Interaction between Theory and Practice in Civil Engineering and Construction
Edited by Komurlu, R., Gurgun, A., Yazdani, S., and Singh, A.

ISBN: 978-0-9960437-2-4

USE OF THE HOLE DRILLING METHOD TO DETERMINE RESIDUAL WELD STRESSES IN BRIDGE CONSTRUCTIONS

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Complex welding operations in orthotropic steel bridge decks introduce residual stresses near the weld region. To estimate fatigue failure of this type of bridge deck, tensile residual yield stresses are usually assumed around the weld region. However, to estimate the residual stress distribution near a weld connection more precisely, a test setup is developed. The weld connection of a closed longitudinal trapezoidal stiffener with the deck plate of an orthotropic bridge deck is investigated. The incremental hole-drilling technique is used to measure the residual stresses with strain gauge rosettes. Strain gauge rosettes are positioned on the deck plate and on a longitudinal stiffener of the orthotropic steel deck. A small hole is drilled through the center of the strain gauge rosettes and strains are measured at incremental depths. The residual stresses are calculated and based on these experimental measurements a distribution of the residual stresses is obtained. Compressive residual stresses exist near the longitudinal stiffener-to-deck plate weld. On the deck plate, the compressive residual stresses are equal to 60% of the yield strength while the compressive residual stresses on the stiffener are 42% of the yield strength. There are tensile residual stresses on both sides of the weld region. However, more research is necessary to confirm this distribution since it is contradictory to expected stresses in literature.

Keywords: Orthotropic steel deck, Strain gauge rosette, Residual stress measurement, Stress analysis, Fatigue failure.

1 INTRODUCTION

Orthotropic steel decks are stiffened in two mutually perpendicular directions with longitudinal and transversal stiffeners welded to the deck plate. Complex welding operations are required that introduce residual stresses in the orthotropic steel deck (OSD). Residual stresses are often ignored in the design of OSDs. This is acceptable when only focusing on the stress variations, thus eliminating the initial stress state. However, residual stress distributions can have large stress gradients due to their non-uniform behavior. These stress gradients make it necessary to perform residual stress measurements in order to correctly estimate premature fatigue failure and stress corrosion cracking (Schajer 2013).

Around the weld region, tensile residual stresses comparable to the yield stress are usually assumed to be present in order to estimate fatigue failure of an OSD (Xiao 2008, Xiao 2006). However, accurate fatigue design of an OSD requires an evaluation of the residual stress distribution. Depending on the sign and location of the residual stresses, the contribution of the residual stresses to the load-induced stresses can be either harmful or beneficial. Tensile residual stresses caused by manufacturing processes such as welding operations tend to be harmful due to their contribution to fatigue failure and stress-corrosion cracking. On the other hand, compressive residual stresses are usually beneficial because they increase wear and corrosion resistance and prevent the initiation of fatigue cracks (Rossini *et al.* 2004).

2 INCREMENTAL HOLE-DRILLING TECHNIQUE

The residual stresses around the weld connection of the deck plate with a longitudinal stiffener of an OSD are evaluated making use of the incremental hole-drilling technique. This is a semi-destructive measuring method where a small hole is drilled into the test material through the center of a strain gauge rosette. These strain gauge rosettes are used to measure the relieved surface strains caused by the introduction of a hole that is formed by drilling in a series of small steps. The measured strains are used to calculate the residual stresses according to the calculation principles specified in ASTM E837-13a 2015. The test method only applies when material behavior is linear-elastic. Therefore, reliable measurements are achieved by limiting the residual stresses to 80% of the yield stress of the material (ASTM E837-13a 2015).

To evaluate the residual stresses near the weld connection of the deck plate with a longitudinal stiffener, the RS-200 Milling Guide, Figure 1, from Vishay Measurements Group was used. To start the strain measurements, zero depth has to be established first. Therefore, the test surface material has to be exposed by drilling only through the material of the strain gauge rosette. The initial uncertainty of the separation of the cutter from the outer surface by the strain gauge rosette and coating can be disregarded by establishing this zero depth (Vishay Measurements Group 2011).

Figure 1. RS-200 Milling Guide (left) and hole-drilled strain gauge rosette (right).

3 TEST SETUP

Residual stress measurements were performed on an OSD with steel quality S235. The deck plate has a total length of 8.2 m and is simply supported at 100 mm from its edges. It spans over a width of 4.1 m and is equipped with six longitudinal and three transversal stiffeners. The deck plate has a thickness of 15mm and the longitudinal stiffeners are 6mm thick. The closed trapezoidal longitudinal stiffeners are 300 mm high, 300 mm wide on top and 125 mm at the lower soffit. The weld toes have a width of 7 mm. For the residual stress measurements, the connection of the deck plate with a longitudinal stiffener is considered, Figure 2.

Strain gauge rosettes are placed on the top and bottom of the deck plate and at the exterior of the longitudinal stiffener in the vicinity of the weld region, Figure 2. There will be no strain gauge rosettes located at the inside of the stiffener because the hole drilling rig has to be perpendicular to the strain gauge rosette and this is not possible at the inside of a stiffener. To measure strains adjacent to the weld, strain gauge rosettes type CEA-13-062UM-120 are used. This is a type B rosette with all three strain gauges located at the same side of the hole, allowing for measuring strains adjacent to the weld. On all other locations, strain gauge rosettes type CEA-13-062UL-120 are used because these type A rosettes are more accurate than type B rosettes.

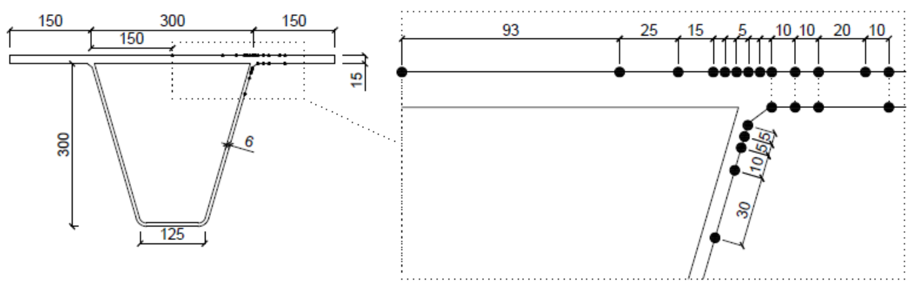

Figure 2. Weld connection of the deck plate with a closed trapezoidal longitudinal stiffener of the test setup with the position of the strain gauge rosettes (right) (dimensions in mm).

A total of 22 strain gauge rosettes are positioned on both the deck plate and longitudinal stiffener and their positions are indicated in Figure 2. A minimum distance between the strain gauge rosettes needs to be respected because the drilling of a hole into the surface results in relaxation effects which extend beyond the boundaries of the strain gauge rosette (ASTM E837-13a 2015, Schajer 2013). This minimum distance is equal to minimum six times the hole diameter. A number of strain gauge rosettes are necessary in the close proximity of the weld connection of the deck plate with the longitudinal stiffener to evaluate the residual stresses near this connection detail. Therefore, the residual stress measurements are performed in different cross sections every 50 mm, starting from the middle of the first span of the OSD. The diameter of the borehole for all strain gauge rosettes is approximately to 2 mm, corresponding to the diameter of the drill. In order to comply with the requirements for linear-elastic material behavior, the maximum drilling depth is to 1 mm (ASTM E837-13a 2015).

4 RESULTS

For each strain gauge rosette, strains are measured at incremental depths of 0.05 mm. The calculation software H-DRILL provided by the manufacturer is used to convert the measured strains into residual stresses according to the principles of ASTM E837-13a (2015). The residual stress distribution into the depth of the material is obtained for every location where a strain gauge rosette is positioned. However, to evaluate the initial stress state caused by welding the longitudinal stiffener to the deck plate, a single value for the residual stress that is representative for the considered strain gauge rosette is chosen. Near-surface stresses are unreliable due to surface preparations of the OSD because the results show large stress peaks higher than yield stress near the surface. It is not clear what the progress of the residual stresses is going to be when drilling deeper into the material and therefore, only the residual stresses at the final hole depth of 1 mm are considered. These residual stresses are used to make a representative distribution of the residual stresses in relation to their distance to the weld.

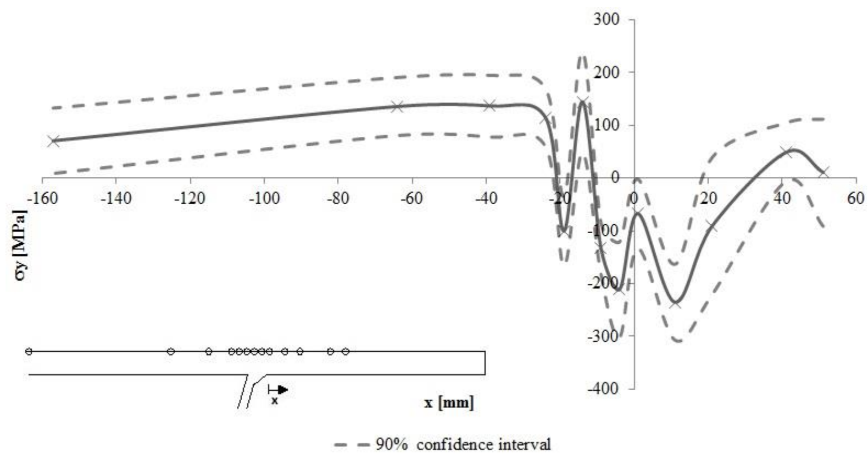

Figure 3. Transversal residual stress distribution surface of deck plate.

A residual stress distribution for the longitudinal and transversal direction is established in relation to the position towards the weld. Only the transversal direction is shown here because the residual stresses in the longitudinal direction are similar in sign and magnitude near the stiffener-to-deck plate weld. The 90% confidence intervals are also plotted and they indicate the expected stress range that has a 90% probability of containing the actual residual stresses. The position where the residual stress was measured is indicated by the distance *x* to the weld toe. The transversal residual stress distribution on top of the deck plate is shown in Figure 3, the distribution for the bottom of the deck plate in Figure 4 and for the longitudinal stiffener in Figure 5.

When the residual stresses on the top, Figure 3, and bottom of the deck plate, Figure 4, are compared, it is clear that the results have a relatively good correspondence at the right-hand side of the weld. Therefore, a uniform residual stress distribution throughout the thickness of the deck plate is assumed.

To evaluate the residual stresses near the longitudinal stiffener-to-deck plate weld, a distinction is made between compressive and tensile zones. The residual stress values assigned to these zones are calculated by averaging the residual stresses of the strain gauge rosettes located in the considered zone. These zones are evaluated in relation to their position towards the weld region.

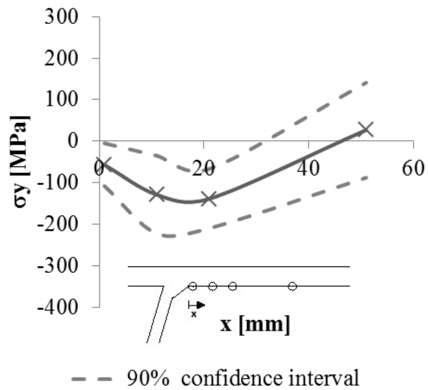

Figure 4. Transversal residual stress distribution bottom side deck plate.

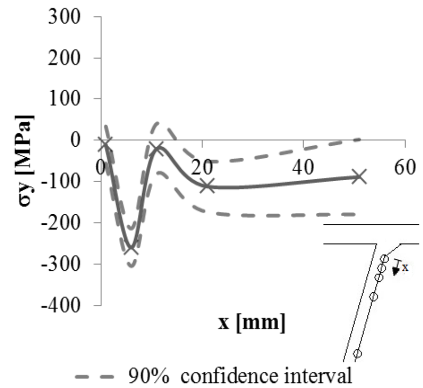

Figure 5. Transversal residual stress distribution longitudinal stiffener.

On the deck plate, two tensile zones and a compressive zone are present. An average tensile residual stress of 121 MPa is present in the deck plate between the two welded webs of the stiffener. This corresponds to 51% of the yield strength. In this zone, one strain gauge rosette that indicated a compressive residual stress is left out. Near the location of the weld on the deck plate, a compressive zone with an average residual stress of 141 MPa or 60% of the yield strength exists. On the right hand side of the weld region, again a tensile residual stress zone with an average value of 34 MPa or 14% of the yield strength is found. For the stiffener, compressive residual stresses near the weld with an average value of 99 MPa or 42% of the yield strength exist while at the weld toe the residual stress is close to zero. This general transverse residual stress distribution is shown in Figure 6; positive values indicate tensile stress.

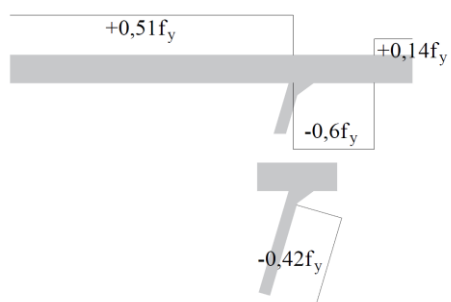

Figure 6. General transverse residual stress distribution (f_y= yield strength).

Residual stresses remain within the material even after the initial cause of the stresses has been removed. Consequently, they are self-equilibrating, i.e. the sum of all stresses in a local area creates zero resultant force and moment. However, the general transverse residual stress distribution, Figure 6, shows that the residual stresses obtained with the experimental measurements are not yet in equilibrium for the considered zone.

5 COMPARISON WITH A THEORETICAL RESIDUAL STRESS DISTRIBUTION

The established residual stress distribution is compared with a theoretical residual stress distribution according to FHWA-IF-12-027 (2012). This theoretical distribution predicts tensile yield stresses to be present near the location of the weld on the deck plate. In between these tensile yield stresses, compressive residual stresses up to 25% of the yield strength are assumed. This distribution for the deck plate is totally different from the measured residual stresses. For the measured residual stress distribution, compressive residual stresses equal to 60% of the yield strength exist instead of tensile yield stresses according to FHWA-IF-12-027 (2012). On both sides of the weld region, the measured residual stresses in the deck plate are tensile while the theoretical residual stresses are compressive. For the stiffener, the sign of the measured residual stresses is equal to the theoretically expected residual stresses, however the value of the measured residual stresses is twice as high as the theoretically expected values.

6 CONCLUSIONS

The residual stresses near the weld connection of the longitudinal stiffener with the deck plate of an OSD are evaluated according to the incremental hole-drilling technique. A residual stress distribution in the transverse direction is obtained. However, when comparing the measurement results with a theoretical residual stress distribution (FHWA-IF-12-027 2012), a large difference in sign and magnitude of the residual stresses was noted. It is possible that the measured strains are still suffering from strain gauge rosette preparation. Therefore, more research will be necessary to verify the distribution of the residual stresses near the longitudinal stiffener-to-deck plate weld obtained with the hole-drilling technique. Bigger strain gauge rosettes can be used to obtain residual stresses deeper into the depth of the surface. In addition, drilling to greater depths can provide a better indication of the residual stresses because the uncertain stresses near the surface can be eliminated.

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