RESIDUAL STRESS INFLUENCE ON FATIGUE CRACK GROWTH IN FRICTION STIR WELDED ALUMINIUM ALLOY 2024-T3

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Abstract. *Alternative welding techniques, as FSW (friction stir welding), has been considered in aeronautical structures manufacturing. Aeronautical structures are designed to be damage tolerant, thus, it is necessary to develop a reliable design procedure based on fracture mechanics. It is known that welding process induces residual stresses in the structure; therefore, the primary purpose of this article is to determine whether (and why) residual stresses induced by FSW increases fatigue life of a cracked structure. To this end, it is necessary to determine stress intensity factors due to residual stresses and modify crack propagation laws so that these factors are taken into account. It is presented a numerical procedure to calculate the number of cycles until fracture using those modified crack propagation laws. In order to calculate stress intensity factors, two methods are employed in this work: finite element method and analytical solutions. The final results of fatigue life obtained using both methods are compared with each other.*

Keywords*: residual stress, friction stir welding, fatigue crack growth*

1. INTRODUCTION

Aeronautical structures are often submitted to loads that cause fatigue. Predicting durability of an aeronautical structure with cracks is important both in the project phase and maintenance phase. Several equations used to calculate fatigue crack rate propagation can be found in the literature, including the so known, and perhaps one of the simplest, Paris law. Walker equation and NASGRO equation are more indicated to model crack propagation rate in a residual stress field since they consider the stress ratio R and can be modified to consider the effective stress ratio R_{eff}.

If ΔK is low, that is to say, if ΔK is near the threshold, NASGRO equation can model properly the crack propagation rate (Harter, 2003). Modelling correctly the crack propagation rate when ΔK is low is very important to obtain accurate calculations of the number of cycles until fracture since most of the cycles the specimen can resist occurs when ΔK is low, i.e., when the crack length is short.

When the crack tip is situated in a region with residual stress, the total stress intensity factor is given by the sum of the stress intensity factor due to the external load and the stress intensity factor due to the residual stress field. Therefore, most of the effort necessary to verify the residual stress effect on the crack propagation rate is to calculate the residual stress intensity factor. To this end, two methods are employed in this paper: the weight function method and finite element method. In Bao (2010a), it is explained how to use those methods. In Bao (2010b), it is proposed a modified version of NASGRO equation, in order to take into account the residual stress effects on the crack propagation rate.

The contribution of this article is to propose a way to calculate numerically the number of cycles until fracture of a cracked specimen that has residual stresses due welding process. When using finite element method, this numerical procedure is adapted in order to reduce the number of required finite element analyses. Furthermore, this work presents reasons for the results found so that other cases (as center cracked specimens with centered residual stress field) become better understood.

2. EVALUATION OF RESIDUAL STRESS INTENSITY FACTORS USING WEIGHT FUNCTIONS

The residual stress intensity factor of a crack with length 'a' in a plate with a given geometry can be calculated by Eq. (1).

$$K_{res}(a) = \int_0^a \sigma_{res}(x)\, h(x,a)\, dx \tag{1}$$

where $\sigma_{res}(x)$ is the residual stress in the crack region as if the crack did not exist and $h(a,x)$ is the weight function that depends exclusively on the crack length and on the specimen geometry.

Bueckner (1970) has developed the weight function showed in Eq. (2) for an edge crack with length '*a*' in a specimen of width *W* and infinite height (Fig. 1).

$$h(a,x) = \frac{2}{\sqrt{2\pi(a-x)}}\left[1 - m_1\left(\frac{a-x}{a}\right) + m_2\left(\frac{a-x}{a}\right)^2\right] \tag{2}$$

where

$$m_1 = 0.6147 + 17.1844\left(a/W\right)^2 + 8.7822\left(a/W\right)^6 \tag{3}$$

$$m_2 = 0.2502 + 3.2889\left(a/W\right)^2 + 70.0444\left(a/W\right)^6 \tag{4}$$

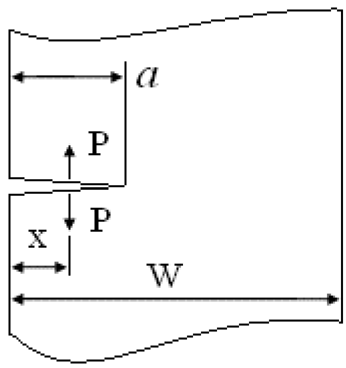

Figure 1. Edge crack in a finite width plate.

Weight functions for other geometries, for example central cracks and C(T) geometry can be found in Bao (2010a). A possible profile of residual stress can be represented by Eq. (5). This profile is plotted in Fig. 2.

$$\sigma_{yy}(x) = \sigma_{yy}^{max}.exp\left(-\frac{1}{2}\left(\frac{x-x_{peak}}{c}\right)^2\right)\left[1-\left(\frac{x-x_{peak}}{c}\right)^2\right] \tag{5}$$

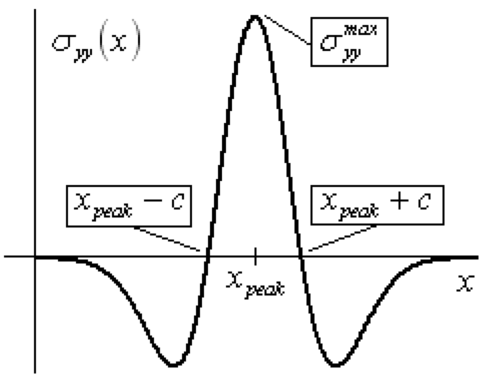

Figure 2. Residual stress profile of Eq. (5)

The weight functions found in the literature normally consider no contact between the two crack surfaces (Rooke, 1981). If the crack surface contact occurs, such functions should be modified to consider this effect. Here it is stated that the application of a minimum external traction load ensures that there is no contact between the two crack surfaces. In this case, the residual stress intensity factors calculated using weight functions become valid and can be employed to validate the procedure developed in this paper.

3. EVALUATION OF RESIDUAL STRESS INTENSITY FACTORS USING FINITE ELEMENT METHOD

In order to evaluate the fracture mechanics behaviour of typical sheets used to produce aeronautical structures, a local bidimensional analysis can be made using a plane stress finite element model. The commercial code Abaqus was used in this work to determine residual stress intensity factors and stress intensity factors due to external loads. The subroutine SIGINI was used to insert the residual stress field in the finite element model.

That subroutine allows the user to insert the residual stress field as a function of spatial coordinates or by a set of elements. Thus, one writes a file in FORTRAN language, where Eq. (5) is inserted, since it is desired to obtain a stress field as a function of coordinates. The peak position of the residual stress profile must be corrected considering the origin location of the finite elements model. For this purpose, it is added the variable x_{peak} to Eq. (5).

Table 1 shows the keywords to be added to the input file so that the subroutine SIGINI can be used.

Table 1. Keywords to be inserted in the input file. The user can choose between 'ramp' and 'step'.

*Initial conditions, type=stress, user, unbalanced stress = ramp
*Initial conditions, type=stress, user, unbalanced stress = step

If nothing is placed after the word 'user', it will be considered the option 'ramp' as default. Therefore, Abaqus always obtains the balance of internal forces in the model.

Equation (5) provides a balanced residual stress profile, since its integration gives zero as result. So if that equation is put in the subroutine file, after the analysis is finished, it will be observed the same residual stress profile which had been inserted. If an unbalanced equation (only with positive values) is put in the subroutine file, it will not be observed the same residual stress profile after the analysis is finished because Abaqus will have worked to obtain the balance of forces.

If a crack is inserted in the model crossing the residual stress profile, it will be observed a stress concentration near the crack tip. In other words, the stress field near the crack tip does not follow the equation inserted in the subroutine file because of the balance of internal forces made by Abaqus. This is showed in Fig. 3.

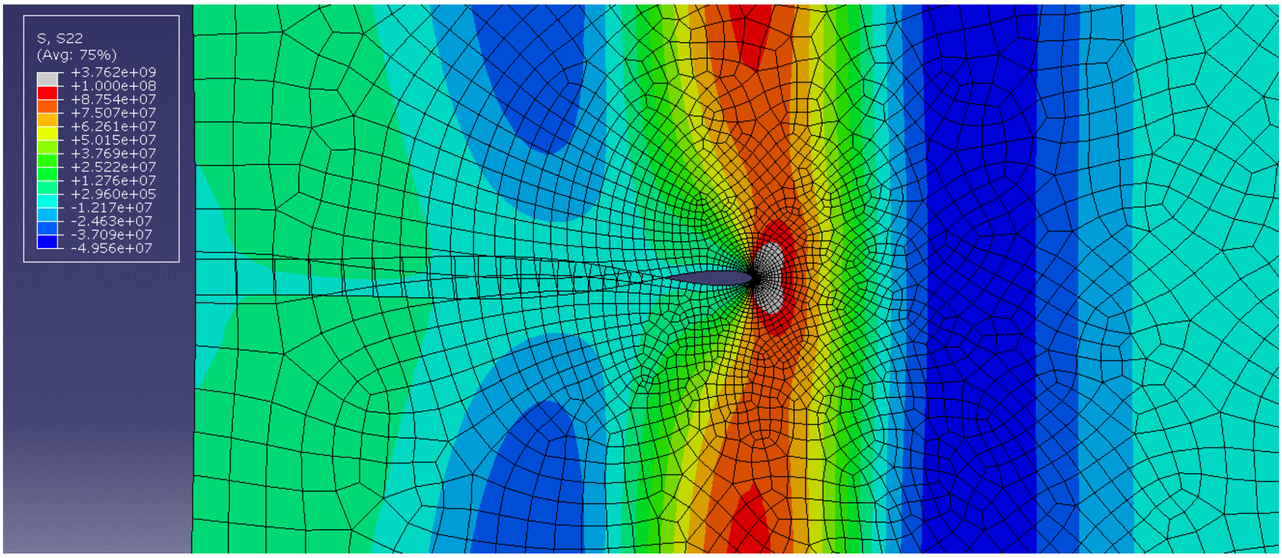

Figure 3. Residual stress field and deformed shape of the specimen without external load. Deformation scale factor: 100

Abaqus allows the insertion of cracks in the model. A special care has to be taken to create a finite element mesh near the crack tip. All the elements are quadratic rectangular. Those connected with the crack tip have a triangular shape but actually are quadratic rectangular collapsed elements with mid-nodes in the quarter point position.

As well as the weight function, the finite element model used in this work does not consider that there is contact between the two crack surfaces as it is showed in Fig. 3. Again, the application of an external traction load ensures the validity of this hypothesis.

When the total stress intensity factor is positive and the external load is not sufficient to separate the crack surfaces, a nonlinear contact problem must be modeled. When the total stress intensity factor is negative, the two crack surfaces are in contact but it is not necessary to consider a nonlinear contact problem. In this case, the total stress intensity factor is set equal to zero.

4. WALKER EQUATION

In this work, the crack propagation rate is calculated using the Walker law (FAA, 2005).

$$\frac{da}{dN} = C\left(\frac{\Delta K}{(1-R)^{1-m}}\right)^n \tag{6}$$

According to Parker (1982), the following criteria must be used to determinate ΔK, since it does not exist negative values for stress intensity factors when the Walker equation is employed (it is considered that the crack propagates only with the positive part of the external cyclical load).

$$\Delta K = K_{max} - K_{min} \quad \text{if} \quad K_{min} > 0 \tag{7}$$

$$\Delta K = K_{max} \quad \text{if} \quad K_{min} \le 0 \tag{8}$$

Furthermore, the following criteria must be adopted to determinate the stress ratio R (Parker, 1982):

$$R = K_{min} / K_{max} \quad \text{if} \quad K_{min} > 0 \tag{9}$$

$$R = 0 \quad \text{if} \quad K_{min} \le 0 \tag{10}$$

There are equations that admit negative stress ratio, for example the so called NASGRO equation (Bao, 2010b). In this case, crack closure effect is considered. This effect is not the focus of this article and it is not considered here.

When there are residual stresses, the superposition principle (Anderson, 2005) can be used to find the total stress intensity factor that is equal to the sum of stress intensity factor due to the external load (K_{app}) and the stress intensity factor due to the residual stresses (K_{res}).

$$K_{tot} = K_{res} + K_{app} \tag{11}$$

In this case, the following criteria must be adopted to calculate ΔK and the effective stress ratio R (Parker, 1982):

$$\Delta K = K_{app}^{max} - K_{app}^{min} \quad \text{and} \quad R_{eff} = \frac{K_{app}^{min} + K_{res}}{K_{app}^{max} + K_{res}} \quad \text{if} \quad K_{total}^{min} = K_{app}^{min} + K_{res} > 0 \tag{12}$$

$$\Delta K = K_{app}^{max} + K_{res} \quad \text{and} \quad R_{eff} = 0 \quad \text{if} \quad K_{total}^{min} = K_{app}^{min} + K_{res} \le 0 \tag{13}$$

The residual stress intensity factor can assume negative values and that makes a physical sense. However, the total stress intensity factor has to assume values higher or equal to zero. It could assume negative values only if it is considered crack closure effects.

5. NUMERICAL SOLUTION OF WALKER EQUATION

The numerical solution of Walker law consists in calculating stress intensity factors to a given crack length (using analytical solutions or finite elements) and then obtain the number of cycles ΔN corresponding to a given crack length increment Δa. This procedure is repeated several times, one to each iteration. It is a 'remeshing' technique of a crack propagation analysis when it is used the finite element method to determinate stress intensity factors. This technique is described with a flowchart in Fig. 4.

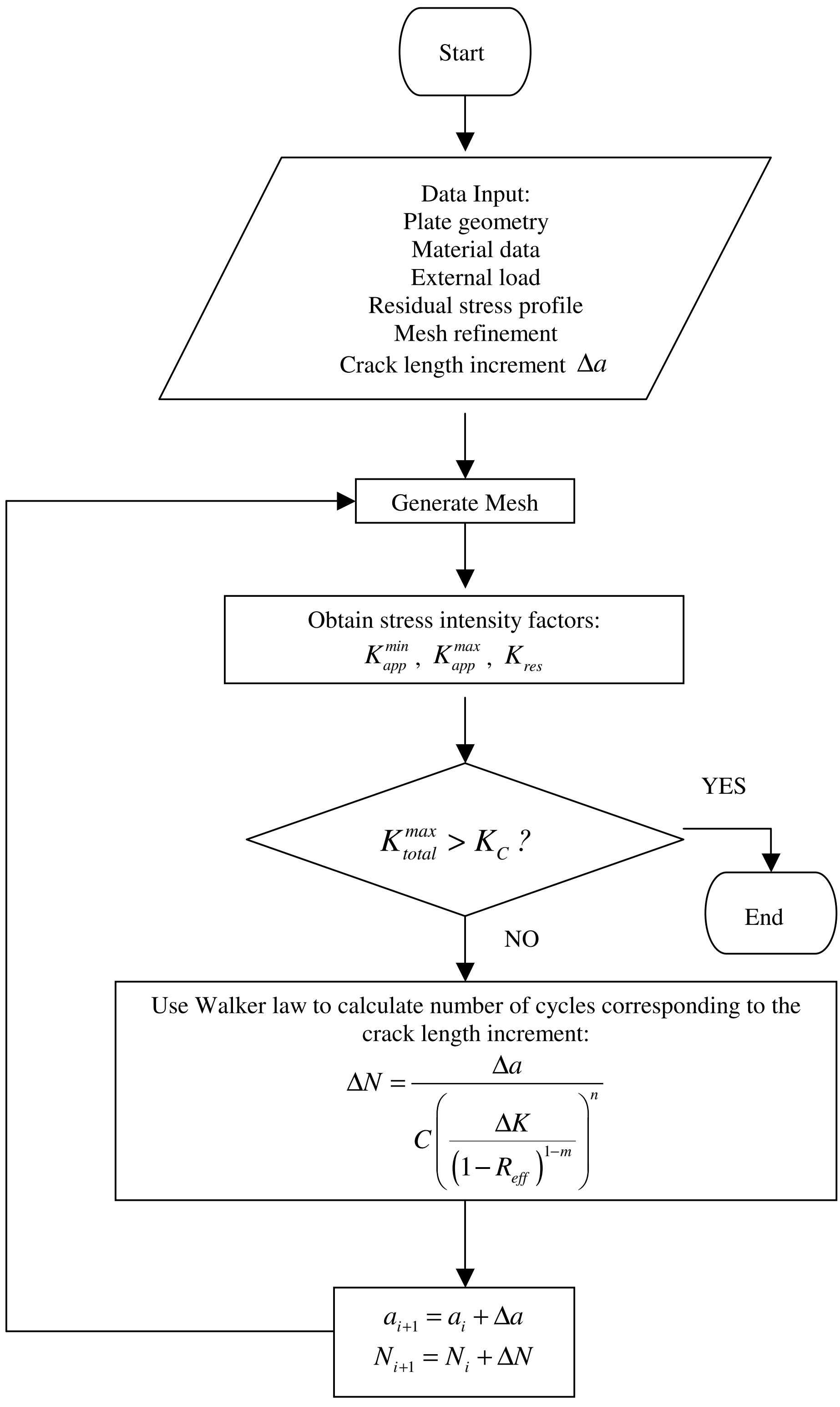

Figure 4. Flowchart of the script made to simulate the crack propagation

6. EDGE CRACK PROPAGATION IN A RETANGULAR SPECIMEN USING FINITE ELEMENTS

It is considered a plate with 1.5 m wide and 3.0 m high. It has an edge crack of initial length 0.015 m. As the crack propagates, it reaches a region where there is a residual stress field due the friction stir welding. The residual stress profile considered can be found in Ge (2006) and it is modelled in this work using Eq. (5), proposed by Bao (2010a). The specimen used by Ge (2006) has 6.3 mm of thickness.

The considered parameters to Eq. (5) are c = 0.03 m, x_{peak} = 0.130 m and σ_{yy}^{max} = 100 MPa. Such parameters generate the residual stress profile of Fig. 5.

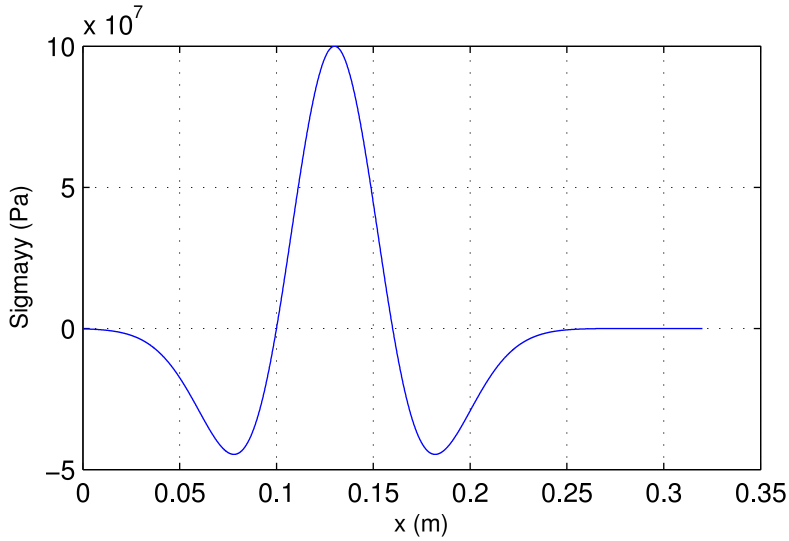

Figure 5: Residual stress σ_{yy} of the considered specimen. The origin is where the crack initiates.

Using Abaqus, it is desired to obtain residual stress intensity factors for several lengths of the crack that propagates through the residual stress field. Such task would need too much effort if it had to be done manually. Thus, it is written a script in python language so that the task is automated.

The script makes Abaqus calculate residual stress intensity factors to several crack lengths ranging from 0.015 m to 0.319 m (a little after the fracture toughness is reached), with increments Δa of 0.001 m.

The same analysis is done using the weight function of Eq. (2). The integrations are done numerically using adaptive Simpson quadrature in Matlab. The Abaqus results are compared with those obtained using weight functions in Fig. 6. The plot shows only until the critical crack length (under the conditions of external load described later).

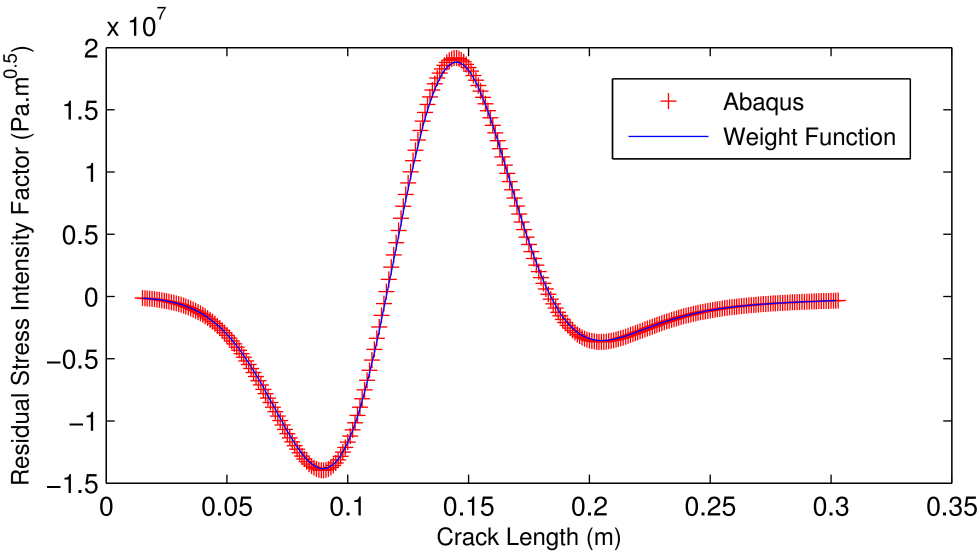

Figure 6: Residual stress intensity factor as function of the crack length.

The same script in python is used to calculate maximum and minimum stress intensity factors due external cyclical load. The maximum K_{total} (showed in Fig. 7) is given by the sum of the residual stress intensity factor and the maximum stress intensity factor due to external load.

As it can be found in Dowling (1999), the Walker law parameters and the fracture toughness under plane strain of 2024-T3 aluminium alloy are C = 1.42.10^{-8}, n = 3.59, m = 0.68 and K_{IC} = 34 MPa.m$^{0.5}$. That value for C parameter is valid if the unit of the stress intensity factor is MPa.m$^{0.5}$ and the crack propagation rate is mm/cycle.

According to FAA (2005), the fracture toughness under plane stress of aluminium alloy 2024-T3 in L-T orientation and with 0.00254 m of thickness is 80 MPa.m$^{0.5}$. This value is used as failure criterion in this article.

Other data needed to the analysis such as the modulus of elasticity and Poisson coefficient can be obtained in the site Matweb (2011). Their values are ν = 0.33 and E = 73.1 GPa.

It is considered an external cyclical load that oscillates between 30 MPa and 60 MPa. These are levels of load sufficient to ensure that there is no contact between the crack surfaces at any moment during the crack propagation. This avoids the need to solve a nonlinear contact problem in this work.

For the conditions above described, employing the flowchart of Fig. 4, it is concluded that the effect of the residual stress field is good to fatigue life of the specimen. Without residual stress, the specimen resists 410479 cycles of load. The critical crack length is 0.301 m. With residual stress, the specimen resists 451063 cycles and the critical crack length is 0.303 m.

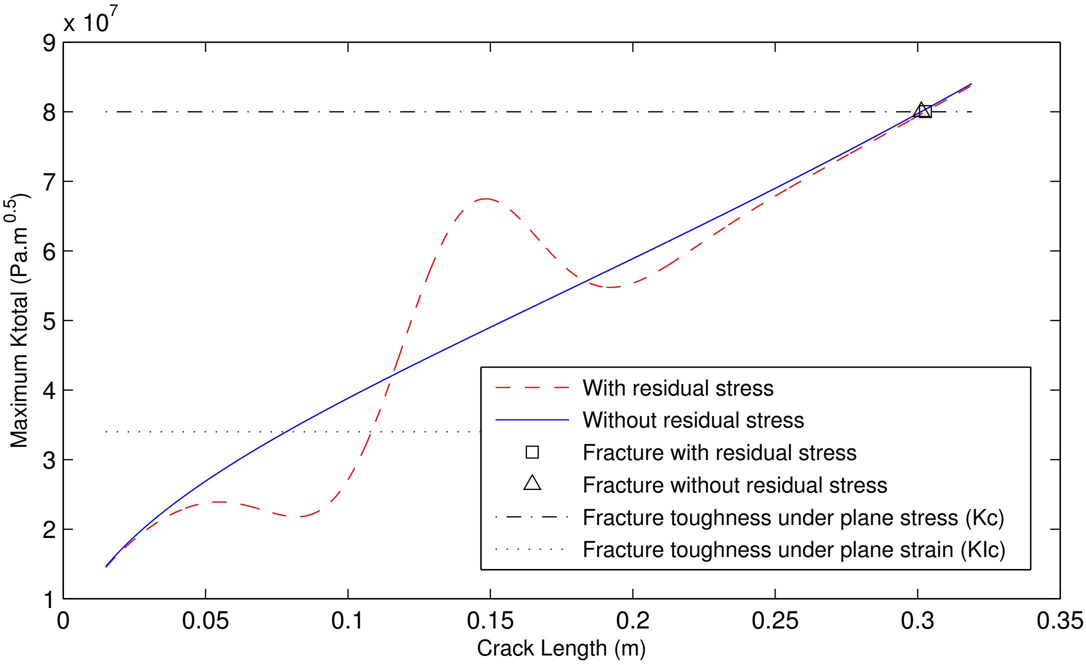

Figure 7. Maximum total stress intensity factor as function of the crack length

Figure 7 shows that the fracture toughness under plane stress is reached almost at the same crack length for both cases: with residual stress and without residual stress. It would be visibly different if the specimen was thick and it was considered plane strain.

Analyzing Fig. 8 it is concluded that the effect of the compressive residual stress is more important than the effect of the traction residual stress since the crack tip has crossed the whole residual stress field and the number of cycles to a given crack length was always higher in the case with residual stress.

Until the crack length reaches 0.116 m, the crack is under the effect of the compressive part of the residual stress field. Thus, the crack propagation rate is lower in this region (see Fig. 9). Since the crack propagation rate is still low, the ΔN found in Fig. 10 are high and any change on the crack propagation rate causes important changes on ΔN. As each ΔN is added to the previous results to find the total number of cycles until the crack length reaches certain value, the final effect is a great increase on the number of cycles until the crack length reaches 0.116 m.

When the crack length is between 0.116 m and 0.183 m, the crack propagation rate under the presence of residual stress is higher than in the case without residual stress. Here, the values of the crack propagation rate are high already and the values of ΔN are low. Consequently, after the crack length has surpassed 0.116 m, changes on the crack propagation rate does not cause significant changes on ΔN, neither on the final number of cycles.

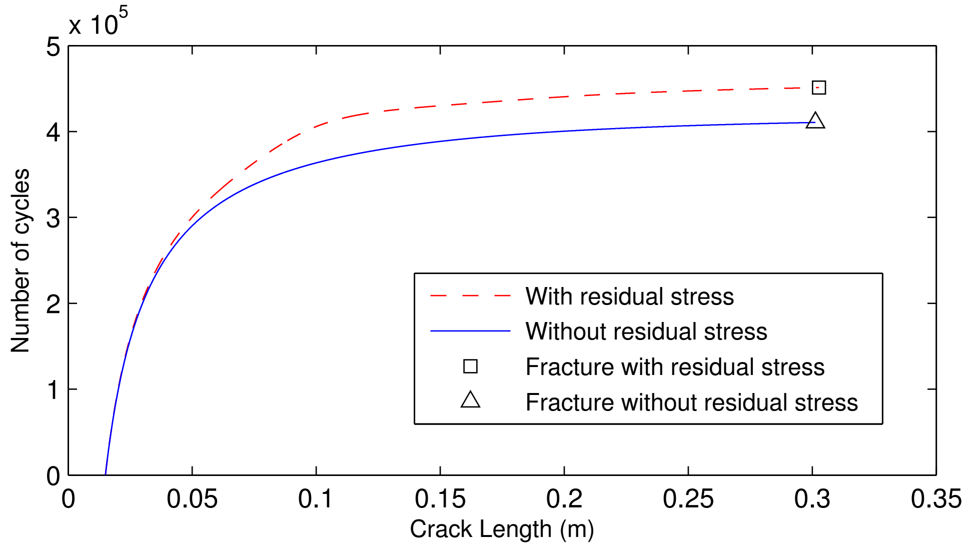

Figure 8. Number of cycles as function of the crack length

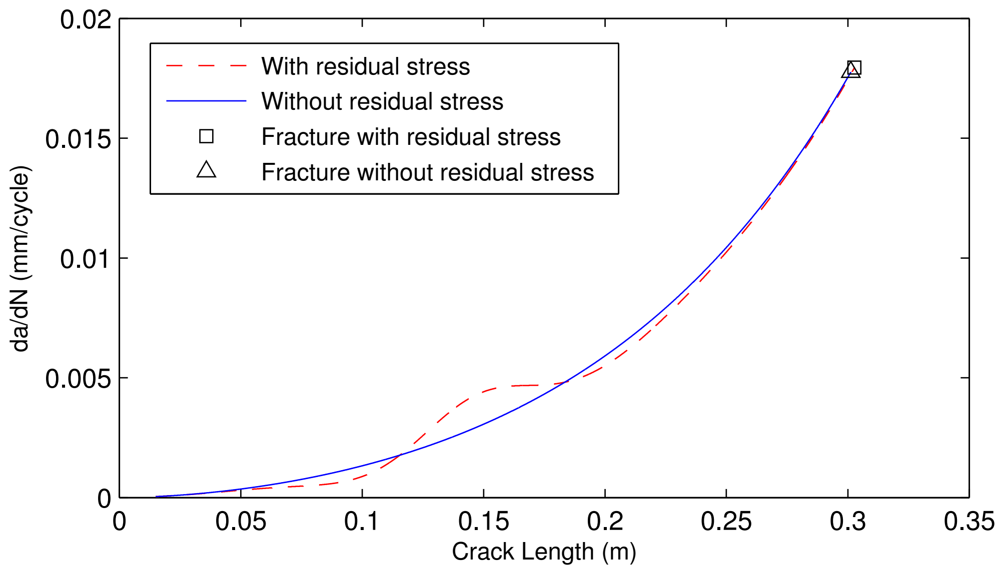

Figure 9. Crack propagation rate as function of the crack length

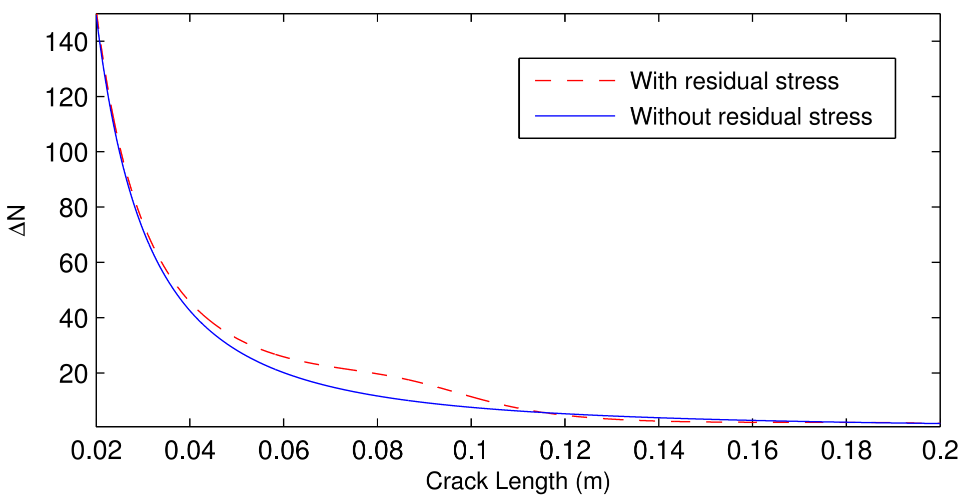

Figure 10. ΔN corresponding to a crack length increment Δa = 0.00001 m

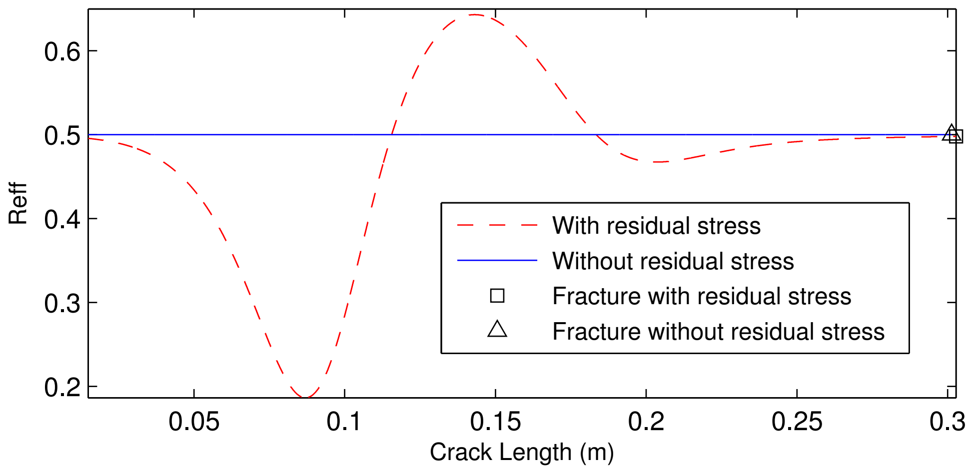

Figure 11. Effective stress ratio R_{eff} as function of the crack length

Figure 11 shows the changes on the effective stress ratio due to the residual stresses. Since R_{eff} changes under the presence of residual stresses, da/dN also changes.

7. CONVERGENCE STUDY USING ANALYTICAL EQUATIONS

In order to predict fatigue life of an edge cracked rectangular specimen using only analytical equations, Eq. (14) and (15) are required to calculate the stress intensity factor due to the external load. They can be found in Tada (2000).

$$K_I = \sigma_{ext}\sqrt{\pi a}F(a/W) \tag{14}$$

$$F(a/W) = \sqrt{\frac{2W}{\pi a}tan\left(\frac{\pi a}{2W}\right)}.\frac{0.752+2.02(a/W)+0.37\left(1-sin\left(\frac{\pi a}{2W}\right)\right)^3}{cos\left(\frac{\pi a}{2W}\right)} \tag{15}$$

The results provided by these equations are in good accordance with those obtained by Abaqus.

The flowchart of Fig. 4 has been implemented twice in MATLAB. One time using analytical solutions of the stress intensity factors and another time using the solutions obtained with Abaqus.

Table 2 shows the convergence of the results as the crack length increment is reduced.

Table 2. Number of cycles until fracture calculated using analytical solutions of the stress intensity factors and using finite element method.

	Number of Cycles			
	Employing analytical solutions of the stress intensity factors		Employing finite elements to obtain stress intensity factors	
Crack length increment Δa [m]	Without residual stress	With residual stress	Without residual stress	With residual stress
0.001	417729	456495	423240	463950
0.0001	406241	444898	***411656***	***452327***
0.00001	405114	443761	***410586***	***451177***
0.000001	405002	443647	***410479***	***451063***

Since the model has large dimensions, the number of elements is about 90000. Reducing the crack length increment in the script made for Abaqus makes the analyses spend too much time. Consequently, it is not feasible to calculate stress intensity factors using very small crack length increments Δa when finite elements are employed. If it is intended to use the flowchart of Fig. 4 to predict the number of cycles until fracture and the finite element method to calculate stress intensity factors, it is recommended to obtain more values of stress intensity factors using quadratic interpolation between every three points (see Fig. 6, it has about 300 points when Δa is 0.001 m). The values in bold in Tab. 2 are obtained using this technique of interpolation. Figures 7, 8, 9, 10 and 11 are obtained using the same technique with an artificial crack length increment of 0.00001 m.

8. CONCLUSIONS

Subroutine SIGINI of Abaqus can be employed to insert a residual stress field in a finite element model of a cracked specimen welded by FSW process. This procedure allows obtaining residual stress intensity factors with good precision when the results are compared with those obtained by weight functions.

It has been presented a numerical procedure to calculate the number of cycles until fracture of a specimen with a crack that propagates through the residual stress field. The results are compared with the case in which there is no residual stress. It is concluded that the residual stress field is good to fatigue life because the effect of the compressive residual stress is more important than the effect of the traction residual stress. The reasons presented for this conclusion suggest that it would be different in the case where the crack initiates in the middle (that is to say, in the positive part) of the residual stress profile.

The critical crack length does not change with the residual stress since the crack tip had already crossed the whole residual stress region when the total stress intensity factor reached the plane stress fracture toughness. Different critical crack lengths would be found if the fracture toughness was lower or the external load was higher.

One of the advantages of employing the finite element method to calculate stress intensity factors consists in the possibility of observing if there is contact between the two crack surfaces. If there is, the finite element method could be employed to model a non linear contact problem between the crack surfaces. Another advantage appears in the case where a central crack propagates through a residual stress field which is not in the centre line of the plate. In this case, there is no weight function to calculate two different residual stress intensity factors, one to each crack tip. The finite element method can handle this case successfully.

Finally, it is verified the effectiveness of a way to artificially reduce the crack length increment when the finite element method is employed to calculate stress intensity factors.

9. ACKNOWLEDGEMENTS

The authors are grateful to Embraer's FSW research group, especially to Fernando Ferreira Fernandez, Andreza Sommerauer Franchim and Marcos Hideki Miyazaki for the technical and financial support, and to University of Campinas - UNICAMP, the institute where this work has been developed.

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