FATIGUE TESTING AND ANALYSIS OF AN ORTHOTROPIC BRIDGE WELDED DETAIL USING STRUCTURAL HOT SPOT STRESS METHOD

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Abstract. At present, more powerful tools for numerical modelling and structural analysis are available for the use in fatigue design and assessment of complex structures. Taking advantage of these tools, structural hot spot stress approach (SHSS) can predict the fatigue life with more accuracy than the nominal stress method. It incorporates the effect of structural geometry into the local stress ranges at the welds and predicts the fatigue life based on these local stress ranges. In this study, application of the method on a joint available in the orthotropic bridge decks was investigated. Fatigue tests were carried out on full-scale specimens. In the analytical part, various finite element models were made. Different modelling techniques to incorporate the weld itself into shell element models were also investigated and compared to the results from the experiments and to those obtained from solid element models.

1   INTRODUCTION

The structural hot spot stress (SHSS) approach has been used for more than 30 years for fatigue assessment of weldments, specifically in the offshore industry. The method was originally developed for welded joints of circular and rectangular hollow sections. It has been later applied successfully to welded plate structures [1]. The SHSS method is advantageous compared to the traditional nominal stress method mainly because of its ability to assess more types and a wider variation of structural details. It incorporates the effect of structural geometry into the local stress ranges at the welds and predicts the fatigue life based on these local stress ranges. In contrast, the nominal stress method uses the far-field stress away from the weld.

Structural hot spot stresses in a detail can be evaluated either experimentally or numerically. The experimental evaluation is carried out by measuring surface stresses in some reference points at a certain distance from the weld toe and then extrapolating them into the weld toe. Similar procedure can be applied in the numerical approach which is based on finite element analysis. However, it is well known that the analytical results are highly dependent on the finite element mesh size and properties [2]. To solve this, the International Institute of Welding (IIW) has compiled extensive regulations regarding the finite element modelling such as element type and size as well as type of extrapolation and location of extrapolation points. On the other hand, some researchers have proposed alternative methods to determine the SHSS. These methods are supposed to be 'mesh size-insensitive' [3,4]. The use of these alternative SHSS evaluation methods has been approved in the newest revision of the IIW code (2009 revision).

Eurocode 3 [5] accepts the structural hot spot stress method for fatigue design of welded steel structures. The Eurocode's design S-N curves and detail categories for the structural hot spot stress method are similar to those of the IIW code. However, Eurocode provides limited or no instructions on the type and size of the finite element mesh nor on the extrapolation procedure.

The SHSS method has been in use in other industries for rather long time. However, the method is less applied in the structural engineering field until recent years. In the field of bridge engineering, Miki & Tateishi [6] proposed parametric geometric stress concentration factors for cope hole details in steel bridge girders. Chan et al. [7] conducted a large study for finite element modelling of a large suspension bridge located in Hong Kong. As part of their study, they used local FE models in conjunction with structural hot spot stress method to evaluate the fatigue life of certain welded details. Schumacher & Nussbaumer [8] investigated the fatigue service life of some welded K-joints of circular hollow sections by experimental measurement of structural hot spot stresses in their test specimens. These types of joints are used in some innovative bridge designs.

This study is within the framework of the research project BriFaG (Bridge Fatigue Guidance). In this research the application of structural hot spot stress method for fatigue life assessment of a welded detail in orthotropic bridge decks is investigated. That is fillet welded rib-to-cross beam joint shown in Figure 1. The structural hot spot stress is evaluated both experimentally and numerically. This paper focuses on the joint between the rib and the web of the cross beam. This is a cruciform joint with load-carrying fillet welds. Both the IIW and Eurocode categorize this type of joints as detail category 90 with reference to cracking from the weld toe. Two cracking locations (hot spots) at the ends of this joint are marked as 'wt' and 'wb' in the figure. These hot spots reside on

the plate edges and are type 'b' hot spots, according to IIW definition. The stress state is more complex in type 'b' hot spots and structural stress cannot be separated completely from the non-linear peak stress [9].

Orthotropic bridge decks consist of a deck plate stiffened by a system of orthogonal longitudinal and transverse stiffeners (i.e. cross-beams and ribs). The ribs could be of open or closed cross sections. The resulting system is a light weight deck for steel road bridges and is especially efficient for use in long-span or suspension bridges, where the reduction in dead weight of the structure is more important. However, their complex geometry combined with various loading situations from traffic loading makes fatigue assessment of these structures more challenging. Many researchers have investigated the fatigue behaviour of the orthotropic decks. Recently, Kolstein [10] has conducted an extensive study on different aspects of the fatigue behaviour of orthotropic decks with closed ribs.
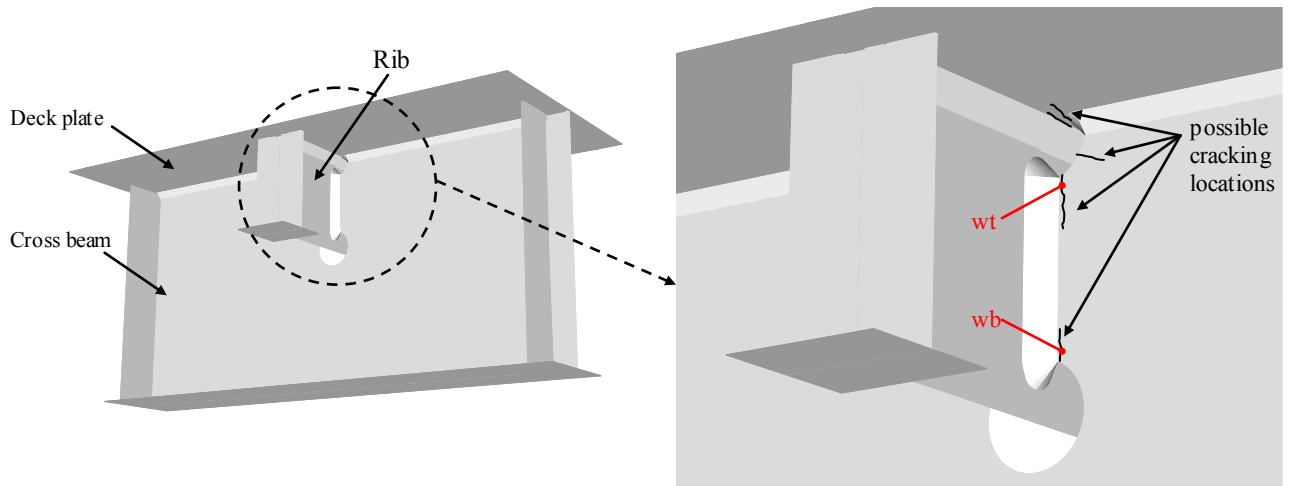

Figure 1.The assessed detail and possible cracking locations in the joint.

2   FATIGUE TESTS

2.1   Specimens and test setup

Three full-scale identical specimens were tested in the experimental part of the study. The geometry and dimensions of the specimens are shown in Figure 2. The joints between the rib, cross beam and deck plate were all fillet welded with a weld throat dimension of a=5 mm. shielded metal arc welding (SMAW) process was used.

Figure 3 shows the test set-up. Two roller supports held the specimen at the cross beam ends. The load was applied in a vertical plane passing through the mid-span of the cross beam by an actuator and via a load cell and through a loading beam. The loading beam divided the load into two equal parts and applied each part to one end of the ribs. The ribs were stiffened by two stiffeners at the point of load application to prevent local buckling. This loading would cause a negative moment in the rib at the joint location, and a positive moment in the cross beam in that location.

2.2   Measurements

Specimens were first loaded statically with a load well below that corresponding to yielding. Elastic strain measurements were conducted at different load levels. Subsequently, high cycle fatigue testing with constant amplitude fatigue load was performed and the number of cycles to crack initiation for different cracking locations was registered. Each specimen was tested with a different load range. The summary of fatigue loading data is presented in Table I. It is worth noting that specimen A2 was tested under two different fatigue load ranges as mentioned in Table I. Palmgren-Miner's linear damage accumulation rule was applied in calculation of damage ratios for this specimen in the subsequent calculations. The load frequency for all specimens was between 2 to 3 Hz.

The hot spot zones (i.e. placement of the strain gages) were located by a primary finite element analysis. These locations can be seen in the close up view in Figure 1. The cracking might also initiate in the weld toe on the rib plate. But for the assessed detail, this was not the case, because of the relatively high thickness of the rib plate (18mm). The stress profiles in the hot spot zones were measured with chain strain gages, as shown in Figure 4. For each hot spot two stress profiles were measured at the two sides of the cruciform joint. This was done only for specimen A4. Specimens A2 and A3 were tested before the start of this study and the arrangement of the strain gages did not correspond to the requirements of the SHSS method
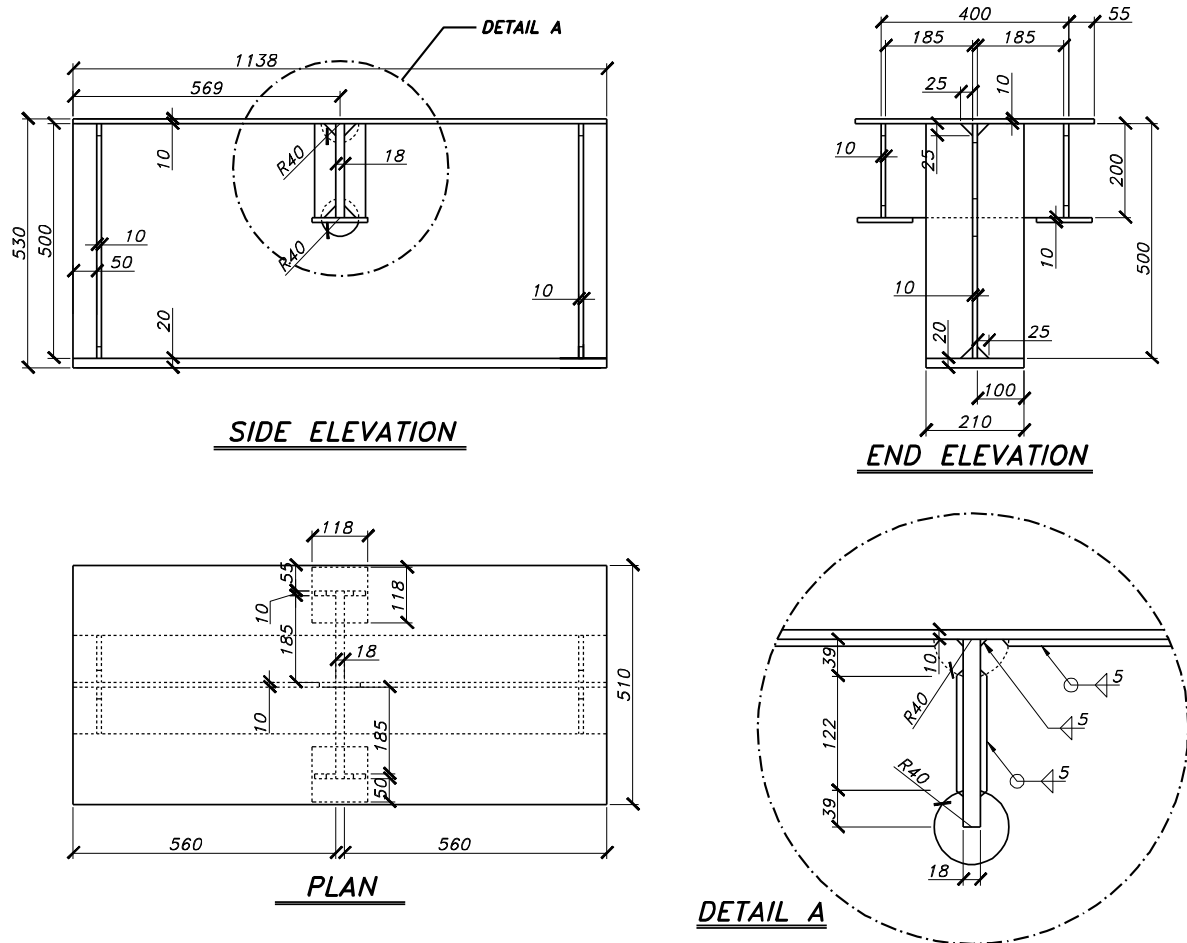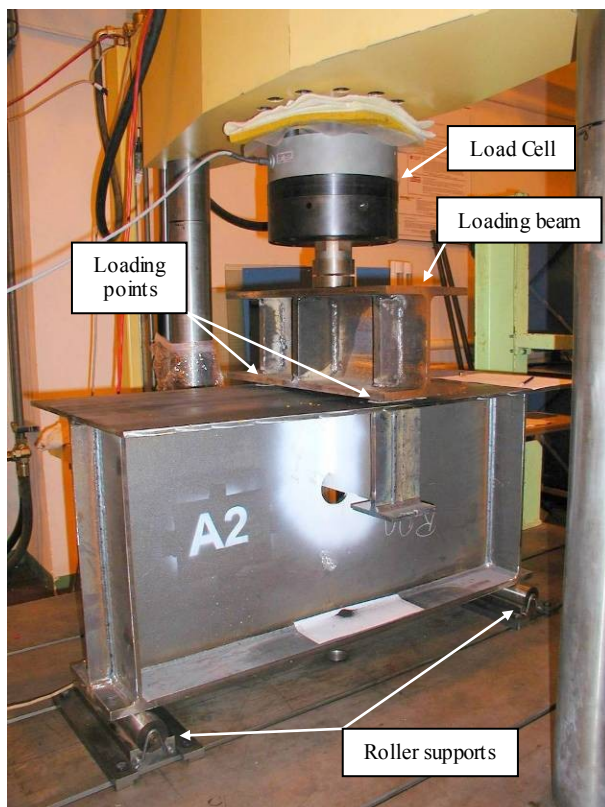
Figure 2. Geometry and dimensions of the tested specimens.
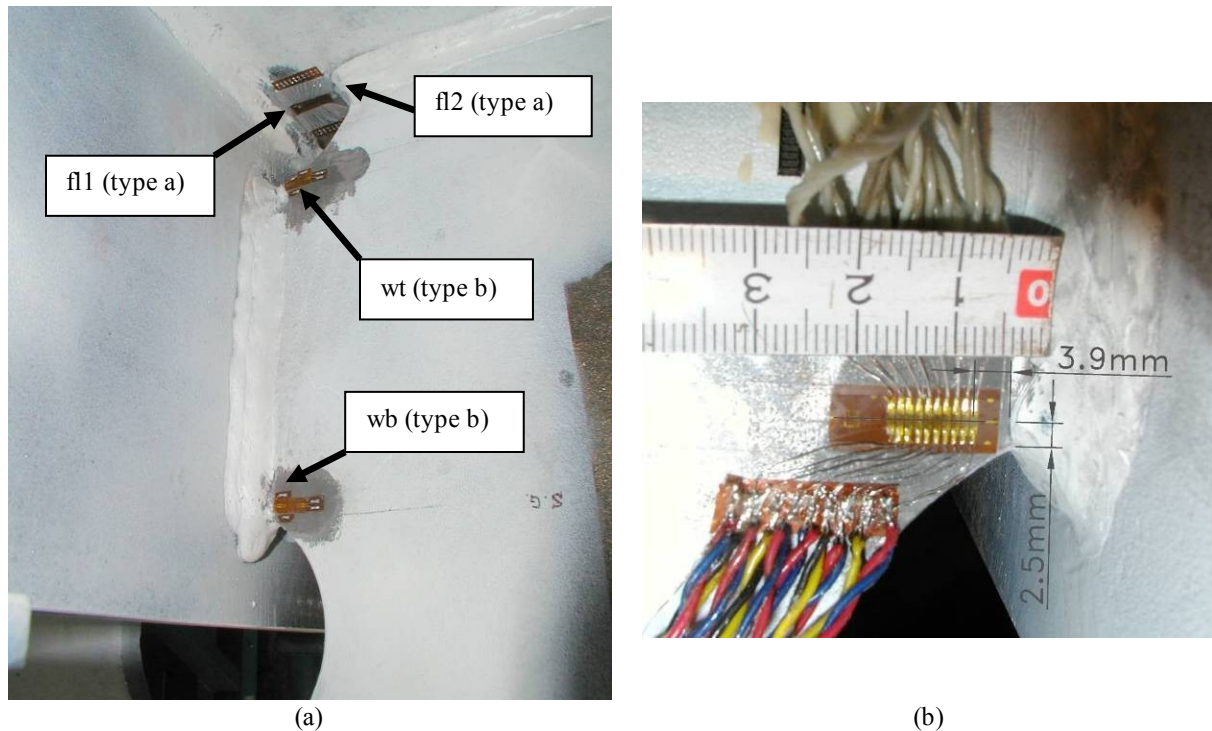

Figure 3. Fatigue test setup.

(a)   (b)

Figure 4 (a) chain strain gauges installed on hot spots. (b) close up view of 'wb' hot spot.

Table I. Fatigue loading data for the specimens.

Specimen	Maximum load [kN]	Minimum load [kN]	Load range [kN]	Number of cycles [n]
A2*	210	10	200	5 527 812
A2 (cont'd test)	410	10	400	1 543 930
A3	360	10	350	5 000 000
A4	10	380	370	Test in progress

*No visible cracks observed in the specimen in this loading stage

The positions of the strain gages on the desired location at type 'b' hot spots (namely 'wb' and 'wt') were somehow problematic. Since the strain gradient in the type 'b' hot spots is steeper and exact placement of strain gauges in both directions, perpendicular to the weld and along the weld, is crucial. This could not be fulfilled completely in the experiment because of the curvature of the plate edge. Figure 4(b) shows the installed strain gauge in 'wb' hot spot. Note that the 2.5 mm measured vertical distance of the strain gage from the hot spot is hardly avoidable. Therefore, the measured SHSS values would be somewhat underestimated.

2.3 Test results

A summary of the crack initiation data from the tests is presented in Table II. The SHSS values were calculated by quadratic extrapolation of stresses at the 3 reference points, located 4mm, 8mm and 12mm from the weld toe. The measured stress profiles and extrapolated stresses at the two sides of hot spot 'wb' are plotted in Figure 5. The difference in the two stress profiles can be attributed to possible misalignments in the joint. This scatter is amplified when the extrapolation to the weld toe is carried out. The structural hot spot stress for 'wb' hot spot measured as $\sigma = 01 MPa$. This value is the average of the hot spot stresses evaluated from the stress profiles at the two sides of the joint. For 'wt' hot spot, the appropriate stress profile was available only on one side of the cruciform joint. The SHSS value measured based on this profile was $\sigma = 04 MPa$. These SHSS values are measured under a load range of 200kN.

Table II. Summary of crack initiation data for specimens A2 to A4.

Specimen	Load range [kN]	Number of cycles to cracking in hot spots [n]			
		wb	wt	fl1	fl2
A2*	400	$3.05*10^5$	$9.07*10^5$	$1.49*10^6$	$1.80*10^5$
A3	350	$1.09*10^6$	$2.53*10^6$	$4.73*10^6$	$9.85*10^5$
A4	370	$3.04*10^5$	N/A**	N/A**	N/A**

* Specimen A2 was first tested for 5 million cycles under a 200 kN load without any visible cracking.
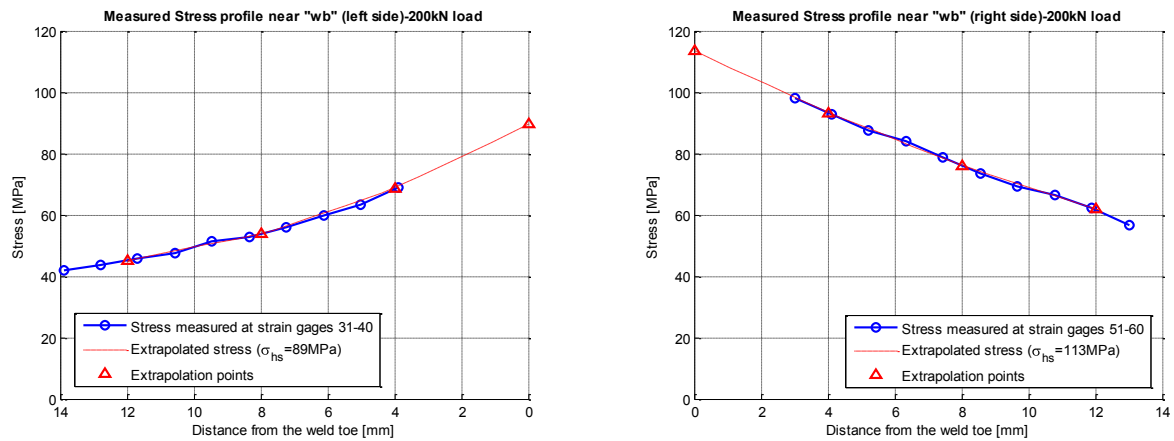** Test in progress.

Figure 5. Measured stress profiles and extrapolated stresses close to 'wb' hot spot.

3 FINITE ELEMENT MODELLING AND ANALYSIS

In order to evaluate the appropriateness of various FE-models for the use in calculating the hot spot stresses in the studied detail, different FE models were constructed and analysed, see **Figure 6**. The regulations proposed by IIW were followed in building the models. The geometry of the models was based on the theoretical dimensions. For shell element models the geometry was based on the mid-planes of the plates in the physical part. Typical steel mechanical properties ($E = 210GPa$ and $\nu = 0.30$) were used for the material properties. 20-node solid elements were used in the solid element model. All models were analyzed under a 4kN reference loading. For the shell element models 8-node shell elements were used. A brief description of each model is presented here:

SH model: Shell element model with a relatively fine mesh ($4mm \times 4mm$ at the hot spot regions). Welds were not modelled. Extrapolation was carried out to the intersection of mid-planes.

OP model: Solid element model with a relatively fine mesh ($4mm \times 4mm$ at the hot spot regions). A quarter of the physical part was modelled because the part was symmetric in two directions. Welds were modelled.
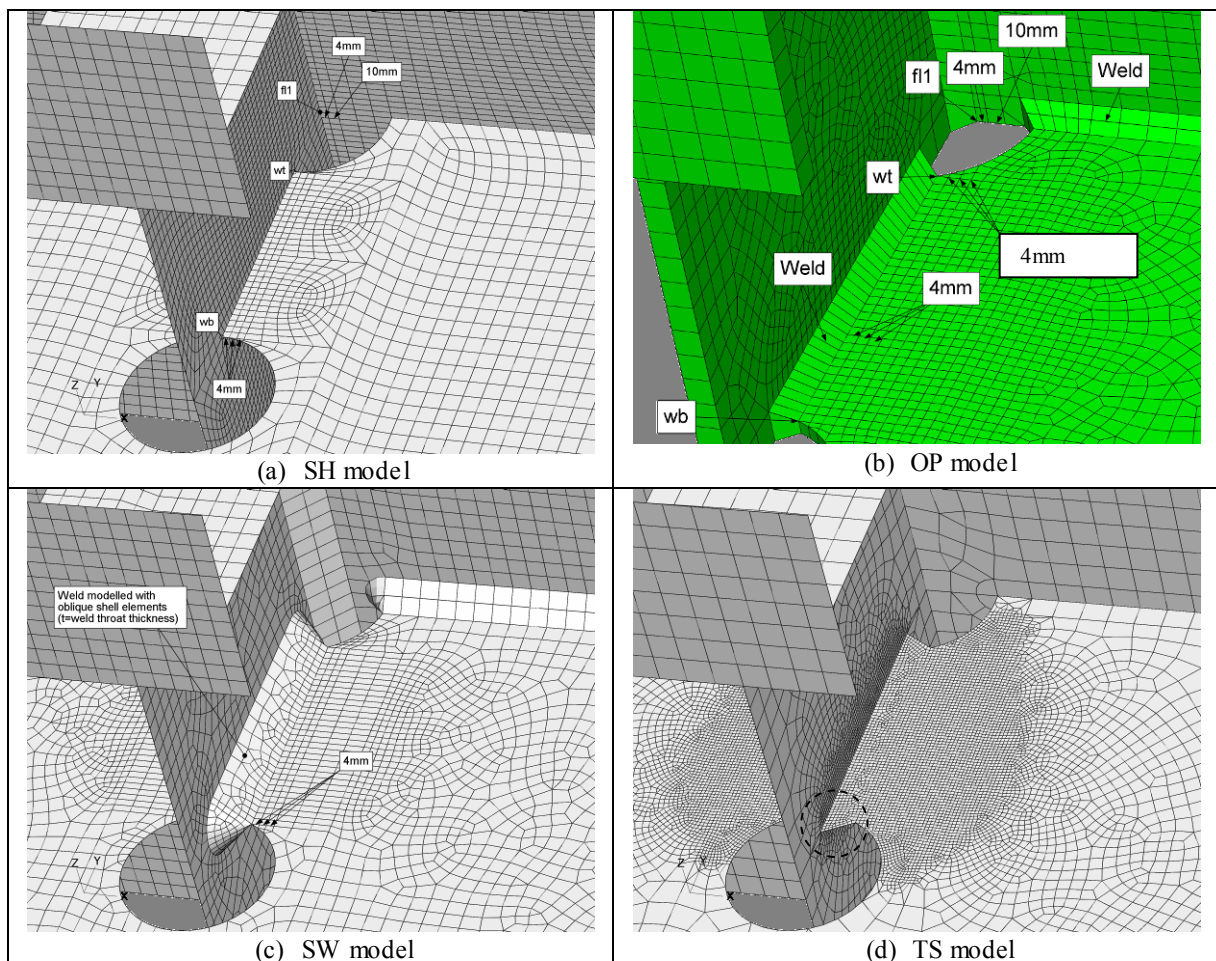

(a) SH model

(b) OP model

(c) SW model

(d) TS model

Figure 6. Various finite element models made for evaluation of structural hot spot stresses.

SW Model: Shell element model with a relatively fine mesh ($4mm \times 4mm$). Geometry and stiffness of the welds was incorporated into the FE model by means of oblique shell elements with a thickness equal to weld throat thickness according to the recommendations by [11]. Extrapolation was carried out into the weld toe.

TS Model: Shell element model with a fine mesh ($2mm \times 2mm$).The weld was modelled by increasing the thickness of the elements in the weld region. Eriksson et al. [11] suggest using this technique for modelling of fillet welds in shell element models. Figure 7 depicts the method employed to estimate the increased thickness for the elements in the weld region. The extrapolation should be carried out to the transition point, where the thickness of shell elements changed. In order to maintain the stress singularity in this point the corner location was adjusted by adding a fillet (circled area in the Figure 6(d)).

Stress contour plots for one of the models (OP model) are shown in Figure 8. Red straight line at bottom cope hole in Figure 8(a) depicts the path for extraction of the stress profile at 'wb' hot spot region.
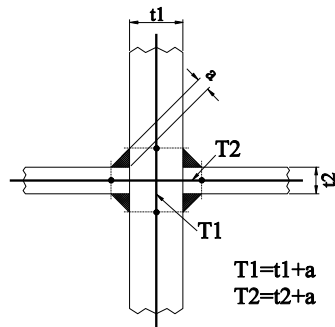

Figure 7. Calculation of increased thickness for shell elements in the weld region [11].
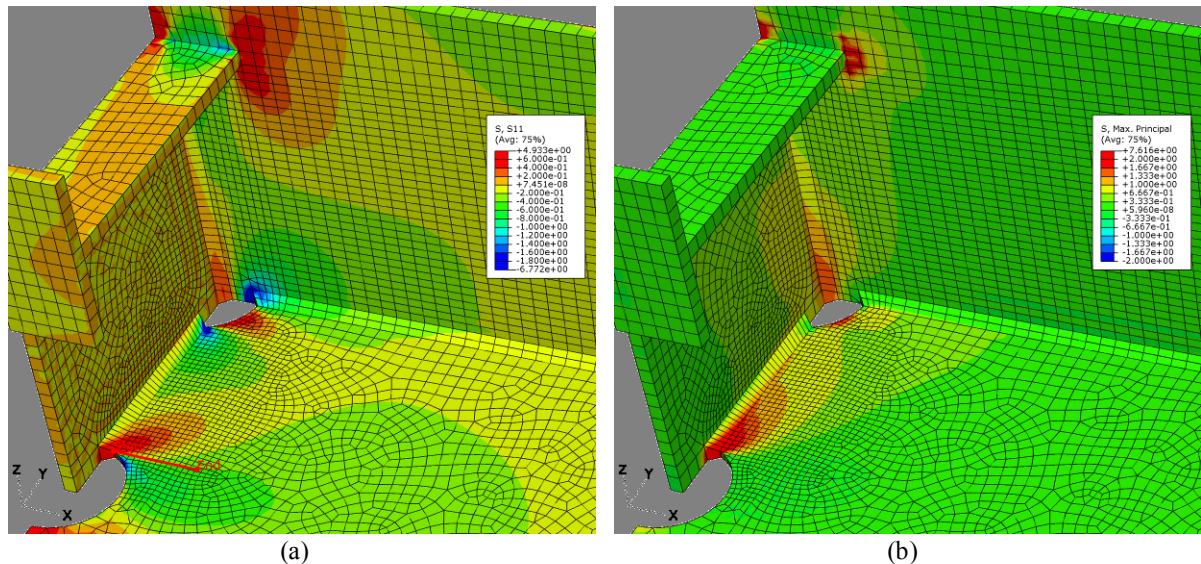

| (a) | (b) |

Figure 8. Stress distribution for 4kN reference load, OP model; (a) Transverse stress, (b) Maximum principal stress.

4   Comparison of analyses results and measurements

Figure 9 shows transverse stress profiles in 'wb' location and the extrapolated stresses for the four models studied. The apparent overestimation of hot spot stresses in the case of SH model (shell element model in which welds were not modelled) is noticeable. The evaluated SHSS values from different models and measurements are summarized in Table III. These values were calculated based on the stress component perpendicular to the weld toe (transverse stress). The hot spot stresses computed based on maximum principal stresses were lower . According to the table, the results from the solid element model (OP model) agreed better with the measured stresses. As it was mentioned in section 2, the source of scatter lies mainly in the misalignments in the joint, which are not introduced in the FE models. For usual offsets, this can increase the hot spot stresses by 45% [12]. The computed SHSS values from the shell element models were compared to the hot spot stresses from the solid element model and to the measured hot spot stresses. The results are shown in **Table III** by means of the stress ratios. It can be observed that the results from SW and TS shell element models, comply better with the solid element model. The weld was included in this two shell element models.

The OP (solid element) model resulted in better estimation of structural hot spot stresses. The calculated SHSS value from this model for the 'wb' hot spot was used together with the number of cycles to crack initiation in the

same point (wb) and compared with the appropriate fatigue strength S-N curve (FAT 90). The results are shown in Figure 10(a). The results comply rather well with the code design curve with a safety margin.

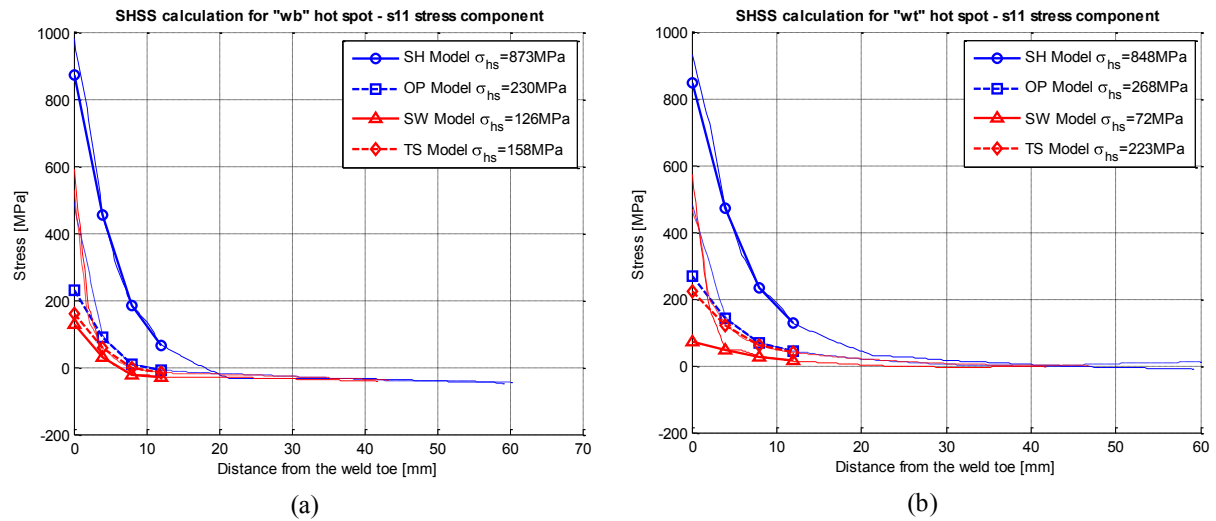(a)   (b)

Figure 9. Profiles of stress component perpendicular to the weld and extrapolated hot spot stresses for four studied models; (a) 'wb' hot spot, (b) 'wt' hot spot.

Table III. Comparison of computed and measured structural hot spot stresses.

Model	'wb' hot spot			'wt' hot spot		
	SHSS for 400kN loading [MPa]	Ratio of SHSS value to solid element model	Ratio of SHSS value to measurement	SHSS for 400kN loading [MPa]	Ratio of SHSS value to solid element model	Ratio of SHSS value to measurement
SH	873	3.80	4.32	848	3.16	4.51
OP	230	1.00	1.14	268	1.00	1.43
SW	126	0.55	0.62	72	0.27	0.38
TS	158	0.69	0.78	223	0.83	1.19
Measured	202	-	-	188	-	-

4.1 Fatigue life prediction based on the nominal stress method

Eurocode 3 includes detail categories for orthotropic bridge decks with open and closed stringers (ribs). The studied joint is categorized as detail category 56 in the code. An equivalent stress range ($\Delta\sigma_1$) should be calculated as a combination of the direct stress range ($\Delta\sigma$) and shear stress range ($\Delta\tau$) in the cross beam at the joint section as follows:

$$\Delta\sigma_{eq} = \frac{1}{2}(\Delta\sigma + \sqrt{\Delta\sigma^2 + 4\cdot\Delta\tau^2}) \qquad (1)$$

This equivalent stress range is then used as nominal stress range. The calculated nominal stresses were used together with the number of cycles to crack initiation from the tests and compared with the corresponding fatigue S-N curve. Figure 10(b) shows that for the studied specimens, the nominal stress method underestimates the damage and thus, overestimates the fatigue life of the specimens. It should be noted that the partial load and resistance factors were eliminated from the calculations to attain a realistic fatigue life which would be comparable to the results from the experiment.
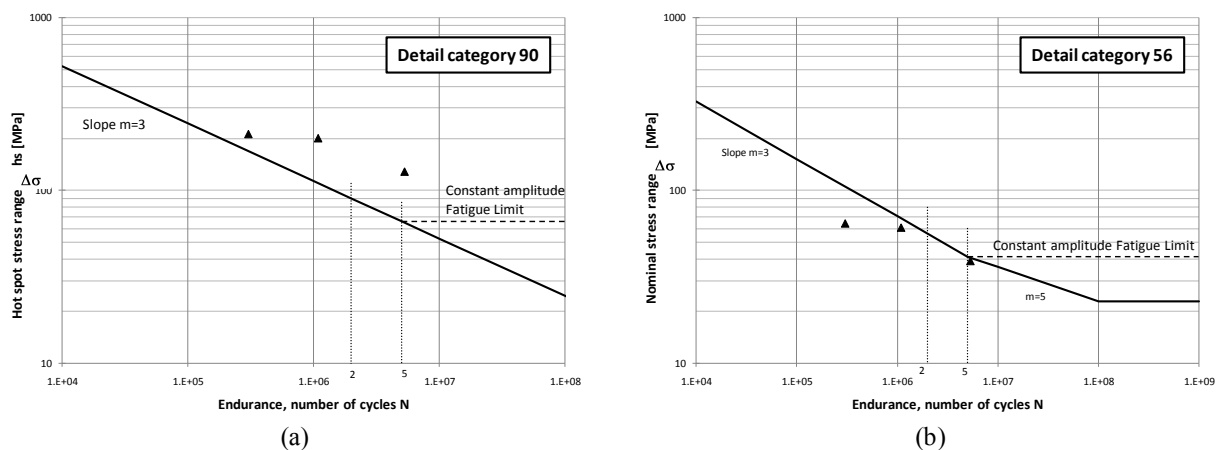

(a)   (b)

Figure 10. Fatigue test data compared to Eurocode fatigue strength curves; (a) SHSS approach, (b) Nominal stress approach.

5   CONCLUSION

The application of structural hot spot stress for fatigue life assessment of a fillet-welded orthotropic bridge detail was carried out by means of full-scale tests and finite element analysis. Three shell element models were considered with the weld modelled in a different way in each of them. The accuracy of these shell element models was assessed by comparing the calculated structural hot spot stress values to the experimental values and to the results from the FE-model with solid element. The agreement between the results from the shell element models and solid element model was not good. As it is stated in [13] it seems that the difference in the SHSS values in shell element models and solid element models is more significant when a geometric feature (such as a cope hole or a notch) exists in the hot spot region. Therefore, it is suggested that solid element models being used for these types of details. Modelling of the weld with solid elements in a shell element model can also be considered [11] but it is a troublesome modelling task.

Finally, the testing and analysis results (from solid element model) were put into relevant fatigue strength S-N curve recommended by the Eurocode, to compare the fatigue life as predicted by the code to the fatigue life in the tests. This comparison was also done for the relevant S-N curve for the nominal stress method. The structural hot spot method was found to be more accurate in predicting the fatigue life of the studied detail.

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