Modelling Residual Strength of Friction Stir Welded Panels by means of Crack Tip Opening Angle (CTOA)

A. Pirondi

Dept. of Industrial Engineering, University of Parma, v.le G.P. Usberti, 181/A, 43100
Parma, Italy

alessandro.pirondi@unipr.it

ABSTRACT. *The objective of this work is to assess numerically the strength of cracked flat friction stir welded panels for aerospace applications, on the basis of simple experiments made on small coupons of material (Kahn Tear Test). The transferability from a geometry to another, in particular the results obtained from Kahn tear tests to the prediction of the R-curve of cracked FSW M(T) panels is performed using the Crack Tip Opening Angle (CTOA). The Kahn Tear Test is reproduced first by means of finite element analysis using a debond procedure based on the attainment of a critical CTOA as a function of crack length. The CTOA extracted from Kahn tests is then used to simulate the R- curve of M(T) panels of different widths. The material considered here is a 6013-T6 aluminum alloy. Two series of values of CTOA are determined: i) considering the material as homogeneous with strength equal to that of the parent material; ii) introducing different strengths locally for the weld TMAZ/HAZ and nugget.*

INTRODUCTION

Light-weight, thin-walled structures used in the aerospace industry are subjected to a complex, time- and cost-consuming validation process, of which the certification of residual strength in the presence of a crack is an important part. Unfortunately, the combination of thickness, yield strength and fracture toughness is generally such that large plasticity develops at the crack tip and, therefore, the stress intensity factor K can no longer describe correctly the fracture process. For this motivation the crack growth in thin metallic structures has been extensively studied in the last decades by means of elastoplastic fracture mechanics (EPFM) and several criteria like J-integral, crack tip opening displacement (CTOD), crack tip opening angle (CTOA) and K_{eff} have been proposed. Among these, CTOA or CTOD at a certain distance behind the crack tip show little, if null, geometry dependence and therefore are suitable for a single-parameter representation of crack resistance and stability under large plastic yielding and extensive crack growth [1].

In a CTOA analysis, it is assumed that the near-tip displacement field is characterized by a specific angle that can be used as a fracture criterion. Using 2-D plane stress or plane strain finite element analysis several authors [2-4] showed that in the early stages of crack growth the CTOA is higher than the value needed in the following steady-state crack growth. This condition is reached after a small amount of crack growth which is generally equal to one to two times the thickness. However, using a constant CTOA Newman [5] modeled crack initiation, crack growth and instability in three different geometries with results very close to the experiments.

Later, several works by Newman, Dawicke et al., reviewed in [1], showed that a constant CTOA can properly model the fracture process if the correct constraint is modeled at the crack tip. For this reason, a 3D FE analysis is better suited, but also 2D analyses with a plain strain core in the crack region and plane stress elements elsewhere can be an acceptable compromise between accuracy and modelling complexity, provided the plane strain core addresses the high constraint around the crack tip. A height of the PSC equal to thickness seems to be a reasonable compromise [1]. The plane stress condition away from the crack region allows a proper modelling of yielding.

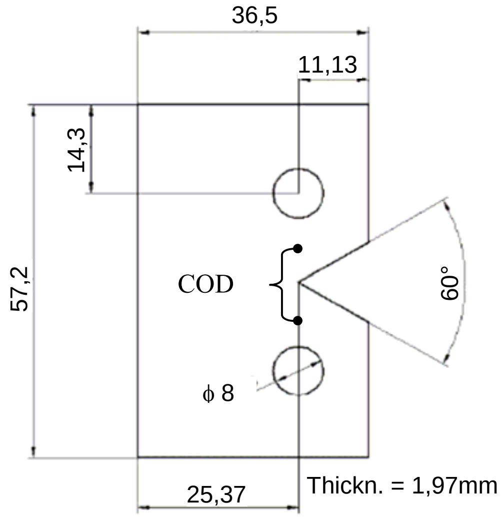
The objective of this work is to assess numerically the strength of cracked flat integral panels manufactured by Friction Stir Welding (FSW), on the basis of simple experiments made on small coupons of material (Kahn Tear Test). The transferability from a geometry to another, in particular of the results obtained from Kahn tear tests to M(T) panels is performed using the Crack Tip Opening Angle (CTOA). The Kahn Tear Test is reproduced first by means of finite element analysis using a debond procedure based on the attainment of a critical CTOA as a function of crack length. The CTOA extracted from Kahn tests is then used to simulate the R- curve of M(T) panels of different widths. The material considered here is a 6013-T6 aluminum alloy. Two series of values of CTOA are determined: i) considering the material as homogeneous with strength equal to that of the parent material; ii) introducing different strengths locally for the weld TMAZ/HAZ and nugget.

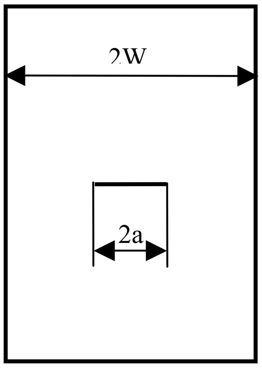
It is worth to underline that the Kahn specimens used in this work were not precracked, therefore the tests were not in agreement with the size requirements set by ASTM [6]. On the other hand, the possibility of using very simple and cheap tests to gain informations about fracture strength can be very important from an industrial standpoint.

TESTING

The material is 6013, a medium strength aluminium alloy commonly used in shipbuilding, automotive and light-weight constructions in general. Although less strong than other aluminium alloys for aerospace applications such as 2XXX series, 6013 is a potential candidate for manufacturing aerospace integral structures due to its good weldability. Concerning specimens considered in this work, Kahn tear specimens were machined out of butt-FSW panels manufactured at EADS Innovation Works in

Munich/Ottobrunn (D), where the tear tests were also performed. M(T) panels 750mm wide were also friction stir welded and tested at EADS Innovation Works, but in this case the experiments were reported in [7]. Finally, 160mm-wide M(T) FSW panels were developed and tested at DLR, Cologne (D), and the experimental data are reported in [8]. It is worth to remark that welding was performed in the T6 condition with no post-welding heat treatment. All of the geometries are reported in Fig. 1. The weld nugget and TMAZ therefore, correspond approximately to a T4 conditions, leading to an undermatched weld.





Dimension	Small M(T)	Large M(T)
2W	160	750
$2a_0$	48	252
B	4.0	2.2*

*socket thickness; sheet thickness = 2mm

Fig.1: geometry of Kahn (left) and M(T) (right) specimens considered in this work.

The stress-strain behaviour of parent material was supplied by EADS CRC, while local tensile properties were measured in [7] on miniaturized specimens extracted from the nugget and the TMAZ/HAZ. The various curves are shown together in Fig. 2.

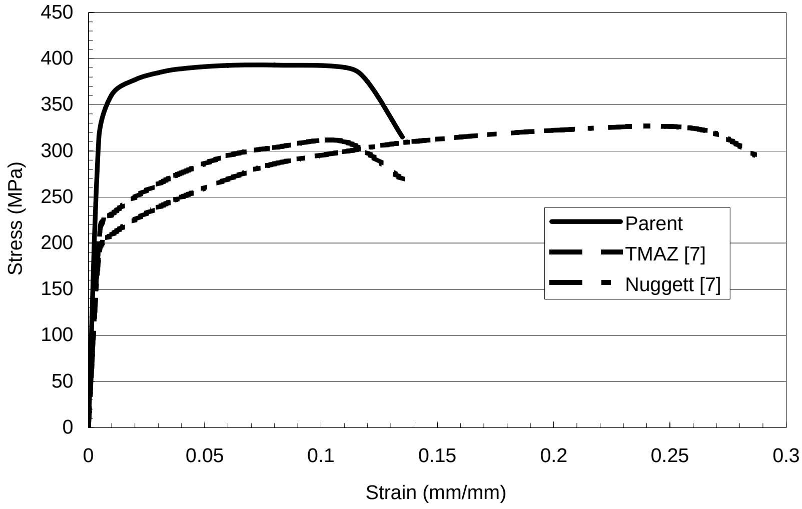


Fig. 2: tensile behavior of the parent and weld materials.

MODELING

Only one half of the Kahn specimen was modeled because of the symmetry with respect to the crack plane. The crosshead displacement of the test machine was transferred to the specimen modeling a rigid pin in contact with the hole contour. In the case of the M(T) panel, only one quarter was modeled and the crosshead displacement was applied directly to the boundary. Crack growth was simulated by means of the *DEBOND option of the FE code Abaqus®. A detailed description and validation of the procedure can be found in [9].

In the case of the simulations with local weld strengths, parent, TMAZ and nugget tensile behavior were assigned to different FE model regions according to the extension evaluated in [7, 8] by means of microhardness measurements and metallographic analysis. The nugget extended for +/- 3mm across the weld centreline, while the TMAZ was concentrated from 5 to 7mm from the centreline, with a very little difference between the various thicknesses of the plates. The crack was placed along the centreline as in the experiments.

RESULTS AND DISCUSSION

Tuning of CTOA

The CTOA has been tuned by trial-and-error on Kahn tear test until a good agreement between simulation and experiments was found. The results of CTOA tuning are summarized in Figs. 3 and 4. The values to be adopted in the homogenous case are consistently lower than in non-homogenous one, as it could be expected from the difference in strength and ductility between parent and weld nugget materials. It is also of interest that in the homogenous, parent strength case, the CTOA increases in the first millimeters then decreases. This occurs also when the local weld strength is used, although in this case it is relatively less evident due to very high initial value. A steady-state value is attained after a small amount of crack propagation comparable to the specimen thickness. This steady-state CTOA is in agreement with those reported in [1] for aluminum alloys.

Simulation of FSW M(T) panels

The results of the application of the CTOA determined in the previous section are shown in Figs. 5 and 6. Both in the case of the 160mm-wide and the 750mm-wide specimens the results of the model with local weld strength and related CTOA is very close to the experiment and works much better than the homogenous model with parent material strength.

Looking at Fig. 5, the slopes of the simulated R-curves long-propagation are very similar after a few millimetres of crack growth, while the difference is played entirely in the first steps where the use of local weld strength allows to model the initial steep raise of the R-curve. In this case the homogenous model with parent material strength underestimates the resistance curve

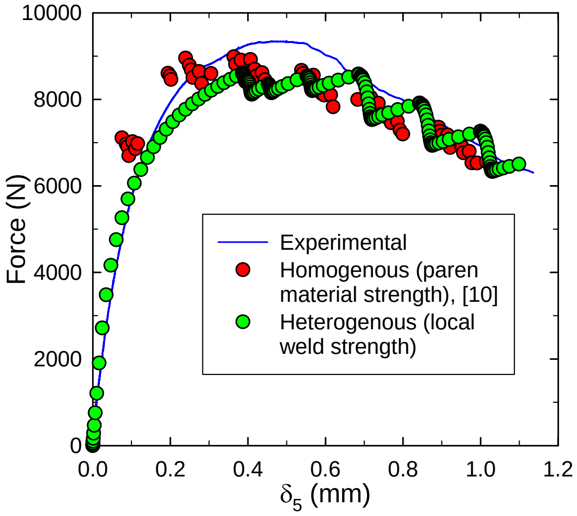


Fig. 3: calibration of CTOA by comparison. of FEM and experiment - Kahn tear test.

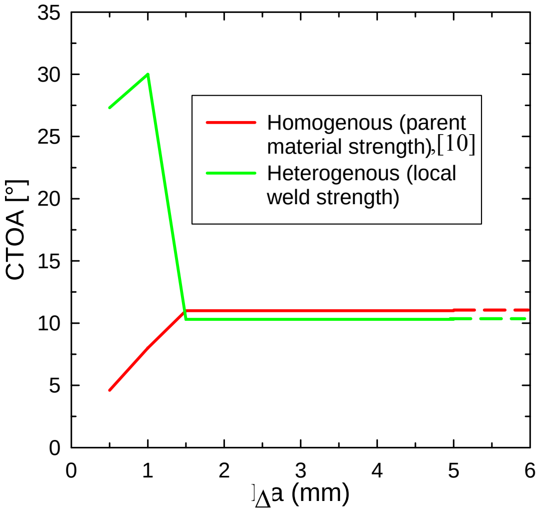


Fig. 4: values of CTOA calibrated on Kahn tear test.

In the case of the 750mm-wide specimen the situation is the opposite that is the homogenous model overestimates the R-curve. This is due to the different representation of crack growth given in the two diagrams. In Fig. 5 the x-axis reports the real crack propagation because the dimensions of the specimen were too small to use the effective crack propagation [11], used instead in Fig. 8:

$$\Delta a_{eff} = \Delta a + \frac{1}{2\pi}\left(\frac{K}{\sigma_y}\right)^2 \qquad (1)$$

The good correlation between the FE model with local weld strength and the experiment shown in Fig. 6 is obtained using the σ_y =205MPa which is an average of the yield strength of nuggett and TMAZ measured in [7]. The point of crack instability in the experiments corresponds to 5-9mm of real crack propagation which is also well-matched by the experiments (Δa=6mm).

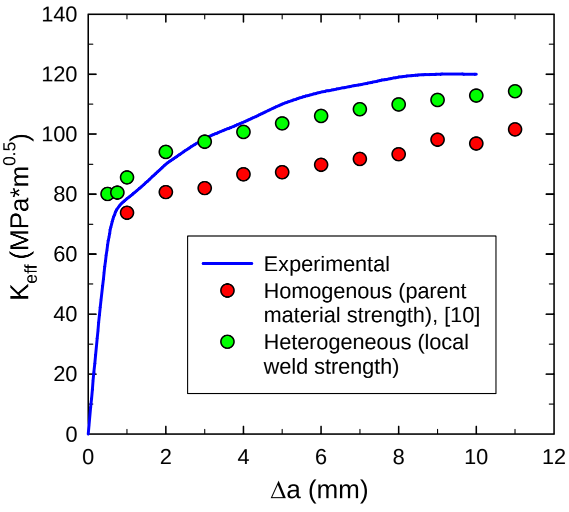


Fig. 5: comparison FEM-experiment, M(T) specimen, 2W=160mm.

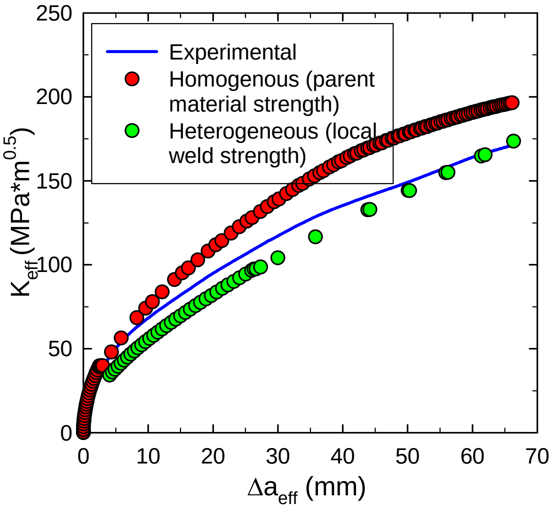


Fig. 6: comparison FEM-experiment, M(T) specimen, 2W=750mm.

PLASTIC DEFORMATION AND CRACK PATH

The experiments [7, 8] recorded generally an instability of the crack path of the kind shown in Fig. 7. After a few millimeters of propagation the crack jumps suddenly in the TMAZ, characterized by a lower strength and fracture toughness [7].

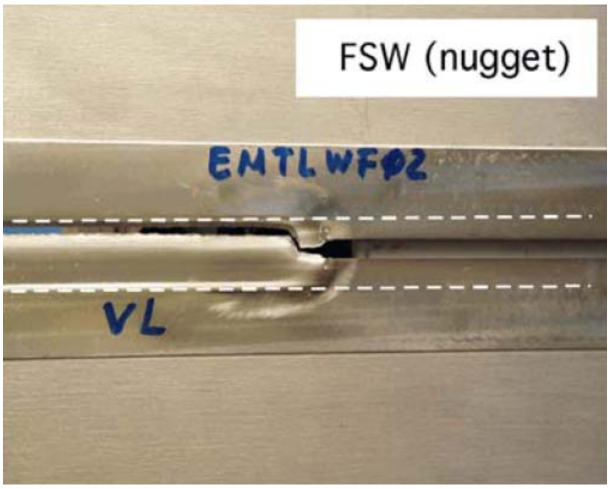


Fig. 7: experimental crack path, [7].

From the optical strain measurements done with the ARAMIS system [7] the instant of fracture instability corresponds to point 5 in Fig. 8, where te plastic zone has spread into the TMAZ and the value of strain is equal or higher than the point at which necking occurs in tensile loading (about 10%, see Fig. 2).

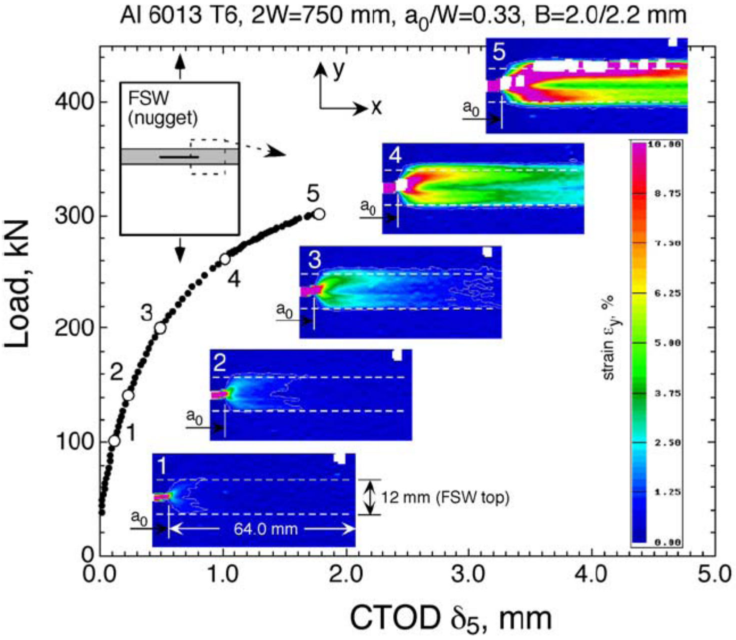


Fig. 8: experimental strain measurement at the crack tip with the ARAMIS system, [7].

The same instant is taken in the FE analysis, Fig. 9, where all the regions that undergo an equivalent plastic strain above 10% are colored in gray (elastic strain is negligible). Despite the coarseness of the mesh which was not generated to examine crack tip stress-strain field in detail, it can be seen that the threshold of 10% has just been attained in the TMAZ. Therefore, even though this kind of modelling does not consider crack path jumps, the conditions for such kind of crack instability can be roughly determined from the examination of the strain field, provided that local weld strength is introduced.

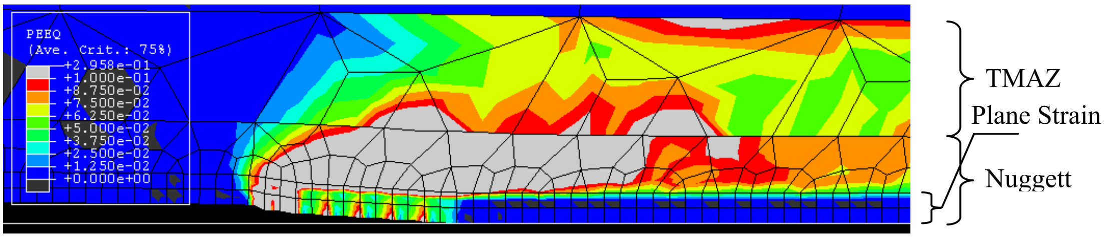


Fig. 9: equivalent plastic strain at the instant of crack jump in the TMAZ in the experiments.

CONCLUSIONS

The objective of this work was to assess numerically the strength of cracked flat integral panels manufactured by Friction Stir Welding (FSW), on the basis of simple experiments made on small coupons of material (Kahn Tear Test). The transferability from a geometry to another, in particular of the results obtained from Kahn tear tests to M(T) panels was performed using the Crack Tip Opening Angle (CTOA).
The introduction of local weld strength improved notably the agreement between FE analysis and experiments with respect to the case where the parent material strength was used for the whole model. Additionally, with local modeling it was also possible to draw some conclusions about the crack path instability.

ACKNOWLEDGEMENTS

This work has been done thanks to the contract between University of Parma-Dept. of Industrial Engineering and EADS Innovation Works, Munich/Ottobrunn (D), on "Damage tolerance of aerospace structures”.

REFERENCES

1. Newman Jr JC. James MA, Zerbst U. (2003) *Eng. Fract. Mech.* **70**, 371-385.
2. Shih CF, De Lorenzi HG, Andrews WR. (1979) *ASTM STP 668*, American Society for Testing and Materials, 65-120.
3. Kanninen MF, Rybicki EF, Stonesifer RB, Broek D, Rosenfield AR, Nalin GT. (1979) *ASTM STP 668*, American Society for Testing and Materials, 121-150.
4. Brocks W, Yuan H. (1991). In: *Defect assessment in component fundamentals and Applications*. pp. 19-33, ESIS publications 9.
5. Newman Jr JC. (1984) *ASTM STP 833*, American Society for Testing and Materials, 93-117.
6. ASTM E 2472-06 (2007). *Annual Book of ASTM Standards, Vol. 03.01*. American Society for Testing and Materials, West Conshohocken, PA, USA.
7. Seib E. (2005). PhD Thesis, TU Hamburg-Harburg (D).
8. Juričić C, Dalle Donne C, Dreßler U. (2001) In: 3rd International Symposium on Friction Stir Welding, Kobe, Japan.
9. Pirondi A, Fersini D. (2009) *Eng. Fract. Mech.* **76**, 88-100.