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Determination of residual weld stresses with the incremental hole-drilling method in tubular steel bridge joints

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Abstract

Tubular arch bridges are susceptible to fatigue problems due to stress concentrations, welding imperfections and tensile residual weld stresses. These bridges are composed of circular hollow section profiles welded together in tubular joints. This paper describes the determination of residual weld stresses in T-joints with the incremental hole-drilling method. The residual stress distribution can be used to determine fatigue crack behavior and fatigue lifetime more precisely.

The incremental hole-drilling method is used to measure residual welding stresses on two similar T-joints. Experimental residual stress measurements were performed with the aid of the RS-200 milling guide. Strain gauge rosettes are attached to the test surface and with the milling guide, a small hole is drilled through the center of the strain gauge rosette. Strains at incremental depths are measured and the residual stresses are calculated according to ASTM E837-13a.

A comparison is made between residual stress distributions obtained with finite element simulation and the experimental measurements. The distributions from finite element simulation show tensile yield stresses close to the weld while the experimental measurements indicate tensile yield stresses only in the axial direction of the primary tube. In all other cases, the residual stresses are tensile within 50% of yield stress or even compressional. However, more measurements on similar test specimens are necessary for a reliable residual stress distribution.

Knowledge of the residual stress distribution is essential to accurately estimate the crack development under fatigue loads. In future research, the residual stresses can be used to study the influence of residual weld stresses on the fatigue lifetime and improve the design of steel tubular joints in arch bridges.

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Keywords: Residual weld stresses; Incremental hole-drilling; Tubular T-joints

1. Introduction

Tubular steel arch bridges are highly appreciated for their aesthetic value. The use of hollow tubes with circular sections and the connections in the nodes where several tubes meet, ensures a smooth shape [1]. These structures are composed of several steel bridge joints where larger primary tubes are welded together with smaller secondary tubes. The fatigue strength is important

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because the numerous welded joints introduce high stresses near the weld toe of the joints. These high stresses are the result of the welding process and the influence of geometric discontinuities on the flow of the stresses, resulting in possible fatigue failure [2].

The welding process introduces residual welding stresses near the welded tubular joints. Residual stress distributions can have large stress gradients due to their non-uniform behavior [3]. These stress gradients make it necessary to perform residual stress measurements in order to estimate the influence on the fatigue strength of the welded joints in tubular arch bridges. The fatigue strength can be increased by the presence of compressive residual stresses [4]. Tensile yield stresses tend to open cracks and have a detrimental influence on the fatigue crack propagating under cyclic traffic loadings on the bridge. Residual stress can make the difference between a fatigue micro crack to grow or not. Moreover, residual stresses can also influence the rate of crack propagation, since the tensile residual stress field is often associated with a shorter fatigue life [5]. Therefore, accurate fatigue design of fatigue-sensitive bridge components requires knowledge of the distribution of the residual welding stresses.

In this paper, the residual stress distribution of tubular T-node joints are experimentally determined with the incremental hole-drilling method. Therefore, a small hole is drilled through a strain gauge rosette which is attached to the primary and secondary tubes of the joint. During the drilling, strains are recorded and these are used to calculate the residual stresses [6]. Several measuring points are chosen on the bridge joint and a residual stress distribution is established. Then, these results are compared with results available in literature.

Nomenclature

D	diameter of primary tube
d	diameter of secondary tube
L	length of primary tube
l	length of secondary tube
T	thickness of primary tube
t	thickness of secondary tube
FEA	finite element analysis

2. Incremental hole-drilling method

The incremental hole-drilling method 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 principles specified in ASTM E837-13a and this test method only applies assuming linear-elastic material behavior [7].

In order to obtain reliable measurements, a certain sequence of actions must be respected. First, the surface has to be prepared. The surface is prepared using silicon carbide abrasive paper to ensure adequate microscopic roughness to promote secure gauge bonding (Ra 1.6 to 3.2 μm). Before attaching the strain gauge rosette, the surface has to be neutralized and degreased [8]. For the residual stress measurement on the tubular bridge joints, three different types of strain gauge rosette configurations were used. Strain gauge rosette type EA-06-125RE-120 is used to drill a hole with an approximate diameter of 4mm up to a depth of 2mm. Measurements for a hole with an approximate diameter of 2mm with a depth of 1mm are performed with strain gauge rosette types CEA-06-062UL-120 and CEA-06-062UM-120 for measurements close to a weld or edge [9]. The different types of strain gauge rosettes and their dimensions are shown in Fig. 1.



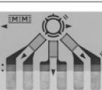
GAGE PATTERN AND DESIGNATION Insert Desired S-T-C No. in Spaces Marked XX. See Note 1		RES. IN OHMS	DIMENSIONS					
			GAGE LENGTH	GRID CTR/LINE DIA.	TYPICAL HOLE DIA.		MATRIX	
					Min.	Max	Length	Width
EA-XX-125RE-120 EA-XX-125RE-120/SE		120 ± 0.2% 120 ± 0.4%	0.125	0.404	0.12	0.16	0.78	0.78
			3.18	10.26	3.0	4.1	19.8	19.8
			Larger version of the 062RE pattern.					
CEA-XX-062UL-120		120 ± 0.4%	0.062	0.202	0.06	0.08	0.50	0.62
			1.57	5.13	1.5	2.0	12.7	15.7
			Fully encapsulated with large copper-coated soldering tabs. Same pattern geometry as 062RE pattern.					
CEA-XX-062UM-120		120 ± 0.4%	0.062	0.202	0.06	0.08	0.38	0.48
			1.57	5.13	1.5	2.0	9.6	12.2
			Fully encapsulated with large copper-coated soldering tabs and special trim alignment marks. Trim line spaced 0.068 in [1.73 mm] from hole center. Limitations may exist in data reduction equations.					

Fig. 1. Strain gauge rosette types [8].

After the attachment of the strain gauge rosette to the surface, the residual stress measurements can start. The RS200 Milling Guide (Fig. 2) is used to evaluate the residual stresses near the welded T-node joint. The drill is positioned right above the center of the strain gauge rosette with the microscope of the milling guide. To begin 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 [10].

The zero depth strain measurement indicates the beginning of the incremental hole-drilling. A series of increments is drilled into the specimen and at each increment, the depth of the hole and the strain relaxation at each gauge is recorded. The relaxed strain data is used to calculate the residual stresses in the plane normal to the hole axis, using calibration constants appropriate for the used strain gauge rosette [3].

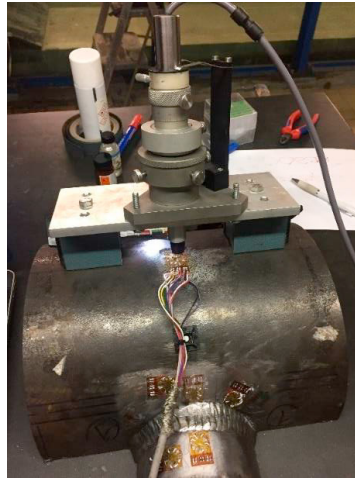


Fig. 2. RS200 Milling Guide

3. Experimental test setup

There are two different test specimens used for the residual stress measurements. Both test specimens are T-node tubular joints but with slightly different dimensions. These are constructed with construction steel S355 with a yield stress equal to 355MPa. The tubular joint is cut in half. A sketch of the test specimen is shown in Fig. 3 with an indication of dimensions which are listed in Table 1. For the two different test specimens, only the length of the secondary tube differs.

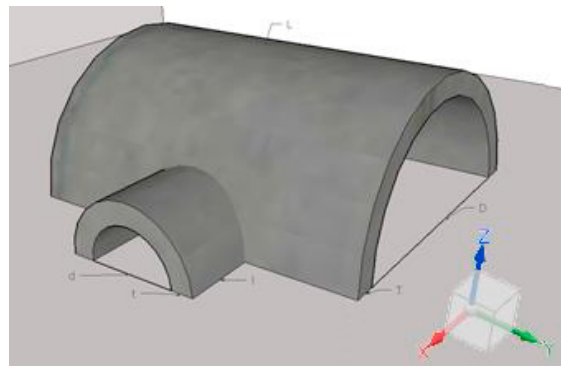


Fig. 3. Sketch of test specimen

Table 1. Dimensions of test specimen

	D (mm)	T (mm)	L (mm)	d (mm)	t (mm)	l (mm)
Test specimen 1	270	18	320	127	18	55
Test specimen 2	270	18	320	127	18	60

On test specimen 1, the drilling depth is 1mm while the drilling depth for test specimen 2 is 2mm. For both test specimens, the circumferential and axial residual stresses will be investigated in function of the distance to the weld and the depth below the surface. The locations for the hole drilling on the two test specimens are predominantly similar. Some small difference in test location on the two different nodes exists due to practical considerations. The strain gauges for test specimen 2 are larger and minimal distances between drilling holes have to be respected, resulting in larger intermediate distances for test specimen 2. The measurement locations for the hole drilling are shown in Fig. 4(a) for test specimen 1 and Fig. 4(b) for test specimen 2. The distance relative and perpendicular to the center of the weld for both the horizontal and vertical direction is shown in Table 2 for test specimen 1 and Table 3 for test specimen 2.

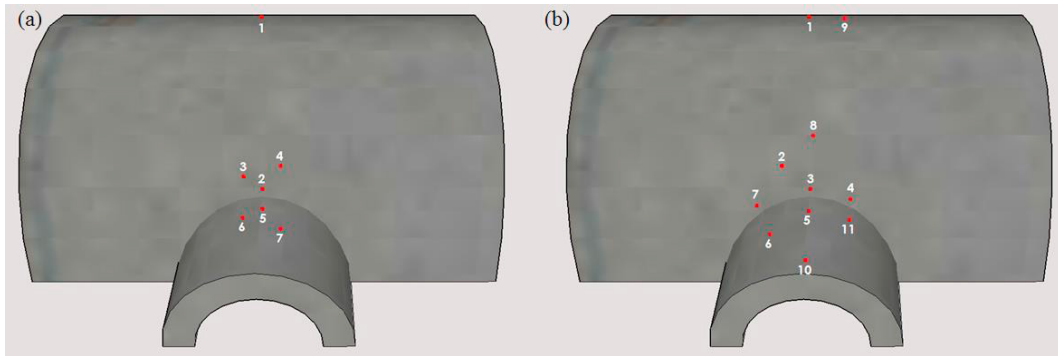


Fig. 4. Measurement locations for (a) test specimen 1; (b) test specimen 2

Table 2. Dimensions of test specimen 1

Measurement location	Vertical distance to weld (mm)	Horizontal distance to weld (mm)
1	150	0
2	2	0
3	11	-23
4	20	24
5	2	0
6	9	-25
7	20	23

Table 3. Dimensions of test specimen 2

Measurement location	Vertical distance to weld (mm)	Horizontal distance to weld (mm)
1	160	0
2	20	-10
3	9	0
4	12	40
5	11	0
6	20	-30
7	12	-47
8	35	0
9	160	32
10	41	0
11	12	33

To determine the zero depth as accurately as possible, the increments are chosen as small as possible in the beginning. This minimal depth step for the micrometer of the milling guide is 0.025mm. Once the zero depth is reached, the increment steps are increased gradually. ASTM provides calibration coefficients for 20 increments but it is recommended to make more increments and smooth it to 20 increments [8].

4. Test results

Strains are recorded during the drilling procedure for the different measuring points. A calculation software H-DRILL is used to convert the recorded strains of a strain gauge rosette into axial and circumferential residual stresses according to the principles of ASTM E837-13a [7]. The residual stress distribution into the depth of the material is obtained for all measuring points where there are strain gauge rosettes positioned. To evaluate the residual stresses caused by welding the primary tube of the T-node joint to the secondary tube, a single representative residual stress value is chosen for each strain gauge rosette. The residual stress distribution into the depth of the material for each strain gauge rosette is studied in order to find the most suitable residual stress value.

4.1. Test specimen 1

The distribution into the depth for all strain gauge rosettes of test specimen 1 is shown in Fig. 5 for the axial direction for both the primary tube (Fig. 5a) and the secondary tube (Fig. 5b). The circumferential direction is shown in Fig. 6a for the primary tube and Fig. 6b for the secondary tube.

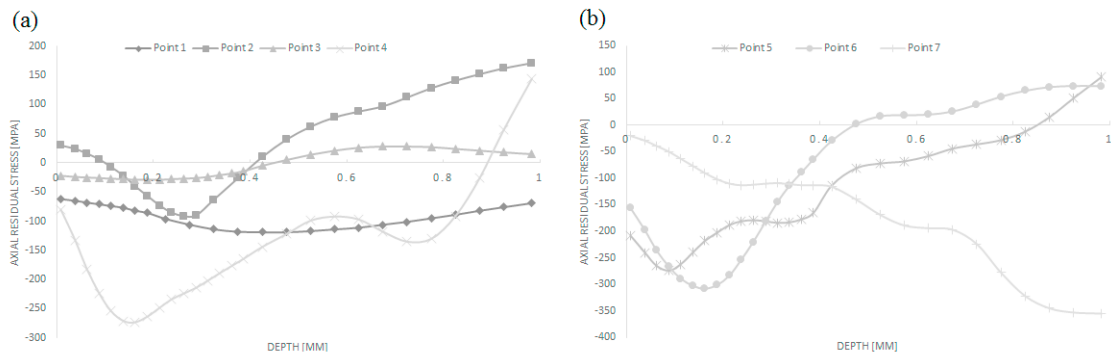


Fig. 5. Residual stress distribution into depth of test specimen 1 for the axial direction on the (a) primary tube; (b) secondary tube

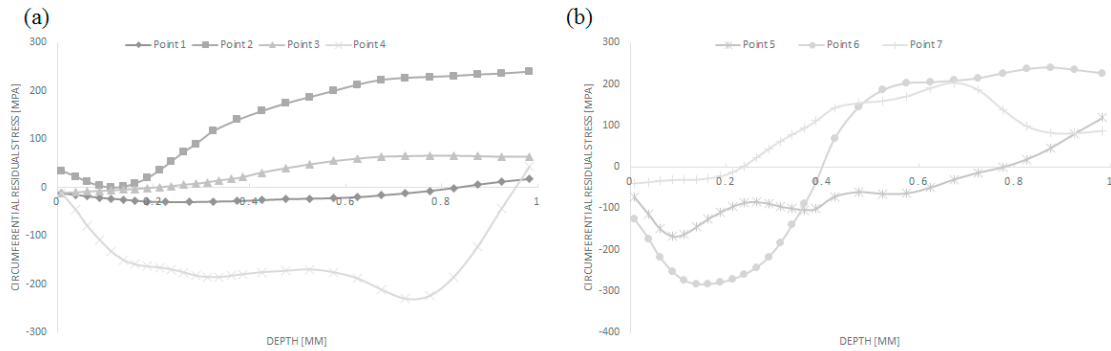


Fig. 6. Residual stress distribution into depth of test specimen 1 for the circumferential direction on the (a) primary tube; (b) secondary tube

The residual stress for the different drilling depths remains below yield stress for all measuring points, except for measuring point 7. The maximum residual stress is found for measuring point 2 at a drilling depth of 1mm and equals 240MPa. This means that the residual stress distributions are acceptable since the stresses remain below 80% of yield stress. Reliable measurements are achieved by limiting the residual stresses to 80% of the material’s yield stress in order to take into account that the test method only applies when material behavior is linear-elastic [7]. The residual stresses for measuring point 7 in the axial direction exceed the limit value of 80% of the material’s yield stress, so these results might be unreliable.

It is not clear what the progress of the residual stresses is going to be when drilling deeper into the material, a drilling depth of 2mm only will be considered for test specimen 2. Therefore, only the residual stresses at the final hole depth of 1mm are considered. These residual stresses are used to make a representative distribution of the residual stresses in relation to their distance to the weld.

Considering the representative residual stress values for the strain gauge rosettes on both the primary and secondary tube of test specimen 1, a residual stress distribution for the axial and circumferential direction is established in relation to the distance

perpendicular to the weld. This distance is determined based on the vertical and horizontal distances to the weld for all measuring locations shown in Table 2. Fig. 7 shows the axial residual stress distribution for the primary tube (Fig. 7a) and for the secondary tube (Fig. 7b) of test specimen 1. Fig. 8 shows the circumferential residual stress distribution for the primary tube (Fig. 8a) and for the secondary tube (Fig. 8b) of test specimen 1. The 90% confidence intervals are shown in dashed lines and they indicate the expected stress range that has a 90% probability of containing the actual residual stresses.

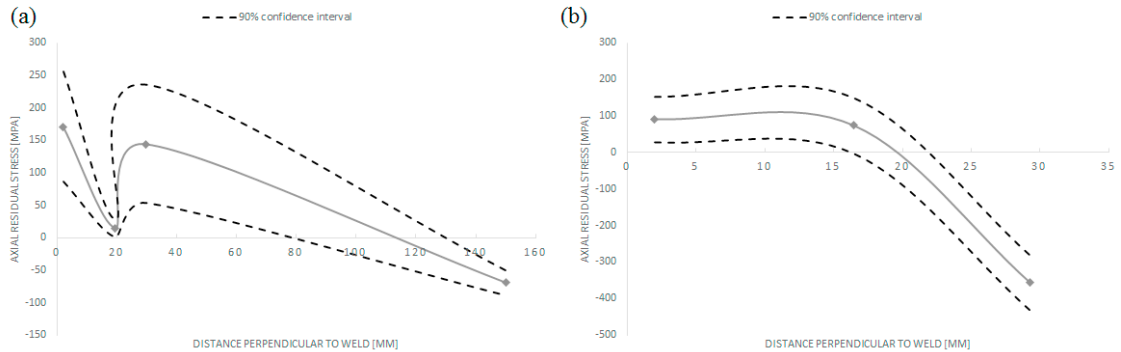


Fig. 7. Axial residual stress distribution perpendicular to the weld for the (a) primary tube; (b) secondary tube

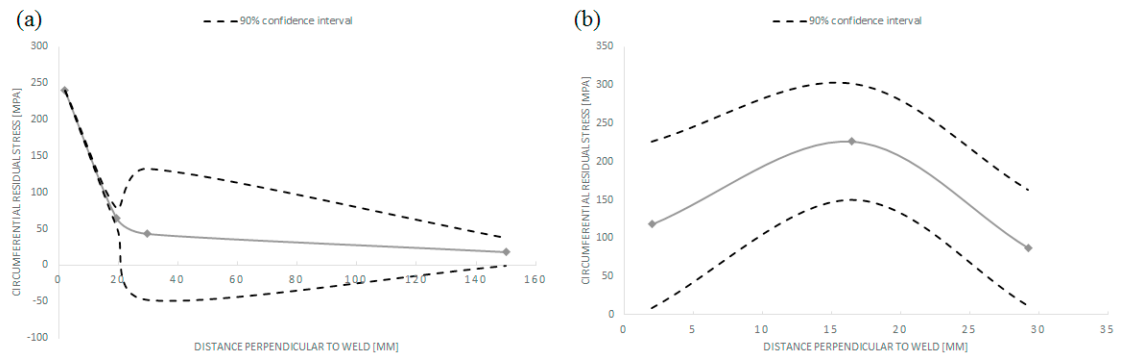


Fig. 8. Circumferential residual stress distribution perpendicular to the weld for the (a) primary tube; (b) secondary tube

Tensile residual stresses have a positive value while compressive residual stresses are considered negative. For the axial direction, the residual stresses are tensile near the weld toe while they shift to compressive residual stresses further away. For the circumferential direction, the residual stresses remain tensile for both the primary and secondary tube.

4.2. Test specimen 2

The distribution into the depth for all strain gauge rosettes of test specimen 2 is shown in Fig. 9 for the axial direction for both the primary tube (Fig. 9a) and the secondary tube (Fig. 9b). The circumferential direction is shown in Fig. 10a for the primary tube and Fig. 10b for the secondary tube.

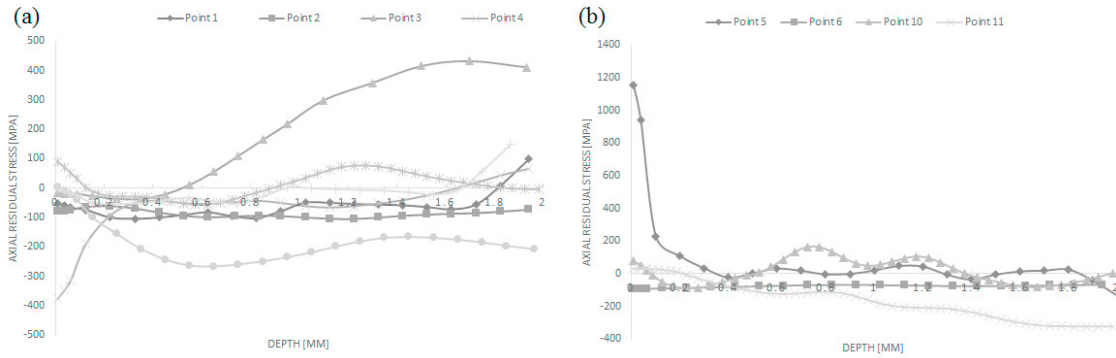


Fig. 9. Residual stress distribution into depth of test specimen 2 for the axial direction on the (a) primary tube; (b) secondary tube

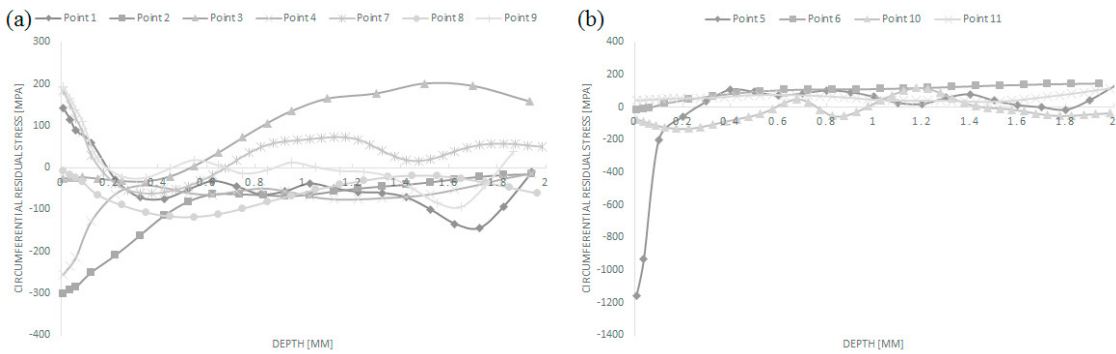


Fig. 10. Residual stress distribution into depth of test specimen 2 for the circumferential direction on the (a) primary tube; (b) secondary tube

The residual stresses near the surface for measuring point 4 on the primary tube in the axial direction are larger than the material’s yield stress. This can be the result of some irregularities near the surface. Also measuring point 5 shows large residual stresses near the surface. These effects can be neglected. In the axial direction, all measuring points except for measuring point 3, the residual stresses remain below the limit value of 80% of the material’s yield stress. Therefore, the results for measuring point 3 might be questioned. For the circumferential direction, there are some high stress peaks near the surface for measuring point 2, 4 and 5 but all remaining residual stress values are below the limit value.

To make a comparison with test specimen 1, the residual stresses at the drilling depth of 1mm and those at the final hole depth of 2mm will be considered for test specimen 2. These residual stresses are used to make a representative distribution of the residual stresses in relation to their distance perpendicular to the weld.

Considering the residual stress values at a hole depth of 1 and 2mm for the strain gauge rosettes on both the primary and secondary tube of test specimen 2, a residual stress distribution for the axial and circumferential direction is established in relation to the distance perpendicular to the weld. This distance is determined based on the vertical and horizontal distances to the weld for all measuring locations shown in Table 3. Fig. 11 shows the axial residual stress distribution for the primary tube (Fig. 11a) and for the secondary tube (Fig. 11b) of test specimen 2 for a drilling depth of 1mm. Fig. 12 shows the circumferential residual stress distribution for the primary tube (Fig. 12a) and for the secondary tube (Fig. 12b) of test specimen 2 for a drilling depth of 1mm. The 90% confidence intervals are shown in dashed lines and they indicate the expected stress range that has a 90% probability of containing the actual residual stresses.

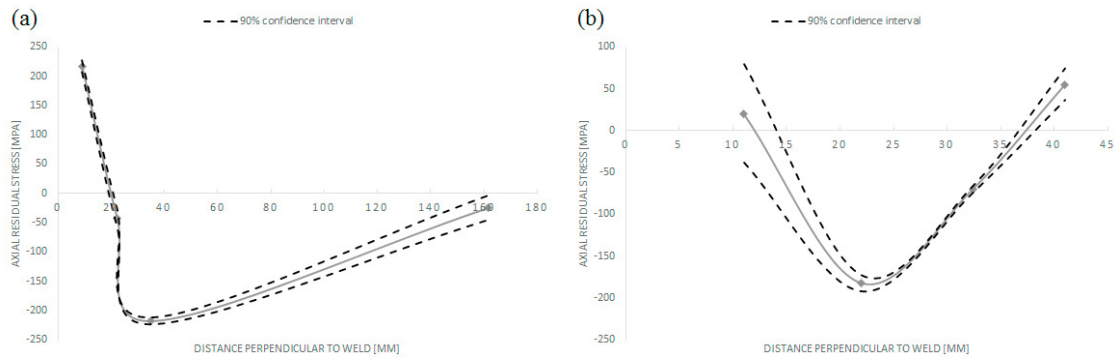


Fig. 11. Axial residual stress distribution perpendicular to the weld for the (a) primary tube; (b) secondary tube for drilling depth 1mm

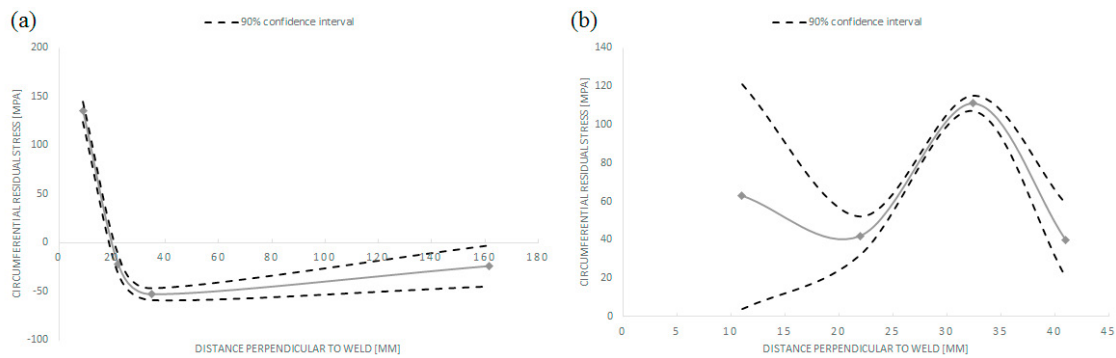


Fig. 12. Circumferential residual stress distribution perpendicular to the weld for the (a) primary tube; (b) secondary tube for drilling depth 1mm

When a comparison is made of the residual stress distributions perpendicular to the weld for drilling depth 1mm between test specimen 1 and 2, some differences are noticed. For the primary tube in the axial direction, the residual stress near the weld toe is for both test specimens highly tensile. The distribution further away from the weld toe is different, the residual stresses for test specimen 1 remain tensile while they become compressive for test specimen 2. Both test specimens end up in small compressive residual stresses. For the secondary tube in the axial direction, the distributions of both test specimens is comparable. However, a larger distance perpendicular to the weld for test specimen 2 is considered and at this largest distance of 41mm, the residual stresses become tensile again.

In the circumferential direction, the residual stresses of both test specimens show a similar distribution. However for the primary tube, the distribution for the second test specimen is shifted downward resulting in compressive residual stresses while the residual stresses for test specimen 1 remain tensile. For the secondary tube, the residual stresses are tensile for both test specimens.

The confidence intervals for test specimen 1 are larger than those for test specimen 2. Therefore, the results of the second test specimen will be more reliable. Also, a larger drilling depth for test specimen 2 is considered giving more detail into the depth of the material and eliminating unreliable surface residual stresses due to surface roughness. So the residual stress distributions of test specimen 2 with a drilling depth of 2mm will be of greater importance. These results are shown in Fig. 13 and Fig. 14.

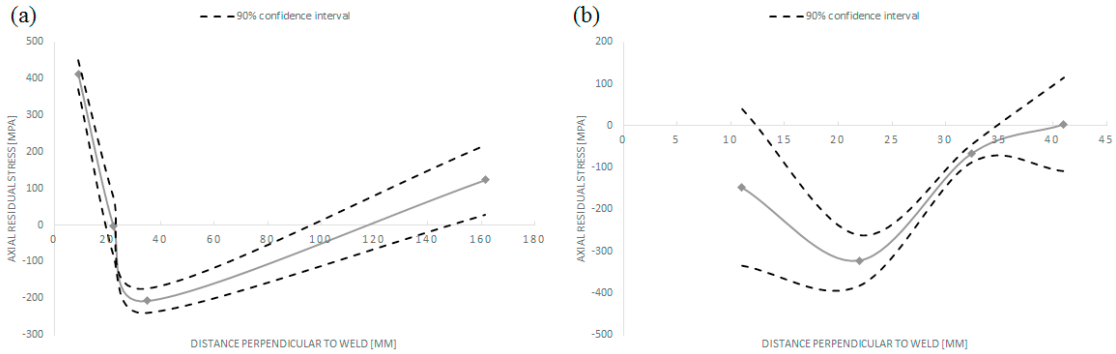


Fig. 13. Axial residual stress distribution perpendicular to the weld for the (a) primary tube; (b) secondary tube for drilling depth 2mm

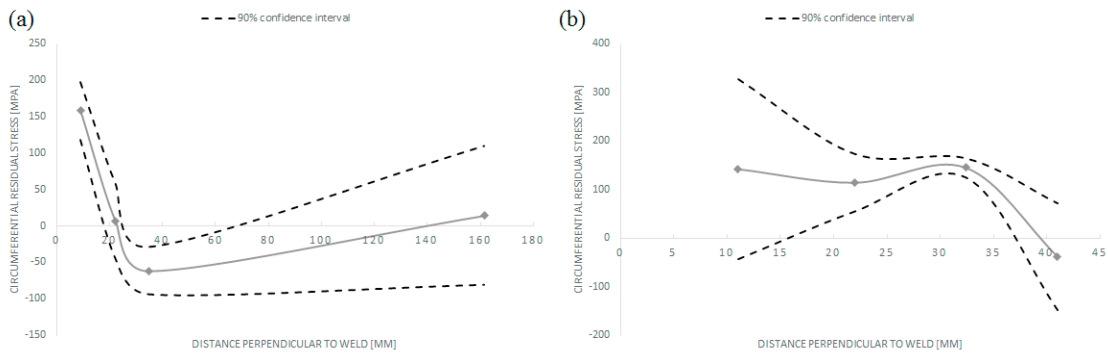


Fig. 14. Circumferential residual stress distribution perpendicular to the weld for the (a) primary tube; (b) secondary tube for drilling depth 2mm

5. Residual stress distribution from finite element analysis

An investigation of the residual stress distribution in welded tubular T-joints performed by Jang et al. [11] is studied to compare with the experimentally obtained residual stresses. An uncoupled three-dimensional thermal-mechanical finite element analysis was performed. The model consists out of round to round tubular members with a thickness of 10mm and diameters of 250mm, 300mm and 500mm. The thickness of these test parts are slightly smaller than those used in this paper. Diameters 250mm and 300mm are similar to the diameter of the primary tube and will be the most relevant to compare. The strength class of the steel is SM400 with a yield stress of 400MPa which can be compared with the specimens used for the experiments. A sketch of the T-node used for the finite element analysis is shown in Fig. 15.

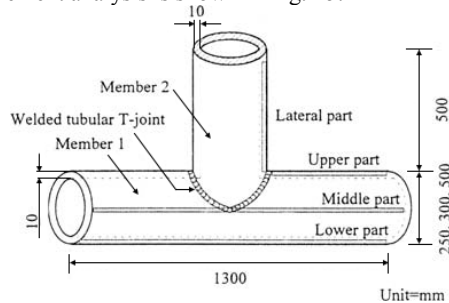


Fig. 15. T-node tubular joint used for finite element analysis [11]

The results for the middle and lower part are especially of interest since the measurements in this paper will particularly be situated between these zones. Only the primary tube will be considered since the diameter of the secondary tube is too different compared with the diameter used for the experimental measurements. The results of the finite element analysis (FEA) are shown in Fig. 15 and Fig. 16. For the circumferential direction, residual stresses are tensile near the weld and are fading out towards the middle part. Residual stresses near the upper part are higher than in the middle and lower part and they reach yield stress. For the axial direction, residual stresses will be highest in the middle part and more gradually decrease towards the lower and upper part.

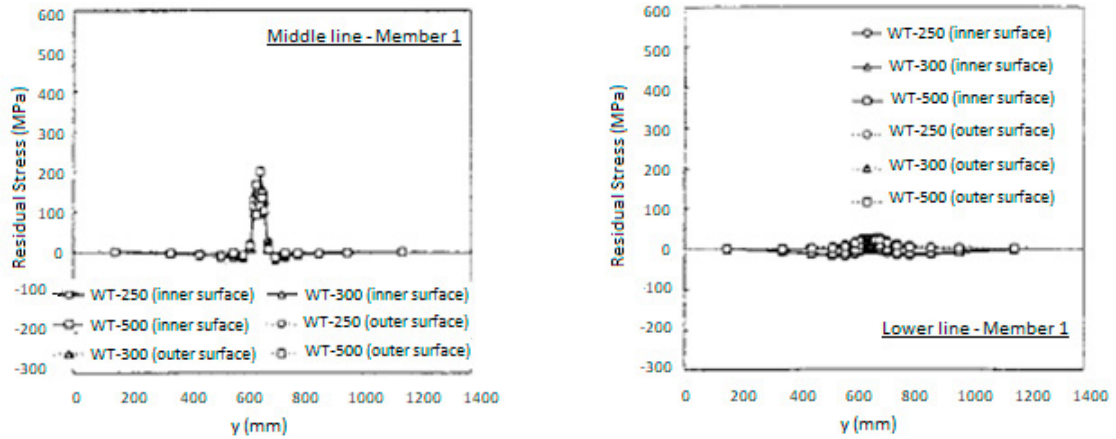


Fig. 16. Residual stresses from FEA in the circumferential direction [11]

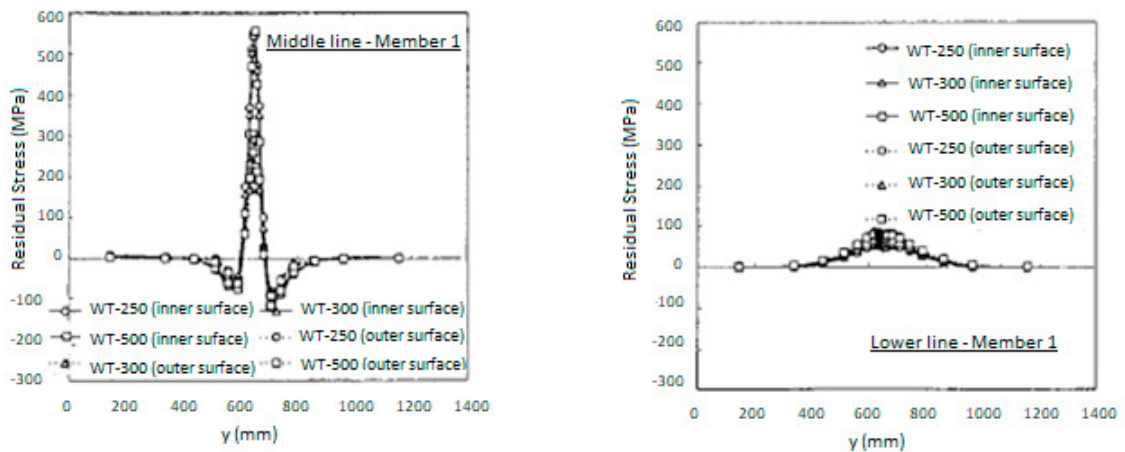


Fig. 17. Residual stresses from FEA in the axial direction [11]

When the residual stress distributions from the FEA (Fig. 16 and Fig. 17) are compared with the experimentally determined residual stress distributions (Fig. 13 and Fig. 14), some general conclusions regarding the residual stresses of welded tubular T-joints can be made. Only the results for the primary tube can be compared with FEA. In the axial direction, the residual stresses close to the weld toe are compared with the residual stresses on the middle line. These residual stresses near the weld toe are tensile residual stresses reaching the yield stress. Further away from the weld toe, the results of the lower line from FEA can be used to compare with the experimental results. There are smaller tensile residual stresses present. So it can be concluded that for the axial direction, the distribution of residual stresses obtained with the hole-drilling method can be compared with the results from FEA.

In the circumferential direction, there are tensile residual stresses smaller than 50% of the yield stress near the weld toe for both the experimental results and the results from FEA. At a larger distance from the weld toe, the residual stresses are close to zero. Also for the circumferential direction, the residual stress results obtained with the hole-drilling method agree well with the FEA on similar tubular T-joints. It should be noted that the residual stress results from FEA are obtained on a structure with a different geometry and a different material than the experimental results from hole-drilling, however the trends of the residual stress distribution are similar.

6. Conclusions

The welding residual stresses for a tubular T-node joint are experimentally determined with the hole-drilling method. There are two similar test specimens used. For the first test specimen, the hole-drilling procedure was executed until a final hole depth of 1mm was reached while the final hole depth of the second test specimen is 2mm. The results for both specimens are compared

and it is opted to prefer the measurements of the second test specimen. The confidence intervals are for most measuring points smaller and more measurement results into the depth of the material are available, eliminating the uncertain near-surface stresses.

A residual stress distribution perpendicular to the weld for both the axial and circumferential direction is obtained. The results are compared with residual stress values obtained with FEA on similar tubular T-joints. Similar trends of the stress distribution are found for the residual stresses in both directions. In the axial direction, there are tensile residual yield stresses near the weld toe and smaller tensile residual stresses at a larger distance. In the circumferential direction, there are tensile residual stresses smaller than 50% of the yield stress present near the weld toe and at a larger distance, the stresses are close to zero. However, more research will be necessary to verify the distribution of the residual stresses of a welded T-joint, especially for the secondary tube.

The presence of tensile residual yield stresses near the weld toe of tubular T-node joints, can affect the fatigue lifetime of these joints. Tensile yield stresses tend to open cracks and have a detrimental influence on the fatigue crack propagating under cyclic traffic loadings on the bridge. Residual stress can make the difference between a fatigue micro crack to grow or not. Moreover, residual stresses can also influence the rate of crack propagation, since the tensile residual stress field is often associated with a shorter fatigue life. Therefore, knowledge of the residual stress distribution is essential to accurately estimate the crack development under fatigue loads. With the hole-drilling method, a residual welding stress distribution can be obtained. The knowledge of this distribution is essential to determine the effect of residual stresses on fatigue life behavior for T-nodes in tubular arch bridges.

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