with the suggested stress magnification formulas given by Eurocode 3 and IIW Recommendations.

The fatigue life cycles of different joints such as butt welded joint with equal plates of thickness, butt welded joint with thickness transition and fillet welded cruciform joint were also calculated. In the first case, no misalignment was included. Afterwards, the stress magnification factors for misalignment suggested by IIW Recommendations are used and the life cycles are recalculated.

Finally a mesh convergence test was performed to control the number of recommended elements given by IIW Recommendations.

Conclusions

Several conclusions can be drawn from the calculations carried out in this thesis:

i. The different stress-based methods for the fatigue calculation of welded joints do *not* lead to consistent predictions of fatigue life; contrary to what is led to believe in the codes and literature, there can be significant differences in the predicted lives, even for the simple, “basic” cases of joints studied in this thesis.

ii. The design codes (Eurocode 3, IIW recommendation) for fatigue design are not very clear, and not consistent, in their definition of how misalignment shall be included in the calculation of stresses for the fatigue life calculation of welded joints with (possible) linear misalignment.

iii. It is obvious, from the calculations carried out in this thesis, that the effective notch stress and the structural hot-spot stress methods require an explicit consideration of misalignment in order to be compatible with the nominal stress method or safe-sided in (almost) all cases. In the nominal stress approach, on the other hand, the calculations in this thesis seem to indicate that "unplanned" misalignment does not need to be taken into account explicitly at all, as long as the tolerances for misalignment mentioned for the different FAT classes in the IIW recommendation (but not in Eurocode 3!) are observed. Eurocode 3 is not clear about this either.

iv. For the two numerical methods (structural stress method, effective notch method), the consideration of misalignment can be carried out explicitly, meaning that misalignment is considered directly in the FEM model. However, this always requires that two models (one with and one without misalignment) are calculated.

v. Alternatively, the IIW recommendation gives analytical, "hand formulae" for the calculation of the misalignment effect. These $\mathbf{k_m}$ factors given by the IIW Recommendations (or, equivalently as k_s factors, in the Eurocode) are used to increase the stress calculated in a system without misalignment. The results in this thesis showed that the formulae are mostly safe-sided for the cases studied, with some exceptions.

vi. One exception to the above statement is represented by cases with boundary conditions that differ from the "simply supported plates", e.g. plates with one-sided encastres (fixed ends) and the other end free. In this case, the actual stress increase due to misalignment is consistently twice as large as predicted by the IIW formulae for $\mathbf{k_m}$. Furthermore, in some cases of the effective notch stress method, misalignment can lead to very inconvenient shapes of smaller weld roots, which in turn leads to very high effective notch stresses. In this case, the effects covered by the IIW formulae for $\mathbf{k_m}$ is not sufficient to cover the stress increase due to misalignment. Thus, the formulae for $\mathbf{k_m}$ are accurate for some cases (for which they were clearly derived), but are not really "general".

vii. For the butt welds at (eccentric) thickness transitions, it was shown very clearly that the nominal stress approach would be severely unsafe if applied without considering the always present, "planned" eccentricity in the joint. This was particularly severe in the studied case, where "free" plates (simple supports at the ends only) were considered, but would still be the case in more realistic boundary conditions, i.e. when the joint plates are for example part of the flange of a bridge girder and are thus additionally vertically supported by the girder web.

viii. Finally, a mesh convergence study has shown that – for some potential crack sources, especially weld toes – the "minimum" mesh sizes according to IIW do net yet lead to results that have "converged" in some of the studied models. For the effective notch stress method, the FAT class is however always connected with a certain mesh size, so it probably would be better if the IIW recommended a "prescribed" mesh size in order to avoid ambiguous results.

REFERENCES

[1] EN 1993-1-9 (2005) “Eurocode 3: Design of steel structures – Part 1-9: Fatigue”

[2] Hobbacher A. (2014) “Recommendations for Fatigue Design of Welded Joints” International Institute of Welding, doc. XIII-2460-13/XV-1440-13

[3] Nussbaumer A., Davaine L. and Borges, L. (2009) “ECCS guides on good design practice and design according to EN 1993-1-9”

[4] Radaj D., Sonsino C. M. and Fricke W. (2006) “Fatigue assessment of joints by local approaches”

[5] Dvorak P., (1994) “Avoiding pitfalls in FEA” Machine Design;11/7/94, Vol. 66 Issue 21, p78

[6] EN 1090-2 (2008) “Execution of steel structures and aluminium structures – Part 2: Technical requirements for steel structures”

[7] ÖNORM EN ISO 9692-1 (2003) “Schweißen und verwandte Prozesse – Empfehlungen zur Schweißnahtvorbereitung; Teil 1: Lichtbogenhandschweißen, WIG-Schweißen und Strahlschweißen von Staehlen”

[8] BS EN ISO (2007) “Welding – Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) – Quality levels for imperfections”

Dies ist eine Veröffentlichung des

FACHBEREICHS INGENIEURBAUKUNST (IBK) AN DER TU GRAZ

Der Fachbereich Ingenieurbaukunst umfasst die dem konstruktiven Ingenieurbau nahe stehenden Institute für Baustatik, Betonbau, Stahlbau & Flächentragwerke, Holzbau & Holztechnologie, Materialprüfung & Baustofftechnologie, Baubetrieb & Bauwirtschaft, Hochbau & Industriebau, Bauinformatik und Allgemeine Mechanik der Fakultät für Bauingenieurwissenschaften an der Technischen Universität Graz.

Dem Fachbereich Ingenieurbaukunst ist das Bautechnikzentrum (BTZ) zugeordnet, welches als gemeinsame hochmoderne Laboreinrichtung zur Durchführung der experimentellen Forschung aller beteiligten Institute dient. Es umfasst die drei Laboreinheiten für konstruktiven Ingenieurbau, für Bauphysik und für Baustofftechnologie.

Der Fachbereich Ingenieurbaukunst kooperiert im gemeinsamen Forschungsschwerpunkt „Advanced Construction Technology".
Dieser Forschungsschwerpunkt umfasst sowohl Grundlagen- als auch praxisorientierte Forschungs- und Entwicklungsprogramme.

Weitere Forschungs- und Entwicklungskooperationen bestehen mit anderen Instituten der Fakultät, insbesondere mit der Gruppe Geotechnik, sowie nationalen und internationalen Partnern aus Wissenschaft und Wirtschaft.

Die Lehrinhalte des Fachbereichs Ingenieurbaukunst sind aufeinander abgestimmt. Aus gemeinsam betreuten Projektarbeiten und gemeinsamen Prüfungen innerhalb der Fachmodule können alle Beteiligten einen optimalen Nutzen ziehen.

Durch den gemeinsamen, einheitlichen Auftritt in der Öffentlichkeit präsentiert sich der Fachbereich Ingenieurbaukunst als moderne Lehr- und Forschungsgemeinschaft, welche die Ziele und Visionen der TU Graz umsetzt.

Nummerierungssystematik der Schriftenreihe:

D – Diplom-, Masterarbeiten/Dissertationen | F – Forschungsberichte
S – Skripten, Vorlesungsunterlagen | V – Vorträge, Tagungen

Institutskennzahl:
1 – Allgemeine Mechanik | 2 – Baustatik | 3 – Betonbau
4 – Holzbau & Holztechnologie | 5 – Stahlbau & Flächentragwerke
6 – Materialprüfung & Baustofftechnologie | 7 – Baubetrieb & Bauwirtschaft
8 – Hochbau & Industriebau | 9 – Bauinformatik
10 – Labor für Konstruktiven Ingenieurbau

Fortlaufende Nummer pro Reihe und Institut / Jahreszahl