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THE EFFECT OF RESIDUAL STRESSES IN FILLET WELDS ON THE FATIGUE BEHAVIOR: A LEFM APPROACH

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Residual stresses are present in many civil structures due to manufacturing actions causing plastic deformations. Nevertheless, these stresses are not often taken into account when considering the design of these structures, especially when assessing fatigue problems. This remains true for orthotropic steel bridge decks. Due to their many complex welding details, these decks are sensitive to fatigue. To increase the understanding of the fatigue behavior of welded details, an improved analyzing tool using linear elastic fracture mechanics is proposed in this paper. Apart from the fatigue life of the weld detail, the crack propagation and crack growth direction are also evaluated with an XFEM model. Application of this method to the case of the orthotropic steel Temse Bridge in Belgium results in crack propagation very similar to reality. It also demonstrates that the fatigue calculations need to include residual stresses to comply with the real behavior of crack propagation.

Keywords: Fatigue, XFEM, Crack propagation, Residual stresses, Temse bridge.

1 INTRODUCTION

Several fatigue problems have been observed in several orthotropic bridge decks across Europe, in the past 10 years—especially in the Netherlands, where many of these bridge decks were constructed (Maljaars *et al.* 2012). Nevertheless, orthotropic bridge decks are widely used in long span steel bridges, since they are extremely lightweight when compared to the load-carrying capacity, and are therefore durable and very efficient. These types of bridge decks consist of a complex network of closed trapezoidal longitudinal stiffeners and transverse web stiffeners welded to a deck plate. Because of various complex welding operations, multiple fatigue problems often appear across the bridge deck. In Europe, their assessment is limited due to the availability of the design codes of Eurocodes. With the prescribed method, the fatigue detail and its nominal stress state is related to SN-curves. These curves are set up based on experimental results to fit with the realistic behavior of the welded connection. However, these experiments have never been updated with current installation procedures and welding techniques. Due to these design imperfections, an overestimation of the dimensions imposes itself when considering orthotropic bridge deck plates. To investigate the complex fatigue behavior with present welding conditions, other methods are needed besides the traditional fatigue calculations. Therefore, a more in-depth analysis is used: fracture mechanics. With this method a detailed crack behavior can be evaluated.

Also, a much larger dataset will be available for estimating the total fatigue lifetime, or even a more realistic evaluation for the remaining lifetime of existing bridges.

2 FINITE-ELEMENT MODELING

A FEM-model has been developed to evaluate the stress distribution and its fracture-mechanics parameters in a stiffener-to-deck plate connection with closed stiffeners. In addition, the model has been made according to the movable part of the Temse Bridge across the river Scheldt in Belgium (Figures 1 and 2).

Figure 1. Temse Bridge across the river Scheldt (Belgium).

Figure 2. Orthotropic deck plate.

After the renovation of the deck in 1994, a 600 mm-long crack was detected in 2004 in the stiffener-to-deck plate detail mid-span between two crossbeams. In this particular case, the crack propagated through the deck plate starting from the weld root. Therefore, the crack propagated without any possible detection through visual inspection unless there was already considerable damage (Figures 3 and 4).

The deck plate of this movable part of the bridge is 12 mm thick and the stiffeners are 8 mm thick. The overall dimensions of the traffic lane are 53.90 m by 7.00 m. The trapezoidal stiffeners are 350 mm high and 300 mm wide on top, with a 90 mm width at the lower soffit. The distance between the longitudinal stiffeners equals 300 mm.

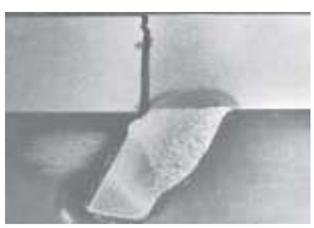

Figure 3. Longitudinal crack through the deck plate (Maddox 1974a).

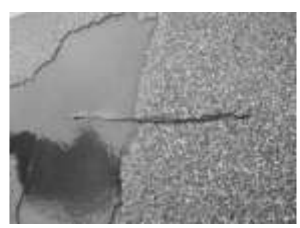

Figure 4. Longitudinal crack through the deck plate at a stiffener-to-deck plate connection.

Figure 5 illustrates the FEM-model consists out of shell elements and beams. By doing this, realistic boundary conditions are available without seriously increasing the computation time. However, for evaluating fracture mechanics parameters, a 3D model with volume elements becomes necessary. Therefore, a more detailed small-scale model is constructed (Figure 6). To relate both models, the displacements are taken from the large model and introduced on the boundaries of the small-scale model.

Concerning the applied stresses, five characteristic lorries (load model 4) are used (Eurocode 1 2013).

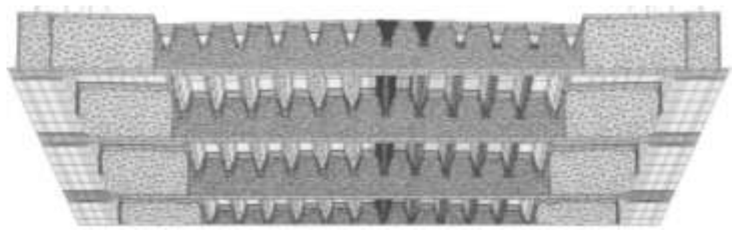

Figure 5. 3D view of the FEM-model of the Temse Bridge.

2.1 Implementation of Residual Stresses

Residual stresses are present in many civil structures due to manufacturing actions causing plastic deformations. Nevertheless, these stresses are not often taken into account when considering the design of these structures. However, the effect of residual stresses may either be beneficial or detrimental, depending on magnitude, sign and distribution of these stresses with respect to the load-induced stresses (Barsoum *et al.* 2009). Therefore, the initial stress state due to a welding operation was introduced into the FEM-model. The easiest and preferred way is to apply the residual stresses according to the literature or to test data. Results from similar fillet welds, such as those in the orthotropic bridge decks, were used. Therefore, tensile yield stresses were introduced into the deck plate at the weld. For the stresses in the stiffener, an additional bending moment and normal force are also introduced. The bending moment was necessary because the weld is welded from one side only, and the filler material and the corresponding heat zone is larger at the weld toe compared to the weld root. For the magnitude of this bending moment and normal force, an assumption is made based on the distribution of the filler material.

3 LEFM DESIGN APPROACH

Linear Elastic Fracture Mechanics (LEFM) calculations were carried out with the abovementioned detailed 3D-model of a stiffener-to-deck plate connection. The method described below refers to the automatic crack propagation method based on XFEM (eXtended Finite Element Model) techniques. With this method, it is possible to evaluate the whole crack propagation without re-meshing the model for every crack propagation step. In addition, not only could the crack growth rate be evaluated, but also the crack growth direction. The XFEM-model uses the Paris law in order to propagate the crack automatically according to the path using the least energy to crack:

$$\frac{da}{dN} = C \cdot \left(\Delta K_I^{eff} \right)^m \tag{1}$$

The Stress Intensity Factor (SIF) ΔK_I^{eff} in this equation is a function of ΔK_I, ΔK_{II}, ΔK_{III}, θ_p (bifurcation angle), and the used material. The parameters C and m are material properties. Structural steel C equals 3.10^{-13} - 4.10^{-13} [N, mm] and m equals 3 [-]

(Maljaars *et al.* 2012, Kühn *et al.* 2008). Because the applied stress Δσ is known as well as the calculated SIF-values, the geometrical dependent parameter f(a) can be evaluated from Eq. (2) for every crack propagation step:

$$\Delta K_I^{eff} = f(a) \cdot \Delta\sigma \cdot \sqrt{\pi \cdot a} \tag{2}$$

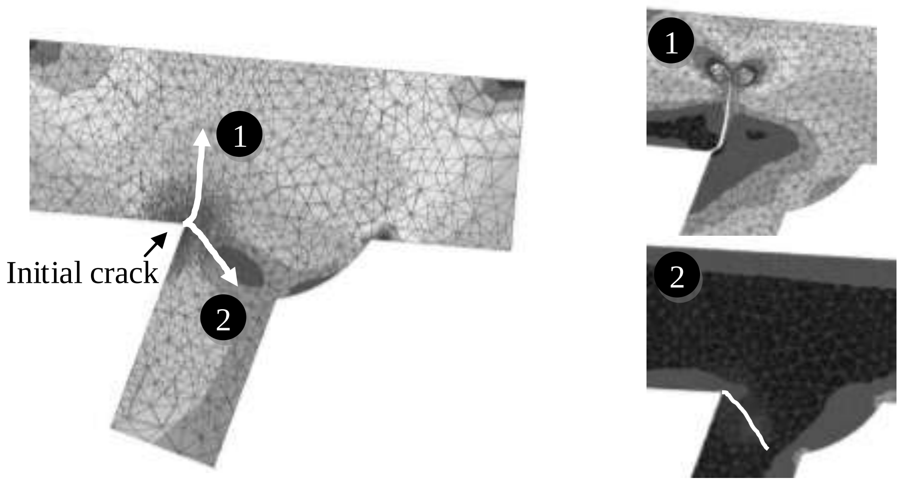

Figure 6. Detailed small-scale 3D model: Possible crack growth directions.

The geometrical parameter f(a) not only depends on the crack length a, but also on the overall dimensions of the bridge deck. Therefore, once this parameter is evaluated for a particular bridge deck geometry and weld detail, it could be used for several other bridges with comparable dimensions. Figure 7 (left) illustrates the geometrical parameter f(a) for the three different wheel types used for load model 4 (Eurocode 1 2013).

According to the placement of the truck at the center of the traffic lane, all the wheel loads were on the right hand side of the detail being considered. Note that the location of the wheel loads does not really matter for the crack propagation. Only the applied stress is important. This remains true for the transversal crack-growth direction. Obviously, when the wheel loads are on the left side of the detail, the stresses have an inverted sign and will create a different curve.

Figure 7 (right) illustrates the geometrical parameter f(a) for the model with and without residual stresses. Only wheel type B is taken into account. It can be noticed that the curves for the model with residual stresses are shifted upwards, resulting in a faster crack propagation. This is remarkable because the applied stress Δσ remains identical. This reflects the importance of the initial stress state in fatigue calculations. It is also logical that a fatigue crack propagates faster if residual stresses are included. Without residual stresses, the wheel loads create a compression zone at the weld root. Therefore, the crack propagation is due to compressive forces. By including residual stresses that equal the yield tensile stress, a tensile stress variation is created.

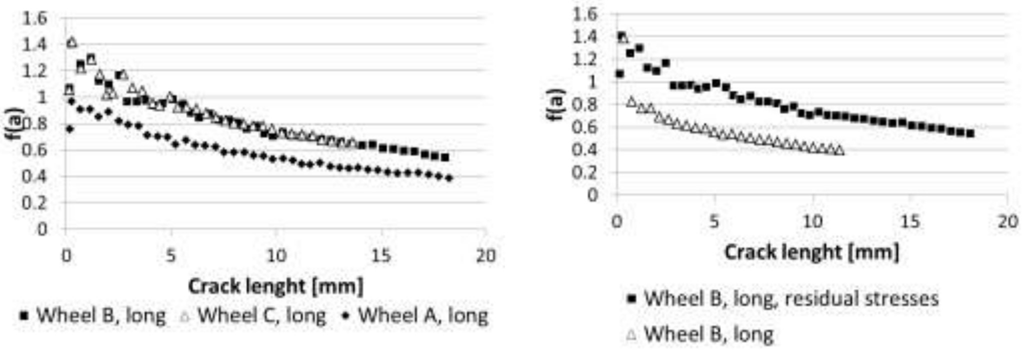

Figure 7. Geometrical parameter f(a). Left: Three different wheel types according Eurocode for the longitudinal crack growth direction. Right: Influence of residual stresses for wheel type B.

Another result concerns the crack growth direction. Without residual stresses, the crack is growing through the stiffener web (Figure 6, bottom right). If residual stresses are included, the crack grows through the deck plate (Figure 6, top right). This also explains why the SIF-values are higher, because the applied stresses in the deck plate differ from those in the stiffeners. It demonstrates that the simulation needs to include residual stress to comply with the real pattern of Figure 4.

Finally, the fatigue life of the structure can be evaluated by integrating Eq. (1):

$$N_f = \int_{a_i}^{a_f} \frac{da}{C \cdot \Delta K_I^{eff\ m}} \tag{3}$$

Figure 8 and Figure 9 visualize the evolution of the crack length as a function of the years of service life for both the transversal and longitudinal crack growth directions. At this point, the fatigue life was evaluated, due to a constant stress amplitude with wheel type B and an axle load of 130 kN. A fatigue evaluation with a realist traffic load distribution will be done in future research. Without residual stresses, the crack does not develop very fast, but remains faster than the crack with residual stresses until approximately 52 years. After that, the crack with residual stresses grows progressively. Because the crack is growing through the deck plate, the continuity of the stress distribution due to membrane forces are interrupted. The stresses are forced into the less rigid body of the closed stiffeners. This explains why the crack propagation through the deck plate is much faster than the crack propagation through the stiffener. The same conclusions hold for the longitudinal crack growth direction.

It should be noted that the speed of the longitudinal crack growth was much faster than the one in the transversal direction. This was identical to the fatigue problems detected at Temse Bridge. The crack first grew longitudinally before fully penetrating the deck plate (or the stiffener). Therefore, the crack avoided visible detection unless there was already sufficient damage.

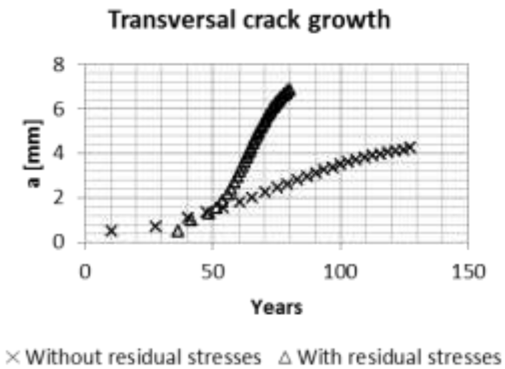

Figure 8. Transversal crack growth: A comparison with or without residual stresses.

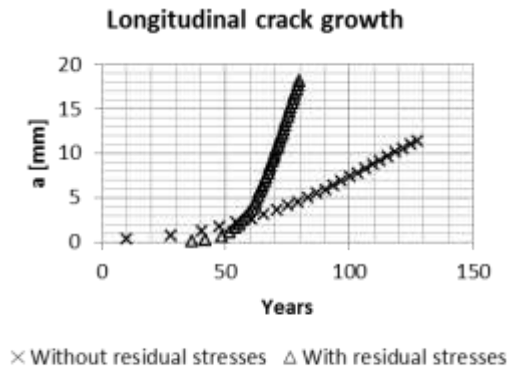

Figure 9. Longitudinal crack growth: A comparison with or without residual stresses.

4 CONCLUSIONS

Although residual stresses are not often explicitly taken into account in design codes, they are of capital importance for both the fatigue life of the structure and the crack growth direction. Sometimes the initial stress state can increase the crack growth speed, which can never be detected with traditional fatigue calculations. It becomes clear that using fracture mechanics as an improved fatigue life assessment in orthotropic bridge decks has many advantages. Every weld detail can be evaluated in depth with much more available data with respect to the traditional fatigue calculations. In addition, geometrical parameter f(a) makes it possible to evaluate similar weld details without an intensive XFEM calculation.

Application of this method to the case of the Temse Bridge in Belgium results in a crack propagation very similar to reality. However, the stresses are still lower in the model than in reality. This explains why the fatigue life in the model is still overestimated. In addition, the weld connection is not as smooth as modeled. These irregularities cause higher stress peaks. In addition, a transversal deck plate weld interferes with this connection and causes higher stress peaks. More detailed verifications are still in progress and will be published in future papers.

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