Non-linear MSD crack growth by DBEM for a riveted aeronautic reinforcement

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A B S T R A C T
A special specimen is created cutting a rectangular notched area from the surrounding of the upper left corner of a wide body aircraft door. Then a constant amplitude fatigue traction load is applied by a special servo-hydraulic machine, in order to induce a Multi Site Damage (MSD) scenario.

The Dual Boundary Element method (DBEM), as implemented in a commercial code, is adopted for a three-dimensional MSD crack growth simulation of such multi-layer and multi-material component. To this aim, the cracked part of a pre-existing global two-dimensional model is extracted and “extruded” in order to generate a three-dimensional submodel, whose boundary conditions are imposed displacements, calculated by the two-dimensional model, along a virtual line corresponding to the submodel boundary.

Non-linear contact conditions are applied between the mating plate surfaces in the area surrounding the cracks, in order to precisely model the plate interactions in the area of interest.

The three-dimensional approach is aimed to improve, with respect to the two-dimensional approach, the correlation between numerical and experimental results (e.g. by an accurate assessment of the secondary bending effects). The obtained improvements on crack growth rates, in the initial part of the crack propagation, justify the increased computational effort that a three-dimensional non-linear approach involves.

The proposed numerical procedure, based on DBEM, is successfully validated for the virtual testing of a complex aeronautic reinforcement.

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1. Introduction

The ability to determine an acceptable fatigue life for the joint structures has become increasingly important with the advent of the damage tolerance criteria, mandated by the Federal Aviation Administration (FAA) regulations for ageing transport aircraft. Consequently, the joint techniques have been compared based on their fatigue behaviour performance, assessed in a deterministic and, recently, also in a stochastic context [1].

In order to develop an effective riveted reinforcement methodology, it is important to be able to accurately determine the complex stress fields created by the doublers, as well as the resulting reduction in the stress intensity factors (SIFs) of a crack on the skin.

During the past decade extensive research has been conducted in the area of riveted patch joint performance: the majority of numerical analyses have been performed using the Finite Element method (FEM) but some work has also been done using the Dual Boundary Element method (DBEM) [2–7].

In this work, using a commercial DBEM code [8], a mechanically fastened reinforcement is simulated, with reference to the experimental test performed on the upper door corner of a commercial aircraft at most critical location.

One of the objectives is to validate the damage tolerance behaviour of the structure as assumed by the theoretical analysis methods.

The modelling of the aforementioned problem has been improved by the authors in the last years: starting with a linear two-dimensional approach where continuity conditions were imposed at the pin-hole interfaces [9], the first step forward was a more accurate modelling of the pin-hole contact conditions and in general of the interactions between the overlapping plates, but still in a two-dimensional approach [10]. This step forward provided better correlated numerical-experimental crack growth rates, but still some discrepancies were present, between numerical and experimental results (crack path and growth rates), in the initial stage of crack propagation.

To circumvent such drawback, a three-dimensional modelling of the reinforcement is proposed to model the initial crack propagation stage. The aim is to allow for secondary bending effects, particularly relevant for cracks whose length is comparable with the plate thickness (longer cracks produce a decrease in the plate bending stiffness and consequently a reduced sensitivity to secondary bending effects [11]).

2. Experimental test

The geometrical and material characteristics for the three riveted plates are shown in Table 1. The test article (T.A.) geometry
is shown in Fig. 1, where the axial strain gauge positions and plate dimensions are shown. The remote fatigue load is calibrated to $P_{\text{max}} = 405 \text{ kN}$ in order to provide a longitudinal stress of 169 MPa at middle corner location (A) in Fig. 1. The stress ratio for the remote fatigue load is $R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} = 0.1$.

The T.A. is an upper panel, cut from the fuselage panel in order to be representative of the aircraft door corner under analysis (Fig. 2). An initial notch is cut on both the skin and the aluminum doubler, and a skin crack propagation for 26,000 cycles is monitored (Fig. 3), starting with an initial measured skin crack of length equal to 3.25 mm; at this stage a doubler crack is initiated too (even if no precise measurement of the initial length is available).

To monitor the crack growth, crack wires are installed at crack tip and along crack propagation line. The test is performed at room temperature dry condition, normal sea level pressure and humidity. The measuring equipment has an overall accuracy such that the acquired load and strain are affected by a maximum error of $+/- 1\%$ of reading.

The test fixture consists of a mechanical framework with two vertical members, one upper beam fixed on the vertical members and one lower beam fixed to the ground floor. A support, fixed at the upper beam, is used to constraint the T.A. that is loaded on the opposite side by two hydraulic jacks fixed at the lower beam. The fatigue and static loads are applied through appropriate plates joined to the T.A. in order to have uniform loading and constraints along the edges.

2.1. DBEM numerical model

A three-dimensional DBEM submodel is “extruded” from part of the whole structure two-dimensional model (Fig. 4). The in-plane displacements, calculated from the two-dimensional model along the cutting line highlighted in Fig. 4 [10], provide the boundary conditions for the three-dimensional submodel. The initial crack length considered is 3.25 mm for the skin (2 mm notch + 1.25 mm experimentally measured crack), and 3 mm for the aluminum doubler (this tentative value is a posteriori confirmed by the simulation outcomes).

Only the initial crack propagation phase, up to a skin crack length equal to about 9.5 mm, is simulated with such three-dimensional approach: the reason is that for longer cracks the two-dimensional approach proved to be sufficiently accurate (Fig. 5a and b) [11], whilst, for shorter cracks some discrepancies were present, in terms of crack growth rates (lower in the numerical simulation than in the experiment), and crack path (straight in the numerical simulation but slightly inclined in the experiment).

Three different layers in the critical area are explicitly modelled by three separate DBEM zones, respectively representative of the skin, of the aluminum doubler and of the titanium doubler (Fig. 6). The three zones interact through numerous rivets (a further zone in the DBEM model) that provide the connection between the different layers.

Table 1
Component materials, reinforcement geometry and allowable specifications

<table>
<thead>
<tr>
<th>Component</th>
<th>Reinforcement Geometry</th>
<th>Allowable Specifications</th>
</tr>
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<tbody>
<tr>
<td>Skin (2524-T351, clad sheet)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness 6 mm</td>
<td>Thickness 8/4 mm</td>
<td>Ftu = 430 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fty = 275 MPa</td>
</tr>
<tr>
<td>Doubler (Ti-6Al-4V, rolled)</td>
<td></td>
<td>Ftu = 930 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fty = 905 MPa</td>
</tr>
<tr>
<td>Doubler (2524-T351, clad rolled)</td>
<td></td>
<td>Ftu = 430 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fty = 68200 MPa</td>
</tr>
<tr>
<td>Doubler (clad rolled)</td>
<td>Thickness 12/10/6/3 mm</td>
<td>Ftu = 930 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fty = 905 MPa</td>
</tr>
<tr>
<td>Titanium fastener</td>
<td>Diameter 9.5/7.9/6.2 mm</td>
<td>Ftu = 430 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fty = 930 MPa</td>
</tr>
</tbody>
</table>

Fig. 1. Test article with dimensions and highlight of strain gage positions.

Fig. 2. Upper corner of an aircraft door.
The analysis is non-linear, because, in the area surrounding the crack (that appearing in Fig. 6 with a regular mesh of quadrilateral elements), the contact between the plates is modelled through gap elements (with zero clearance), whereas, in the remaining part of the plate interfaces and at the mating pin-hole surfaces, sliders are used to provide the exclusive possibility for a relative sliding displacement (this is not strictly correct but reduces the computational effort without significantly affecting the accuracy).

In Fig. 6, the initial modelled cracks are shown on a deformed contour plot of Von Mises stresses. The initial DBEM model is based on 4177 elements (56691 degrees of freedom), that are linear everywhere but in the cracked area and on the crack surfaces, where reduced quadratic (8-nodes) elements are used in order to catch the stronger stress singularities; the geometry interpolation is quadratic everywhere. During the propagation, the number of elements slightly increases, due to the new elements added on the growing cracks by a fully automatic remeshing process. In Fig. 7 the SIFs from the two- and three-dimensional analysis are shown: the latter exhibits a variability of SIFs along the crack front as due to the secondary bending phenomena (Fig. 8).

SIFs are calculated by the $J$-integral method [12] and the crack path is calculated by the minimum strain energy density criterion [13].

The crack growth rates are provided by the closure corrected Paris formula (Eq. 1):

$$
d_{a}/dN = C(\Delta K_{eff})^m = C(U(R))^m(\Delta K)^m = C(\Delta K)^m,
$$

where $\Delta K_{eff} = U(R)\Delta K = (0.54 + 0.46R + 2.37R^2)\Delta K$, and $C = C(U(R))^m$

When the stress ratio $R = 0.1$, the fatigue constants for the Al 2524 T351, as provided by ALENIA laboratories, are:

- $C = 1.26e-13$ and $m = 3.5$, with $\Delta K$ expressed in MPa mm$^{1/2}$ and $da/dN$ in mm/cycle.

With the aforementioned submodelling approach, one important aspect to take into account is the variation, caused by the two-dimensional crack propagation, of the displacements on the internal points placed along the "cutting line" of the two-dimensional model (Fig. 9a). When such variations become non negli-
ble an updating of the boundary conditions on the three-dimensional submodel becomes mandatory. Being the aforementioned variations sufficiently small (Fig. 9b), the displacements imported by the two-dimensional analysis of the initial cracked configuration, and applied on the three-dimensional submodel boundaries, are kept constant for the whole crack propagation.

In Figs. 10–12, the SIF variations along the crack fronts are shown with reference to the crack propagation steps: as expected the propagation is dominated by mode I, even if non negligible mixed mode conditions are still present. In Fig. 13a and b, the Von Mises stresses on the final cracked scenario are shown: it is possible to observe a straight crack propagation direction of the skin crack break out point (Fig. 13a), as for the two-dimensional analysis, whereas a deviation is recorded for the experimental crack path.

A non negligible improvement is obtained with such more realistic three-dimensional approach against the two-dimensional one, with reference to numerical and experimental skin crack growth rates (Fig. 14). In particular the satisfactory numerical-experimental correlation becomes evident if we look at the dashed line in Fig. 14, that is obtained by shifting the experimental crack line, in such a way to intersect the corresponding numerical line at a
It is worth mentioning that the numerical two-dimensional crack length is better compared with the corresponding three-dimensional crack length measured at half thickness, whereas the experimental skin crack length is to be compared with the experimental skin crack length equal to 6 mm; namely we renounce to the comparison in the very initial crack propagation stage where the material fatigue properties are probably altered by the notch cutting operations.
three-dimensional crack length measured at the visible break out point (Fig. 14).

3. Conclusions

This application shows how efficient is the DBEM and in particular the specific modeling strategy adopted for the simulation of the aforementioned fracture problems, providing the aircraft companies with an efficient tool aimed at inspection interval assessment and fracture analysis in general.

Even with a three-dimensional approach slight discrepancies are still present, between numerical and experimental data (crack growth rates and crack path), but only in the initial crack propagation stage affecting the area surrounding the skin and doubler notches, where the fatigue material properties may be negatively affected by the notch cutting operations. The crack growth rate dis-
crepancy is anyway reduced by the three-dimensional modeling, that, in addition, can show the peculiar through the thickness shape of the crack front, as determined by the secondary bending. Moreover, it can be emphasized the reduced preprocessing times of the DBEM approach: the crack insertion and the whole crack propagation is fully automatic, with repeated remeshing realized at each crack step without user intervention.

Further analysis can be easily set up to study the MSD scenario coming out from cracks initiated at the holes of the riveted connection, knowing that even a two-dimensional approach can provide satisfactory accuracy when analyzing propagation of through cracks in such kind of aeronautic components.

References


