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A comparative study of different fatigue failure assessments of welded bridge details

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ABSTRACT

Five different welded joints frequently used in steel bridges have been selected to investigate the accuracy and applicability of three fatigue assessment methods. The first method, also categorised as the global method, is the nominal stress method, while the more advanced methods are the hot spot and the effective notch stress methods. Solid element based finite element models for welded bridge details were created by following the modelling requirements of each fatigue assessment method. A statistical evaluation based on the results of the finite element analyses and the fatigue test data collected from the literature was performed to determine the mean and characteristic fatigue strength. In addition, the standard deviation for each data series was also determined to conclude how well each method describes the fatigue strength of each welded detail. A method with a lower standard deviation is regarded as more accurate. Moreover, the evaluated results from each method were compared with the recommended fatigue strength values in the Eurocode 3 (EN 1993-1-9:2005) and IIW codes. In the light of the test results in this study, it appears that the codes are in reasonable agreement with the test data, even though a few examples of the opposite occurred. The conclusion based on the revised results in this article indicates that the nominal stress method yields satisfactory results, despite its simplicity. When considering the effort involved in creating FE models for numerical analysis, it seems clear that the choice of the nominal method is fairly acceptable.

1. Introduction

It ought to be obvious that steel bridges should be designed in such a way that they provide sufficient static capacity corresponding to an evenly distributed load over the entire bridge surface, for example. However, as the loads consist of traffic loads from cars, trucks and trains, which cause fluctuating loads, the governing design state in most cases will be the fatigue limit state, FLS. When a train with a number of coaches passes over the bridge, the fluctuating stress in different details will be produced by the traffic loads. It is evident that, during the service life of the bridge, the total number of load cycles will exceed several million. As a result, the fatigue problems for critical details should be controlled by using a correct fatigue life estimation procedure. Over the years, a substantial number of tests have been performed in order to categorise fatigue-loaded details and thereby determine their fatigue strength. A wide range of different plate thicknesses, welding process, throat sizes, fillet welds, butt welds, angles, widths and lengths and combinations of these have been used in these fatigue tests. This large amount of information has been processed and is included in most design standards and recommendations.

The most renowned, widely used method for assessing fatigue in welded structures is the nominal stress method [1–3]. In fatigue design codes such as Eurocode 3 [4] or IIW [5], a large number of structural details with strength curves corresponding to fatigue loaded details are given. However, in many cases, the welded details in steel bridge structures are far more complicated than the basic, common details presented in design codes. It can be difficult sometimes to identify a suitable detail and using a simplified detail can lead to inaccurate fatigue life estimations. To overcome this problem, a local stress determination method using the finite element method, which takes account of the stress-raising effects due to the geometrical changes and complex loading conditions, might provide an accurate estimate of the load effects in fatigue-critical details.

The aim of this article is to investigate the accuracy and benefit of choosing a more advanced method when assessing the fatigue strength of commonly used welded details in steel and composite bridges. These methods are the nominal stress, the hot spot stress and the effect notch stress methods. The fatigue experiment data of the five frequently used welded details in steel and composite bridge structures have been collected from the literature to confirm the performance of these three most frequently used fatigue assessment methods.

The five selected details for this study are presented in the next chapter, together with a description of the way the evaluation

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procedure relating to the fatigue assessment methods has been performed. The results for each individual detail using these methods are then presented and discussed.

2. Methodology

As stated earlier, the first method is the nominal stress method that has been used in the fatigue design of steel structures from an early stage. This method is included in several design codes and can be regarded as a kind of standard method with which the other two will be compared. The second method is the hot spot stress method which considers a fictitious stress at a fatigue-critical point, the so-called hot spot point, where the stress is considered representative of the component [2,5,6]. The hot spot stress is generally extrapolated on the basis of two or three reference points on the surface of the detail, depending on whether linear or quadratic extrapolation is used. The hot spot stress method takes account of all the stress-raising effects emanating from the macro-geometrical changes to the detail in the stress calculation, apart from the actual weld. The method is fairly easy to use and keeps the size of the models at a fairly moderate level. FE models could be created using either 2D plane elements or a 3D shell, as well as solid elements. The weld is usually included in FE models with solid elements, while, in FE models with shell elements, the welds are generally modelled in welded details with complex geometry and loading conditions [7]. The calculated hot spot stress at the weld toe is then used together with the recommended S-N curve to estimate the fatigue life of welded details. However, the method is only applicable to fatigue failures starting from the weld toe [8].

The third fatigue life assessment method used in this study is the effective notch stress method proposed by Radaj et al. [3]. Apart from taking the geometrical changes into account, as the hot spot method does, the effective notch stress method also takes the effects of the weld itself into account. This method is based on stress averaging in Neuber's micro-support theory for steel with a reference radius of 1 mm in a plate thickness of 5 mm and above [5]. For smaller plate thicknesses, Zhang and Richter [9] have proposed the use of a reference radius of 0.05 mm, which is based on the relationship between the stress intensity factor and the notch stress. The effective notch stress method can be used in both 2D plane elements and 3D solid elements. The effective notch stress at fatigue-critical points can be computed using the submodelling technique, as a very fine-meshed region around the critical points is required to capture the maximum elastic stress [5]. The finite element sub-modelling technique is generally used to transfer the displacements when defining node-base sub-regions or to transfer the stresses at the integration points when defining surface-based sub-regions from the coarsely meshed global model to the refined meshed local models.

The following five welded details frequently used in steel and composite bridges have been selected to conduct the study.

- Plate-edge details.
- Overlapped joints.
- Longitudinal attachments.
- Cope-hole details.
- Cover-plate details.

A large number of test results were available in the literature. However, only the test data in which all the information about the specimen, such as the width, length, thickness, welds size, and material data, was available have been selected for re-analysis in order to create well-defined finite element models of the specimens which are then used to calculate the relevant stresses. A total of 1500 fatigue test results have been re-analysed.

The stress defined at fatigue-critical points, i.e. crack initiation points, according to the three methods, is computed for each test series. For the sake of consistency, only 3D structural solid elements were used in the finite element models following the IIW recommendations for the modelling work. In all finite element models, the welds were modelled using 3D structural solid elements. For the determination of hot spot stresses at the weld toe in the investigated details, the quadratic surface stress extrapolation technique recommended by the IIW was used. As mentioned earlier, as the determination of the effective notch stress requires a very finely meshed model around the critical point to capture the maximum elastic stress, the sub-modelling technique was used to compute the effective notch stresses.

The fatigue tests collected from the literature contained only the tests performed under constant amplitude fatigue loading (CAFL). Furthermore, to exclude the beneficial effects of compression stress caused by fatigue loading, the fatigue test specimens only subjected to stress ratios of $R > 0$ were considered. The numbers of cycles to failure are then plotted against the computed stresses in a logarithmic scale. The test results exclusing the runouts are then evaluated using linear regression analysis by which the characteristic fatigue strength, the slope of the curve, the standard deviation and so on can be determined. In order to compare the evaluated results with the recommended S–N curves in the Eurocode and IIW, the linear regression analysis based on a 75% confidence level of 95% probability is performed as recommended in these codes. Finally, the result of the evaluation procedures is compared with the recommended S–N curves.

2.1. Fatigue strength of the welded details

In this section, the results of the evaluation for the three methods based on the chosen five details are presented.

2.2. Plate-edge details

Plate-edge details are fairly common in fatigue-loaded structures. A typical example is gusset plates in bridge beams. For this detail, a total of 1016 test specimens have been evaluated [10–

Table 1
Dimensions and number of evaluated fatigue test specimens.

Types of joints	No. of specimens	Main plate		Gusset plate	
		Thickness (mm)	Width (mm)	Thickness (mm)	Length, L (mm)
Detail 1A	710	8–20	40–170	8–20	50–400
Detail 1A[a]	24	8	100–200	8	80–200
Detail 1B	46	10–20	50–120	10–12.7	50–450
Detail 1C	120	18–20	30–200	8–20	60–450
Detail 1D	17	12.7–31.75	114	12.7	102–203
Detail 1E	57	10	60	10	150
Detail 1F	44	8–20	170–200	8–20	100–320

[a] With no return welds.

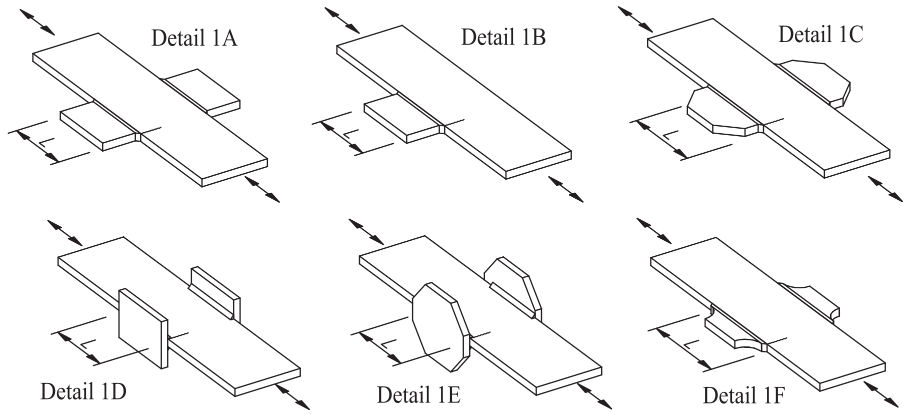

Fig. 1. Different types of investigated plate edge detail.

22]. The specimens cover a wide range of different geometries and dimensions; see Fig. 1 and Table 1.

2.2.1. Fatigue assessment according to the nominal stress approach

The results of the fatigue test data based on the nominal stress amplitude are presented in Table 2. For this type of attachment, the length and the geometrical shape of the gusset plate have a significant influence on the magnitude of stress concentration at the plate termination; i.e. where fatigue cracks are initiated. For this reason, the fatigue test data were evaluated by considering the variations in the geometry of the specimens, see Fig. 1. Apart from detail 1F, which is a special case, it is clear that the fatigue strength of plate-edge attachments is dependent on the length of the gusset plate, which is reduced when the length of the attachment is increased. The 30 tests of detail 1C show, however, a higher fatigue strength, even though the attachment length is the longest. These tests belong to one specific series in which the attachment was tapered at 63° and in which the gusset plate was thinner than the main plate. These two reasons might explain the relatively high fatigue strength of this particular test series. Details 1D and 1E – where the gusset plate is normal in relation to the main plate – show the same trend as the other detail types.

It is worth mentioning here that Eurocode 3 disregards the effect of the attached plate length on the fatigue strength of plate-edge details. In addition, a detail category 40 is assigned to this detail (irrespective of the length of the gusset plate) which, considering the results of the current evaluation appears to be somewhat conservative. When grouping the plate-edge details corresponding to Eurocode's recommendation of detail category 40, the characteristic value is calculated as 60.3 MPa and the standard deviation is 0.224 with a fixed slope of 3.

Table 2
Fatigue test results based on the nominal stress approach with a fixed slope of 3.

Detail configurations	No. of specimens	St. dev.	$\Delta\sigma_{mean}$ (N/mm^2)	$\Delta\sigma_C$ (N/mm^2)
$L \leqslant 100$ (detail 1A, 1A[a], 1B and 1C)	386	0.180	81.3	64.7
$100 < L \leqslant 200$ (all details except 1F)	80	0.226	70.8	52.9
$200 < L \leqslant 300$ (detail 1A, 1B and 1D)	53	0.223	67.4	50.0
$L > 300$ (detail 1C)	30	0.244	84.5	60.0
$1/6 < r/L < 1/3$ (detail 1F)	41	0.170	87.1	68.9
Detail 1D, $L = 102$	6	0.060	81.4	73.1
Detail 1D, $L = 203$	11	0.093	76.2	65.7
Detail 1E, $L = 150$	57	0.084	77.5	68.7

[a] With no return welds.

2.2.2. Fatigue assessment according to the hot spot stress approach

The results of the evaluation of the 616 test points (considering only $R > 0$) according to the hot spot stress approach are plotted in Fig. 2.

Since the crack at the weld toe is located on the edge of the plate, the hot spot point is defined as "type b" according to IIW. By definition, the effect of all the geometrical parameters of the different specimens is implicitly considered in the hot spot stress method. One S–N curve is needed to describe the fatigue strength of all the tests. Needless to say, variations in welding technique, weld quality, possible size effects and so on are still expected to contribute to some scatter in the test results. The standard deviation when all tests are considered is 0.219 when performing a linear regression analysis with a free slope with a mean value of 131.1 MPa and a characteristic value of 94.3 MPa. With a fixed slope of 3, the characteristic value is calculated as 103.6 MPa, with a standard deviation increasing to 0.232.

It was expected that the scatter when evaluating the experimental data using the hot spot stress approach would be smaller than the scatter from the nominal stress approach, as, according to the definition of the hot spot stress method, the calculated stress includes the geometrical effects of the details. The hot spot stress method yields a standard deviation in excess of that obtained with the nominal stress evaluation when considering the group of detail category 40. In comparison with Table 2, one can see that the standard deviation from the hot pot stress method is larger than those obtained with the nominal stress method, except one group. One reasonable explanation for this observation is that the scatter inherent in the test results is primarily caused by welding techniques, weld quality and the type and size of local defects rather than by the variation in the geometrical properties of the test specimens. Nevertheless, fatigue category 100 appears to give a good representation of the fatigue strength of this particular detail.

2.2.3. Fatigue assessment according to the effective notch stress approach

The results when evaluating the fatigue test data according to the effective notch stress approach are presented in Fig. 3. The standard deviation is 0.270 and the slope is 2.27 when performing a linear regression analysis with a free slope. The mean and characteristic values when considering a slope of 3 are 331.9 MPa and 235.7 MPa respectively. Again, the standard deviation here is in excess of that obtained in the nominal stress and the hot spot stress evaluation, which confirms the conclusion drawn above. Detail category 225, which is proposed in the IIW recommendations for fatigue evaluation with the effective notch stress approach, appears to give a reasonable representation in this case.

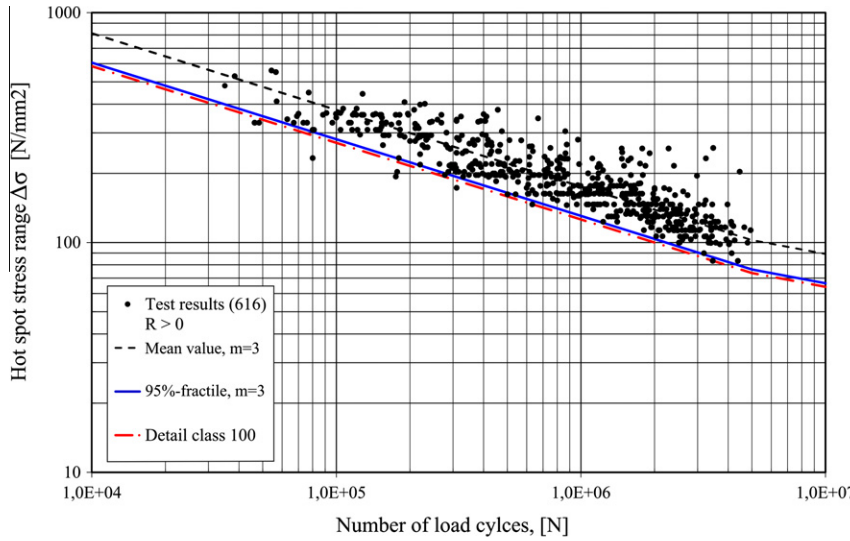

Fig. 2. Fatigue test results for plate-edge joints according to the hot spot stress approach.

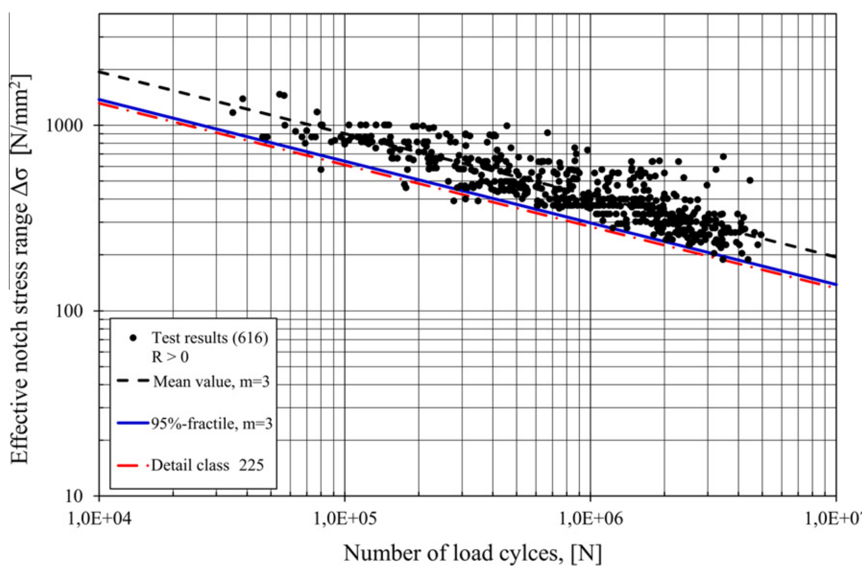

Fig. 3. Fatigue test results for plate-edge joints according to the effective notch stress approach.

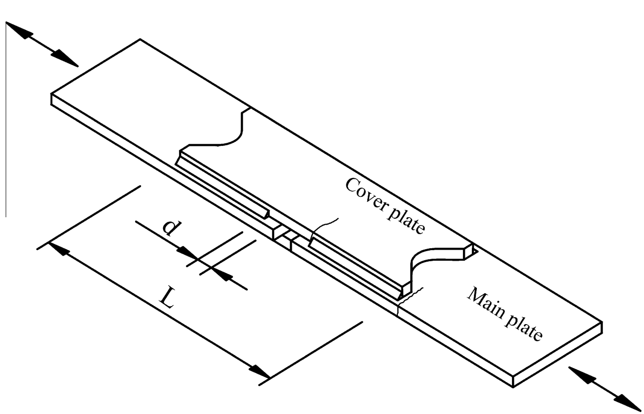

Fig. 4. Overlapped specimens for fatigue testing.

2.3. Overlapped joints

The evaluation of fillet welded overlapped joints included 19 test specimens [23] with the configuration shown in Fig. 4. The geometrical parameters that are considered for this detail are given in Table 3. Two different failure modes are recognised; cracking in the main plate, denoted 2MP1 and 2MP2, and cracking in the cover plates, denoted 2CP1 and 2CP2.

2.3.1. Fatigue assessment according to the nominal stress approach

The results of the statistical evaluation with a fixed slope of 3 according to the nominal stress approach are presented in Table 4 and Fig. 5 for the two different cracking modes.

It is apparent from the results that the fatigue strength of welded overlapped joints is higher when fatigue cracking takes place in the main plate. This has been recognised by some design codes, such as Eurocode. Another observation is that specimens with longer welds show slightly higher fatigue strength in both cracking modes (compare specimens 2MP2 and 2CP2 with

Table 3
Dimensions and number of evaluated fatigue test specimens.

Types of joints	No. of specimens	Main plate		Cover plate		
		Thickness (mm)	Width (mm)	Thickness (mm)	Length, *L* (mm)	*d* (mm)
Detail 2MP1	5	12.7	114.3	12.7	228.6	0[a]
Detail 2MP2	5	12.7	114.3	12.7	381	12.7
Detail 2CP1	4	12.7	114.3	9.5	228.6	12.7
Detail 2CP2	5	12.7	114.3	9.5	381	12.7

[a] Welded to the edge of the cover plate.

Table 4
Fatigue test results based on the nominal stress approach with a fixed slope of 3.

Crack location	No. of specimens	St. dev.	$\Delta\sigma_{mean}$ (N/mm^2)	$\Delta\sigma_c$ (N/mm^2)
Main plate cracking	10	0.135	78.0	61.8
Cover plate cracking	9	0.169	54.2	41.1

specimens 2MP1 and 2CP1). However, the number of available test results is not enough to draw a firm conclusion regarding the effect of weld length in this detail.

2.3.2. Fatigue assessment according to the hot spot stress approach

The results of the evaluation according to the hot spot stress approach are presented in Table 5 and Fig. 6. Again, the test data have been divided into two groups depending on the location of cracking; cracking at the weld toe in the main plate defined as "type a" hot spot point and cracking at the weld toe on the edge of the cover plate defined as "type b" hot spot point. Although the amount of available test data is somewhat limited, the results clearly indicate distinct fatigue strength values for the two cracking modes. The Eurocode suggests the detail category 90 for both cracking modes. Considering the test data available, this value appears to be inappropriate for cracking in the main plate (see Fig. 6a). The recommended detail category appears to be in better agreement regarding the second cracking mode; i.e. cracking in the cover plate (see Fig. 6b). Apparently, more test data on details with similar configuration are needed before a firm conclusion can be drawn.

Table 5
Fatigue test results based on the hot spot stress approach with a fixed slope of 3.

	No. of specimens	St. dev.	$\Delta\sigma_{mean}$ (N/mm^2)	$\Delta\sigma_c$ (N/mm^2)
All test data	19	0.202	110.3	82.3
Main plate cracking	10	0.120	98.7	80.3
Cover plate cracking	9	0.141	124.7	98.9

2.3.3. Fatigue assessment according to the effective notch stress approach

The results for the effective notch stress method are highly dependent on how the weld end is modelled. The complicated weld geometry for this specific joint made it somewhat difficult to use the effective notch stress method. In this investigation, a simplified model for the weld end has been adopted; see Fig. 7a. The test data are presented in Fig. 7b in terms of the effective notch stress. When all the test data are evaluated together with a fixed slope of 3, the standard deviation is 0.195, with a characteristic strength of 303.2 MPa. All the test data lie well above the detail category 225, which is proposed in the IIW recommendations for evaluation using the effective notch stress method. Moreover, the fatigue test data in this case are clearly separated for the two different cracking modes. As in the case of the hot spot stress, the specimens with cracks starting in the main plate display slightly lower fatigue strength. This indicates that the lower fatigue strength for this cracking mode is an inherent feature in these tests specimens rather than a result of a higher stress concentration at the weld end.

2.4. Longitudinal attachments

This detail (Fig. 8) covers a total of 286 test results [24–39] with a wide variation in dimensions and geometrical properties. As the fatigue strength of plates with longitudinal non-load-carrying attachments is known to be a function of the length of the attachment plate, the test results were primarily categorised according to the attachment length, in five different classes, as shown in Table 6.

2.4.1. Fatigue assessment according to the nominal stress approach

The results after evaluating the test results with a fixed slope of 3 based on the nominal stress approach are presented in Table 7. The detail categories for this detail are divided into groups according to their length. The test results are in agreement with

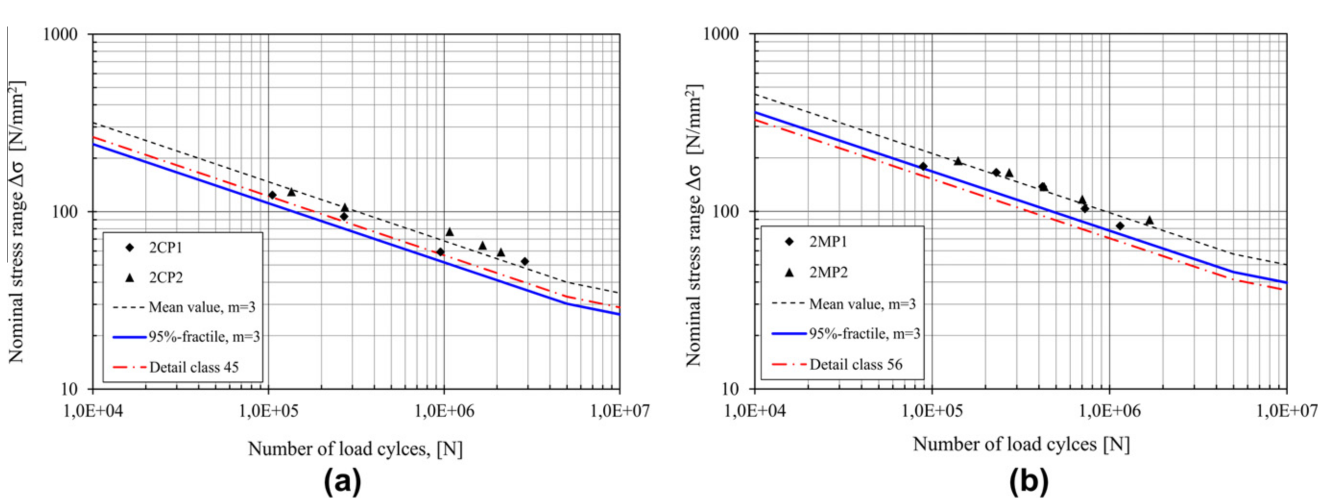

Fig. 5. Test results based on the nominal stress approach; (a) cracking in the main plate; (b) cracking in the cover plate.

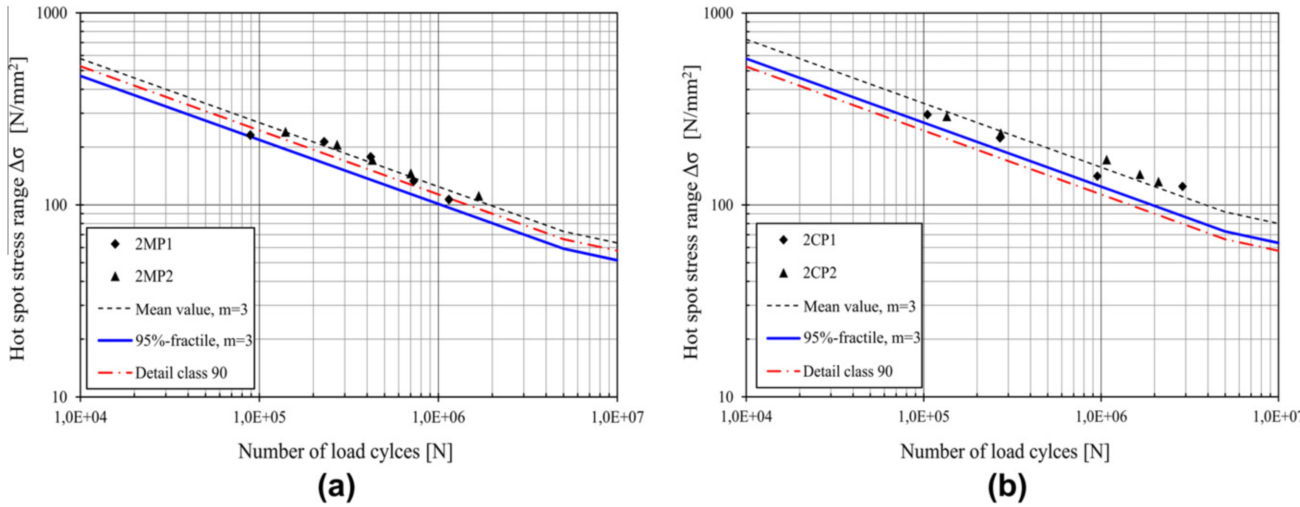

Fig. 6. Fatigue test results for overlapped joints according to the hot spot stress approach: (a) cracking in the main plate; (b) cracking in the cover plate.

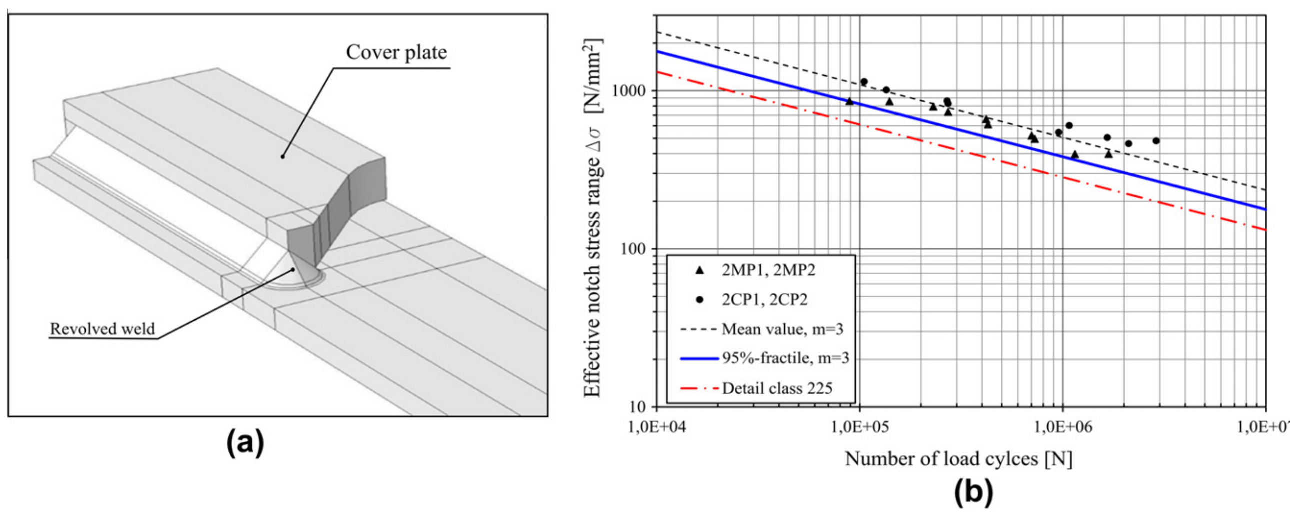

Fig. 7. (a) Revolved weld end used for notch stress analysis. (b) Fatigue test results for overlapped joints according to the effective notch stress approach.

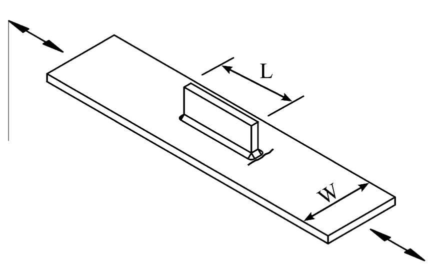

Fig. 8. Investigated longitudinal attachment.

Table 6
Number of specimens and geometry of investigated welded details.

(mm)	No. of specimens	Main plate		Long. attached plate	
		Thickness (mm)	Width, *W* (mm)	Thickness (mm)	Length, *L* (mm)
L = 200	10	4	100	4	200
L = 150	193	4.8–25.4	75–100	4.8–25.4	150
L = 100	55	10–25	80–152.4	10–25	100
L = 60	11	16	90	16	60
L = 50	17	8	80	8	50

the Eurocode 3, except for the joints with the 50 mm long attachment which have a slightly lower fatigue strength (77.3 MPa) than that specified in the recommended detail category 80.

2.4.2. Fatigue assessment according to the hot spot stress approach

The hot spot point is defined as "type a" for longitudinal attachments according to IIW, since the crack at the weld toe is located on the main plate. The test results for the hot spot stress approach are plotted in Fig. 9. In this figure, quadratic extrapolation of the hot spot stress has been used. With a free slope, the standard deviation is 0.138 and the characteristic strength is 88.8 MPa. With a fixed slope of 3, the standard deviation becomes 0.150 and the characteristic fatigue strength 94.2 MPa. Linear extrapolation was also examined for this detail, giving a standard deviation of 0.150 and characteristic fatigue strength of 93.1 MPa. Considering the results with a fixed slope of 3 in Fig. 9, it appears that the detail category 90 should be used for this detail instead of the detail category 100 which is recommended by the Eurocode 3.

Table 7
Fatigue test results based on the nominal stress approach.

(mm)	No. of specimens	St. dev.	$\Delta\sigma_{mean}$ (N/mm^2)	$\Delta\sigma_c$ (N/mm^2)
$L = 200$	10	0.157	75.4	56.9
$L = 150$	193	0.123	88.8	75.9
$L = 100$	55	0.164	91.3	73.6
$L = 60$	11	0.056	85.8	77.9
$L = 50$	17	0.088	88.6	77.3

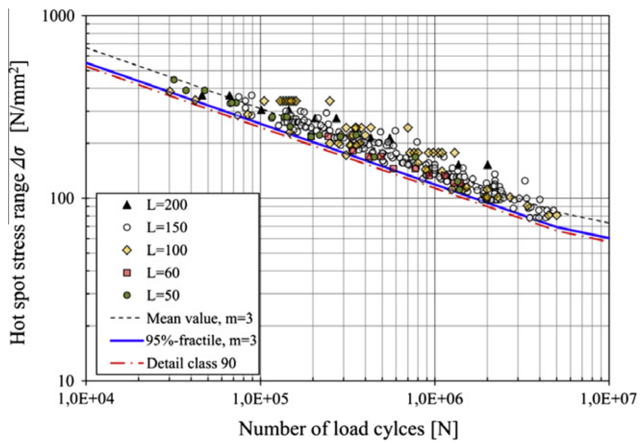

Fig. 9. Fatigue test results for longitudinal attachments according to the hot spot stress approach.

2.4.3. Fatigue assessment according to the effective notch stress approach

Among the 286 test specimens considered for this detail, only a limited number of tests were fully described in the source literature. For this reason, only these tests [25,30–32] are included in the effective notch stress evaluation. The results with a fixed slope of 3 are presented in Fig. 10. The standard deviation is 0.136 and the slope is 2.70 using free linear regression. When the slope is set at 3, the standard deviation is 0.145 and the characteristic strength 301.1 MPa. As can be seen from Fig. 10, the test data are in good agreement with the recommended detail category 225 for the effective notch stress method.

2.5. Cope hole details

Cope holes are usually used as field-welded joints in bridge girders to facilitate the transversal butt welds in the flanges and

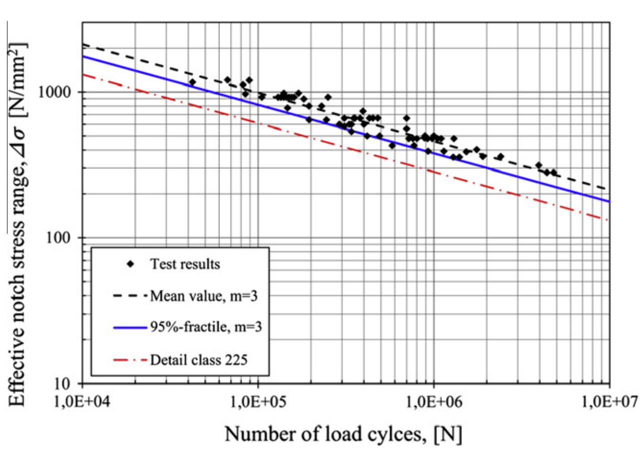

Fig. 10. Fatigue test results for longitudinal attachments according to the effective notch stress approach.

Table 8
Dimensions and number of evaluated fatigue test specimens for cope holes.

Types of joint	No. of specimens	Main plate		Attachment		τ_a/σ_m
		Thickness (mm)	Width (mm)	Thickness (mm)	Cope-hole radius (mm)	
Detail 4A	7	25.4	127	4.8	25.4	0
Detail 4B	8	9	200	9	35	0
Detail 4C	7	8	80	6	26	0.2
Detail 4D	7	16	250	9	25–40	0.67–0.98

avoid weld crossing. The size of the cope hole is also chosen to provide access for the NDT of the butt welds. The fatigue test results for 29 different specimens from four different sources [40–43] have been collected to evaluate this detail. Table 8 represents a detailed overview of various test configurations, as illustrated in Fig. 11.

2.5.1. Fatigue assessment according to the nominal stress approach

As is shown in Table 9, the fatigue strength of the evaluated cope-hole details is very inconsistent. A closer look at the results in Table 9 reveals that, despite the conspicuous geometrical variation in details 4A and 4B, they exhibit almost identical fatigue strength. However, detail 4D, which is more similar to 4A, shows a dramatic fall in terms of fatigue strength. A more thorough assessment of the tests reveals a pronounced dependence of the fatigue life of cope-hole details on the ratio of shear stress to normal stress in the specimens (τ_a/σ_m). It is clear that the relatively low fatigue strength of details in test series 4D is due to the presence of considerable shear stresses at the anticipated crack location, i.e. weld toe in the cope-hole section. The destructive effect of shear stresses on the fatigue life of cope-hole details has been previously confirmed by Miki and Tateishi [42]. For this reason, any evaluation of the test results, based on the nominal stress in these details, should consider the ratio τ_a/σ_m as an important parameter that affects the fatigue strength of cope-hole details. While this has been recognised in the IIW code, the Eurocode 3 assigns detail category 71 to cope-hole details irrespective of the ratio τ_a/σ_m.

2.5.2. Fatigue assessment according to the hot spot stress approach

The test results of all cope-hole details evaluated on the basis of the "type a" hot spot stresses are plotted in Fig. 12. It is apparent that, although the test data do not lie in one group, the scatter of the results, compared with the nominal stress method, is reduced. Linear regression analysis with a fixed slope of 3 gives a standard deviation of 0.281 compared with the value of 0.614 obtained from the nominal stress method. However, the calculated characteristic fatigue strength of 70.6 MPa is considerably lower than that specified in IIW and Eurocode (detail category 100). If the results for detail 4D, which has the highest τ_a/σ_m ratio, are excluded, detail category 100 appears to be a reasonable representation.

The low hot spot stress value obtained for detail 4D is assumed to be due to the presence of a large amount of shear stress in the web which causes the weld to become load carrying. In such a case, the weld at the cope hole transfers the existing shear stress, in addition to the normal stresses caused by the bending of the beam. So, in order to account for such severe loading conditions, the application of a further reduction in detail category 90 for cope holes in beams when using the hot spot stress approach is recommended.

It is noteworthy that, for detail 4C, for which the surface stress extrapolation according to the IIW recommendation was not feasible due to the small radius of the cope hole in relation to the flange thickness, hot spot stress is calculated as 1.12σ $(0.5t)$ according to

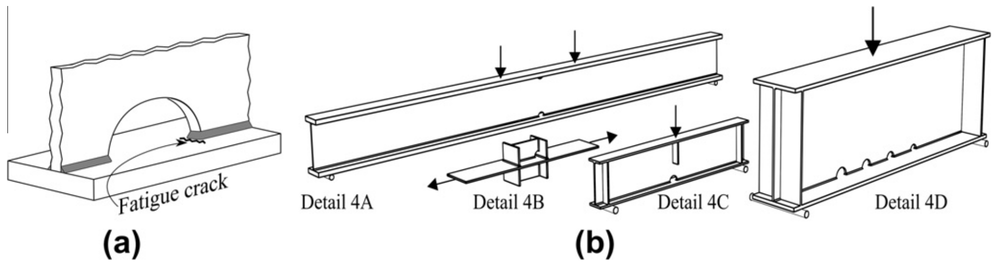

Fig. 11. (a) Fatigue crack location in specimens with cope holes; (b) different cope-hole test configurations.

Table 9
Statistical evaluation of cope-hole test results using linear regression analysis with a fixed slope of 3.

Type of joint	St. dev.	$\Delta\sigma_{mean}$ (N/mm^2)	$\Delta\sigma_C$ (N/mm^2)
Detail 4A	0.157	83.8	72.5
Detail 4B	0.093	88.9	71.9
Detail 4C	0.055	74	64.7
Detail 4D	0.345	30	16.7

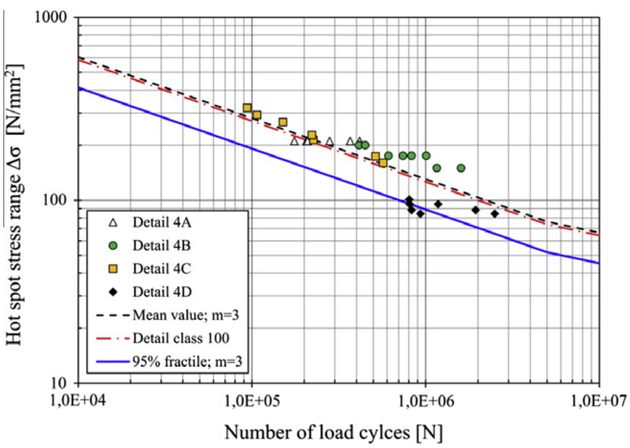

Fig. 12. Fatigue test results for cope-hole details according to the hot spot stress approach.

[44]. Moreover, in order to calculate the hot spot stress concentration factor, the nominal stress for beam specimens is calculated as the stress in the mid-section of the cope hole using the net cross-section and the simple beam theory formula.

2.5.3. Fatigue assessment according to the effective notch stress approach

Considering Fig. 13, in which the fatigue test data are evaluated with the effective notch stress method, the scatter of the test data is noticeably reduced. All the test data lie within the same narrow scatter band with standard deviation of 0.162 which is the lowest standard deviation obtained for this detail based on different evaluation methods. Moreover, linear regression analysis reveals a slope of 2.74 accompanied by the characteristic value of 216.1 MPa. When the slope is set at 3, the standard deviation is 0.155 and the characteristic strength 230.3 MPa. As can be seen from Fig. 13, the test data are in good agreement with the recommendations for a detail category of 225 for the effective notch stress method.

2.6. Cover plate details

Partial-length cover plates are usually welded to the flanges of steel bridge girders in order to increase the moment capacity and

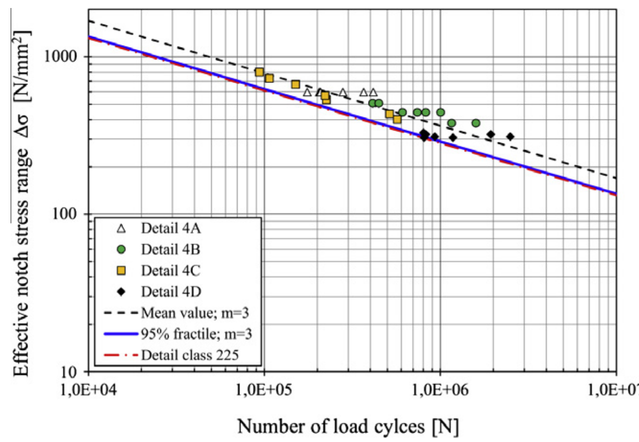

Fig. 13. Fatigue test results for cope-hole details according to the effective notch stress approach.

consequently the permissible traffic load and span of the bridge. In this paper, the constant amplitude fatigue test results for 183 cover plate specimens have been evaluated [45,46]. The specimens cover a wide range of geometrical variations, such as the cover-plate to main plate thickness ratio (t_c/t_m) and the cover plate end shape; see Fig. 14 and Table 10.

2.6.1. Fatigue assessment according to the nominal stress approach

Conforming to the data shown in Table 11, the fatigue strength of cover plates appears to be particularly affected by the ratio t_c/t_m. It is apparent that cover plates with the lowest t_c/t_m ratio exhibit the highest fatigue strength. However, this effect disappears for details with $t_c/t_m > 1$. These details demonstrate the same fatigue strength. Moreover, as the fatigue test results for cover plates with various end shapes lie latently within the same scatter band, it can be concluded that changing the cover plate end shape does not affect the fatigue strength of cover plate details.

While Eurocode 3 has limited the effect of t_c/t_m to ratios of only less than and higher than one, the IIW code considers several intervals. Consequently, when considering the evaluated data in this study, Eurocode's recommendations appear to be more consistent.

2.6.2. Fatigue assessment according to the hot spot stress approach

The test results for all cover-plate details are shown in Fig. 15. As was expected, the geometrical effects of different shapes and configurations are implicitly accounted for by the hot spot stress approach and all the data lie within narrower scatter band with standard deviation of 0.116 for a free slope (free slope, $m = 3.05$). This observation is also supported by the statistical analysis. The standard deviation of all the test data decreases significantly from 0.149 using the nominal stress approach to 0.116 for the hot spot stress approach. The recommended detail category 100 also appears to be a reasonable representation of the fatigue strength of this detail.

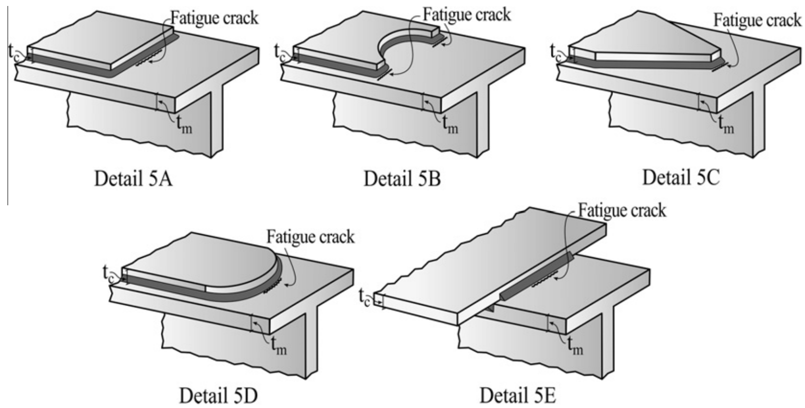

Fig. 14. Different cover-plate test configurations.

Table 10
Dimensions and number of evaluated fatigue test specimens for cover-plate details.

Types of joint	No. of specimens	Main plate		Cover plate		t_c/t_m
		Thickness (mm)	Width (mm)	Thickness (mm)	Width (mm)	
Detail 5A1	30	9.525	171	19.05	114	2
Detail 5A2	102	9.525	171	14.3	114	1.5
Detail 5A3	5	19.05	127	12.7	101.6	0.67
Detail 5B	5	19.05	127	12.7	101.6	0.67
Detail 5C	6	19.05	127	12.7	101.6	0.67
Detail 5D	5	19.05	127	12.7	101.6	0.67
Detail 5E	30	9.525	171	14.3	229	1.5

Table 11
Statistical evaluation of cover-plate test results using linear regression analysis with a fixed slope of 3.

Category	No. of specimens	St. dev.	$\Delta\sigma_{mean}$ (N/mm^2)	$\Delta\sigma_C$ (N/mm^2)
$t_c/t_m = 0.67$	21	0.147	79.7	64.8
$t_c/t_m = 1.5$	132	0.104	62.2	54.4
$t_c/t_m = 2$	30	0.103	62.7	54.3

2.6.3. Fatigue assessment according to the effective notch stress approach

The test results according to the effective notch stress approach are shown in Fig. 16. It is apparent that the scatter of the test data is reduced compared with the nominal stress method. When all the test data are evaluated together with a fixed slope of 3, the standard deviation is 0.135 which is little smaller than that obtained in the nominal stress method (0.146) and larger than obtained in the hot spot stress method (0.116). The reason for this anomalous observation is assumed to stem from the fact that, when using the effective notch stress method, the exact weld geometry should be modelled in order to obtain accurate results. However, the precise weld geometry is often unknown when assessing the test data.

The mean and characteristic fatigue strength values when considering a slope of 3 are 406.0 and 341.6 MPa respectively which lie well above detail category 225 recommended by IIW for evaluation using the effective notch stress method.

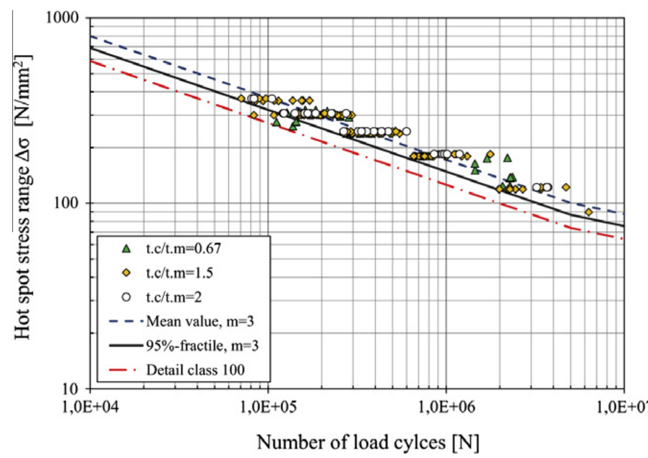

Fig. 15. Fatigue test results for cover-plate details according to the hot spot stress approach.

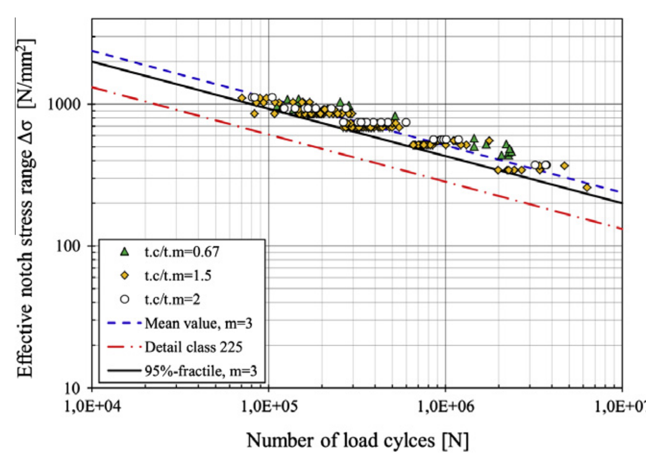

Fig. 16. Fatigue test results for cover-plate details according to the effective notch stress approach.

3. Discussion of results

3.1. General conclusions

The standard deviations obtained from the three different methods are all of the magnitude (more and less) which was unexpected. Since the refined and advanced methods take account of the stress-raising effects, it was expected that these methods would produce smaller scatter. However, variations in welding technique, weld quality and possible size effects may have contributed to some scatter in test results, which is confirmed by the scatter obtained from the hot spot stress method. The scatter from this method, for example, was the smallest, due to the fact that the method ignores the weld effects in the stress calculations. In spite of the fact that the scatter from the three life assessment methods is more or less the same, the results when estimating the fatigue strength of the welded details using the advanced methods are in better agreement with the fatigue test results in comparison with estimating the fatigue strength of the fatigue test specimens when using the nominal stress method. This is also consistent with recent studies performed by [47,48].

Another common conclusion for the studied welded details is that the detail category 225 recommended by the IIW for the effective notch stress method appears to produce reasonable agreement with the fatigue test results.

3.2. Plate edge details

The length of the attached plates has a significant effect on the fatigue strength capacity of welded plate-edge joints. The fatigue strength of the joints will decrease as the length of the attached plate increases. This is not, however, recognised in the Eurocode 3, where the fatigue strength of 40 MPa is assigned to this detail, irrespective of the length of the attached plate. This recommendation appears to be somewhat conservative considering the results of the current evaluation.

The IIW recommends using fatigue strength of 90 and 100 MPa, depending on the length of the attached plates for the hot spot stress method, while no recommendation is given in Eurocode 3. According to the definition of the method, only one S–N curve should be sufficient for this detail. The reason for the two S–N curves is that the attached plate might become more load-carrying as the length increases.

3.3. Overlapped joints

A distinct difference in fatigue strength could be seen for this detail, depending on the failure location. The fatigue strength was higher when the fatigue failure occurred in the main plate. This difference is also recognised in both the Eurocode and IIW.

The Eurocode and IIW recommend using fatigue strength of 90 MPa when using the hot spot stress method. Based on the current results, this appears to be inappropriate for cracking in the main plate. It does, however, provide a better estimate for cracking in the cover plate.

3.4. Longitudinal attachment

The fatigue strength of this type of detail is a function of the length of the attached plates. This has been recognised in both Eurocode 3 and IIW recommendations. The results from this investigation showed that Eurocode 3 provides a good representation of the fatigue strength of this detail. However, the result for the 50 mm length of the attached plates appears to be non-conservative. The IIW recommendation for the failure in the main plate with the present test results is consistent with the test results, apart from the attached plate length of 200 mm.

Based on the present results, a fatigue detail category of 90 MPa should be more consistent with the test results rather than the recommended fatigue detail category of 100 MPa when using the hot spot stress method.

3.5. Cope-hole details

For cope-hole details, shear stress has a fairly adverse effect on fatigue strength. This effect has been recognised by the IIW, where the fatigue strength of this detail is a function of the ratio of shear (τ) to normal (σ) stress. In Eurocode 3, however, one C class is assigned irrespective of the τ_a/σ_m ratio.

From the present evaluation, it can be seen that the detail category 100 recommended by IIW for non-load-carrying welds for the hot spot stress method is not consistent with the test results. However, if the results for detail 4D, which has the highest τ_a/σ_m ratio, are excluded, the detail category 100 appears to be a reasonable representation.

3.6. Cover plate details

The fatigue strength is dependent on the t_c/t_m ratio; it increases as the ratio decreases. This effect has been recognised in both Eurocode 3 and IIW recommendations. The present evaluation study showed that the recommendations given by Eurocode 3 are more consistent with the suggestion of either of two values, for a ratio above or below 1. In the IIW, several intervals are given. The results of the evaluation of the fatigue test also indicate that the fatigue strength is independent of the shape of the weld end.

The recommended fatigue detail category of 100 MPa in the Eurocode and IIW for the hot spot stress method appears to produce reasonable agreement with the results of the current evaluation.

4. Conclusions

The standard deviations for the five different details in this investigation are of approximately the same magnitude for most of them, regardless of the choice of method. One exception, however, is cope hole details, where the standard deviation not only decreases as sophisticated methods are used, but the difference between the basic and most advanced method is also quite large. However, it is difficult to determine the details for which the more advanced methods will provide a significant improvement in the estimation of the fatigue strength. Moreover, there are no recommendations when it comes to modelling weld ends for complex details such as cover plates when applying the effective notch stress method. The advanced methods also require a significant effort for both modelling and computation. This is especially true for the effective notch stress method because of the requirements regarding mesh density which results in very large models to be solved using the sub-modelling technique.

Acknowledgements

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