Modelling and analysis of crack turning on aeronautical structures

Doctoral Thesis

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Ottoburnn / Barcelona April 2007

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7 Summary and Conclusions

The main objective of this Ph.D. thesis was to assess and predict crack turning under nearly in-plane opening mode situations on structures that reproduce aeronautical conditions. The industrial environment in which this work has been carried out requires a fast prediction of the structural behaviour to provide useful inputs to aircraft designers. It is for this reason that the crack turning prediction was investigated by means of Linear Elastic Fracture Mechanics and Finite Element Analysis.

A screening of existent commercial and non-commercial tools was carried out in respect to their fracture mechanics capabilities on two and three dimensional models, their design abilities, implementation as well as their complexity. Although, there are many software possibilities, only those within the reach of the author were evaluated. This screening and evaluation, after the above definition, resulted in the selection of the commercial analysis tool called StressCheck®.

During this work it has been shown the importance and necessity of a second parameter for the characterisation of the stress field at the crack tip besides the stress intensity factor or the *J*-integral. Among the different proposed second parameters, the uniform non-singular stress, normal to the crack line and dependent on the type of loading and specimen geometry, i.e. the *T*-stress, was selected for crack turning predictions due to both calculation simplicity and its independence of the crack tip distance.

An important step was the implementation of the *T*-stress extraction facility in the tool and to show its reliability. The latter was proved by means of literature and analytical calculations on doubler cantilever beam specimens. The assessment of crack propagation on the middle cracked tension and two stringer specimen governed by the Paris and Forman crack growth regimes was satisfactory compared with experimental results using the material data from simple standard specimens.

Although the validity of linear elastic fracture mechanics is restricted, it was applied for the prediction of crack turning for quasi-static loading while paying attention to the possible plastification of the specimen. The assumption that linear elastic fracture mechanics can be applied under quasi-static loading when plasticity in front of the crack is not negligible is only justified in literature data showing good agreement when comparing experimental crack turning results with crack path predictions using the criterion proposed by Finnie & Saith, Kosai, Kobayashi & Ramulu and Shimamoto et al. [4, 62, 65, 66], in this work called the *WEF*-criterion, or the criterion defined by Buczek & Herakovich [71] and Boone et al. [72], called the *WEFO*-criterion.

First crack path simulations showed a lack of performance to predict crack turning. Therefore, deep analyses were performed regarding modelling details and boundary conditions. Taking into account these results, crack path predictions were performed. The best prediction by means of the existing criteria was reached by the *WEFO*-criterion, which is the maximal principal stress criterion implemented with the *T*-stress and taking into account anisotropic effects. However, the path predictions for T-L and L-T specimens were similar. A challenge of this Ph.D. thesis was then to overcome the lack of prediction on crack turning provided by this latter criterion, i.e. to reproduce the observed path-differences due to anisotropy effects and when charging the specimen under quasi-static or cyclic loading.

These deficiencies on the crack path predictions are related with the definition of the crack path instability point. Some literature results have shown that in some experiences the crack behaved in a stable manner, i.e. no turning, even if $T > 0$. Moreover, *WEF* and *WEFO* criteria define crack instability to be related with a material specific distance, r_c, but, there is no agreement about its definition.

Based on both tests, simulation results and observations noted during this work, a compilation criterion was proposed. This is based on the work of Pettit [9] and the normalised *T*-stress, T_R, proposed by Pook [16]. Its reliability was successfully proved on the double cantilever beam-test results. The crack path predictions on the cruciform specimen were not as satisfactory. It should be emphasised that even at its worst, on the cruciform specimen, the developed criterion was the most accurate.

7.1 Confirmed observations

The main observations collected from the experimental tests and simulations on *DCB*-specimens, which agree with literature, are summarised as follows.

a) Crack turns more sharply in L-T than in T-L direction under both quasi-static and cyclic loading and longer notch lengths produce higher crack turnings.

b) Under quasi-static loading tests, crack turning took place at a relatively short distance of the crack tip due to geometric imperfections, which would give rise to small amounts of K_{II} at the root of the notch. Especially, for aluminium 2024-T3 alloys, where cracks are often looped around iron and silicon inclusions.

c) The modelling of specimen details, as the notch thickness, was found to play a crucial role on the crack path predictions.

d) The directional instability of cracks on doubler cantilever beam specimens can be explained by the bending stresses induced in the long loading arms.

e) Cracks tend to be attracted by boundaries and they are increasingly stable as a boundary is approached.

f) Finally and during the iteration process it was observed that K_{II} can frequently drive the crack along a trajectory that, from purely global considerations, is not necessarily the most energetically favourable.

7.2 Conclusion

The main objective of this work was accomplished; StressCheck tool is proposed in combination with the developed criterion to predict crack paths, including crack turning, for structures or specimens loaded under near in-plane opening mode conditions. The criterion takes into account the anisotropy of the material and the kind of loading, i.e. quasi-static or cyclic loading.

Furthermore, based on the performed analyses a proof of confidence is furnished to apply crack turning in the design process on airplane structures loaded near in-plane opening mode:

a) The computations of the stress intensity factors and T-stresses must be done under geometric non-linear analyses.

b) The selection of the boundary conditions has been identified as capital. Therefore a concisely analysis of the test or the in-service conditions must be done before to carry out the predictions.

c) The results obtained with ARAMIS, a strain mapping system, have shown that the crack-tip plasticity dimensions can be considered limited to a small region on the studied area also for quasi-static loaded specimens. However, pre-testing or assumptions have to be taken regarding the force applying at each crack length. But, it has to be noted that this can be calculated defining the crack to grow when critical crack tip opening angle/displacement or ultimate yield strength are reached.

7.3 Future work

This work has produced new interesting conclusions on crack turning assessment and raised many challenges for future consideration. These would include the verification of the criteria for other structures and materials. Furthermore, a scientific interest would remain on the prediction of crack turning on structures loaded under pure in-plane opening mode.

Cracked, stiffened structures -such as aircraft fuselage and wings- are often analysed as if they were flat; for wings and fuselages with circumferential cracks, this assumption is justified observing that the curvature of the structure is not indispensable to the problem and that the out-of plane displacements remain small in the deformed structure. However, for fuselages with longitudinal cracks, the curvature is essential to the problem, because combined with the internal pressure, it forms the main load on the structure. In addition, out-of-plane displacements will not remain small for the skin in the neighbourhood of the crack (bulging).

Therefore, a prediction of crack turning on a real structure taking into account geometrically non linear effects would be of importance to evaluate the applicability of the crack turning capabilities elaborated until the actual state of the art and in this work.