BIDIMENSIONAL STRESS ANALYSIS AND SIF'S ASSESSMENT OF A CRACKED AERONAUTIC DOUBLER-SKIN ASSEMBLY BY BEM AND FEM

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ABSTRACT

The riveted patch repair performance of a cracked tension panel, with through-cracks initiated on the most loaded holes, is simulated using a commercially available Boundary Element code (BEASY) and Finite Element code (ANSYS). A bi-dimensional stress analysis on a single sided repair configuration is performed by both methodologies, consequently the occurrence of out-of-plane bending and its impact on the through-thickness SIF's (Stress Intensity Factors) variation is neglected. The connection between the two layers is modelled using a discretely distributed system of 32 rivets. Special elements are used to model the crack: discontinuous elements by BEM and quarter point elements at the crack tip by FEM. Different loading configurations are considered depending on the presence of a biaxial or uniaxial remote load and the non linear hole/rivet contact is simulated by gap elements. The most stressed skin holes are highlighted and the effects of a through crack from such hole is analysed in terms of SIF's and stress redistribution. The accuracy in SIF's assessment by BEM and FEM, together with their respective computational and pre-processing efforts is determined. Such bidimensional analysis allows for a straightforward pre-processing phase and very short run times: a peculiar arrangement of the pin configuration in the BEM analysis allows to take into account the real in plane plate stiffness and the transversal pin stiffness even in a 2D analysis (this is straightforward by FEM).

KEYWORDS

FEM; BEM; Doubler-skin assembly; SIF; Non linear contact analysis

INTRODUCTION

The ability to determine an acceptable fatigue life for the damaged structure has become increasingly important with the advent of the damage tolerance criteria mandated by FAA (Federal Aviation Administration) regulations for ageing transport aircraft. Consequently, the repair techniques have been compared based on their fatigue behaviour performance [1,2]: in particular, in this work, mechanically fastened doublers for damaged aircraft skin will be analysed.

In order to develop an effective riveted repair methodology it is important to be able to accurately determine the complex stress fields created by the repair as well as the resulting reduction in the stress intensity factor (SIF). Numerical simulations are useful to identify the most fatigue critical locations where to check the effect of a possible crack by a crack propagation simulation under a given spectrum load. During the past decade extensive research has been conducted in the area of riveted patch repair performance, also in comparison with bonded patch repair (more recent): the majority of numerical analysis has been performed using the finite element method (FEM) [3, 4] but some work has also been done using the boundary element method (BEM) [5-7].

PROBLEM DESCRIPTION AND RESULTS

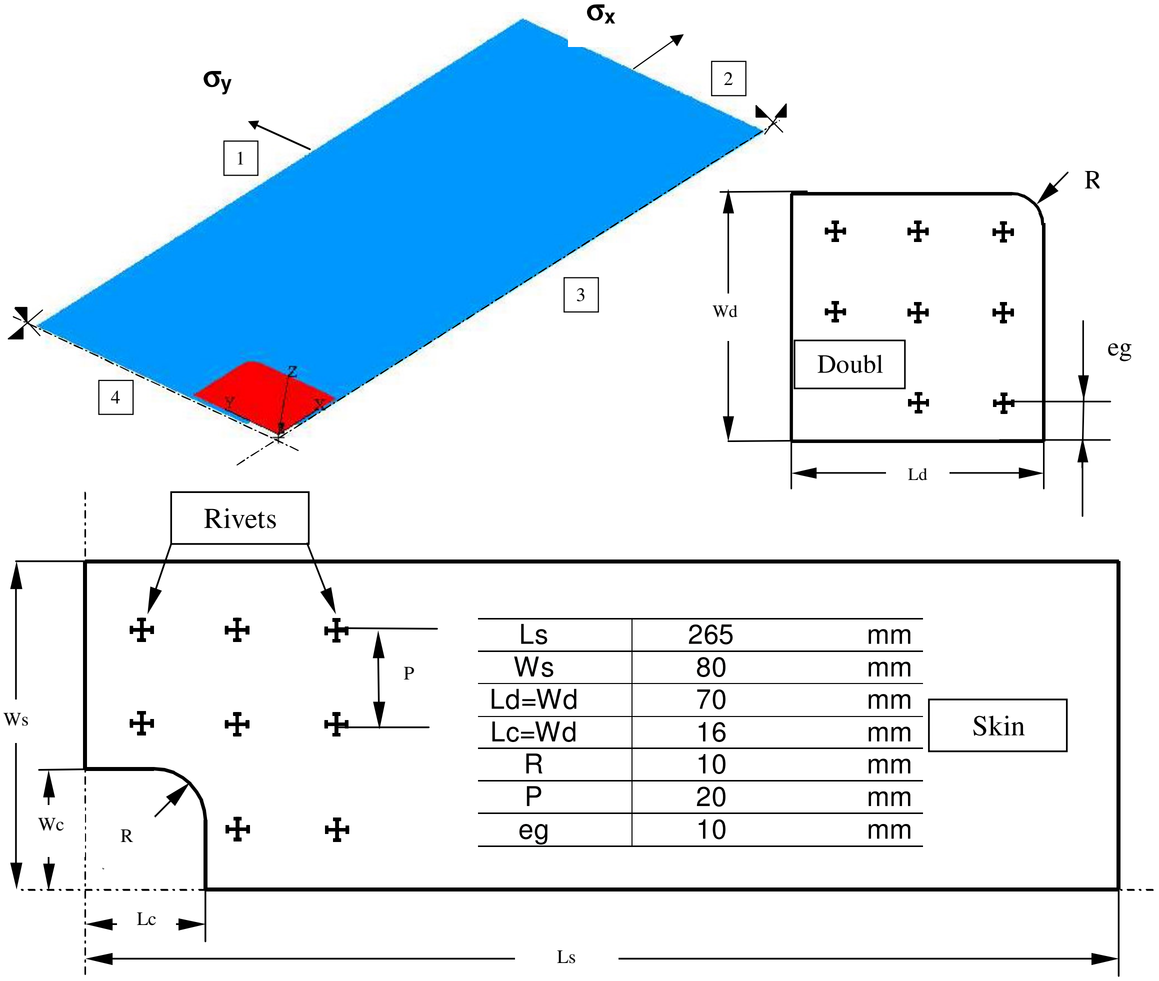
The present work focuses on the use of bi-dimensional BEM and FEM analysis to investigate the riveted repair fatigue performance of a fuselage skin panel, with a single doubler applied over a cutout (to remove prior damage), with and without hole edge-cracks and undergoing a bi-axial stress (Fig. 1). The panel, patch, and rivets have been assumed thin so that out-of-plane bending, which occurs as a result of the asymmetry of the repair with respect to the applied load, is not considered, even if in general not negligible [8]. Anyway, the bidimensional approximation is particularly useful when the objective is to study many possible repair configurations (different patch thickness, rivet diameter, number of repair patches…) and consequently reduced run times and a lean pre-processing phase are prerequisites. Plate thickness and rivet stiffness are illustrated in table 1, whilst material properties and symmetry conditions (only one quarter of the assembly will be analysed) in table 2. Both BEM and FEM analysis are based on linear small displacement theory.

The BEM non linear contact analysis extends some previous BEM work by performing a fully bi-dimensional modelling of the skin-doubler assembly that in [9,10] was modelled as a single plate, constrained in the holes in order to simulate the presence of the other plate. In this work the two plates (skin and doubler), attached by the rivet connection, are both explicitly modelled and the connection is modelled by two circles (Fig. 2), representative of the two half of the rivet respectively engaged, by gap elements, with the two corresponding skin and doubler holes. Such circles are connected by internal springs with a stiffness (K_x, K_y) corresponding to the shear rivet stiffness (table 1).

The load case considered is related to a fuselage panel positioned just above the aircraft windows so that the longitudinal (σ_y =bending + axial pressure stress) and hoop stresses (σ_x = tangential pressure stress) are almost equal: in particular it was assumed as worst case $\sigma_x = \sigma_y = 100$ MPa (the design values are generally lower for Al 2024-T3) and a rivet-hole interference $i=0$ (in real applications there is a slight interference of about 0.25% of the pin radius). With reference to the skin, that is most prone to fatigue initiation, due to its lower thickness compared with the doubler, the calculated Von Mises stresses are illustrated in Fig. 3 for BEM and FEM and they are well in accordance. The assembly BEM analysis, whose run times are about one minute on a powerful PC, is based on about 1200 linear elements (they are more efficient than quadratics for contact analysis) and a deformed plot is shown in Fig. 4; the FEM mesh (Fig. 5), is based on about 36000 elements/105000 nodes (PLANE 82, CONTACT 178 and COMBIN 14) and the related run time is about one hour.

In order to choose a crack initiation site on the skin, the maximum principal stresses have been plotted with particular reference to the most loaded skin hole (Fig. 3), whose most loaded point was selected (Fig. 6) for the initiation of a 1 mm radial through crack (Fig. 7).

The commercially available BEM code implements the DBEM (Dual Boundary Element method) for crack problems (displacement and traction boundary integral equations on opposite sides of the crack surface are simultaneously imposed); both crack surfaces are discretized with discontinuous quadratic boundary elements (special element capable of handling the discontinuous stress field located at the crack front) and the SIFs are calculated from the J-integral technique [11]; run times and number of elements are about the same as without the crack. The FEM crack analysis takes advantage of special quarter point elements (the mid-point nodes are shifted to the quarter-point locations to account for the crack tip singularity) and the SIF's are calculated in the post-processing phase by the crack opening displacement method (COD); the number of elements required slightly increase for the mesh refinement around the crack tip and consequently the run times. The loading condition on the crack tip is pure mode I, due to the crack orientation perpendicular to the maximum circumferential stresses and the SIF provided by such non-linear iterative contact analysis is K_I= 325 MPa mm$^{1/2}$ by DBEM and K_I=340 MPa mm$^{1/2}$ by FEM (the level of agreement is considered satisfactory if the aim is to analyse many alternative repair configurations in order to select that with highest fatigue performance). Such SIF's are obtained considering a null coefficient of friction at the rivet-hole interface because such effect is negligible (especially if the coupling is with interference); moreover the presence of friction would enforce a longer calculus due to the need for splitting the applied load in load steps (incremental-iterative analysis). Modelling the real pin-hole interference and even the proper friction coefficient is of the uttermost importance in case of part-through crack but this would involve a 3D analysis.



Ls	265	mm
Ws	80	mm
Ld=Wd	70	mm
Lc=Wd	16	mm
R	10	mm
P	20	mm
eg	10	mm

Fig. 1: Skin doubler assembly with dimensions (only one quarter because of the symmetry).

Skin thickness	Doubler thickness	∅ rivets	Rivet stiffness (K_x, K_y)	Rivet stiffness (K_z)
1.2 mm	1.4 mm	4.0 mm	2.9E+4 N/mm	2.9E+5 N/mm

Table 1: Assembly component dimensions and rivet mechanical properties.

1	Tz, Rx, Ry ,Rz
2	Tz, Rx, Ry ,Rz
3	Ty,Rx,Rz
4	Tx,Ry,Rz

	Materials
Skin	Al 2024-T3 (E=72390 MPa, ν=0.33)
Doubler	Al 2024-T3 (E=72390 MPa, ν=0.33)

Table 2: Rotational and translational (see Fig. 1) constraints (left); material properties (right).

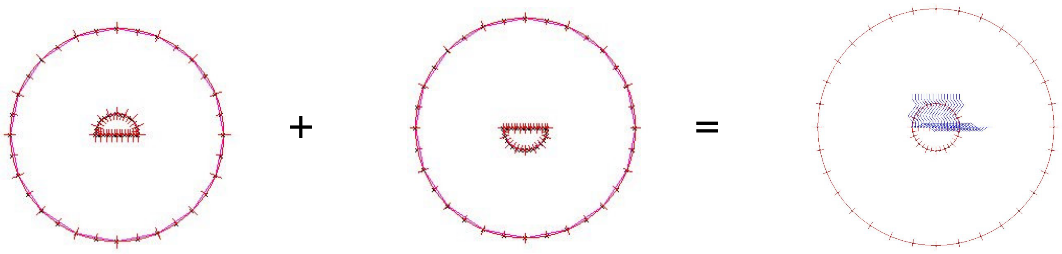


Fig. 2: Rivet half engaged with skin (left), with doubler (centre) and assembled rivet (right).

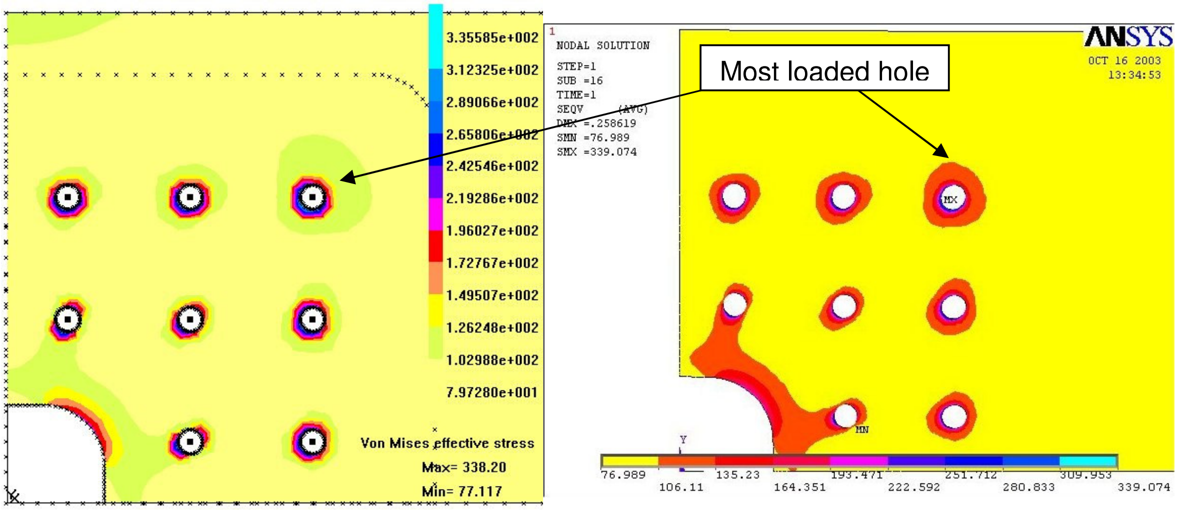


Fig. 3: Von Mises stresses for the skin by BEM (left) and FEM (right) with $\sigma_x=\sigma_y=100$ MPa.

CONCLUSIONS

Because the solution method and modelling technique of the BEM differ slightly from the FEM there are some inherent advantages and disadvantages in using the BEM (DBEM) for this type of analysis. Important advantages include simplified modelling of the cracked area, direct calculation of SIF values, reduced run times (at least for 2d analysis) and accurate crack growth simulation (it is straightforward to model multiple crack propagation, load spectra effects, etc.). A disadvantage is that the BEM commercial code used for this analysis is currently limited to geometrically linear analysis [11] and, in order to take into account the secondary bending, it is necessary to switch to a time consuming fully 3d analysis (this drawback could be circumvented by a global-local approach based, for example, on a coupled FEM-BEM approach); moreover it could be difficult to take into account elasto-plastic effects.

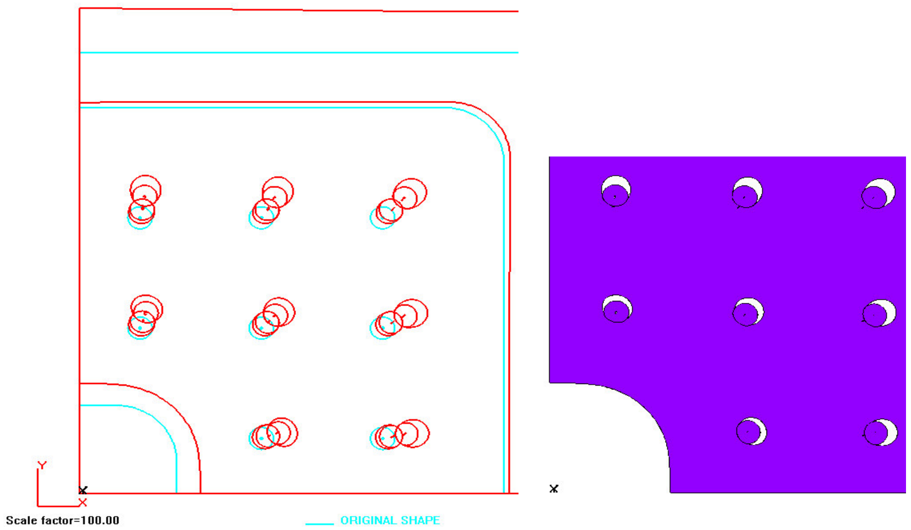


Fig. 4: Deformed plot for the skin-doubler assembly (left) and only skin (right).

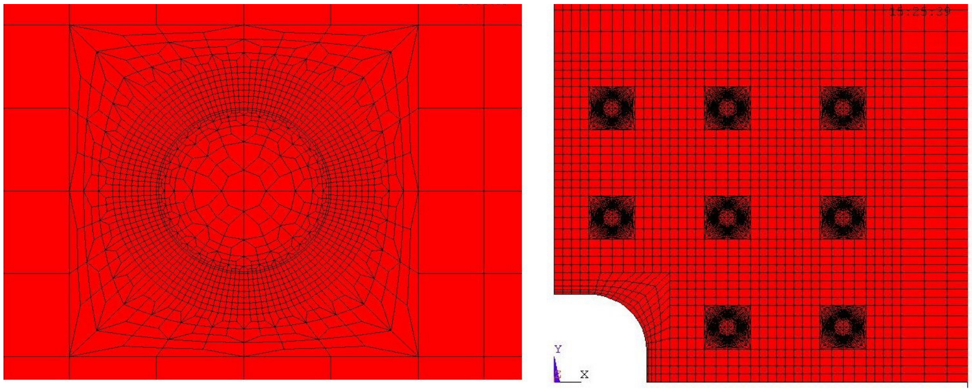


Fig. 5: FEM mesh for the skin (right) and close up of the area surrounding an hole (left).

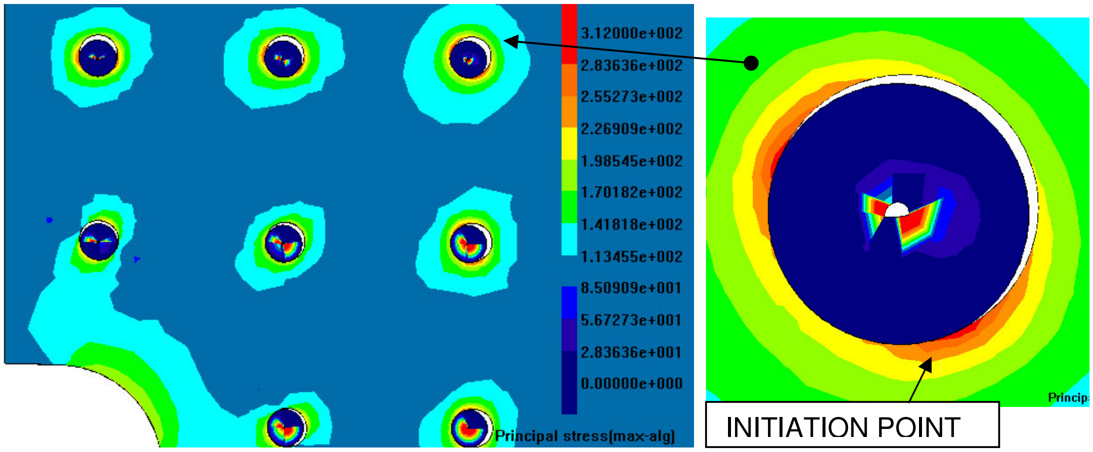


Fig. 6: Skin max. principal stress (left); close up with most stressed initiation point (right)

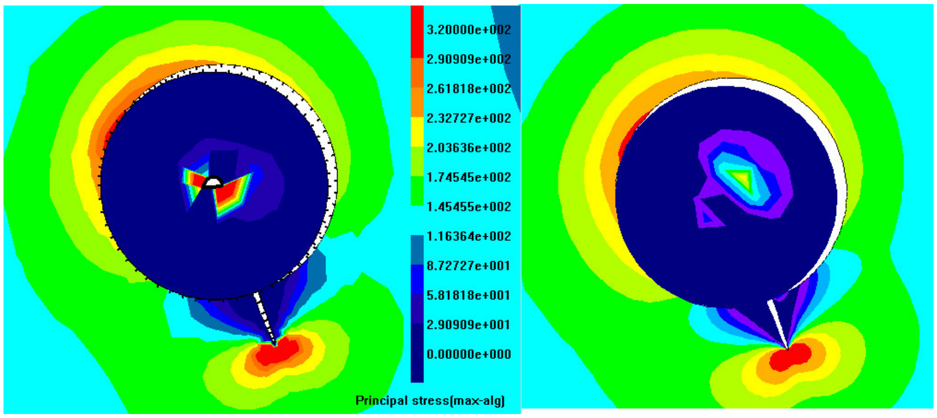


Fig. 7: Maximum principal stresses for the skin cracked hole by FEM (right) and DBEM (left).

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