FINITE ELEMENT RESIDUAL STRESSES ANALYSIS AND FATIGUE ASSESSMENT OF A PIPE-TO-PLATE WELDED JOINT

A. Chiocca, F. Frendo, L. Bertini
University of Pisa, Department of Civil and Industrial Engineering, 56122 Pisa
email: andrea.chiocca@phd.unipi.it

INTRODUCTION AND OBJECTIVES

Residual stresses are an inseparable consequence of the most common manufacturing processes, resulting in high magnitude and not easy predictable stress field inside the material. Fatigue design codes usually account residual stresses through highly conservative assumptions, resulting in poorly optimized designs or unexpected failures. To this regard, the following work investigates the influence of residual stresses in the fatigue assessment of a pipe-to-plate welded joint made of S355JR structural steel (**Fig. 1**). An uncoupled thermo-structural finite element simulation was performed in order to evaluate the overall residual stress field in the specimen due to the welding process. The thermal problem was firstly solved and then the results, in terms of nodal temperatures, were used in the structural analysis. Secondly, the resulting residual stresses were embedded in a finite element model as initial condition prior to fatigue loading application.

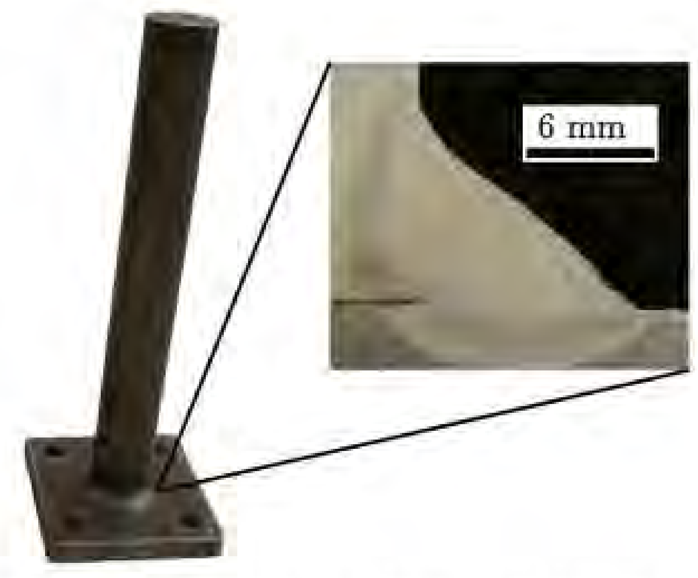

Fig. 1 Real sample with highlighted welding cross section

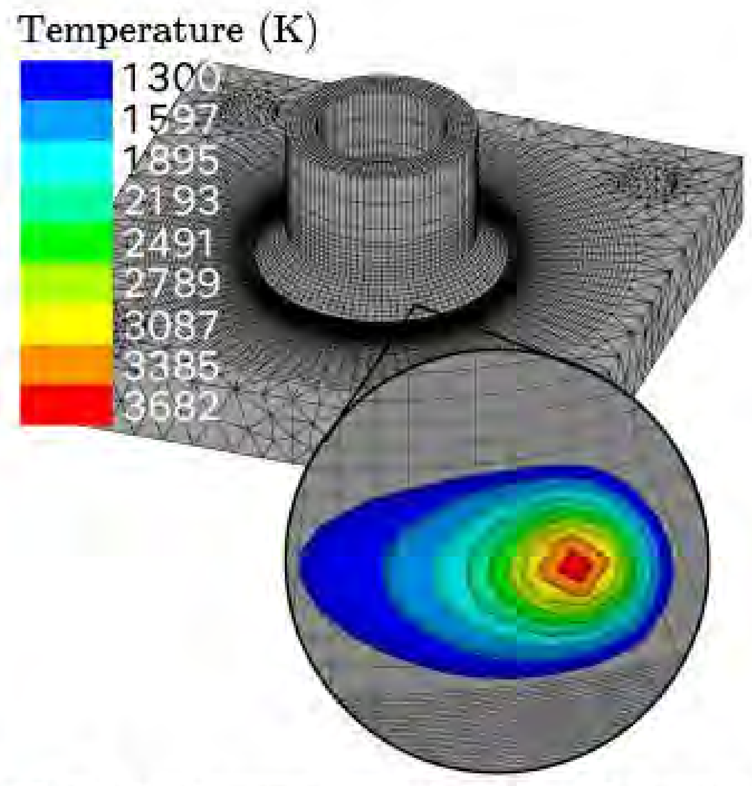

Fig. 2 Isotherms resulting from Goldak's double ellipsoid

RESIDUAL STRESSES EVALUATION - THERMAL ANALYSIS

Firstly, the thermal simulation of the welding process was carried out, in this case, the model aims at achieving only the temperature time-history due to the welding process (**Fig. 2**). The element birth & death technique was implemented to deactivate and subsequently, at given times, re-activate the elements belonging to the weld seam with a given initial temperature T_i. The amounts of elements that needed to be de-activated and then re-activated were determined directly from a cross-section of the weld seam (**Fig. 3**). The "fictitious" initial temperature (T_i) used as a setting parameter was proven to be able to reproduce the temperature distribution at the nodes, with very good agreement if compared to more complex methods [1]. The setting parameter T_i can directly be determined through comparison with experimental results of temperature measured during the welding process.

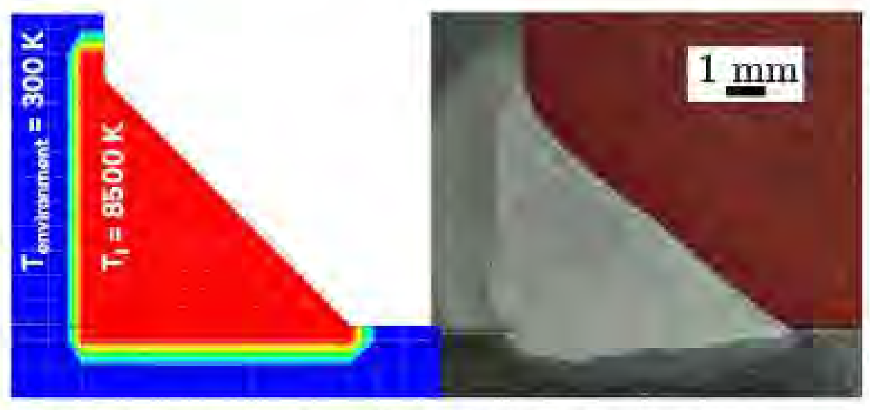

Fig. 3 Numerical and experimental cross section of the weld seam

RESIDUAL STRESSES EVALUATION - STRUCTURAL ANALYSIS

The welding process was then reproduced from a mechanical point of view through the structural analysis. The load resulting from the thermal simulation previously solved was applied to the nodes of the FE model. In this stage, the structural stresses and strains over time were computed starting from the temperature evolution during the simulated welding process (**Fig. 4**). During the structural simulation, only elements with a temperature below the melting point were activated by means of the element birth & death technique. The process shows in **Fig. 5** was automated through a macro code written in Ansys APDL environment. The result thus obtained represents what is expected from the solidification of a pool of molten metal during the welding process.

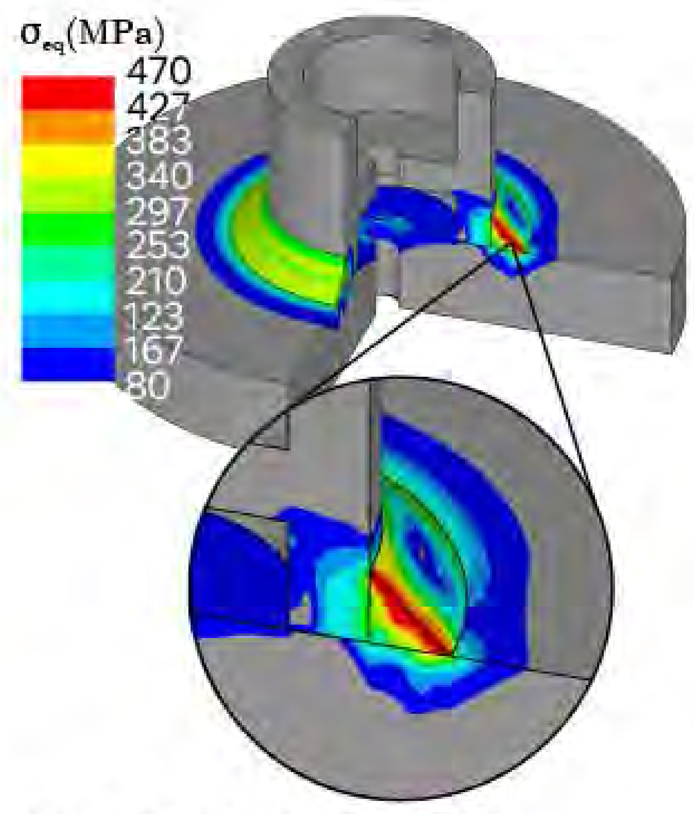

Fig. 4 Residual stress field produced as a result of the welding process

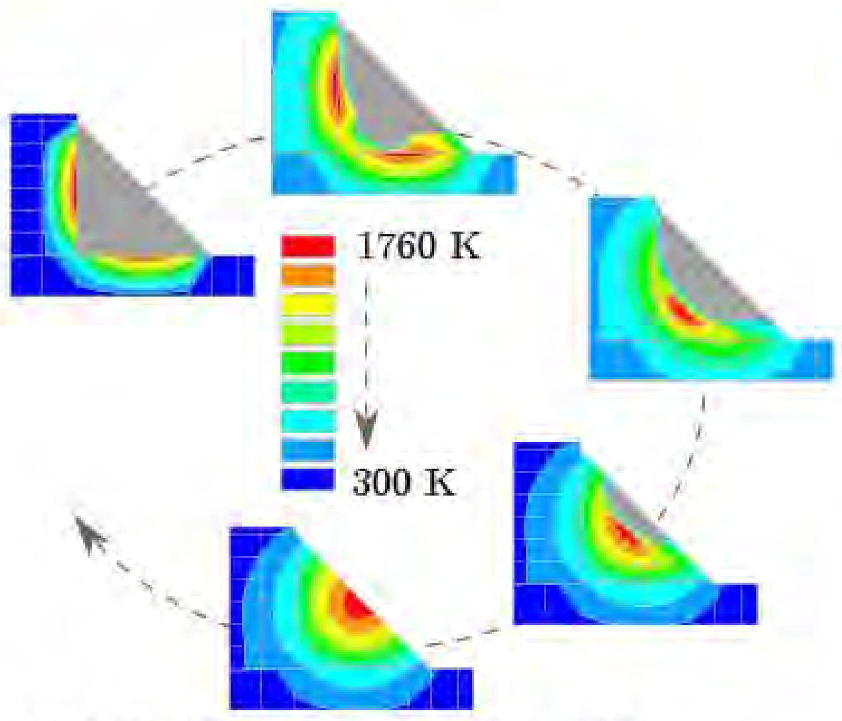

Fig. 5 Cooling sequence of a weld seam section

VALIDATION OF THE UNCOUPLED THERMAL-STRUCTURAL ANALYSIS

An incremental cutting procedure was performed at the bottom of the plate in order to acquire a series of experimental relaxed strains, representative of the residual stress state in the welded region (**Fig. 6**). Such a procedure was reproduced through a numerical simulation in order to validate the overall numerical analysis through comparison with several strain gauges readings. For ease of viewing, only results of relaxed radial strain for a fixed hole depth are shown in **Fig. 7**, where experimental data are presented through mean value and standard deviation, while numerical results are displayed through a convex envelope of relaxed radial strains as a function of the hoop coordinate. The comparison shows how numerical simulation accurately predicts experimental results.

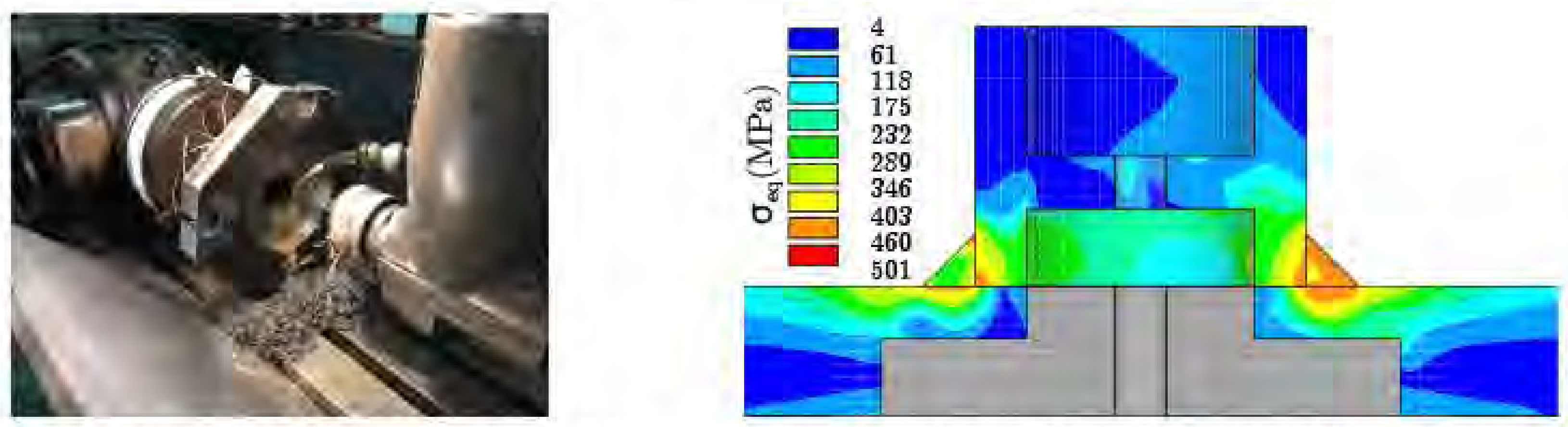

Fig. 6 Experimental machining of the specimen's plate (left) and numerical simulation of the process (right)

FATIGUE ASSESSMENT INCLUDING RESIDUAL STRESSES

Residual stresses evaluated from the thermal-structural simulation were then used for a fatigue assessment. The purpose of the fatigue analysis was to highlight possible differences in the damage experienced by the specimen if residual stresses were introduced. Several studies have already been carried out on the same specimen geometry under different fatigue loadings but neglecting residual stresses [2-4]. Therefore, experimental tests for pure bending and pure torsion in as-welded and stress relieved conditions were performed with a load ratio R=-1. Fatigue loadings were replicated by means of Ansys Workbench submodeling, while critical plane factors, such as Fatemi-Socie and Findley, were evaluated using Matlab. Results are shown in **Fig. 9**, specifically, the critical plane factor of Fatemi-Socie over the number of cycles to failure were evaluated, showing a major contribution of residual stresses in case of pure torsion.

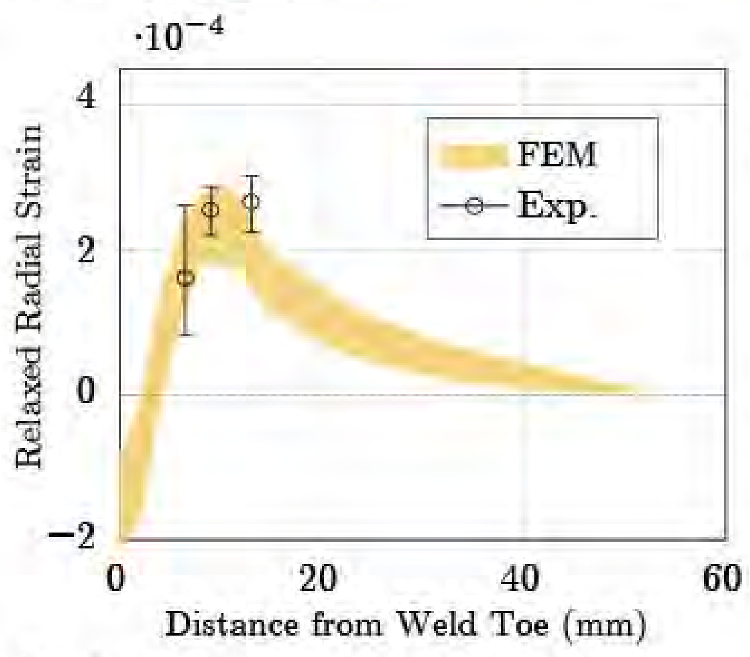

Fig. 7 Relaxed radial strains over distance from the weld toe for a hole depth of 10 mm

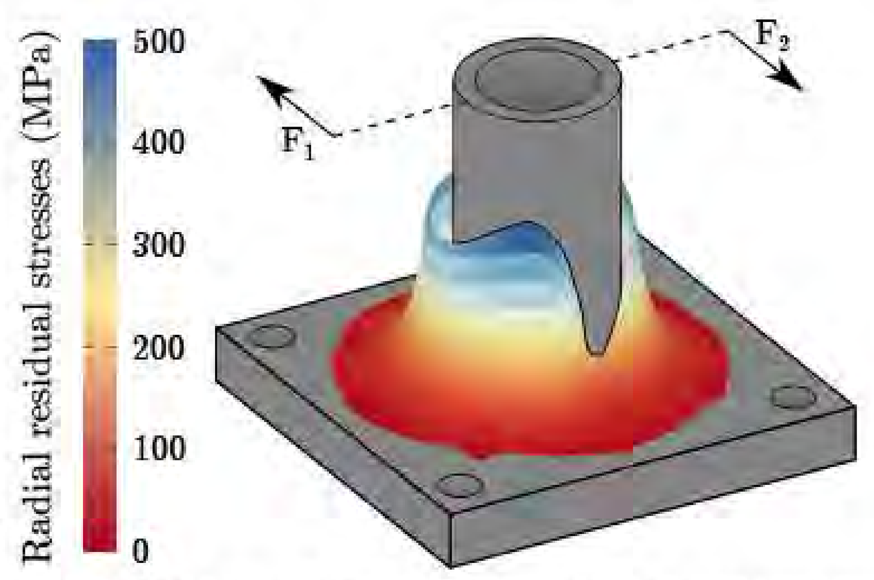

Fig. 8 2D plot of the radial residual stresses on the plate surface and actuation forces used for fatigue loading of the specimen

RESULTS OBTAINED

The thermal-structural model developed has proven to be easy to implement and it shows a very good agreement with the experimental data. The model is easily adaptable to different welding processes and joint geometries due to the simplified thermal source model employed. Results of residual stresses have been implemented within an FE-model in order to perform fatigue assessment. A dependence on residual stresses has been identified, especially in the case of pure torsion. At the moment, different load case scenarios are being investigated in order to assess the influence of residual stresses over fatigue life.

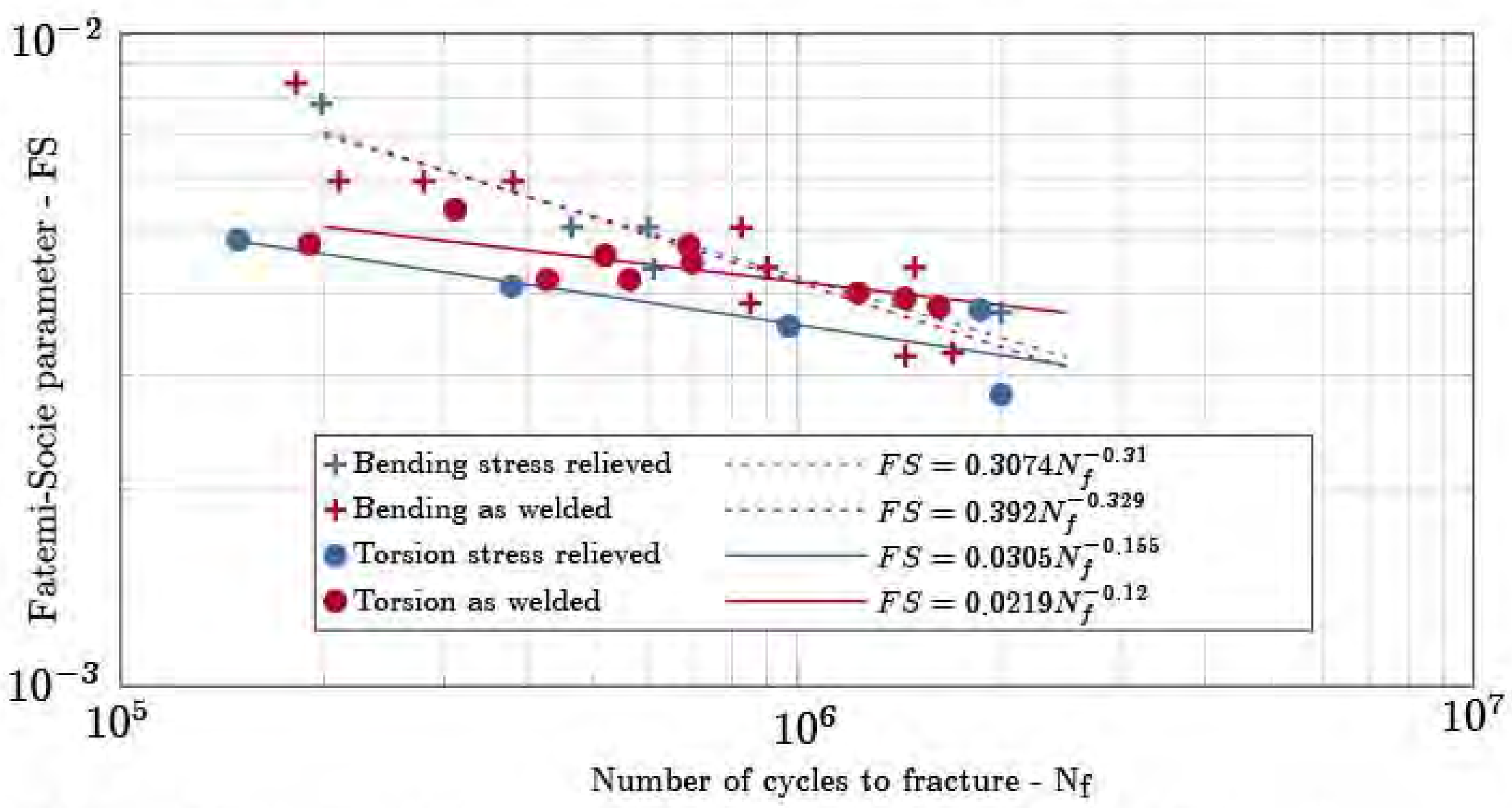

Fig. 9 Fatemi-Socie critical plane parameter Vs. Number of cycles to fracture for pure bending and pure torsion fatigue tests considering stress relieved and as welded conditions

REFERENCES

[1] A. Chiocca, F. Frendo, and L. Bertini, "Evaluation of heat sources for the simulation of the temperature distribution in gas metal arc welded joints," Metals, vol. 9, p. 1142, 2019.
[2] F. Frendo and L. Bertini, "Fatigue resistance of pipe-to-plate welded joint under in-phase and out-of-phase combined bending and torsion," International Journal of Fatigue, vol. 79, pp. 46–53, 2015.
[3] L. Bertini, F. Frendo, and G. Marulo, "Effects of plate stiffness on the fatigue resistance and failure location of pipe-to-plate welded joints under bending," International Journal of Fatigue, vol. 90, pp. 78–86, 2016.
[4] F. Frendo, G. Marulo, A. Chiocca, and L. Bertini, "Fatigue life assessment of welded joints under sequences of bending and torsion loading blocks of different lengths," Fatigue & Fracture of Engineering Materials & Structures, 2020.