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DETERMINING RESIDUAL STRESSES IN WELDED CONNECTIONS OF ORTHOTROPIC STEEL BRIDGE DECKS WITH A HOLE-DRILLING TECHNIQUE

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Manufacturing processes such as welding operations cause residual stresses that are present in most civil structures. They cause plastic deformations without any external loads and are therefore often overlooked during design. Nevertheless, residual stresses can have profound influences on material strength and fatigue life. This is also true for orthotropic steel bridge decks, which have many complex welding details. Because little is known about the distribution of residual stresses due to welding, a semi-destructive experimental test setup is developed for a stiffener-to-deck plate connection on an orthotropic steel bridge deck. In particular, the hole-drilling technique is used. With this experimental test setup, a clear distribution of the residuals stresses becomes visible. Residual stresses up to the yield strength can be found near the weld and up to 50% of the yield strength elsewhere. However, more research is needed to verify why the sign of the stresses is opposite to the expected stresses in the literature.

Keywords: Fatigue, Strain gauge rosettes, Fracture mechanics, Stress distribution.

1 INTRODUCTION

Residual stresses are unintentionally introduced by almost every manufacturing process, including rolling, forming, milling, welding, etc. Sometimes they are even intentionally introduced by the use of surface treatment such as shot-peening. The effect of these residual stresses can be either beneficial or detrimental, depending on magnitude, sign and distribution of the introduced stresses. The presence of tensile residual stresses is mostly harmful due to their contribution to fatigue failure. However, residual stresses create plastic deformations without any external load. Therefore, residual stresses are ignored when evaluating fatigue failure using Eurocode 3 (2015), because only the stress variations are considered. A possible solution is the use of fracture mechanics as a fatigue evaluation tool. This method allows adding an initial stress state on top of the stress variations due to an external load (Barsoum and Barsoum 2009, Nagy et al. 2014). However, in most cases, more research about the real magnitude and distribution of residual stresses in structures is still needed.

This is also true for orthotropic steel bridge decks, which suffer from fatigue problems due to the extensive use of weld details. These bridge decks consist of a complex network of closed trapezoidal longitudinal stiffeners and transverse web stiffeners welded to a deck plate. They are widely used in long-span steel bridges, since they are extremely lightweight when compared to load-carrying capacity, and are therefore durable and very efficient.

Since the introduction of orthotropic bridge decks, fatigue problems at welding details have been observed across Europe. Increased traffic intensity and traffic loads is one reason. But even recently-constructed bridges could develop fatigue cracks (Maljaars *et al.* 2012), indicating a lack of knowledge of fatigue behavior in these bridge decks. To avoid fatigue cracks, often the plate thickness is increased, leading to a less lightweight construction. A clear pattern of residual stresses and corresponding fatigue behavior must be studied to understand the real fatigue life of a structure.

2 HOLE-DRILLING TECHNIQUE

Different methods have been developed to evaluate residual stresses for different types of components. For this paper, a semi-destructive measuring technique is used: hole-drilling. It is the most widely-used general-purpose technique for measuring residual stresses in materials (Schajer 2013). In addition, good accuracy and reliability can be achieved for incremental depths.

2.1 Principle

The hole-drilling technique involves drilling a small (blind) hole into the test material at the location where the residual stresses are to be evaluated (Figure 1). The hole-drilling results in a redistribution of residual stresses in the material surrounding the hole, with localized deformations occurring in the test specimen.

Figure 1. Hole-drilling setup: RS-200 milling guide (left), hole-drilling strain gauge rosette near weld (right top), milling operation (right bottom).

The corresponding strains are simultaneously measured with strain-gauge rosettes. When measuring at incremental depths, non-uniform residual stresses can be evaluated at each drilled depth with the given standardized test procedure according ASTM E837-13a (2015). This test method applies in cases where material behavior is linear-elastic. Therefore, the measured stress level is limited to 80% of the yield strength. At this level, there is some plastic deformation of the drilled hole due to stress concentration effects. As a result, the method described in the ASTM leads to an overestimation of the real stresses, of up to 30% when 80% of the yield strength is achieved. This could cause problems when evaluating residual stresses near welds, because yield stresses or higher are expected. According to Giri *et al.* (2015), the error on the measured stresses due to plasticity effects depend upon several factors, such as stress ratio, the ratio of applied stress to yield strength of work material, and the diameter of the drilled hole. In addition, the stress errors when reaching yield stress tends to be lower than the errors at 50% of the yield stress.

2.2 Orthotropic Bridge Decks

Little is known about the distribution of residual stresses due to welding in orthotropic steel bridge decks. The welding operation between the closed stiffeners and the deck plate is very difficult (Figure 3). Due to the lack of space inside the closed stiffeners, the welding operation needs to be done from the outside of the stiffener. In addition, Eurocode prescribes a high criterion on the lack of penetration. Therefore, a high heat input is used when welding. According to FHWA-IF-12-027 (2012), tensile yield stresses or greater can be found at a weld or in a narrow zone adjacent to a flame cut (Figure 2). Between the zones of yield stresses, compressive stresses of 25% of the yield strength are present. However, the scheme of Figure 2 is not very accurate, and is based on plates with open stiffeners.

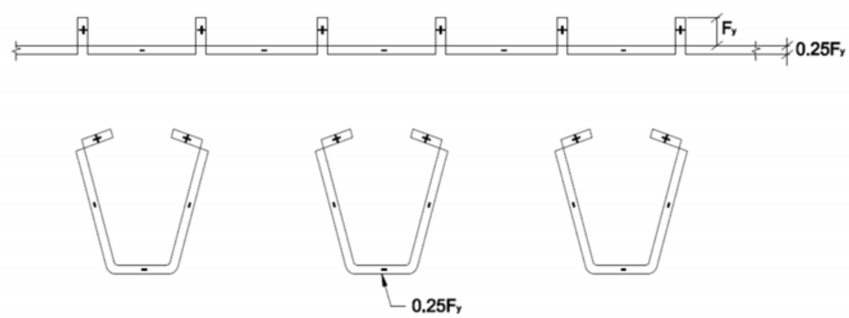

Figure 2. Approximate residual stress distribution in an orthotropic steel bridge deck for the rib-to-deck plate weld. F_y = yield strength.

2.3 Test Setup

For the verification of the distribution of residual stresses around a stiffener-to-deck plate weld, a test specimen of a real orthotropic bridge deck with steel quality S235 (Figure 3) has been set up. The overall dimensions of this bridge deck are 7.8 m long and 3.8 m wide. The closed longitudinal trapezoidal stiffeners are 300 mm high, 300 mm wide on top, and 125 mm at the lower soffit (Figure 3, left). The deck plate is 15 mm thick and the stiffeners are 6 mm thick.

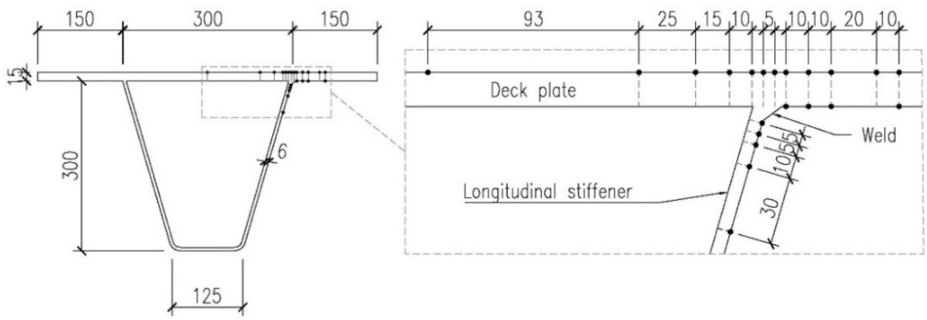

Figure 3. Test setup on an orthotropic steel bridge deck located around a stiffener-to-deck plate weld. Left: Dimensions of a part of the bridge deck. Right: hole-drilling strain gauge rosettes locations (dimensions in mm).

Figure 3 indicates the location of the installed hole-drilling strain gauge rosettes. There are no measuring points inside the stiffener, because the milling guide has to be perpendicular to the strain gauge rosette and that is not feasible at the inside. Because the hole-drilling introduces relaxation effects which extend beyond the boundaries of the strain gauge rosette, minimum distance recommendations between adjacent holes should be respected (ASTM E837-13a 2015, Schajer 2013). This should be at least six times the hole diameter. For this test setup, a bore hole of about 2 mm is used. Therefore, the minimal spacing should be at least 12 mm. Due to the small spacing near the weld, different cross-sections are used with 50 mm of spacing, allowing for the placement of the strain gauge rosettes in such a pattern as to respect minimal spacing. The used strain gauge rosettes are of type A, except the ones at the weld toe. For these, strain gauge rosettes of type B are used. According to the standard test procedure of ASTM, the maximum drilling depth is limited to 1mm for the used strain gauges. This guideline reduces the local stress concentration effect and allows residual stress measurements to be made for stresses of up to 80% of the material yield stress.

The orthotropic steel bridge deck for this test was an existing bridge deck without any asphalt layer. This implies that a relatively thick layer of paint had to be removed before the strain gauge rosettes could be installed. Due to the used grinding technique with abrasive paper, the near surface stresses are unreliable. It was visible in the results that the effect of grinding died out at a depth of 0.5 mm. Therefore, the results in this paper only discuss the residual stresses at the final depth of 1 mm.

2.4 Results

The strains of every hole-drilling strain gauge rosette were measured at incremental depths of 0.05 mm. With the software tool H-Drill supplied by the manufacturer, using the standard test procedure of ASTM, these strains were converted to residual stresses.

Figure 4 to Figure 6 illustrate the transversal residual stresses at 1mm surface depth for all the measured strain gauge rosettes. Although the data of the longitudinal residual stresses is not shown, the results near the weld were quite similar in sign and magnitude. At the location in the middle of the stiffener on the deck plate (most left location on Figure 3), the longitudinal residual stresses were zero.

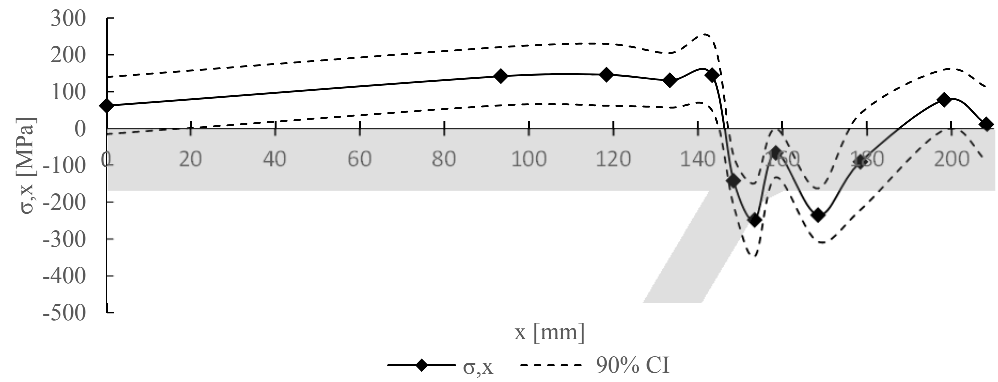

Figure 4. Transversal residual stress (σ_x) distribution on the surface of the deck plate. CI = Confidence Interval.

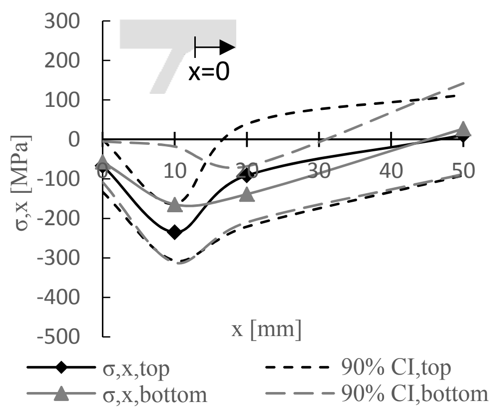

Figure 5. Transversal residual stress on the surface ($\sigma_{x,top}$) compared with that on the bottom of the deck plate ($\sigma_{x,bottom}$).

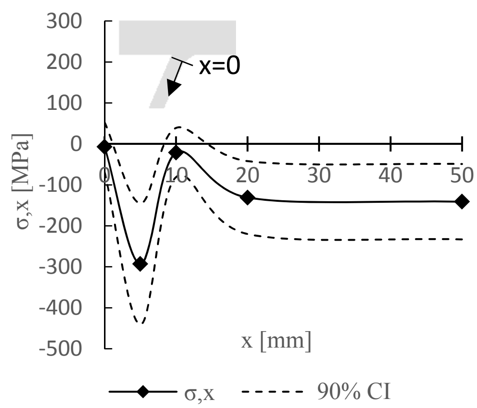

Figure 6. Transversal residual stress in the stiffener.

Figure 4 indicates a relatively constant value of approximately 110 MPa tensile residual stresses in the deck plate between the welded stiffener webs. This corresponds to almost 50% of the yield strength of 235 MPa. At the weld location, residual stresses were compressive and amounted to 158 MPa, 67% of the yield strength. On the right-hand side of the weld, residual stresses tended to zero. However, more hole-drilling measurements are necessary to confirm this. Figure 5 compares the stresses on the right-hand side of the weld for both the stresses on top and on bottom of the bridge deck. The stresses were almost identical, indicating a uniform residual stress distribution within the deck plate. At a distance of 10 mm to the weld, note the high-stress peak of 235 MPa on top of the plate and 165 MPa on the bottom. Therefore, compressive yield stresses were present near the weld location, but not at the weld toe itself. The same conclusion can be made for the residual stresses in the stiffener web (Figure 6). Although the highest residual stress indicated 293 MPa, it had to be limited to 235 MPa because the method being used was only available in the elastic region. In addition, calculated stresses above 80% of the yield strength were overestimated with this method. Finally, further away from the weld, the residual stresses in the stiffener had a constant compressive value of approximately 136 MPa or 58% of the yield stress.

If compared with the expected values of Figure 2, it seems that the measured stresses have an opposite sign. At the weld region, compressive residual stresses around the yield strength were found. This contradicts the expectations of Figure 2 and the literature (Barsoum and Barsoum 2009, Teng *et al.* 2001). More research is needed with bigger strain gauge rosettes to drill up to 2 mm of surface depth to verify these conclusions. Possibly the measured stresses still suffer from near-surface stresses due to fabrication processes, such as rolling and strain gauge preparations. In the zone outside the weld and between the stiffener webs, a constant value of 50% of the yield strength was found. This is twice as much as expected. The same conclusion is valid for the stiffener web itself, except the residual stresses were now compressive.

3 CONCLUSIONS

The hole-drilling technique is a very useful technique to verify the residual stresses within the plate thickness of the test specimen. Its reliability is very high if the surface preparation and drilling technique is performed with care. In addition, a clear distribution of the residual stresses was determined without significantly damaging the test specimen. With fatigue tools such as fracture mechanics, an improved analysis can be performed allowing a better understanding of the fatigue crack behavior. More research is needed to verify the distribution of the residual stresses at greater depths, especially to verify why the stresses have an inverted sign compared to the literature. In addition, drilling at greater depths could reveal the stress distribution within the thickness of the stiffener webs.

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