BEHAVIOR OF HIGH-STRENGTH STEEL WELDED TUBULAR CONNECTIONS UNDER LOW-CYCLE FATIGUE

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1. ABSTRACT

The present work examines the behavior of welded tubular connections made of high strength steel, subjected to extreme loading conditions with emphasis on their low-cycle fatigue performance. This work is part of a large research effort which consists of two main parts. In the first part an experimental investigation of ten (10) tubular X-joints made of high strength steel is conducted. Experimental testing has been designed in order to examine the joint behavior under axial, in-plane and out-of-plane monotonic and cyclic loads, at loading levels well beyond the elastic regime. In the present paper, the experimental performance of two (2) tubular welded joints subjected to strong cyclic out-of-plane bending loading is examined.

The second part of the work consists of a numerical analysis, aimed at simulating the experiments and performing a parametric study. The overall joint behavior and local phenomena that take place at the weld toe are simulated and the simulation results are compared with the experimental findings.

2. INTRODUCTION

The performance of welded tubular joints under cyclic loading has been numerically and experimentally examined by many researchers. The existing design guidelines (e.g. CIDECT [1]) as well as the majority of experimental work refer to the analysis and design of these joints under high-cycle fatigue loading and only limited research effort is focused on the examination of the low-cycle fatigue performance of those joints [2], [3], [4]. In addition, no information is available for the low-cycle fatigue of tubular joints made of high strength steel.

In the present paper, the experimental performance of two (2) tubular welded joints subjected to strong cyclic out-of-plane bending loading is examined. Furthermore, a detailed finite element model of the joint is developed in ABAQUS. The weld region of the joint is modeled considering different material properties in this area. Several plasticity models are employed to simulate the material behavior, and the model parameters are properly calibrated based on uniaxial monotonic and cyclic material coupon test results.

The overall joint behavior and the local phenomena at the weld toe are simulated and the simulation results are compared with the experimental findings. Special attention is given to the evaluation of the stress and strain fields at the so-called “hot-spot” locations. Stress concentration factors are calculated and compared with the proposed values found in the literature. Cyclic plasticity phenomena such as the accumulation of plastic strains at those points are also examined.

3. EXPERIMENTAL WORK

3.1 Specimen details and setup geometry

The experiments are conducted at the University of Thessaly. Two (2) X-joint tubular specimens are considered (*Fig. 1*) with overmatched and undermatched welds, subjected to out-of-plane bending (OPB). The welds of the joints have been manufactured according to the provisions of AWS D1.1/D1.1M:2004. Four-point bending is applied to the braces of the specimens through a steel cross-beam with two special ball-joint hinges and appropriate wooden grip assemblies. Both ends of the specimen are supported on a double-hinge ‘roller’ system. The moment lever arm created by this configuration is 830 mm. The nominal cross-section for the brace is CHS193.7x10 and for the chord is CHS355x12. Details of the overall geometry, loading system and instrumentation for the OPB tests are shown in *Fig. 2*.

Strain gages are placed at critical locations to measure the specimens’ deformations. More specifically, uniaxial 5-element strip gages are attached to the top of the chord (hoop direction) with the closest being 5 mm away from the weld toe (chord saddle) to study the concentration next to the weld. In addition, wire position transducers and DCDT’s are used for load-point displacement and support displacements measurements, respectively.

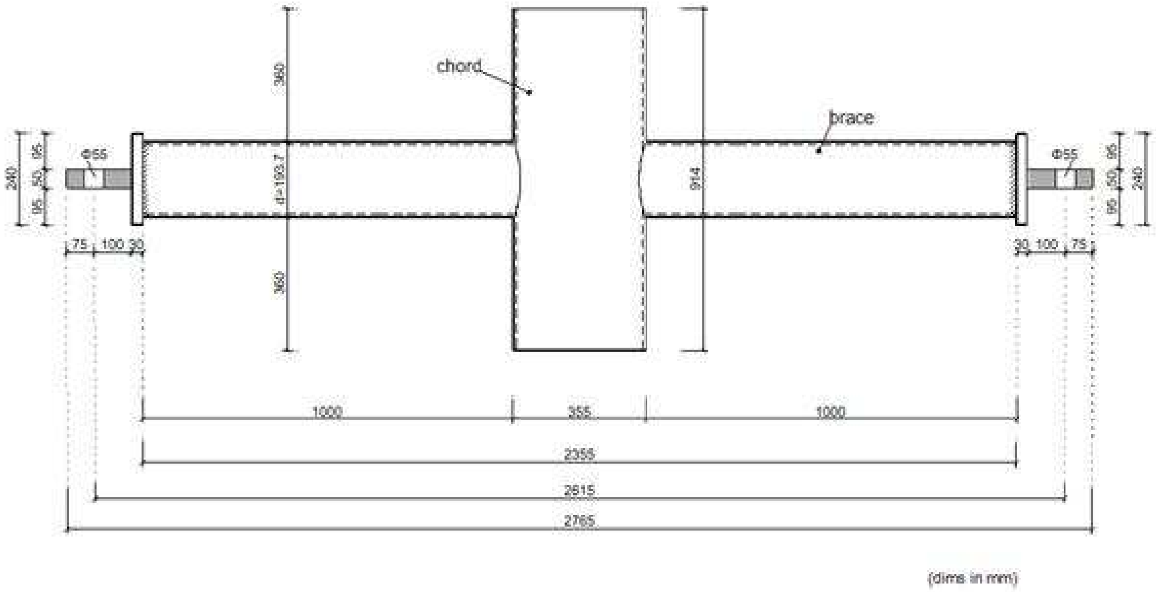
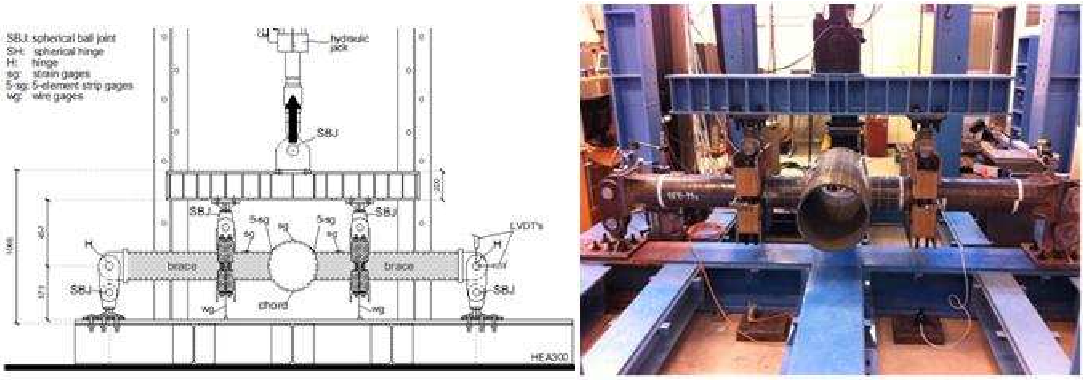


Fig.1. Specimen geometry for the OPB tests.

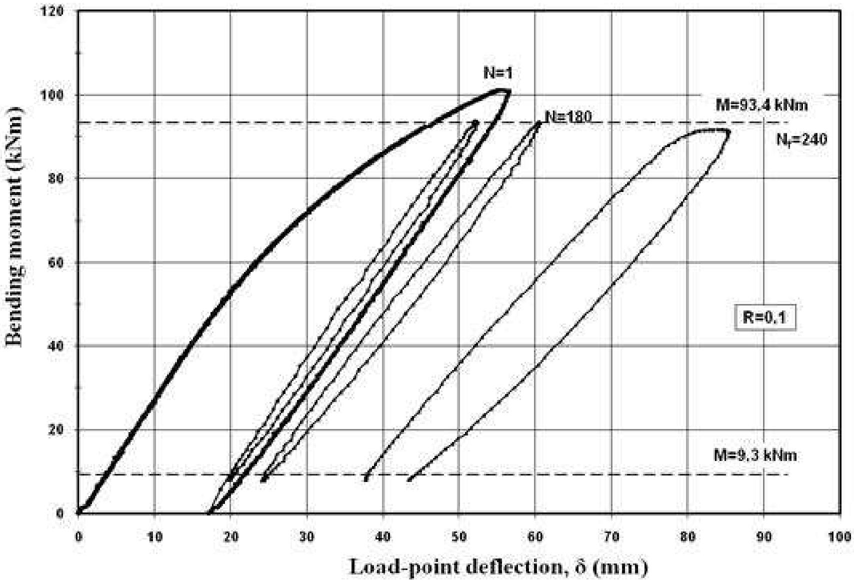


(a) (b)

Fig.2. Test setup, loading system and instrumentation for the out-of-plane bending tests.

3.2 Experimental results

The joint is first subjected to a monotonic bending OPB loading equal to 100 kNm and subsequently the bending load was cycled at $R=0.1$ and $M_{max}=93.4\ kNm$. The moment vs. deflection diagram of the X-tubular joints with the undermatched weld for specified number of cycles indicates a rapid degradation and accumulation of deformations after the 180th cycle, as shown in *Fig. 3*(a). The specimen with the undermatched weld conditions failed after 240 loading cycles, while the specimen with the overmatched weld under the same loading conditions failed after 200 cycles, showing a rather similar behavior with slightly lower fatigue strength. Both failures due to low-cycle fatigue occurred at the weld toe area, as shown in *Fig. 3*(b).



(a)

(b)

Fig.3. (a) Maximum bending moment vs. load-point deflection curves, (b) Cracked chord at the weld toe.

4. NUMERICAL SIMULATION

4.1 Material modeling

The actual yield stress of the TS590 steel material is 746 MPa and the corresponding material stress-strain curve from tensile tests on steel coupon specimens is depicted in *Fig. 3.* It is worth noticing that the measured material yield stress is 26.4% higher than the nominal value resulting to a significant increase of the carrying capacity of the joint. The simulations presented are based on the actual material properties (not the nominal).

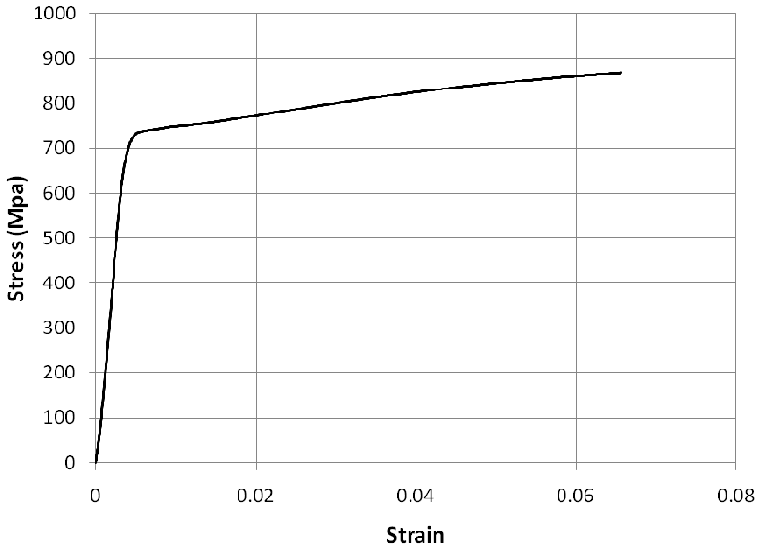
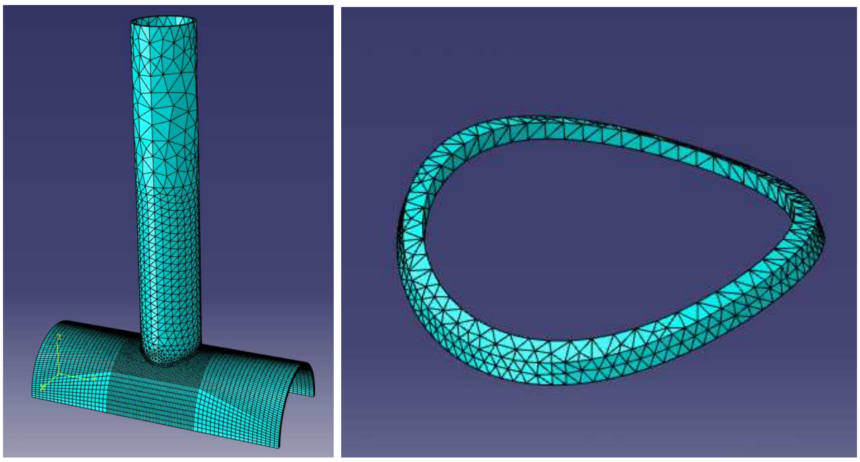


Fig. 3. Uniaxial steel material stress-strain curve.

4.2 Finite element model

The numerical model used represents the actual dimensions of the welded joint. The weld geometry has been modeled as a separate part, according to the provisions of the Structural Welding Code AWS D1.1/D1.1M:2004. This allows for the application of different material properties in this region of the specimen in order to examine the effect of overmatching or undermatching weld conditions on the structural performance of the joint.

The model is developed in ABAQUS and uses 20-noded, quadratic, reduced integration solid elements (C3D20R) for the chord and the weld region, whereas 4-noded solid elements (C3D4) are used for the brace. Moreover, the mesh size is denser near the weld region in order to provide accuracy in the simulation results and time-effective simulations. Only half of the joint is modeled, taking advantage of symmetry and applying the appropriate symmetry conditions. The model is shown in *Fig. 4.*



(a) (b)

Fig. 4. Numerical model developed: (a) General view (b) Weld region.

5. FINITE ELEMENT RESULTS

The numerical results have been initially obtained using a material model of J_2 flow plasticity with isotropic hardening. The joint geometry was modeled according to the nominal dimensions of the tubular members. In comparison with the corresponding test results, it is observed that the numerical model underestimates the joint strength. The reason is that the chord thickness is not uniform along the perimeter due to the manufacturing process and may vary up to 10% based on actual measurements on the tested specimen. Therefore, for improving the simulation results, an equivalent uniform thickness of the chord is adopted maintaining a constant outer diameter equal to 355 mm. As displayed in *Fig. 5*, the predictions of the numerical model in the elastic range can be numerically represented quite accurately, if an equivalent uniform thickness of 12.5 mm is adopted for the specimen chord. The main difference between tests and analysis with increasing displacement is that according to numerical results, inelastic behavior initiates earlier than in the experiments. This results in a difference of about 4% in the maximum load capacity (displacement equal to 52 mm).

The stresses and strains measured on the chord of the joint are mainly in the hoop direction as shown by both the experimental and numerical results. This is an indication that the difference in joint capacity between tests and analysis is attributed to possible variation in the adopted material properties in the hoop direction. To investigate this effect, an anisotropic material model is used, adopting a Hill formulation of the yield surface. Considering an increase of the yield strength in the hoop and through-thickness directions equal to 5%, the simulation results approach the measured values. For the precise identification of the material anisotropy, a number of ring crushing tests are programmed, and based on these measurements, the material model including material anisotropy will be updated.

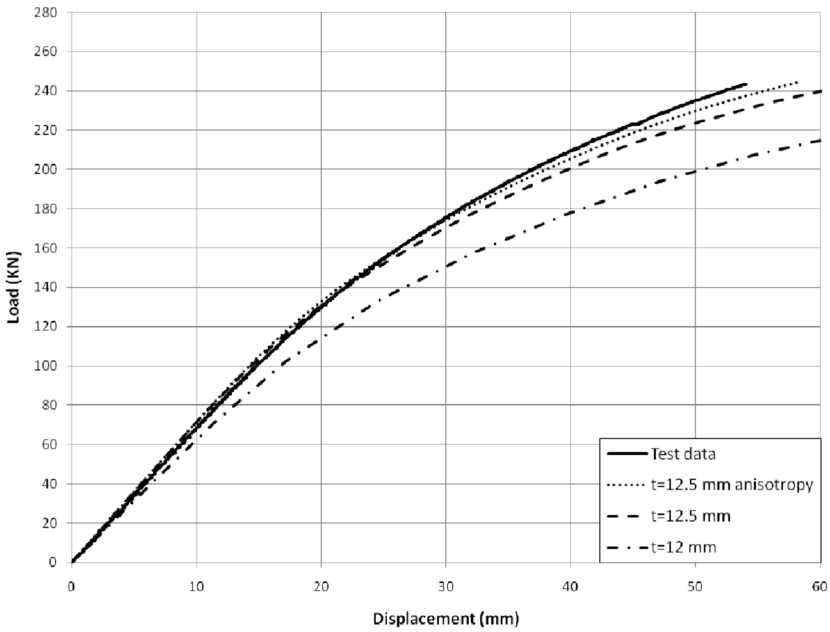


Fig. 5. Comparison of the numerical and experimental load vs. displacement curves.

The stress concentration factor (SCF) has been also evaluated for the nominal chord thickness of 12 mm. According to CIDECT No. 8 [1], the corresponding SCF for the joint under consideration is equal to 9.82 and according to Wordsworth and Smedley [5] it is equal to 10.25. According to the numerical results, the evaluated SCF is equal to

11.79 if linear extrapolation is used, as presented in *Fig. 6.* The predicted value is in reasonable agreement with the one proposed by Wordsworth and Smedley [5].

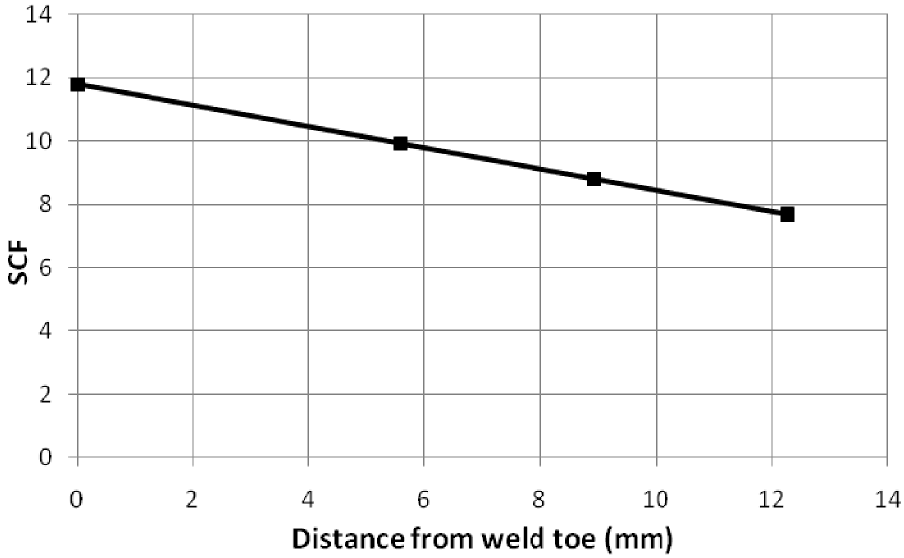
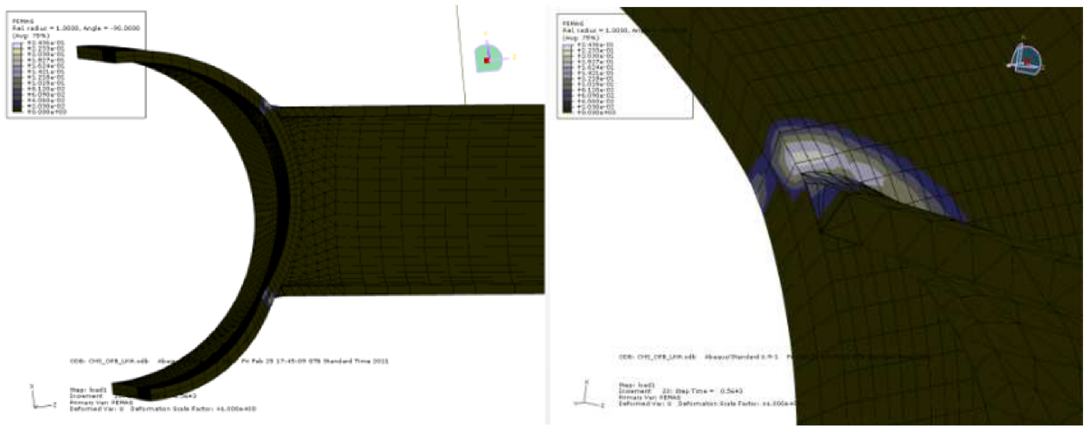


Fig. 6. SCF evaluation.

Towards better understanding of chord deformation near the weld toe, the deformed chord geometry is presented in *Fig. 7*, which corresponds to a joint section at the chord middle plane. The concentration of plastic deformation near the weld-toe area is significantly higher than the one located at the weld of the joint, so that the location of cracking initiation at the weld-toe is verified.

Several check points (C.P.) have been introduced in the brace and chord part of the joint, as illustrated in *Fig. 8.* It is noticeable that when bending loading is applied, the brace part of the joint (C.P. 1) as well as the chord part very close to the weld toe (C.P. 2) are always in tension. In C.P. 3, which is located 11 cm from the weld toe along the hoop direction in the chord, the material initially experiences tensile strains which subsequently change sign and become compressive strains as the bending loading is increased. Between this location of the chord and the chord top (C.P. 4 and 5) the strains are always compressive. This indicates that there is a significant change of chord curvature near the weld toe region.



(a) (b)

Fig. 7. Mid-span section (a) Deformed chord geometry (b) Weld-toe region.

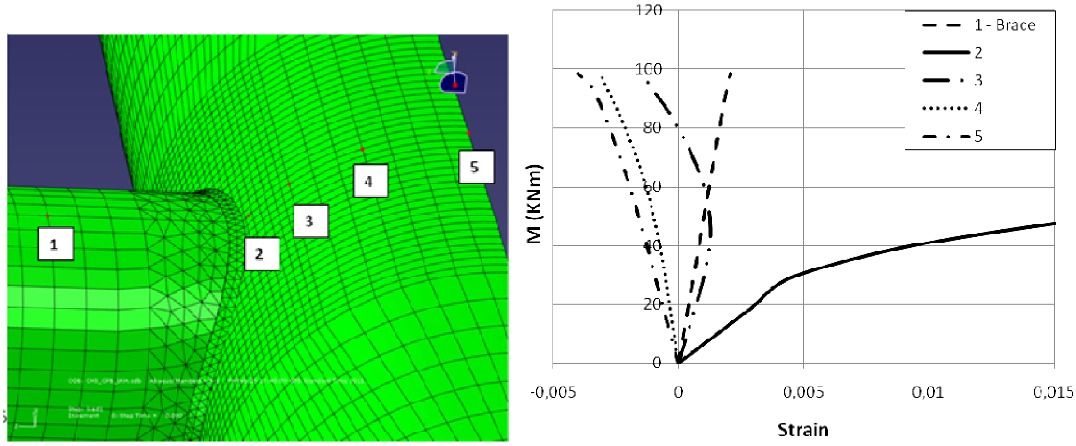


Fig. 8. Strain values at various check points.

6. ACKNOWLEDGMENT

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ΠΕΡΙΛΗΨΗ

Η παρούσα εργασία εξετάζει τη συμπεριφορά συγκολλητών σωληνωτών κόμβων από χάλυβα υψηλής αντοχής που υπόκεινται σε ακραίες συνθήκες φόρτισης με έμφαση στη συμπεριφορά τους σε ολιγοκυκλική κόπωση. Η παρούσα εργασία είναι μέρος μιας ευρύτερης ερευνητικής εργασίας που αποτελείται από δύο μέρη. Το πρώτο μέρος περιλαμβάνει πειραματική μελέτη της συμπεριφοράς δέκα (10) συγκολλημένων σωληνωτών κόμβων μορφής Χ από χάλυβα υψηλής αντοχής. Τα πειράματα έχουν σχεδιαστεί με σκοπό να μελετηθεί η συμπεριφορά του κόμβου σε μονοτονική αξονική ή καμπτική φόρτιση (εντός και εκτός του επιπέδου του κόμβου) όπως επίσης και ανακυκλιζόμενη αντίστοιχη φόρτιση σε επίπεδο πέρα από το όριο ελαστικής συμπεριφοράς. Στην παρούσα εργασία παρουσιάζεται η συμπεριφορά δύο (2) κόμβων που υπόκεινται σε ισχυρή κυκλική κάμψη εκτός επιπέδου.

Το δεύτερο μέρος της εργασίας αναφέρεται σε αριθμητική ανάλυση προσομοίωσης των πειραμάτων και παραμετρική μελέτη. Η συνολική συμπεριφορά του κόμβου καθώς και τοπικά φαινόμενα που λαμβάνουν χώρα στον πόδα της συγκόλλησης προσομοιώνονται κατάλληλα και τα αποτελέσματα της προσομοίωσης συγκρίνονται με τα πειραματικά αποτελέσματα.