RESIDUAL STRESSES BEHAVIOR UNDER FATIGUE CRACK CYCLIC LOADING: A FINITE ELEMENT ANALYSES

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ABSTRACT

It is very well known that the residual stresses affect the fatigue crack behavior. However, very little it is known how the residual stresses are affected by the fatigue crack cyclic loading. This paper focuses this aspect of the fatigue behavior. In order to perform numerical finite element computation, a regular rectangular steel plate is modeled with a mesh following the shape characteristics of the Compact Tension Specimen. Plastic strains are induced in the rectangular steel plate, by applying irregular external loading, resulting a residual stress field similar to the one occurs in the welded butt joints. A Compact Tension Specimen with a residual stress field is obtained by deactivating some of the finite elements of the rectangular steel plate mesh. The Compact Tension Specimen is cycled loaded, simulating a fatigue process, and the residual stress field is evaluated under the influence of the crack tip plastic zone. The Crack Opening Displacement results are compared for the cases with and without residual stresses. The non-linear evaluation of the stresses is performed by the finite element code LUSAS.

1 INTRODUCTION

The mechanical elements and structures may fail during service, even, when is submitted to small loads, compared to the ones established by the design conventional approaches. Many different reasons may cause this premature flaw. The residual stresses and cracks are, without a doubt, the main reasons, [1].

The residual stresses are those stresses that remain in the body after eliminating the application of the external loads or heating transfer. The residual stresses are usually caused by the manufacturing processes, such as, conformation, foundry, shot blasting, welding, etc. Some of these processes, highlighting among these the welding, can introduce cracks. For this reason, in this work, emphasis has been given to simulate the fracture and fatigue behaviors of welded structures type, such as, oceanic platforms, ships, pipelines, etc, [1].

The main objective of this investigation is to see the behavior around a crack of the residual stresses when the structure is subjected to a cyclic loading. Through the application and releasing of a high-intensity irregular external load on a steel plate, it is obtained a residual stress field similar to the existent ones in butt welded joints. The stress field is estimated by the Finite Element Method using the commercial code LUSAS, [2]. Then, by deactivating some finite elements of the steel plate mesh, a Compact Tension Specimen (CTS), used for fracture toughness evaluation, is obtained. The resulting residual stress field surrounds the Compact Tension Specimen crack tip. Therefore, it is possible to evaluate the influence of the crack on the residual stress field, when the CTS is submitted to cycled external loading. The stress and strain evaluations were performed by the commercial code of finite elements LUSAS, [2].

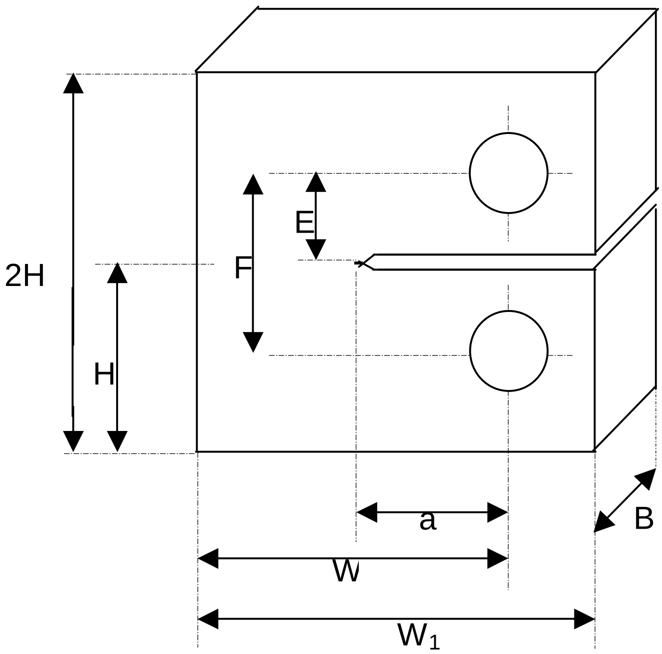
2 SPECIMEN CHARACTERISTICS

In the first phase of this study, it was considered an API60X steel plate, with the following dimensions: 48 mm x 46 mm x 10 mm. The mechanical properties of the API60X steel are presented in the Table 1, below.

Table 1 - Mechanical properties of the API60X steel

ELASTICITY MODULUS	**E** = 2 E+05 Mpa
POISON COEFICIENT	n = 0,3
DENSITY	r = 7.840 Kg/m^3
YIELD STRESS	s_e = 413 Mpa
ULTIMATE STRENGTH	s_u = 517 Mpa
FRACTURE TOUGHNESS	$\mathbf{K_{IC}}$ = 1651 N/mm$^{3/2}$
CRITIC CRACK OPENING DISPLACEMENT	$\mathbf{COD_C}$ = 0,80 mm
CRITIC CRACK ROOT OPENING DISPLACEMENT	$\mathbf{CTOD_C}$ = 0,24 mm

The Compact Tension Specimen geometry and dimensions are presented in the Figure 1, which is used model for the numerical computational analysis.



DIMENSIONS

a = 18,05mm
B = 10,0 mm
W = 38,4 mm
W$_1$ = 48,0 mm
E = 10,56 mm
F = 21,12 mm
H = 23,04 mm

FIGURE 1 - Compact Tension Specimen (CTS)

3 RESIDUAL STRESSES GENERATION

The steel plate is modeled by using a finite element mesh, following the Compact Tension Test geometry. A large number of smaller elements are used in the area around future position of the crack tip. With the purpose to introduce plastic strains, a high-intensity irregular external load is applied and released resulting in a residual stress field. The Figure 2, schematically, presents the mesh configuration, the boundary conditions and the external loads applied. The external loads were applied gradually, increasing from zero to a maximum value of 307 KN, using 48 small steps. The maximum value is kept constant during 4 steps and reduced to zero in others 48 steps. Therefore, a total number of 100 steps is used. The residual stress field in the direction Y resultant is presented in Figure 3, obtained after running the non-linear finite element analysis, using the commercial code LUSAS, [2].

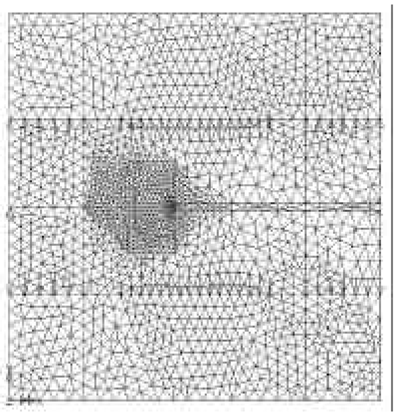


FIGURE 2 – Finite Element Mesh and Conditions

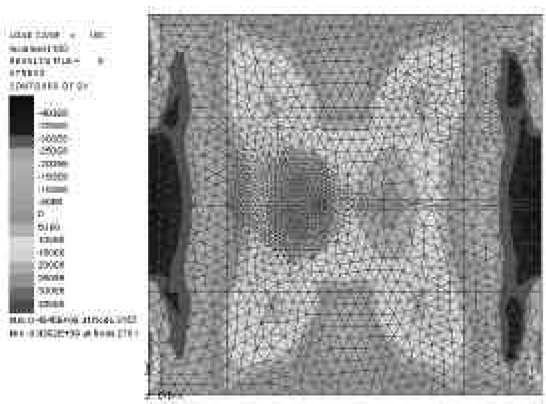


FIGURE 3 - Residual Stress Field (σ_{yR})

Then, some of the elements are disabled, changing the steel plate to the Compact Tension Specimen geometry and redistributing the residual stresses. The Figure 4 presents the residual stress field in the direction Y, (σ_{yR}) in the CTS. The residual stress profiles in the direction Y, (σ_{yR}), along the center line for the steel plate and for CTS are presented in Figure 5.

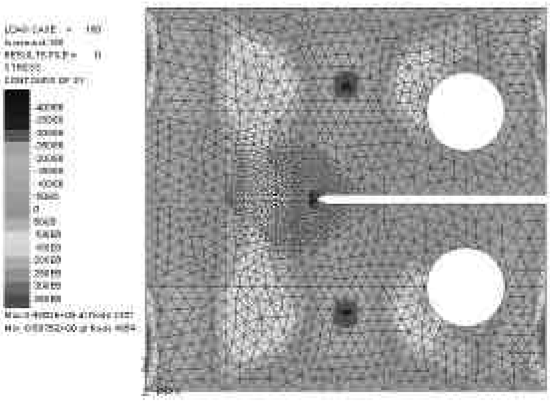


FIGURE 4 - Residual Stresses (σ_{yR}) for CTS

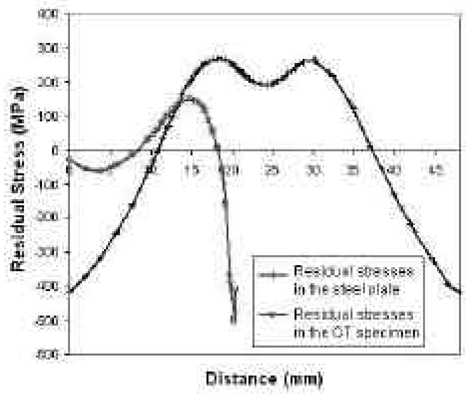
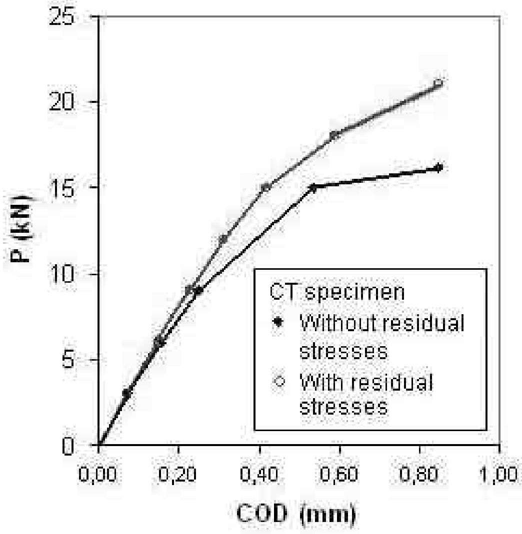


FIGURE 5 - Residual Stress Profiles (σ_{yR})

4 FRACTURE BEHAVIOR

Fracture toughness test simulations (P x COD - Crack Opening Displacement) are performed with and without residual stresses, which results are shown in the Figure 6. The residual stress profiles in the Y direction (σ_{yR}) are presented in the Figure 7, for a maximum force of 24 kN, appropriately distributed in the holes of the CTS.



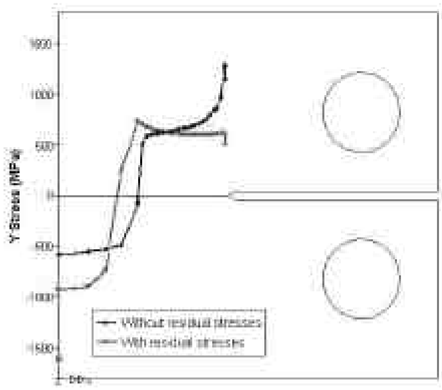


FIGURE 6 - Simulation of the Fracture Toughness Test FIGURE 7 - Stress Profiles for P=24 kN (σ_y)

5 RESIDUAL STRESS BEHAVIOR UNDER CYCLIC LOADING

The cyclic loading history, with the forces applied in the holes of the CTS, for a total number of 20 cycles and a maximum load value of 12 kN, is schematically presented in the Figure 8. The Figure 9 presents the residual stress fields in the Y direction, (σ_{yR}), at the end of 20 cycles.

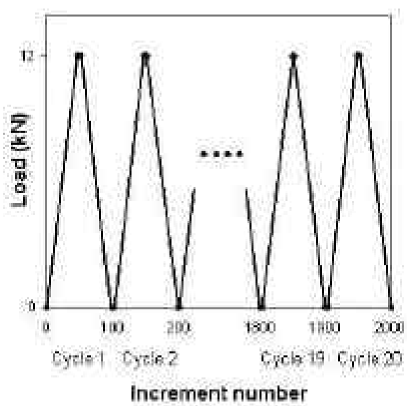


FIGURE 8 –Cyclic Loading History

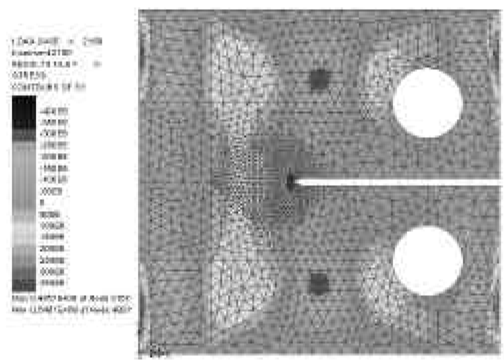


FIGURE 9 - Residual Stresses (σ_{yR}) after 20 Cycles

The evolution of the stress in an finite element adjacent to the crack tip, for the maximum and null loading values, in this case, residual stresses, during the 20 cycles of the application of the load, is presented in the Figure 10. Similarly, the Figure 11 shows the evolution of the stresses in a finite element, approximately, 6 mm from the crack tip.

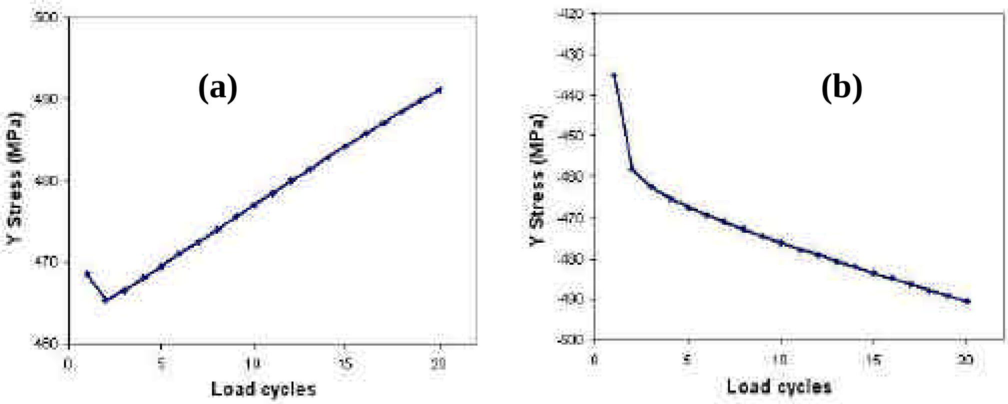


FIGURE 10 - Evolution of the Stress Levels in the Y direction, in an Adjacent Element to the crack Tip, for the Maximum Loading (a) and Null Loading (Residual Stress) (b).

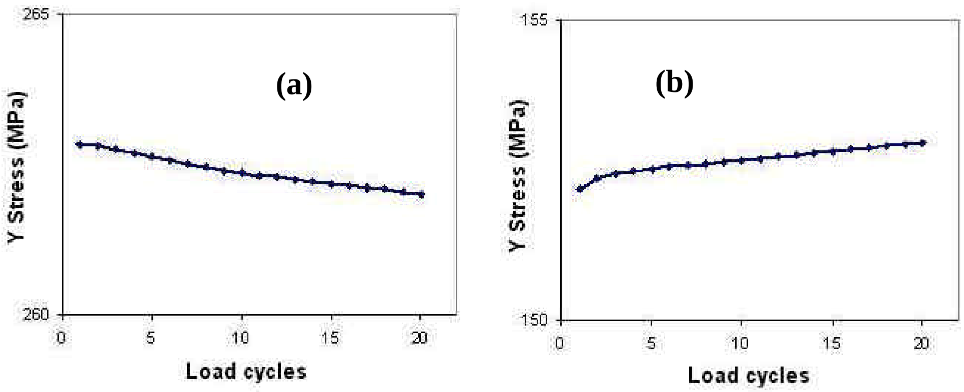


FIGURE 11 - Evolution of the Levels of stress in the Direction Y, in an Element around 6 mm distant from the crack Tip, for the maximum loading (a) and for the Null Load - residual stress (b).

6 CONCLUSION

The application and releasing of a high-intensity loads produces a residual stress field in the Y direction, whose profile along the centerline of the plate has a similar shape to those that appear in butt joints, with multiple weld passes, [1]. The reached maximum residual stress was close to ¾ of the intensity of the maximum stress that appear in butt-welded joints. The residual stresses in the others directions were not investigated, since they have little influence in the crack propagation in the CTS, [1].

The introduction of the crack produces a redistribution of the residual stresses. The stresses in the direction Y, in the crack face became null, in the vicinities of the crack tip became high-intensity compression and, at a distance larger distance from the crack tip, became traction. The simulation of the fracture toughness test, at least for the stress profiles obtained, shows that the CTS with residual stresses has better fracture behavior than the one without residual stresses.

The absolutes values of the stresses, around the crack tip, increase with the number of cycles, for the CTS with residual stresses. This phenomenon happens, even, for low intensity loads (COD < ½ CODC), inducing the fatigue fracture for smaller number of cycles that is usually expected for CTS without residual stresses. For more distant points, located inside the area of traction residual stresses, the variation happens in an opposed and weaker way.

The commercial code of finite elements LUSAS, [2], was shown appropriate for the non-linear analysis developed in this study. The use of other commercial codes did not present as good results as the ones obtained by the LUSAS.

In order to validate the numerical computational procedures, an experimental investigation is foreseen in futures studies.

REFERENCES

[1] E. Gonçalves, Analysis of Fracture Welded Structures", PhD Thesis, Massachusetts Institute of Technology, USA, 1981.

[2] LUSAS Finite Element System - Theory Manual", UGLY Ltd., Kingston upon Thames, Surrey, United Kingdom, 2000.