

Crack propagation in Multi Site Damage conditions for a riveted joint

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An MSD crack growth simulation is presented, carried out by means of a Boundary Element code (BEASY), for a two-dimensional analysis of a cracked butt-joint. An equivalent 2D crack length is proposed for an approximated 2D analysis of a 3D problem (part elliptical crack front). The aim of this work is to validate such assumptions by comparing the numerical results with the experimental data, obtained from a fatigue tested riveted butt-joint of aluminum 2024 T3.

1. INTRODUCTION

In this work an MSD crack growth simulation is presented, carried out by means of a Boundary Element (BE) code in a two-dimensional analysis of a butt-joint undergoing a traction fatigue load. The 2D model represents just an approximation of the real phenomena because of the secondary bending effects which are illustrated in Figg. 1a-b (with reference to a lap-joint, but the phenomenon is completely equivalent for a butt-joint) and which are responsible for a non-straight crack propagating front. But, this drawback can be circumvented by adopting an equivalent straight initial crack front as explained in the following.

For the crack propagation the well-known Paris law is adopted: $\frac{da}{dN} = C\Delta K^n$, with $n=2.144$ and $C=4.72*10^{-10}$ (the fracture mechanics parameter C and n for the alluminum 2024T3 are provided by the experimenter), $\Delta K = \Delta K_{eff} = \Delta K_I^2 + 2\Delta K_{II}^2$ (Tanaka formula) expressed in $\text{MPa}\sqrt{\text{mm}}$ and da in mm. It has been checked that, during the propagation, the SIF's range was included in the interval of validity of Paris law, by skipping the very initial crack growth (all the cracks start with a minimum initial length) because of the threshold phenomenon and the final crack growth (by means of a link-up condition), which is dominated by very high growth rates when $K_{MAX}=K_C$ (K_C is the material toughness). The specimen modelled is representative of the riveted joint existing between the upper shell and the lower shell on the front fuselage section, manufactured for the Dornier Do328 aircraft. It is designed and loaded in the experimental tests, in such a way to reproduce, as close as possible, the real in-service stress-strain state.

2. PROBLEM DESCRIPTION

The butt-joint on which the crack growth analysis is performed is illustrated in Fig.2; the applied fatigue load is a longitudinal traction whose amplitude is $t=100$ Mpa. The material properties are: Young modulus $E=72500$ MPa and Poisson ratio $\nu = .33$. The rivet pitch is $p=20$ mm. In the BE model a convergence analysis was performed on SIF's values, in order to calibrate the model and in particular to decide how many pins it was necessary to explicitly model, rather than just introducing longitudinal constraints on 180 degrees of the hole boundary.

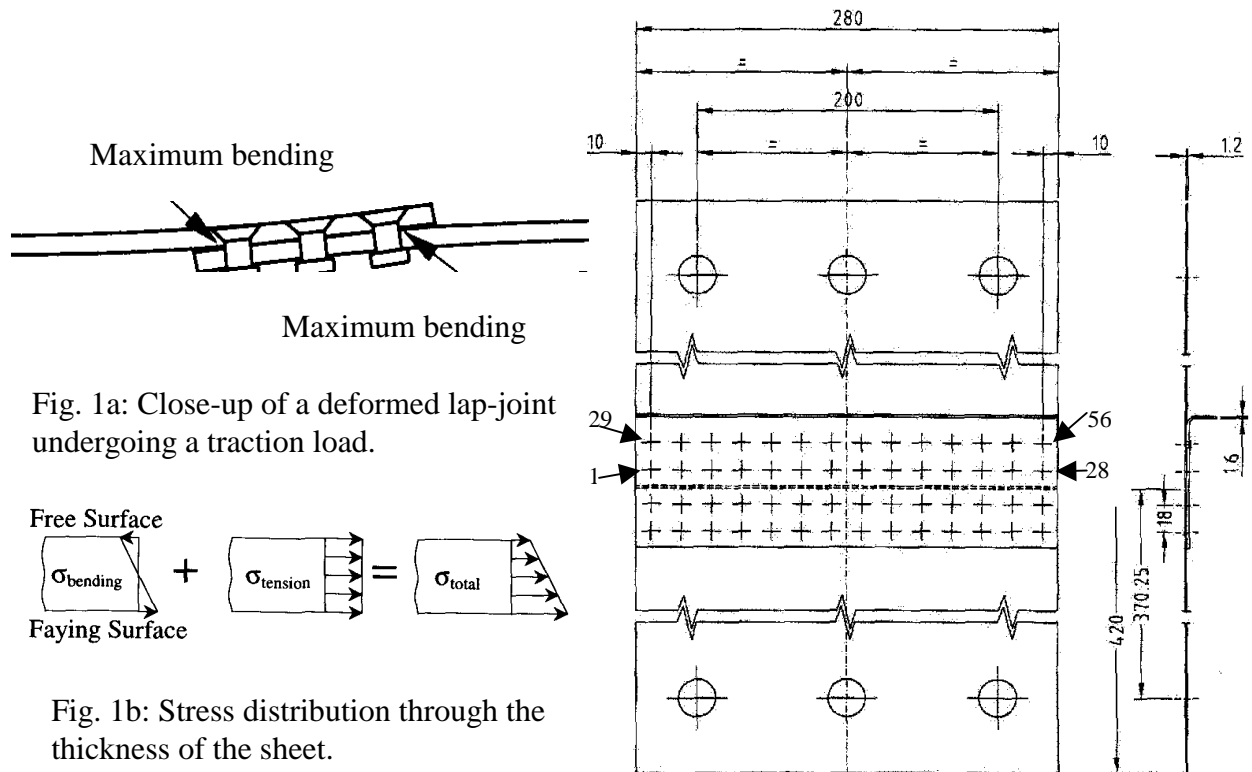


Fig. 1a: Close-up of a deformed lap-joint undergoing a traction load.

Fig. 1b: Stress distribution through the thickness of the sheet.

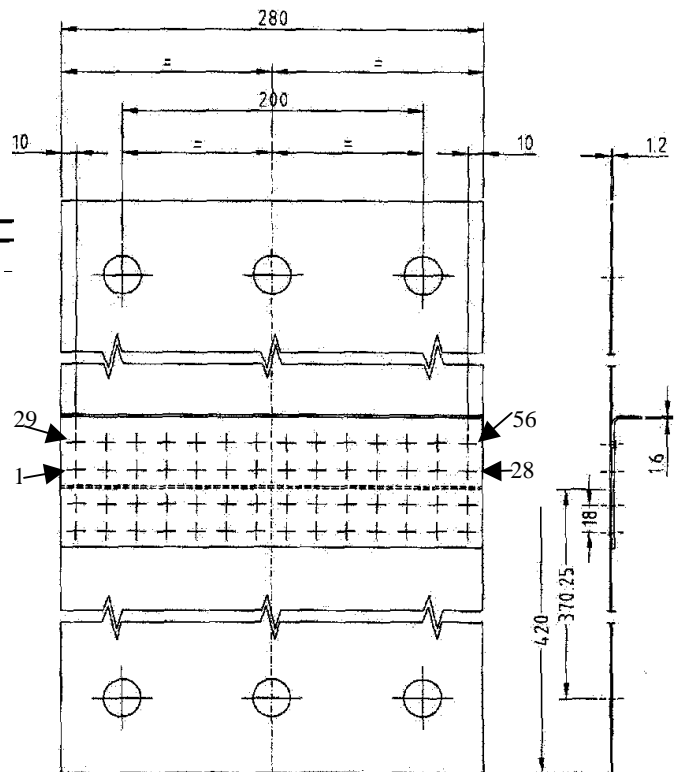


Fig. 2: Butt joint.

Gap elements have also been introduced, to better tackle contact conditions but the solution improvement has been judged quite negligible (less than 2%), except in case of very short cracks emanating from the holes, more sensitive to pin-hole contact conditions. For this reason, and due to the computational effort of a non-linear analysis (causing an unacceptable increase in run times), they have not been used any more. The J-integral technique was adopted for SIF's evaluation, being more stable than Crack Opening Displacement method with respect to crack mesh refinements. On the J-integral path, 33 integration points are used (the increment of accuracy with 66 points was completely negligible). Few hours of computer run times are needed to run the whole propagation, on a common PC and an easy preprocessing phase is allowed by the BEM approach. The mesh used for the butt-joint is based on about 327 quadratic elements: a p-convergence study has been realized showing that cubic elements provide an accuracy improvement of less than 2% and that 2 quadratic elements per 90 degrees are sufficient on the cracked hole, except for very short cracks, where

3 elements are recommendable (possibly with a scaling ratio). All the undamaged holes are modelled with 6 elements, constrained in y-direction.

3. CRACK PROPAGATION ANALYSIS AND RESULTS

The crack growth has been simulated between 73500 and 113885 cycles. Initiation length of cracks (in left or right hole side) is not taken as the visual observation length at 73500 cycles on the free surfaces, as provided from the experimenter, because of the following reasons:

1. the length monitored in the experimental phase is related to the external surface (“penetrated crack”), but it is evident that the crack first appear on the faying surface, which undergoes the tensile secondary bending stress together with the tensile stress (Fig.2b). As a matter of fact, due to the superimposed secondary bending the crack assumes a part elliptical shape (Fig. 3), in such a way that it is already abundantly extended on the faying surface when appearing on the external surface;
2. in more details: it is possible to make a prevision of the hidden part through crack length, right before the appearance of the external crack front, observing that [1] the ratios between the two ellipse semi-axis, a and c and between a and t (specimen thickness), even if variable at initiation, are always equal to $a/c=0.575$ and $a/t=0.880$ at the moment of the static break through of the remaining ligament (Fig. 3); $k = \sigma_{\max \text{ tension}} / \sigma_{\max \text{ bending}}$;

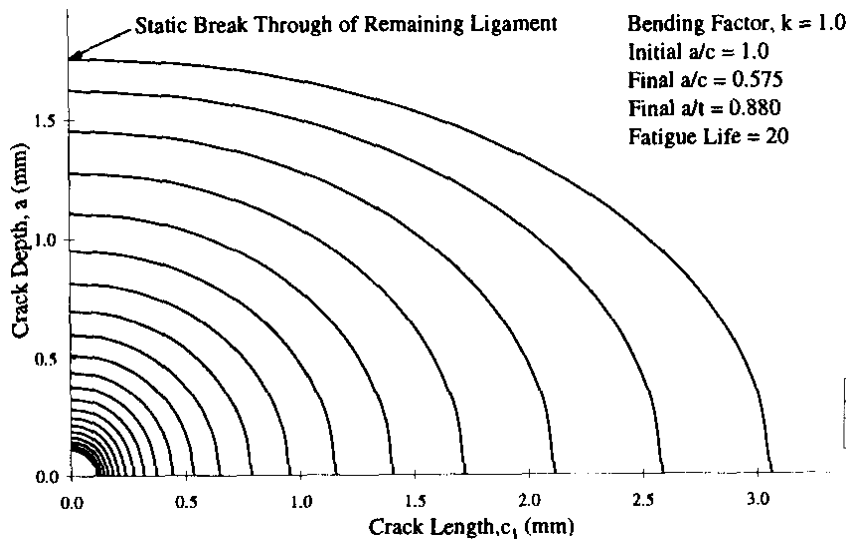


Fig.3: Crack shape development

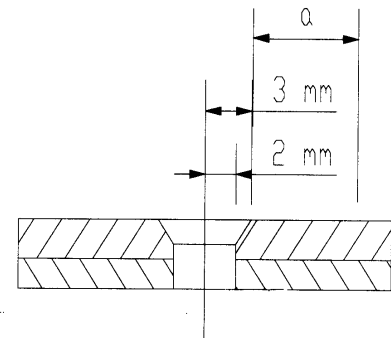


Fig.4: Rivet hole.

3. in our particular case, when the crack (as reported by the experimenter) appears on the external surface it is possible, by using the aforementioned relationships, to know the shape of the part elliptical crack front, obtaining: $t=1.2 \text{ mm} \Rightarrow a=1.06 \text{ mm} \Rightarrow c=1.84 \text{ mm}$. (Take care of the different meaning of a in Figg. 3 and 4).

Keeping into account this values, the shape of the real hole (Fig. 4) with respect to the modelled one (a cylinder of radius 2.4 mm), and having decided to model an equivalent straight initial crack of length $c/2$, we have prolonged the initial crack length values proposed by the experimenter of 1 mm. The results of the MSD propagation are presented in Table 1. During the propagation some cracks will link-up and the criteria chosen to assess such

condition is the overlapping of the crack tip plastic zones: $L=r_{p1}+r_{p2}$ where L is the residual ligament and $r_p=K_{eq}^2/(S_y^2 * 6.28)$ [2]; S_y is the yield stress and K_{eq} the Irwin corrected equivalent SIF (obtained by virtually prolonging the physical crack length of a quantity $r_y = r_p$ [3]). With such bidimensional approach a good agreement with the experimental crack growth rate [4] is obtained and it is possible to capture the essential features of the response even if the secondary bending is not modelled. With BEASY code [5] it is quite easy to follow the crack propagation because it is possible an automatic remeshing as the crack grows; the manual intervention is just necessary to initiate new cracks.

TIP (two per each hole, numbered sequentially and measured on the free surface)										
N	38	39	40	41	42	43	44	45	47	51
73500				1.82	1.42					
78810				2.63	2.28					
84030				3.36	3.04	1.16				
88830				4.46	4.18	2.24				
93280				5.2	4.94	2.84				
97330				5.92	5.7	3.43				
99500				6.54	6.37	3.94			1.19	
102850				7.23	7.14	4.52			1.77	
105770				7.86	7.91	5.13	1.50		2.17	
108000		1.15	1.12	9.27	link-up	link-up	2.28	1.19	3.20	
110500		1.83	1.94	10.3			3.25	1.78	3.60	1.12
112000	1.20	2.59	link-up	link-up			4.02	2.14	4.00	1.43
113885	1.81	3.57					5.02	2.61	4.36	1.69

Table 1: Crack propagation lengths (mm) versus constant amplitude load cycles (see Fig.2)

4. CONCLUSIONS

It is important to point out the need, in a bidimensional crack propagation model for a butt-joint, to model the part elliptical crack front at initiation with an “equivalent” prolonged straight crack, where the penetrated front will experience an increasingly lower stress, compared with the hidden front surface. In this case there will not be the “catch up” behaviour that is typical of the pure tensile case (the “penetrated” crack front reach immediately the more prominent front surface because of the higher SIF’s) [1].

REFERENCES

1. Fawaz, S.A., “Fatigue Crack Growth in Riveted Joints”, *Doctoral Thesis*, Delft University Press, The Netherlands, 1997.
2. Broek, D., *The Effects of Multi-Site-Damage on the Arrest Capability of Aircraft Fuselage Structures*, FractuREsearch, TR 9302, (June 1993).
3. T.L. Anderson, *Fracture Mechanics fundamentals and applications*, Department of Mechanical Engineering, Texas A&M University, 1991.
4. G. Cattaneo, G. Cavallini, R. Galatolo, SMAAC (Testing of “Simple” Specimens), Document No. SMAAC-TR-3.2-07-1.3/AEM, June 1998.
5. Beasy Crack Growth Guide Book, Computational Mechanics BEASY, Ashurst, Southampton, 1994.