Residual Stress Effects in Tubular K-joints Crack Growth

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Abstract. Seeking light and transparent bridge designs, engineers and architects have found an efficient and artistic way to fulfill their requirements: steel tubular bridges.

Like any other welded structure, the joints of this kind of bridge suffer from high tensile weld residual stresses. Combined with high stress concentrations, tensile residual stress is a relevant factor in fatigue crack development. Therefore, an experimental study has been carried out on tubular joints in order to characterize the 3D residual stress field, using mainly the Neutron Diffraction method. On the other side, two large-scale welded tubular truss beams were tested under constant amplitude fatigue loading. It is revealed that the peak tensile residual stress, exceeding the yield stress of the material, is localized at ~2 mm under the surface and allows cracks to develop in compressive joints. The influence of residual stresses on stable crack propagation is analyzed based on fracture mechanics theory.

Keywords: residual stresses, tubular structures, fatigue, fracture mechanics, neutron diffraction, hole-drilling, steel bridge

PACS: 07.10.Lw, 62.20.me, 46.50.+a.

INTRODUCTION

In steel tubular bridges, hollow section tube members are welded together in K-joints to form truss beams or in KK-joints to form tridimensional structures. These joints have been shown to be critically susceptible to fatigue (traffic) loadings. Indeed, the stress field at the weld toe of these joints is particularly complex: geometrical discontinuities imply applied stress concentration at the weld location, even increased by local stress concentration induced by the local weld geometry (toe angle, toe radius, welding imperfections). In addition to these applied stresses, high tensile residual stresses due to the welding process superimpose with them.

The crack propagation model used to evaluate fatigue life has to take into account this stress field complexity, strongly influenced by size effects. For welded joints, it has been shown [1] that stable crack growth dominates the total fatigue life (domains where the failure criteria is a detectable crack or the failure of the specimen). Since welding imperfection of 0.1 to 0.2 mm depth are present in the vicinity of the weld toe [2], they imply high plastic strains and act as a crack initiator meaning that there is almost no crack initiation phase in the fatigue life.

In order to characterize the applied stress field, fatigue design rules expressed in terms of the hot-spot stress at the weld toe are used. As hot-spot stress includes the effects of joint geometry and the type of loads (stress concentration effect described above), it is a useful tool even if S_{hs}–N curves are not able to correctly capture the size effect without a correction. From the above, it can be seen that design rules and studies are available concerning the applied stress concentration, and also that the welding imperfections have already been studied. However, to the best of our knowledge, no data is available concerning three-dimensional residual stresses in tubular K-joints.

Therefore, a residual stress measurement campaign was carried out using the incremental hole-driling method and the neutron diffraction method. In the present study, the results of these residual stress measurements are presented and compared with results of fatigue tests experiments. It turns out that the most important tensile residual stresses are on the first millimetres from the surface and are oriented perpendicularly (or transversely) to the weld direction. A transversal distribution equation for K-joints is proposed in this paper. As recommended by several authors [3], a model based on fracture mechanics using the concept of effective stress intensity factor range, has been chosen to study the residual stress field effects on stable crack growth. This model is capable to simulate the crack-closure effect. Therefore, it is a particularly relevant model to study joints loaded under compression where tensile residual stresses may suppress crack closure.

FATIGUE TEST RESULTS

As illustrated in Figure 1, two large scale tubular truss beams specimens S6 and S7 (8.6 m long and 1.8 m height) were tested under a constant amplitude load Q positioned at the center of the upper chord (Qmax=610 kN, Qmin=60 kN). The only difference between the Circular Hollow Sections (CHS) forming the truss is the wall thickness of their chord section (20 mm or 30 mm). CHS truss members, made of ferrite/pearlite carbon steel S355 J2H, are welded together using a metal active gas (MAG 136) process.

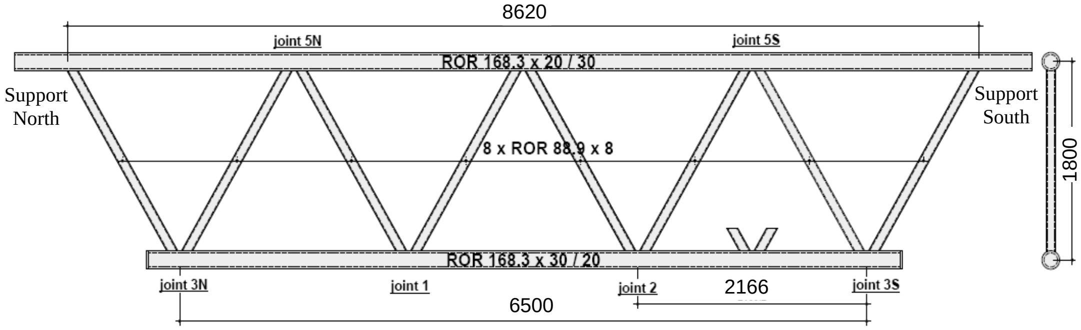

FIGURE 1. Tubular truss beam dimensions of specimens S6 and S7.

An ACPD (Alternative Current Potential Drop) measuring system was used to monitor precisely crack development during the fatigue tests and served also for model validation. More information concerning this technique can be found in Nussbaumer & Borges [4].

For both specimens, fatigue cracks were observed both in joints with the chord in tension as well as in joints in compression (in all non treated joints joints 1, 2, 3N, 3S, 5N and 5S), which confirmed the necessity to account for welding residual stresses in the model. It was observed that crack propagation occurred first from hot spot 1c (weld toe in-between the braces, compression brace side) until the crack reached about 2 mm deep. Then, the crack growth decreased and, simultaneously, a crack started to develop from hot spot 1 (tension brace side). Both crack continued to grow with different propagation rate as depicted in Figure 2, the failure was caused by a fatigue crack in a joint on the tension chord (joints S6-3S at 242 000 cycles and S7-3S at 111 000 cycles). Figure 2 shows that the propagation rate on the tensile side follows a continuous increase whereas on the compressive side it tends to drop once the crack reaches a depth of 4 to 5 mm (corresponding to a crack depth of 2 mm in the vertical plan since the crack angle is approximately of 60°).

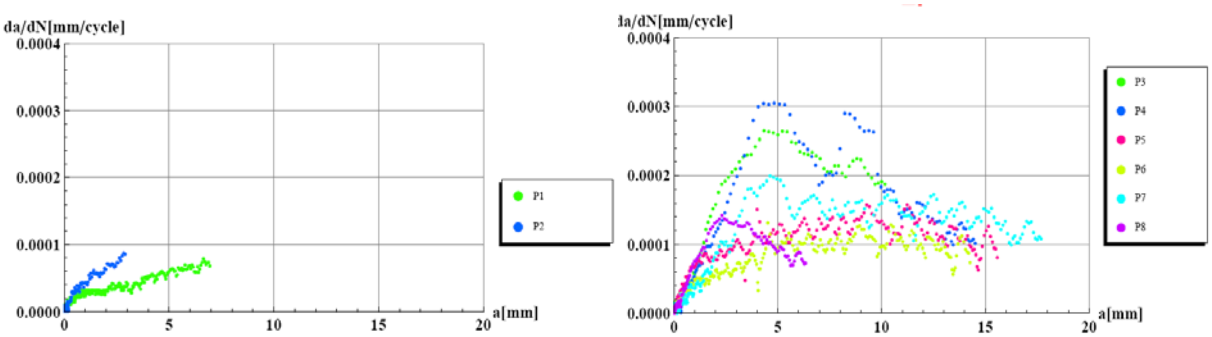

FIGURE 2. Crack propagation rate versus crack depth a (calculated in the crack plan): (a) on the left, tensile brace side of joint S6-5N, (b) on the right, compressive brace side of joint S6-5N.

RESIDUAL STRESS MEASUREMENT RESULTS

The hole-drilling semi-destructive method and the neutron diffraction non-destructive method were used to evaluate the magnitude and distribution of residual stresses induced by the welding process. Results from both methods were in good agreement, however tri-dimensional residual stress field through the depth of the sample can only be provided by neutron-diffraction. Residual strains were successfully measured in the gap between the brace welds of a non-cracked K-joint from the truss beams tested under fatigue. It provides transversal (perpendicular to the weld toe), longitudinal (parallel to the weld toe) and radial strain mappings. Mappings expressed in terms of the deduced stresses are depicted in Figure 3. This figure shows that, first of all, transversal residual stresses reach the yield stress value of the material (which is approximately 355 MPa) and are greater than longitudinal ones. This phenomenon does not occur with better-known tubular butt weld joints. Indeed, transversal residual stress magnitudes remain high in the gap region of K-joints due to an important restraining effect between the braces. These tensile stresses are dominated by the “bending” type distribution providing important range of high tensile residual stresses away from the weld whereas in the “self-equilibrating” type distribution, residual stresses are confined in the weld vicinity.

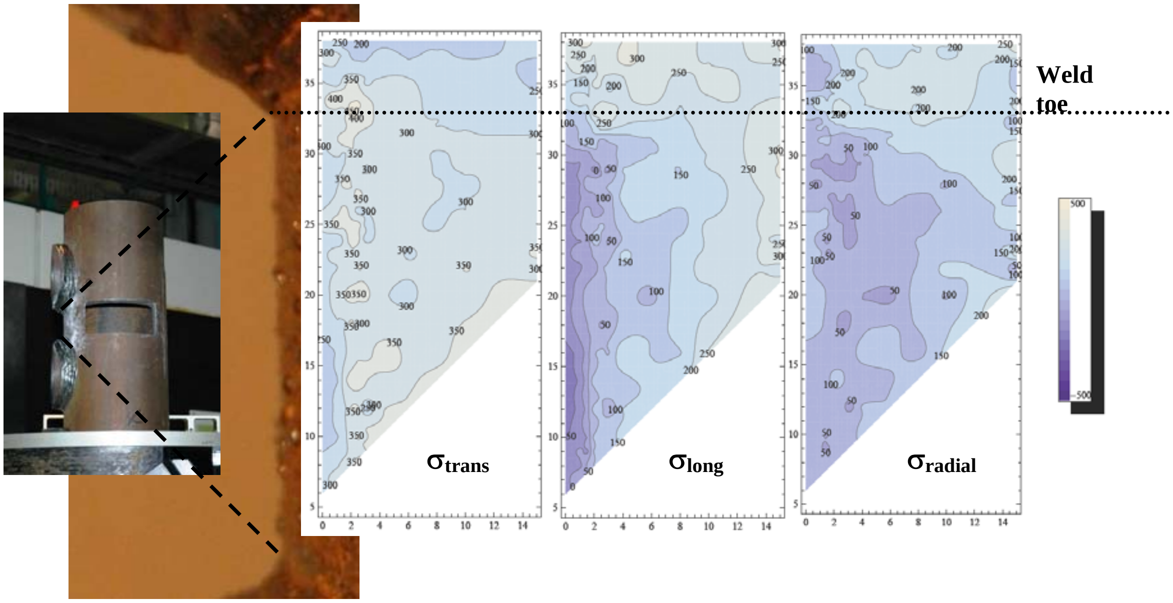

FIGURE 3. Residual stress mappings deduced from neutron diffraction measurements at Institut Laue-Langevin (France).

Moreover, this particular orientation of the greater residual stresses is also the orientation of the externally applied stresses, as a consequence they will superimpose. That is the reason why transversal residual stresses have to be characterized carefully for this kind of joints. Based on neutron diffraction measurements, a distribution function is proposed in Equation 1.

$$\sigma_{\text{res, trans}} = 355.(1.05 + 1.65.(\frac{b}{T}) - 35.5.(\frac{b}{T})^2 + 111.(\frac{b}{T})^3 - 131.(\frac{b}{T})^4 + 52.5.(\frac{b}{T})^5) \qquad (1)$$

EFFECTIVE SIF RANGE MODEL

Based on fracture mechanics theory, a model has been studied to predict the fatigue behavior of tubular K-joints. The effective SIF range ΔK_{eff} resulting from this model is compared with the ΔK_{eff} deduced from test results of joint S6-5N for tensile and compressive sides (see Figure 4).

As described in [3], the basis for this model is the well-known Paris law modified to include a threshold SIF range, ΔK_{th}, and to replace the applied SIF range ΔK_{app} by the effective SIF range ΔK_{eff}, taken into account the applied stress range, the residual stress distribution and the crack closure effects. The ΔK_{app} is calculated using the method proposed in [5], and the SIF due to residual stress distribution K_{res} from the one proposed in [6]. Equations 2 summarize the main hypothesis of the model.

$$N = \int_{a0}^{ac} \frac{da}{C.(\Delta K_{\text{eff}}^{\ m} - \Delta K_{th}^{\ m})} \qquad \begin{aligned} \Delta K_{eff} &= Min(K_{app,\max} - K_{app,\min}, K_{app,\max} - K_{op}) \\ K_{op} &= -(K_{res} + K_{pl}) \end{aligned} \qquad (2)$$

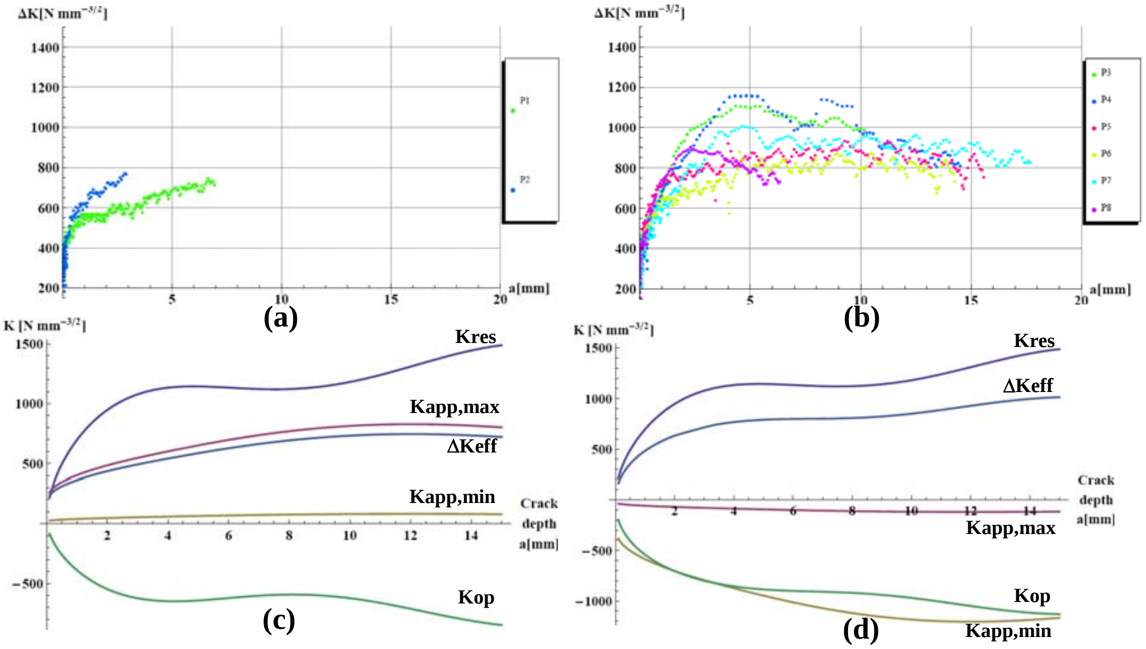

FIGURE 4. SIF versus crack depth a (calculated in the crack plan): (a) ΔK_{eff} measured in S6-5N (tensile side), (b) ΔK_{eff} measured in S6-5N (compr. side), (b) SIF calculated from the model in S6-5N (tensile side), (b) SIF calculated form the modelin S6-5N (compr. side).

It appears from these plots that, even under the compressive applied stress $K_{app,max}$ and $K_{app,min}$ in S6-5N (compr.side), the ΔK_{eff} is still positive, explaining why crack propagate in joints loaded under compression. This is possible only because K_{op} is negative and less than $K_{app,max}$, meaning that the magnitude of the positive K_{res} is greater than the magnitude of the negative crack closure K_{pl} induced by crack tip plasticity. In K-joints geometry, transversal residual stresses distribution is able keep K_{res} important for all crack depths allowing the crack to continue growing. However, from 5 mm depth, transversal residual stresses are not high enough to keep K_{op} more negative than $K_{app,min}$, implying that ΔK_{eff} is slightly reduced. This reduction is directly linked with the crack propagation rate decrease described in Figure 2 (b).

In other words, in joints loaded under compression, the tensile residual stress distribution plays an important role because it determines the magnitude and the shape of ΔK_{eff}, and hence explains if crack propagate faster, slower or just stopped. This is not the case for joints loaded under tension, since K_{op} is usually lower than $K_{app,\ min,}$ tensile residual stresses has no influence on the crack propagation of these joints.

CONCLUSION

Compressive joints are usually not considered in fatigue life consideration. However, it has been demonstrated in this paper that crack can also propagate in this kind of joints due to welding residual stresses. Tubular K-joints are particularly susceptible to residual stress effect because of the restraining effect in the gap region creating high tensile residual stresses critically oriented transversely to the weld direction.

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