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Fatigue Assessment of Weld Terminations in Welded Cover-Plate Details; a Comparison of Local Approaches

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Abstract: Local fatigue assessment approaches have drawn engineers' attention since their advent. However, up to now, none of the available fatigue assessment codes has explicitly given instructions for assessing details with weld terminations using these approaches. In the present paper, the structural hot spot stress concept, according to different suggestions, as well as the effective notch stress method are reviewed and applied to cover-plate details, with and without transverse end weld. The predicted fatigue lives according to these methods are compared with each other and with a large set of fatigue test results. Eventually, based on the comparisons, recommendations for the assessment of weld terminations are given.

1 Introduction

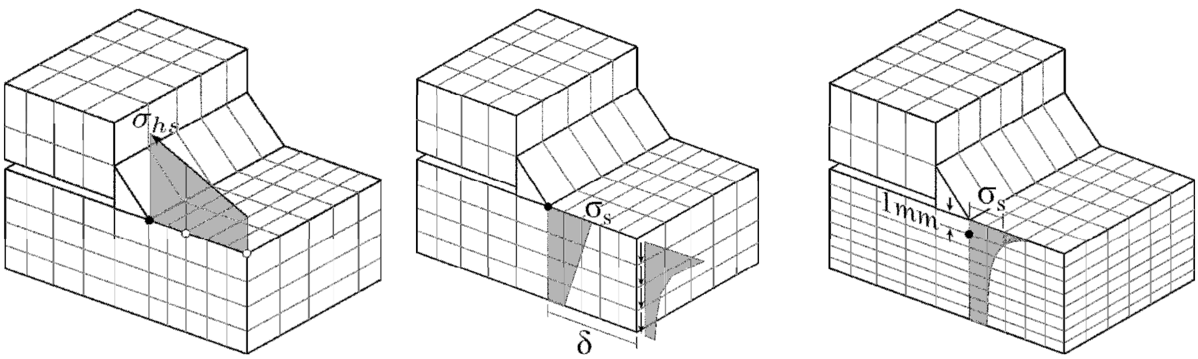
The profound developments of the computer technologies in the past few decades have led to the increasing application of computer based numerical methods. As a result, procedures for the application of new FE methods for fatigue assessment of welded details have been proposed in the literature [1-4]. Moreover, the advancements of welding techniques have resulted in more complex welded details, to which neither a nominal stress nor a design category can be assigned [5]. Therefore, local fatigue assessment approaches, which are based on the local characteristics of fatigue phenomenon, have increasingly adopted by fatigue design associations [6,7]. As these methods are generally based on numerical methods such as the finite element method, the modelling and calculation instructions have been progressively updated. However, up to now, none of the fatigue related codes and guidelines have explicitly given instructions for assessing the weld terminations using the local concepts.

The stress distribution over the plate thickness in the vicinity of a weld toe is non-linear. This peculiarity of stress distribution in welded components is primarily attributed to two distinct stress raising factors; macro-geometric stress raisers and weld notch effect. The Structural Hot Spot Stress (SHSS) disregards the notch effect caused by the weld profile and comprises all other geometric variations at the crack initiation area (hot spot) [1,8]. The hot spot stress, by definition, is a fictitious value. Nevertheless, as demonstrated in [1], in plate and shell structures it corresponds to the sum of membrane and bending stresses at the weld toe.

The conventional method for the SHSS determination is to extrapolate the perpendicular surface stress component at certain reference points to the weld toe [7]. The utilized stress can be obtained either from experiment or appropriate finite element modelling. In addition to that, over the last few years, by further advancements of computational possibilities, other variants of the structural hot spot stress method have been developed. Among these methods, particularly the approaches proposed by Dong et al. [9] and Xiao and Yamada [10] have drawn more attention. Fig. 1 shows a summary of the most common structural stress determination approaches.

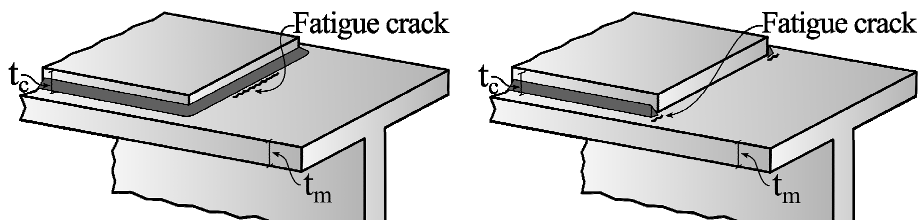
A relatively more advanced local fatigue assessment approach is known as the effective notch stress method. This method, that does not consider the elastic-plastic material behaviour at the crack tip, is based on the highest computed elastic stress (notch stress) at the critical points, i.e. weld toe and weld root. The notch stress is consisted of the sum of geometrical stress and non-linear stress peak and consequently includes all the stress raisers effects at the local notch. The effective notch stress method was first introduced by Radaj and Sonsino [3], by considering stress averaging in the micro-support theory according to Neuber Rule with a fictitious radius of 1mm for plates thicker than 5mm [7].

In order to investigate the credibility of the abovementioned fatigue assessment methods in case of weld terminations, partial length cover-plate details with and without transverse end weld are studied. Partial-length cover-plates are usually welded to the flanges of steel bridge girders in order to increase the moment capacity and consequently the allowable traffic load and span of the bridge. Numerous studies [6-8] have shown that the cover-plate end zones have a very low fatigue resistance, see Fig. 2. According to the most well-known fatigue design codes and guidelines, the cover-plate end is the most severe of all details. The availability of fatigue test results for this detail, with various end zone configurations, has made it suitable for this case study.



a) Surface stress extrapolation b) Dong method c) Xiao and Yamada method

Fig. 1: Structural stress according to different approaches



a) With transverse end weld b) Without transverse end weld

Fig. 2: Fatigue cracks in cover-plate ends with different end weld configurations

2 Structural hot spot stress determination methods

2.1 Surface stress extrapolation

The surface stress extrapolation is the conventional method to exclude the non-linear stress peak from the surface stress and determine the SHSS. In this method the SHSS can be achieved by extrapolating the surface stress towards the weld toe at certain reference points. These points are located within a reasonable distance from the weld toe where the stress is not influenced by the weld geometry. Comparative investigations have shown that for the fatigue cracks initiating from the main-plate surface, the reference points are located at distances from weld toe which are fractions of the plate thickness. It is generally accepted that at a distance of 0.4t from the weld toe, the stress is not anymore affected by the weld geometry. An assumption of linear stress distribution is normally sufficient. In such a case, the second extrapolation reference point is placed at 1.0t from the weld toe. However, in cases of pronounced non-linear structural increase towards the weld toe (e.g. welded cover-plate on a beam flange), linear extrapolation might underestimate the actual SHSS. Alternatively, a quadratic extrapolation of the stresses at 0.4t, 0.9t and 1.4t is suggested.

The surface stress profile in front of the weld toe can be obtained by means of finite element analysis. Nevertheless, systematic stress analysis of various details with different element types and mesh qualities have confirmed that certain rules for the finite element modelling and stress evaluation have to be essentially followed to obtain comparable results [2,8,11,12]. IIW recommendations [7], proposes two meshing densities for shell and solid elements; fine and coarse mesh. In this study, quadratic extrapolation of the stresses obtained from 3D solid element models with fine meshes is used.

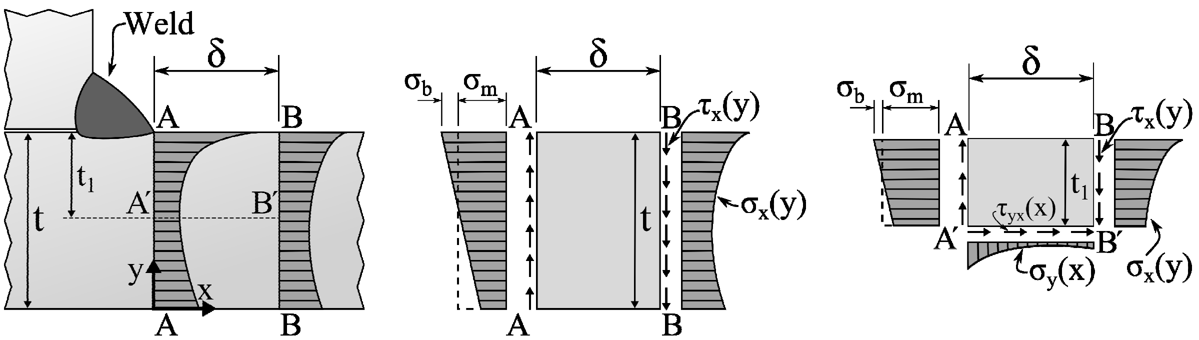
2.2 Dong method

Dong [9] has proposed another method for the structural stress calculation based on trough thickness stress linearization at a distance δ from the weld toe. As approaching the weld toe, the obtained stress values become affected by the asymptotic singularity caused by the notch. Consequently, the local stresses near the notch are mesh size sensitive. The Dong method is claimed to be mesh insensitive as it makes use of the stresses at a distance δ from the weld toe. In this method, the structural stress can be derived by establishing the equilibrium conditions at the weld toe for the normal and shear stresses acting in the distance δ (see Fig. 3). As illustrated in Fig. 3c, for the case of non-monotonic through thickness stress distribution, such as symmetric fillet welded attachments or thick sections, the linearization is performed to a finite depth $t_1 \leq t$. Subsequently by imposing equilibrium conditions between sections A-A´ and B-B´, it can be concluded that the structural stress components must satisfy the following conditions:

$$\sigma_m = \frac{1}{t_1} \cdot \int_0^{t_1} \sigma_x(y) \cdot dy + \frac{1}{t_1} \cdot \int_0^{\delta} \tau_{yx}(x) \cdot dx \tag{1}$$

$$\sigma_m \cdot \frac{t_1^2}{2} + \sigma_b \cdot \frac{t_1^2}{6} = \int_0^{t_1} \sigma_x(y) \cdot y \cdot dy + \delta \cdot \int_0^{t_1} \tau_{xy}(y) \cdot dy + \int_0^{\delta} \sigma_y(x) \cdot x \cdot dx \tag{2}$$

Although the Dong method is claimed to be mesh insensitive, investigations reported in [11,12] have shown a considerable mesh sensitivity in case of solid elements. Disregarding the influence of the shear stresses acting in the lateral faces of the elements has been found to be the reason for this observation. Nevertheless, according to [12], at δ= 0.4t, the influence of the side shear stresses is negligible.



a) Trough thickness stress distribution b) Monotonic stress distribution c) Non-monotonic stress distribution

Fig. 3: The structural stress according to Dong

2.3 Xiao and Yamada method

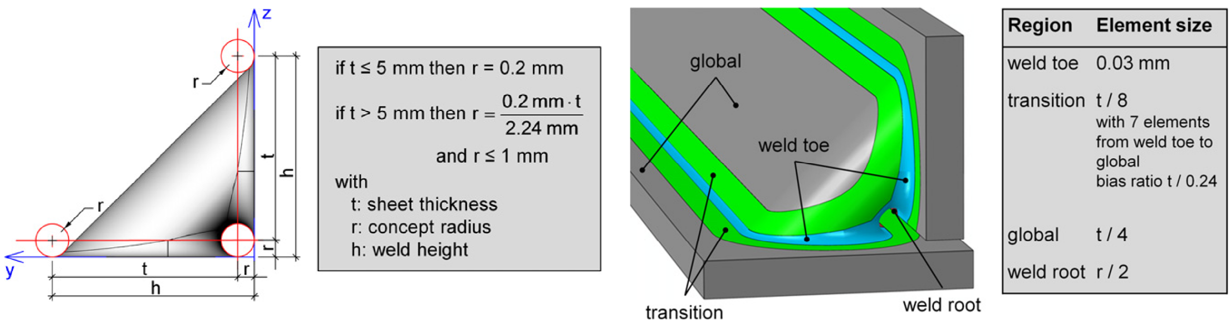
Xiao and Yamada [10] have proposed an unconventional structural stress concept based on the calculated stress at depth 1mm below the weld toe. In order to obtain the structural stress according to this procedure, the finite element model has to be constructed with a necessarily fine mesh that is capable of providing the stress at 1mm in depth with an acceptable accuracy.

This method has been evaluated in various investigations [13,14]. The results are generally reported to be in good agreement with experimental evaluations. Fricke and Kahl [13] have recommended using only elements without mid-side nodes in case of shell elements of 1mm length. Furthermore, based on assessments of partially load-carrying cover-plates and fully load-carrying lap joints, Feltz and Fricke [14] suggested utilizing maximum principal stress component of the finite element analysis results.

3 Effective Notch Stress (ENS) method

The fatigue life, irrespective of the joint geometry, can be correlated to the effective notch stress range using a single design class. The notch stress can only be computed using numerical methods such as the finite element method. For plates thicker than 5mm, weld toe or root is rounded with the reference radius of 1mm. However, in order for the numerical methods such as the finite element method to be capable of calculating the total stress at the critical sections, a sufficient element density has to be maintained. Thus, in order to get accurate results, it is principally important in this method to model the anticipated crack initiation area with an extremely fine mesh. This can be achieved by using 3D solid elements as well as 2D planar elements as long as a certain mesh size is generated.

Fricke [15] has given the practical information for analysis according to this method. It should be noted that, although the approach can be applied to complex details, it requires considerably more modelling and analysis work effort than the SHSS approach. Despite the fact that the practical application of the ENS method is generally well-defined, it is devoid of any instructions regarding the assessment of weld terminations. Aiming to obtain valid weld end's representative modelling and assessment procedures, Kaffenberger et al. [16] conducted a comparative experimental and numerical study. The study was primarily aimed to obtain recommendations for thin sheet structures. Therefore, in order to avoid modelling incompatibilities for thicker structures, a standardised model is proposed for t=2.24 mm and r=0.2 mm. The proposed model can be scaled up linearly for other plate thicknesses as shown in Fig. 4. The authors have demonstrated the applicability of this model to plates up to 20 mm thick.



a) Construction of idealised weld end b) Meshing recommendations

Fig. 4: Modelling of weld terminations according to the ENS method as proposed in [16]

4 Fatigue life assessment of cover-plate details

4.1 Existing fatigue test data

I-beams with welded cover-plates are among the most fatigue tested details. This is, on the one hand, due to the frequent application of this detail in the bridge industry, and on the other hand, as a consequence of its very poor exhibited fatigue strength. In this study, a total number of 260 fatigue test data of square-ended cover-plate details, with and without transverse end welds, are collected [17,18] (see Fig. 2). Table 1 presents a summary of the collected test series, while all the test data are plotted in Fig. 5. It should be mentioned that, the crack initiation location was reported similarly depending on the end weld configuration, in all cases. For the case of welded end cover-plates (W), the fatigue crack initiated from the weld toe in the flange mid-section, whereas fatigue cracking initiated from the weld end in the side-section of the flange for not-welded end cover-plates (NW), see Fig. 2.

Table 1: The collected fatigue test series of square-ended cover-plate details; statistical evaluation of the data is performed according to EC 3 and with a fixed slope of 3.

Detail	Data	End weld	Main plate [mm]		Cover plate [mm]		t_c/t_m	$\Delta\sigma_{mean}$	$\Delta\sigma_C$	St.D.
			Thickness	Width	Thickness	Width		[MPa]	[MPa]	
CT W	30	W	9.5	171	19	114	2	62.7	54.3	0.103
CT U	18	NW	9.5	171	19	114	2	64.9	56.2	0.100
CR W	102	W	9.5	171	14.3	114	1.5	62.0	54.4	0.099
CR U	99	NW	9.5	171	14.3	114	1.5	68.4	58.5	0.121
CS W	5	W	19	127	12.7	101	0.7	79.6	72.0	0.056
CS U	6	NW	19	127	12.7	101	0.7	89.6	72.1	0.116
All tests	260	W&NW	-	-	-	-	-	65.4	54.8	0.136

As it is apparent in Table 1, cover-plates without end welds exhibit negligibly higher fatigue strength than those with transverse end welds. Therefore, it can be concluded that, the fatigue life of cover-plate details is practically independent of the end weld configuration. This observation, which is consistent with the previous studies [17,19], implies that the stress concentration severity of cover-plates with and without transverse end welds has to be identical. Furthermore, the fatigue assessment of seam welds according to local approaches is well established and verified. Hence, a comparative study of cover-plates with and without end welds can be performed to evaluate the validity of the applied approach for fatigue assessment of weld ends.

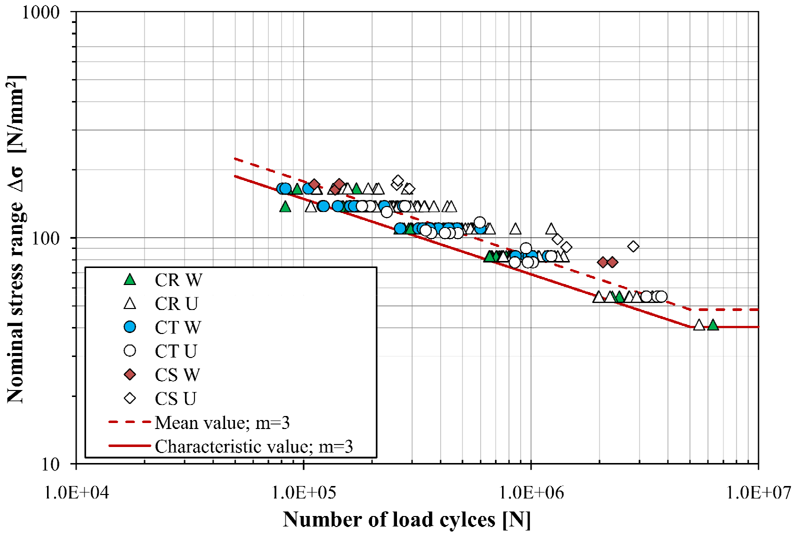


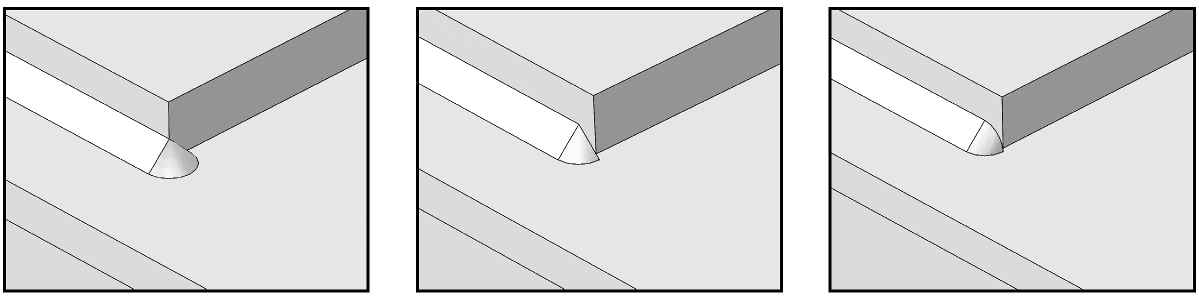
Fig. 5: Fatigue test results of square-ended cover-plate details

4.2 Fatigue life assessment according to the SHSS approach

As discussed before, the structural hot spot stress can be obtained in different ways. The basis of all these methods is to exclude the notch effect from the total stress value. Thus, as long as the same weld stiffness is provided, the hot spot stress would be independent of the weld shape. This characteristic of the SHSS approach makes it less affected by a correct representation of the weld profile compared to other local fatigue assessment methods. The effect of modelling the shape of weld ends is investigated in this study by computing the hot spot stress for different weld end models as depicted in Fig. 6. The results confirm the insignificant variation of the structural hot spot stress value for the investigated details.

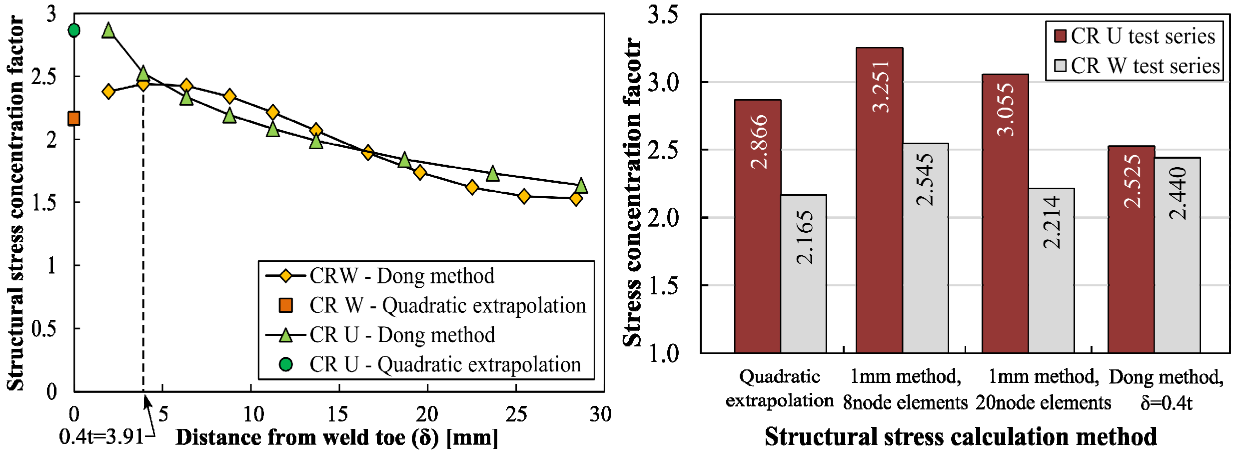
For the Dong stress calculation, the cover-plates with transverse end welds were treated according to the non-monotonic through thickness stress distribution with t_1 equal to the flange thickness. This was due to the presence of web plate underneath the crack initiation location in these details. For the case of cover-plates without transverse end welds, a monotonic stress distribution through the flange thickness was assumed.

Calculation of the hot-spot stress according to the Dong method requires a determination of the section at which equilibrium is to be satisfied. There is thus a need to study how the calculated hot spot stress varies as a function of the distance δ. As shown in Fig. 7a, the structural stress obtained from the Dong method deviates as δ changes. This finding supports the notion raised in other studies that disregarding the shear stresses on the element sides, makes the Dong method δ-dependent. However, as proposed in [12], this effect is minimized by choosing δ=0.4t.



a) Type a b) Type b c) Type c

Fig. 6: Different methods to model the weld end



a) Structural stress concentration factor as a function of distance from weld toe (δ)

b) Structural stress concentration factors obtained from different methods for cover-plates

Fig. 7: Variations of the structural stress concentration factor

The structural stress calculation results obtained from different methods for CR cover-plate test series are plotted in Fig. 7b. As it was shown in Table 1 for this test series, cover-plates without transverse end weld (CR U) have exhibited slightly higher fatigue lives than those with transverse end weld (CR W). Nevertheless, as it is apparent in Fig. 7b, a higher stress concentration factor is obtained for cover-plates without transverse end weld, irrespective of the SHSS derivation method. This observation, which is inconsistent with the experimental results, is significantly reduced when the hot spot stress is calculated according to the Dong method, where the two derived stress concentration factors are almost identical.

Fig. 8 demonstrates the fatigue lives for the cover-plate details derived from fatigue tests and predicted by different fatigue assessment approaches according to Eurocode3 [6]. As can be seen, when using the SHSS approach, the predicted fatigue lives for cover-plate details without transverse end weld are significantly more conservative than those for cover-plate details with transverse end weld. However, the fatigue life predicted by the Dong method is in a better agreement with the test results. For the case of cover-plates with transverse end weld, both the conventional extrapolation [7], and Xiao and Yamada [10] methods are capable of predicting the fatigue life with an acceptable accuracy, provided that 20node quadratic elements are used. The nominal stress method, on the other hand, considers a single fatigue design class for cover-plate details irrespective of the end weld condition, and accordingly yields

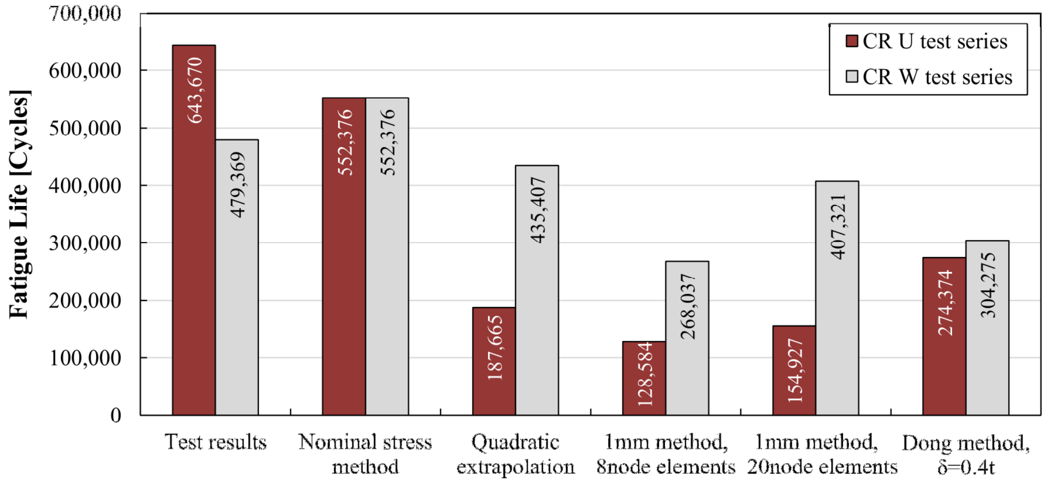


Fig. 8: Fatigue lives for the cover-plate details derived from fatigue tests and predicted by different fatigue assessment approaches

the same fatigue life prediction for both test series. When using the nominal stress method, the predicted fatigue life for the CR U test series is very close to the test results, whereas it is only slightly overestimated for the CR W test series. Having mentioned that, the nominal stress classifications have been directly obtained from experimental results, the acceptable consistency of fatigue life predictions can be justified.

As discussed before, the structural stress derived according to the Dong method is dependent on the distance from weld toe (δ). As a result, as shown in Fig. 9, different fatigue lives are predicted as δ varies. It is apparent from this chart that, for this particular detail more precise fatigue life estimations are derived when δ is chosen between 0.9t and 1.4t. In addition, the predicted fatigue lives are consistent with the test results in which slightly higher fatigue lives are reported for not welded end cover-plate details.

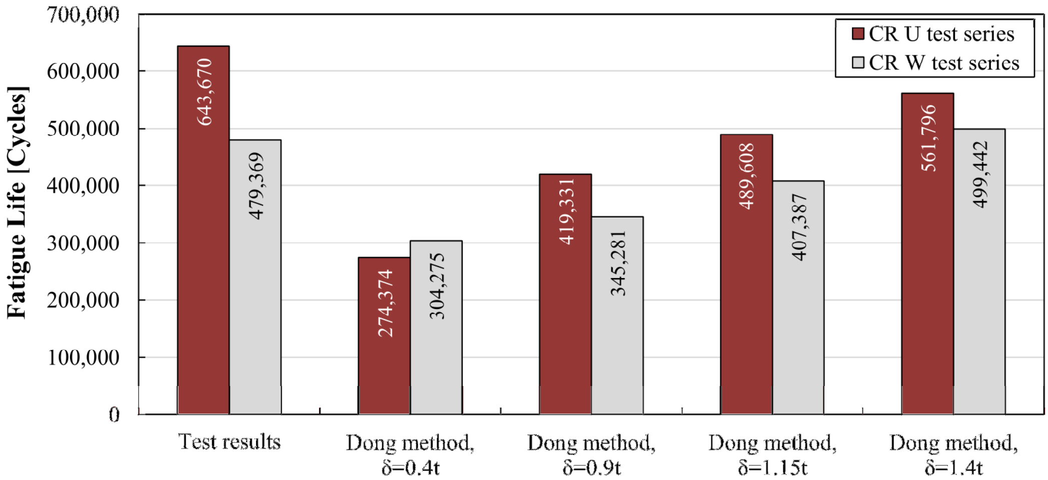


Fig. 9: Fatigue lives for the cover-plate details derived from fatigue tests and predicted by the Dong method with varying δ

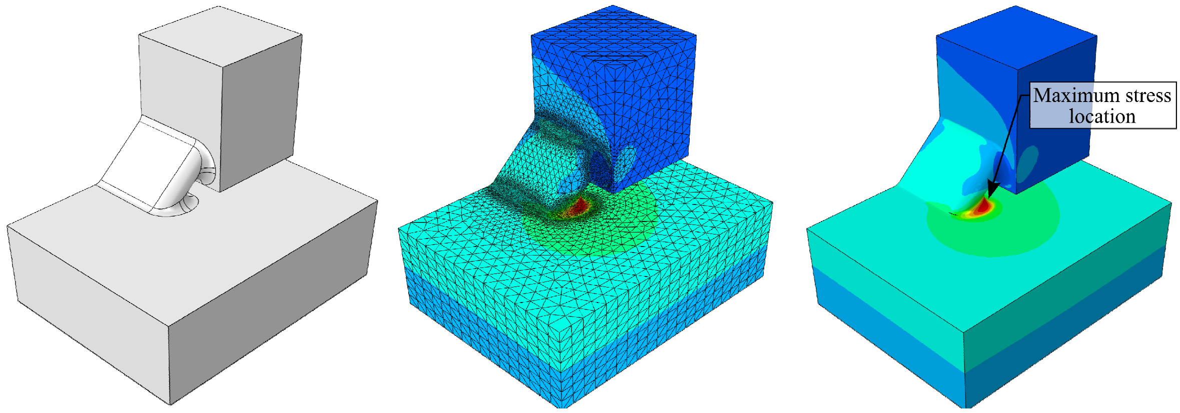
4.3 Fatigue life assessment according to the effective notch stress method

In contrast to the SHSS approach, the effective notch stress method is highly dependent on the local weld geometry as it comprises all the stress raising effects including those caused by the notch at the weld. Therefore, it is vital to model the weld geometry at the critical location in an appropriate way.

In this study, for the case of cover-plate details with transverse end welds, the fatigue assessment according to the ENS method is performed as recommended in [15]. However, for cover-plate details without transverse end welds, several modelling techniques are investigated. Fig. 6 and Fig. 10 demonstrate these models in which fatigue assessments have been conducted separately according to the recommendations given by Fricke [15] and Kaffenberger et al. [16], respectively. For the latter case, two rounding radiuses equal to 0.5mm and 1mm are investigated.

As it can be seen from Fig. 10, the calculated maximum stress location is exactly at the crack initiation location reported in the fatigue tests. On the contrary, when the weld end is modelled as shown in Fig. 6, the maximum stress is obtained at the junction of weld end and cover-plate. However, if some of the elements at this area are excluded, the maximum stress location would be found at the correct location as reported in the tests.

The effective notch stress concentration factors obtained from the investigated models are plotted in Fig. 11. It is apparent that, on the one hand, all of the investigated models yield con-



a) Modelled weld end geometry b) Meshed geometry c) Maximum principal stress plot

Fig. 10: Modelled weld end for a cover-plate detail fatigue analysis according to the ENS method [16]

servative results with stress concentration factors higher than that for CR W series. On the other hand, the FE model constructed as shown in Fig. 6a appears to result in the closest stress concentration factor. It should be also noted that, the proposed model in [16] seems also to produces relatively acceptable results if the correct rounding radius is exercised.

5 Conclusions

The following main conclusions can be drawn from this study:

1. Similar to the case of weld toe cracking, the SHSS for details with weld end terminations is quite insensitive to the shape of the weld end and the way the latter is modelled.
2. For cover-plate details with transverse end weld, quadratic extrapolation and Xiao - Yamada methods yield appropriate results if 20node quadratic elements are used. However, when 8node elements are used, the Xiao and Yamada method predicted highly conservative fatigue lives and is supposed as the least appropriate method.
3. For cover-plate details without transverse end weld, the Dong method seems to give the most accurate results. For this particular detail, the Dong stress calculation with δ varying between 0.9t and 1.4t revealed more experimentally-verified results.
4. In order to obtain accurate results according to the effective notch stress method, the exact weld geometry has to be modelled. The analysis results confirm a better agreement

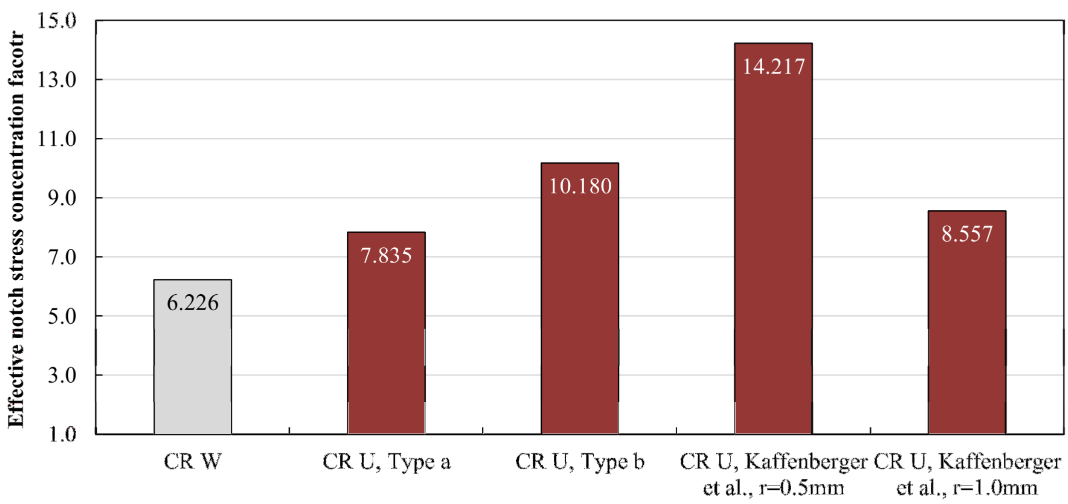


Fig. 11: The effective notch stress concentration factor obtained from several modelling techniques

with the test results when the weld termination is modelled as shown in Fig.6a.

5. Providing that an appropriate rounding radius is applied, acceptable results can be expected from the method proposed by Kaffenberger et al. [16] for weld end assessments. A radius of 1mm seems to yield the best results for the details studied in this paper.

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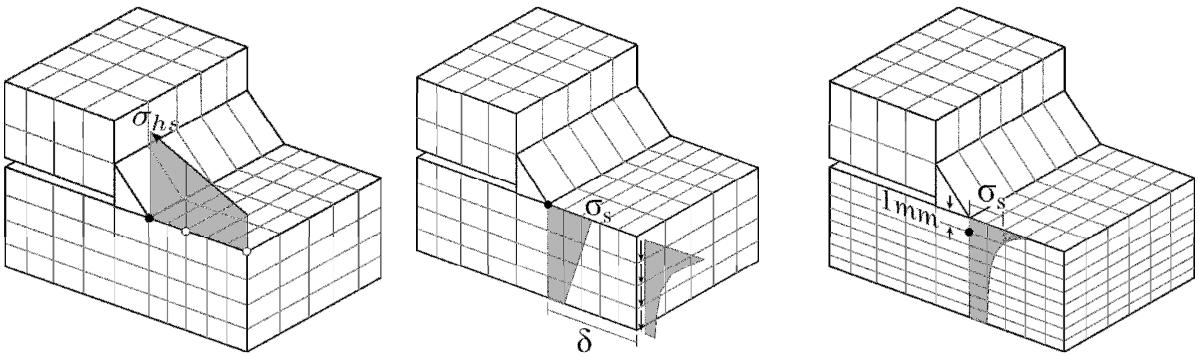
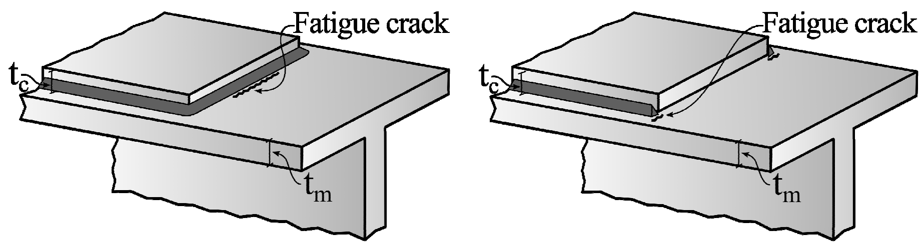
In order to investigate the credibility of the abovementioned fatigue assessment methods in case of weld terminations, partial length cover-plate details with and without transverse end weld are studied. Partial-length cover-plates are usually welded to the flanges of steel bridge girders in order to increase the moment capacity and consequently the allowable traffic load and span of the bridge. Numerous studies [6-8] have shown that the cover-plate end zones have a very low fatigue resistance, see Fig. 2. According to the most well-known fatigue design codes and guidelines, the cover-plate end is the most severe of all details. The availability of fatigue test results for this detail, with various end zone configurations, has made it suitable for this case study.



a) Surface stress extrapolation b) Dong method c) Xiao and Yamada method

Fig. 1: Structural stress according to different approaches



a) With transverse end weld b) Without transverse end weld

Fig. 2: Fatigue cracks in cover-plate ends with different end weld configurations

2 Structural hot spot stress determination methods

2.1 Surface stress extrapolation

The surface stress extrapolation is the conventional method to exclude the non-linear stress peak from the surface stress and determine the SHSS. In this method the SHSS can be achieved by extrapolating the surface stress towards the weld toe at certain reference points. These points are located within a reasonable distance from the weld toe where the stress is not influenced by the weld geometry. Comparative investigations have shown that for the fatigue cracks initiating from the main-plate surface, the reference points are located at distances from weld toe which are fractions of the plate thickness. It is generally accepted that at a distance of 0.4t from the weld toe, the stress is not anymore affected by the weld geometry. An assumption of linear stress distribution is normally sufficient. In such a case, the second extrapolation reference point is placed at 1.0t from the weld toe. However, in cases of pronounced non-linear structural increase towards the weld toe (e.g. welded cover-plate on a beam flange), linear extrapolation might underestimate the actual SHSS. Alternatively, a quadratic extrapolation of the stresses at 0.4t, 0.9t and 1.4t is suggested.

The surface stress profile in front of the weld toe can be obtained by means of finite element analysis. Nevertheless, systematic stress analysis of various details with different element types and mesh qualities have confirmed that certain rules for the finite element modelling and stress evaluation have to be essentially followed to obtain comparable results [2,8,11,12]. IIW recommendations [7], proposes two meshing densities for shell and solid elements; fine and coarse mesh. In this study, quadratic extrapolation of the stresses obtained from 3D solid element models with fine meshes is used.

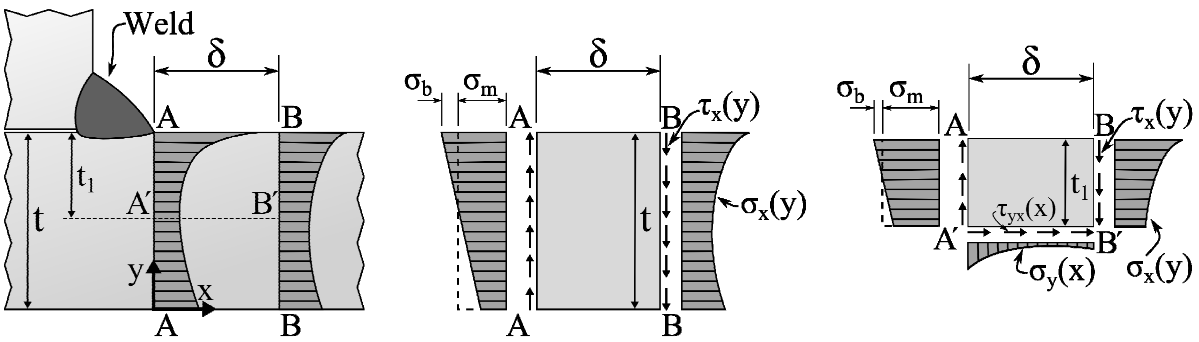
2.2 Dong method

Dong [9] has proposed another method for the structural stress calculation based on trough thickness stress linearization at a distance δ from the weld toe. As approaching the weld toe, the obtained stress values become affected by the asymptotic singularity caused by the notch. Consequently, the local stresses near the notch are mesh size sensitive. The Dong method is claimed to be mesh insensitive as it makes use of the stresses at a distance δ from the weld toe. In this method, the structural stress can be derived by establishing the equilibrium conditions at the weld toe for the normal and shear stresses acting in the distance δ (see Fig. 3). As illustrated in Fig. 3c, for the case of non-monotonic through thickness stress distribution, such as symmetric fillet welded attachments or thick sections, the linearization is performed to a finite depth $t_1 \leq t$. Subsequently by imposing equilibrium conditions between sections A-A´ and B-B´, it can be concluded that the structural stress components must satisfy the following conditions:

$$\sigma_m = \frac{1}{t_1} \cdot \int_0^{t_1} \sigma_x(y) \cdot dy + \frac{1}{t_1} \cdot \int_0^{\delta} \tau_{yx}(x) \cdot dx \tag{1}$$

$$\sigma_m \cdot \frac{t_1^2}{2} + \sigma_b \cdot \frac{t_1^2}{6} = \int_0^{t_1} \sigma_x(y) \cdot y \cdot dy + \delta \cdot \int_0^{t_1} \tau_{xy}(y) \cdot dy + \int_0^{\delta} \sigma_y(x) \cdot x \cdot dx \tag{2}$$

Although the Dong method is claimed to be mesh insensitive, investigations reported in [11,12] have shown a considerable mesh sensitivity in case of solid elements. Disregarding the influence of the shear stresses acting in the lateral faces of the elements has been found to be the reason for this observation. Nevertheless, according to [12], at δ= 0.4t, the influence of the side shear stresses is negligible.



a) Trough thickness stress distribution b) Monotonic stress distribution c) Non-monotonic stress distribution

Fig. 3: The structural stress according to Dong

2.3 Xiao and Yamada method

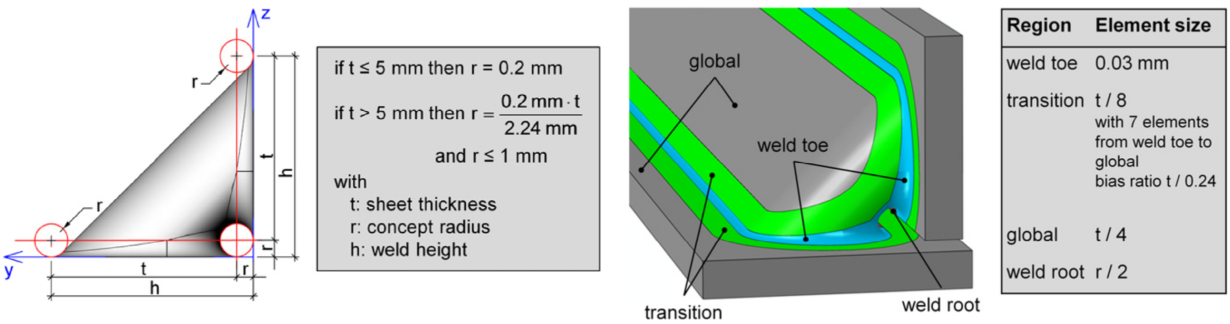
Xiao and Yamada [10] have proposed an unconventional structural stress concept based on the calculated stress at depth 1mm below the weld toe. In order to obtain the structural stress according to this procedure, the finite element model has to be constructed with a necessarily fine mesh that is capable of providing the stress at 1mm in depth with an acceptable accuracy.

This method has been evaluated in various investigations [13,14]. The results are generally reported to be in good agreement with experimental evaluations. Fricke and Kahl [13] have recommended using only elements without mid-side nodes in case of shell elements of 1mm length. Furthermore, based on assessments of partially load-carrying cover-plates and fully load-carrying lap joints, Feltz and Fricke [14] suggested utilizing maximum principal stress component of the finite element analysis results.

3 Effective Notch Stress (ENS) method

The fatigue life, irrespective of the joint geometry, can be correlated to the effective notch stress range using a single design class. The notch stress can only be computed using numerical methods such as the finite element method. For plates thicker than 5mm, weld toe or root is rounded with the reference radius of 1mm. However, in order for the numerical methods such as the finite element method to be capable of calculating the total stress at the critical sections, a sufficient element density has to be maintained. Thus, in order to get accurate results, it is principally important in this method to model the anticipated crack initiation area with an extremely fine mesh. This can be achieved by using 3D solid elements as well as 2D planar elements as long as a certain mesh size is generated.

Fricke [15] has given the practical information for analysis according to this method. It should be noted that, although the approach can be applied to complex details, it requires considerably more modelling and analysis work effort than the SHSS approach. Despite the fact that the practical application of the ENS method is generally well-defined, it is devoid of any instructions regarding the assessment of weld terminations. Aiming to obtain valid weld end's representative modelling and assessment procedures, Kaffenberger et al. [16] conducted a comparative experimental and numerical study. The study was primarily aimed to obtain recommendations for thin sheet structures. Therefore, in order to avoid modelling incompatibilities for thicker structures, a standardised model is proposed for t=2.24 mm and r=0.2 mm. The proposed model can be scaled up linearly for other plate thicknesses as shown in Fig. 4. The authors have demonstrated the applicability of this model to plates up to 20 mm thick.



a) Construction of idealised weld end b) Meshing recommendations

Fig. 4: Modelling of weld terminations according to the ENS method as proposed in [16]

4 Fatigue life assessment of cover-plate details

4.1 Existing fatigue test data

I-beams with welded cover-plates are among the most fatigue tested details. This is, on the one hand, due to the frequent application of this detail in the bridge industry, and on the other hand, as a consequence of its very poor exhibited fatigue strength. In this study, a total number of 260 fatigue test data of square-ended cover-plate details, with and without transverse end welds, are collected [17,18] (see Fig. 2). Table 1 presents a summary of the collected test series, while all the test data are plotted in Fig. 5. It should be mentioned that, the crack initiation location was reported similarly depending on the end weld configuration, in all cases. For the case of welded end cover-plates (W), the fatigue crack initiated from the weld toe in the flange mid-section, whereas fatigue cracking initiated from the weld end in the side-section of the flange for not-welded end cover-plates (NW), see Fig. 2.

Table 1: The collected fatigue test series of square-ended cover-plate details; statistical evaluation of the data is performed according to EC 3 and with a fixed slope of 3.

Detail	Data	End weld	Main plate [mm]		Cover plate [mm]		t_c/t_m	$\Delta\sigma_{mean}$	$\Delta\sigma_C$	St.D.
			Thickness	Width	Thickness	Width		[MPa]	[MPa]	
CT W	30	W	9.5	171	19	114	2	62.7	54.3	0.103
CT U	18	NW	9.5	171	19	114	2	64.9	56.2	0.100
CR W	102	W	9.5	171	14.3	114	1.5	62.0	54.4	0.099
CR U	99	NW	9.5	171	14.3	114	1.5	68.4	58.5	0.121
CS W	5	W	19	127	12.7	101	0.7	79.6	72.0	0.056
CS U	6	NW	19	127	12.7	101	0.7	89.6	72.1	0.116
All tests	260	W&NW	-	-	-	-	-	65.4	54.8	0.136

As it is apparent in Table 1, cover-plates without end welds exhibit negligibly higher fatigue strength than those with transverse end welds. Therefore, it can be concluded that, the fatigue life of cover-plate details is practically independent of the end weld configuration. This observation, which is consistent with the previous studies [17,19], implies that the stress concentration severity of cover-plates with and without transverse end welds has to be identical. Furthermore, the fatigue assessment of seam welds according to local approaches is well established and verified. Hence, a comparative study of cover-plates with and without end welds can be performed to evaluate the validity of the applied approach for fatigue assessment of weld ends.

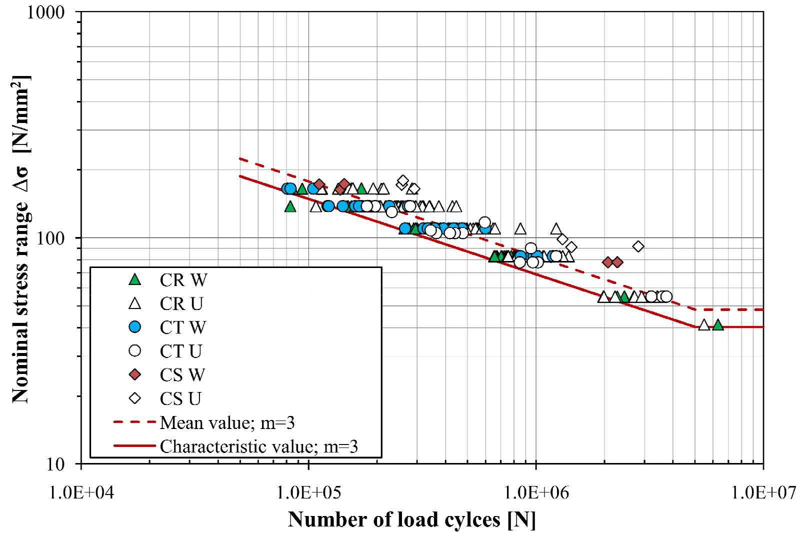


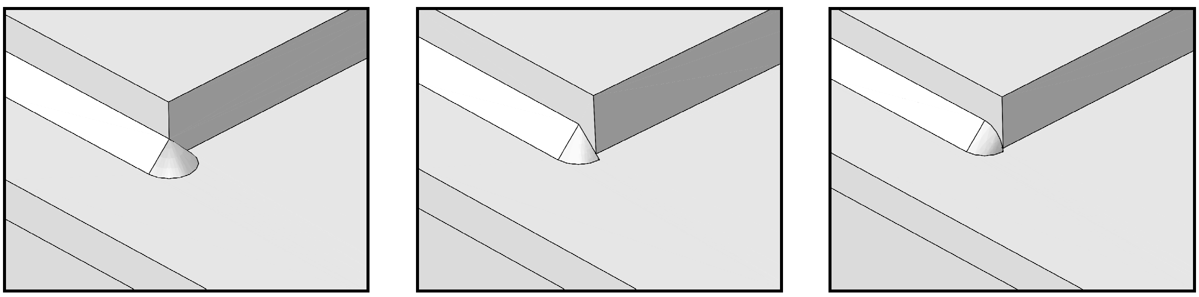
Fig. 5: Fatigue test results of square-ended cover-plate details

4.2 Fatigue life assessment according to the SHSS approach

As discussed before, the structural hot spot stress can be obtained in different ways. The basis of all these methods is to exclude the notch effect from the total stress value. Thus, as long as the same weld stiffness is provided, the hot spot stress would be independent of the weld shape. This characteristic of the SHSS approach makes it less affected by a correct representation of the weld profile compared to other local fatigue assessment methods. The effect of modelling the shape of weld ends is investigated in this study by computing the hot spot stress for different weld end models as depicted in Fig. 6. The results confirm the insignificant variation of the structural hot spot stress value for the investigated details.

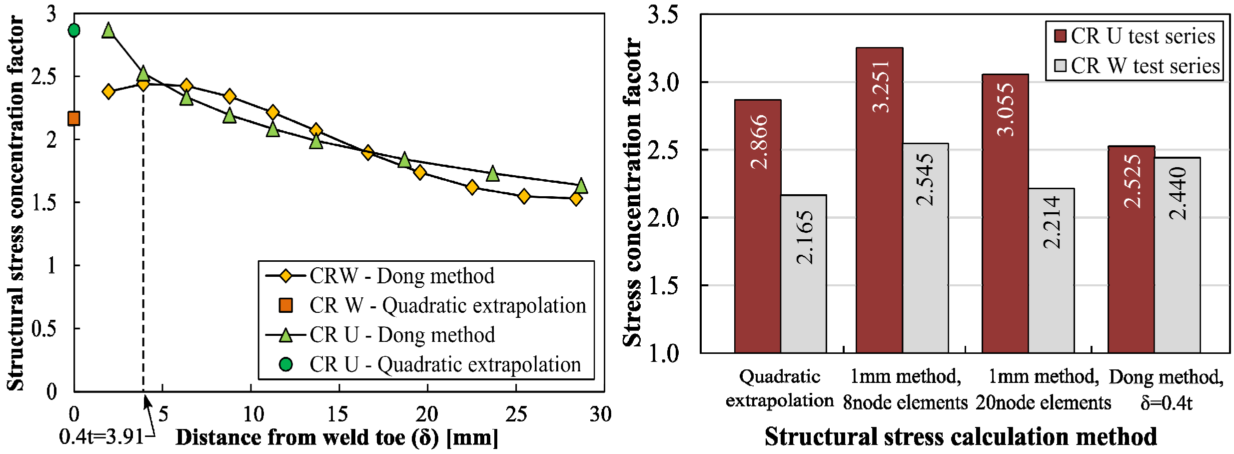
For the Dong stress calculation, the cover-plates with transverse end welds were treated according to the non-monotonic through thickness stress distribution with t_1 equal to the flange thickness. This was due to the presence of web plate underneath the crack initiation location in these details. For the case of cover-plates without transverse end welds, a monotonic stress distribution through the flange thickness was assumed.

Calculation of the hot-spot stress according to the Dong method requires a determination of the section at which equilibrium is to be satisfied. There is thus a need to study how the calculated hot spot stress varies as a function of the distance δ. As shown in Fig. 7a, the structural stress obtained from the Dong method deviates as δ changes. This finding supports the notion raised in other studies that disregarding the shear stresses on the element sides, makes the Dong method δ-dependent. However, as proposed in [12], this effect is minimized by choosing δ=0.4t.



a) Type a b) Type b c) Type c

Fig. 6: Different methods to model the weld end



a) Structural stress concentration factor as a function of distance from weld toe (δ)
b) Structural stress concentration factors obtained from different methods for cover-plates

Fig. 7: Variations of the structural stress concentration factor

The structural stress calculation results obtained from different methods for CR cover-plate test series are plotted in Fig. 7b. As it was shown in Table 1 for this test series, cover-plates without transverse end weld (CR U) have exhibited slightly higher fatigue lives than those with transverse end weld (CR W). Nevertheless, as it is apparent in Fig. 7b, a higher stress concentration factor is obtained for cover-plates without transverse end weld, irrespective of the SHSS derivation method. This observation, which is inconsistent with the experimental results, is significantly reduced when the hot spot stress is calculated according to the Dong method, where the two derived stress concentration factors are almost identical.

Fig. 8 demonstrates the fatigue lives for the cover-plate details derived from fatigue tests and predicted by different fatigue assessment approaches according to Eurocode3 [6]. As can be seen, when using the SHSS approach, the predicted fatigue lives for cover-plate details without transverse end weld are significantly more conservative than those for cover-plate details with transverse end weld. However, the fatigue life predicted by the Dong method is in a better agreement with the test results. For the case of cover-plates with transverse end weld, both the conventional extrapolation [7], and Xiao and Yamada [10] methods are capable of predicting the fatigue life with an acceptable accuracy, provided that 20node quadratic elements are used. The nominal stress method, on the other hand, considers a single fatigue design class for cover-plate details irrespective of the end weld condition, and accordingly yields

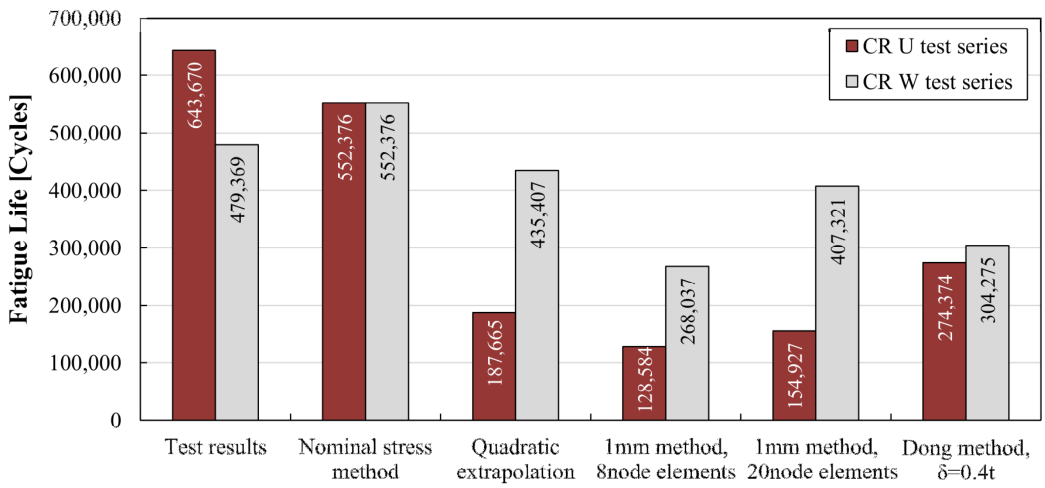


Fig. 8: Fatigue lives for the cover-plate details derived from fatigue tests and predicted by different fatigue assessment approaches

the same fatigue life prediction for both test series. When using the nominal stress method, the predicted fatigue life for the CR U test series is very close to the test results, whereas it is only slightly overestimated for the CR W test series. Having mentioned that, the nominal stress classifications have been directly obtained from experimental results, the acceptable consistency of fatigue life predictions can be justified.

As discussed before, the structural stress derived according to the Dong method is dependent on the distance from weld toe (δ). As a result, as shown in Fig. 9, different fatigue lives are predicted as δ varies. It is apparent from this chart that, for this particular detail more precise fatigue life estimations are derived when δ is chosen between 0.9t and 1.4t. In addition, the predicted fatigue lives are consistent with the test results in which slightly higher fatigue lives are reported for not welded end cover-plate details.

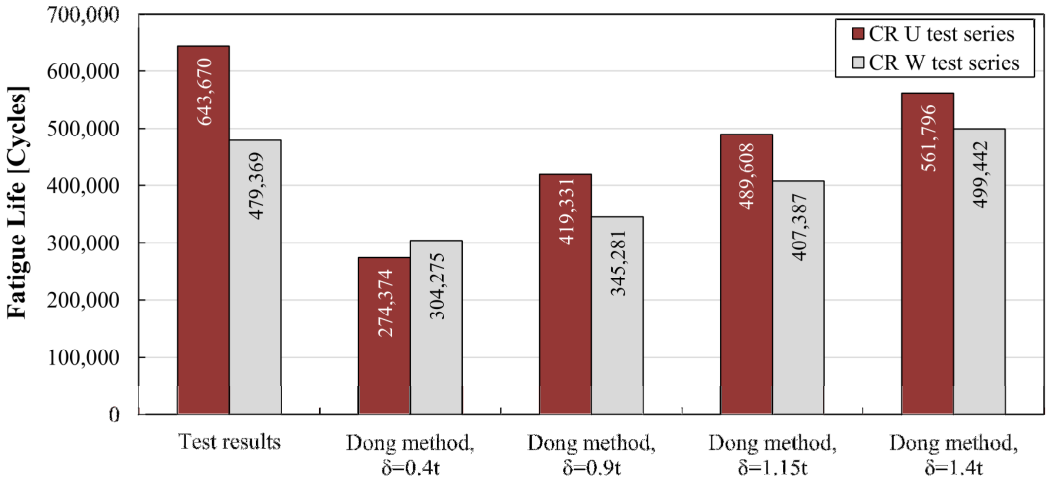


Fig. 9: Fatigue lives for the cover-plate details derived from fatigue tests and predicted by the Dong method with varying δ

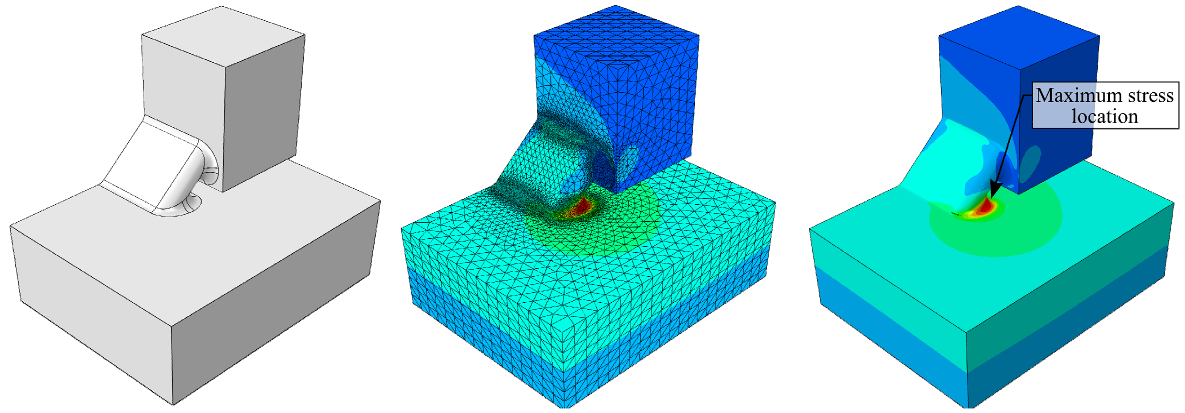
4.3 Fatigue life assessment according to the effective notch stress method

In contrast to the SHSS approach, the effective notch stress method is highly dependent on the local weld geometry as it comprises all the stress raising effects including those caused by the notch at the weld. Therefore, it is vital to model the weld geometry at the critical location in an appropriate way.

In this study, for the case of cover-plate details with transverse end welds, the fatigue assessment according to the ENS method is performed as recommended in [15]. However, for cover-plate details without transverse end welds, several modelling techniques are investigated. Fig. 6 and Fig. 10 demonstrate these models in which fatigue assessments have been conducted separately according to the recommendations given by Fricke [15] and Kaffenberger et al. [16], respectively. For the latter case, two rounding radiuses equal to 0.5mm and 1mm are investigated.

As it can be seen from Fig. 10, the calculated maximum stress location is exactly at the crack initiation location reported in the fatigue tests. On the contrary, when the weld end is modelled as shown in Fig. 6, the maximum stress is obtained at the junction of weld end and cover-plate. However, if some of the elements at this area are excluded, the maximum stress location would be found at the correct location as reported in the tests.

The effective notch stress concentration factors obtained from the investigated models are plotted in Fig. 11. It is apparent that, on the one hand, all of the investigated models yield con-



a) Modelled weld end geometry b) Meshed geometry c) Maximum principal stress plot

Fig. 10: Modelled weld end for a cover-plate detail fatigue analysis according to the ENS method [16]

servative results with stress concentration factors higher than that for CR W series. On the other hand, the FE model constructed as shown in Fig. 6a appears to result in the closest stress concentration factor. It should be also noted that, the proposed model in [16] seems also to produces relatively acceptable results if the correct rounding radius is exercised.

5 Conclusions

The following main conclusions can be drawn from this study:

1. Similar to the case of weld toe cracking, the SHSS for details with weld end terminations is quite insensitive to the shape of the weld end and the way the latter is modelled.
2. For cover-plate details with transverse end weld, quadratic extrapolation and Xiao - Yamada methods yield appropriate results if 20node quadratic elements are used. However, when 8node elements are used, the Xiao and Yamada method predicted highly conservative fatigue lives and is supposed as the least appropriate method.
3. For cover-plate details without transverse end weld, the Dong method seems to give the most accurate results. For this particular detail, the Dong stress calculation with δ varying between 0.9t and 1.4t revealed more experimentally-verified results.
4. In order to obtain accurate results according to the effective notch stress method, the exact weld geometry has to be modelled. The analysis results confirm a better agreement

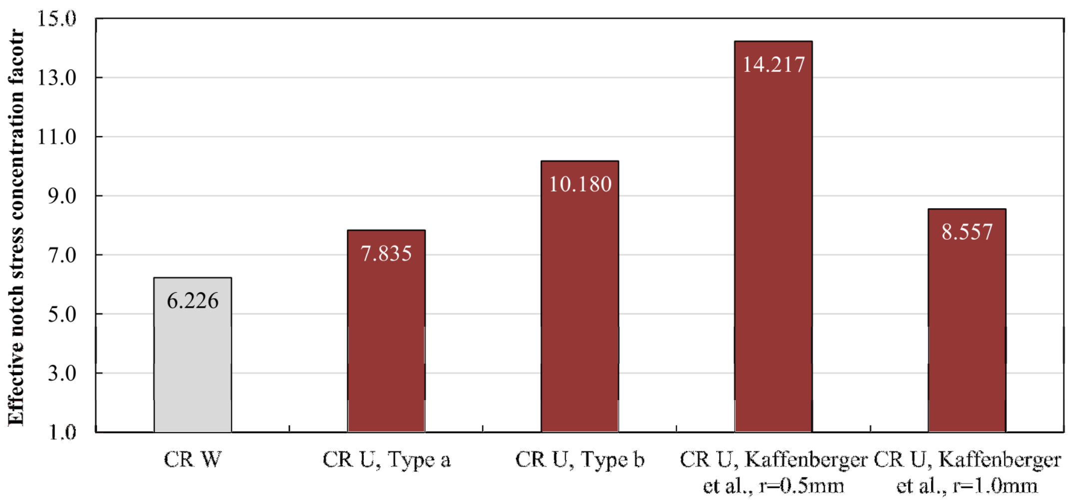


Fig. 11: The effective notch stress concentration factor obtained from several modelling techniques

with the test results when the weld termination is modelled as shown in Fig.6a.

5. Providing that an appropriate rounding radius is applied, acceptable results can be expected from the method proposed by Kaffenberger et al. [16] for weld end assessments. A radius of 1mm seems to yield the best results for the details studied in this paper.

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