5-b-26: MODELLING INTERFACIAL FAILURE IN ADHESIVELY BONDED STRUCTURES

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Abstract

Force controlled interface elements [1,2] have been used to model crack propagation in an elastic continuum. Direct failure prediction in an elastic continuum, following crack initiation and its subsequent propagation, has been achieved by use of strain tripped elements with energy based unloading [3-5]. The use of these was limited to elastic problems. A local damage based rupture element is developed that can be used for interfacial failure prediction in adhesively bonded structures. The modelling technique accounts for material plasticity and is applicable to both cracked and non-cracked problems under mode-I and mixed mode quasi-static loading. Experimental data obtained from extensive tests of standard fracture specimens have been used to validate the developed technique.

Cleavage Finite Element Model

The finite element model of the cleavage test specimen is shown in figure 1.a. The model consists of aluminium substrates bonded with a 2 mm-thick layer of the epoxy adhesive named Permabond E27. A localised refinement scheme has been applied at a number of different crack lengths along the interface as shown in figure 1.b. The continuum element used for both the adhesive layer and the aluminium substrates was a 4-node quadrilateral plane strain type as defined in ABAQUS element library. An exponent Drucker-Prager material model was used to model the non-linear response of the adhesive layer and the aluminium substrates were considered linear elastic.

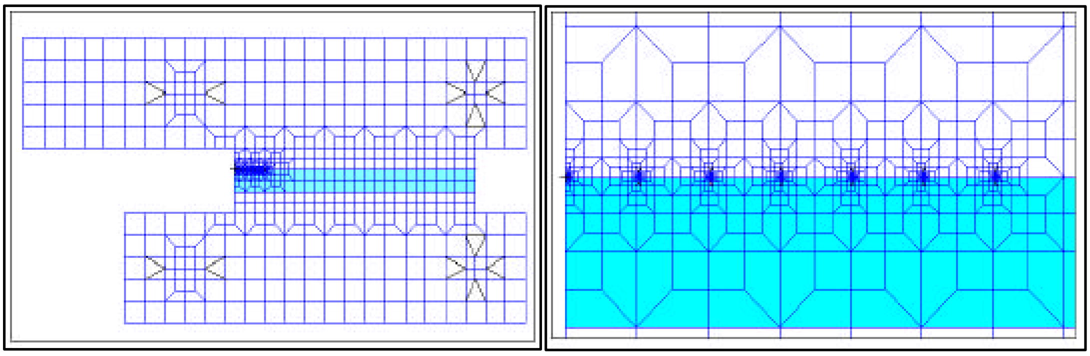


Fig. 1- Finite element model of the cleavage test specimen with aluminium substrates bonded with epoxy adhesive E27, a) whole model, b) localised refinement

The Rupture Element

The 3-node rupture element has two nodes connecting the crack faces and a third node that is coincident with a node in the continuum. The element behaviour and its correlation with the continuum elements are shown in figure 2. The algorithm used in the development of the rupture element is described in figures 3 and 4.

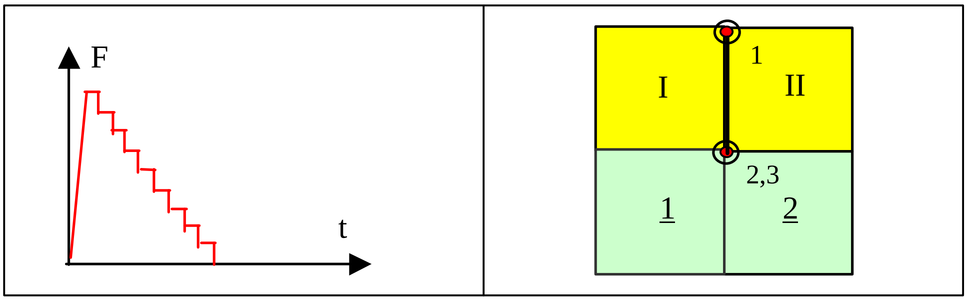


Figure 2- Rupture element behaviour and its correlation with the continuum elements

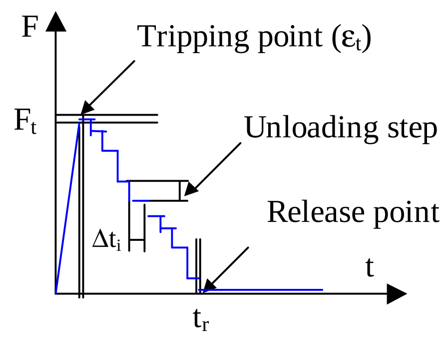
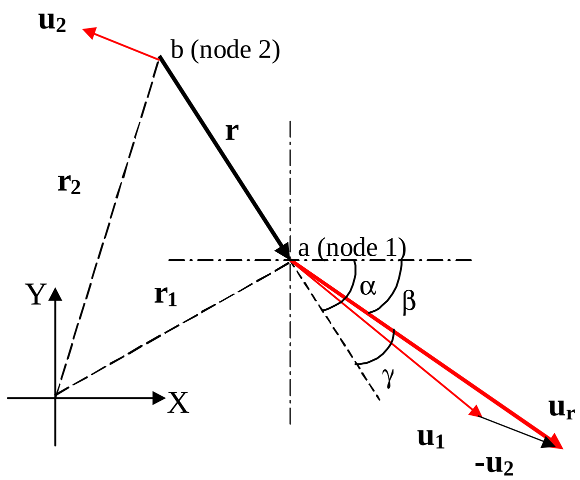
	Tripping strain approximation: $u_r=u_{2y}-u_{1y}$ $e_{av}=u_r/l$ $e_t<e_{av}<1.02e_t$ Cut back factor (f): $f=0.1(e_t-e_b)/(e_e-e_b)$ (b: begin inc., e: end inc.)
Unloading factor, if $(Dt_i/t_f)<1.0$ $f_i=f_{i-1}+0.2(Dt_i/t_f)$, $t_f=0.2\,t_r$ Load during unloading: $F_i=(1-f_i)F_t$ Load reduction step: $DF=0.2(Dt_i/t_f)F_t<0.2F_t$	Release point approach: $0.98<f_i<1.0$ Cut back factor (f): $f=0.1(1.0/f_i)$, if: $f_i>1.0$

Fig. 3- Tripping, unloading and release algorithm for the rupture element

The element routine is written based on the algorithm shown in figure 3 using Fortran programming language. In the element definition two nodes (i.e. nodes 2 and 3) span the potential crack line whilst nodes 1 and 2 are used to calculate the average strain in the continuum from the relative nodal displacements. A very high stiffness is introduced into the element representing the connectivity of the crack surfaces through nodes 2 and 3. This remains until the average strain in the direction normal to the crack reaches a specified level representing the level of continuum plasticity. The stiffness is then removed and the element is unloaded over a very small time period. The fully unloaded element represents material rupture.



$$\vec{r} = \vec{r}_1 - \vec{r}_2$$
$$\vec{u}_r = \vec{u}_1 - \vec{u}_2$$
$$Tan\,\alpha = r_y / r_x$$
$$Tan\,\beta = u_{ry} / u_{rx}$$
$$\gamma = \alpha - \beta$$
$$e_{av} = |\vec{u}_r| Cos\,\gamma / |\vec{r}|$$

Figure 4- Updating algorithm used for the rupture element to calculate the average strain

The Element Implementation

A series of rupture elements incorporated into the finite element model along the assumed crack line (the upper interface) are used to model progressive crack propagation. A calibrated tripping strain is used for failure prediction in cracked and non-cracked specimens under mode-I and also in mixed mode loading. To assess and validate the predictive technique, experimental data is compared with the model predictions. Figure 5 shows the deformed model (left) with the crack length of around 3 mm. The other figure (right) shows The crack extended from the initial tip at 3 mm towards the end of the refined mesh (where the rupture elements are incorporated), can be seen in figure 5 (right).

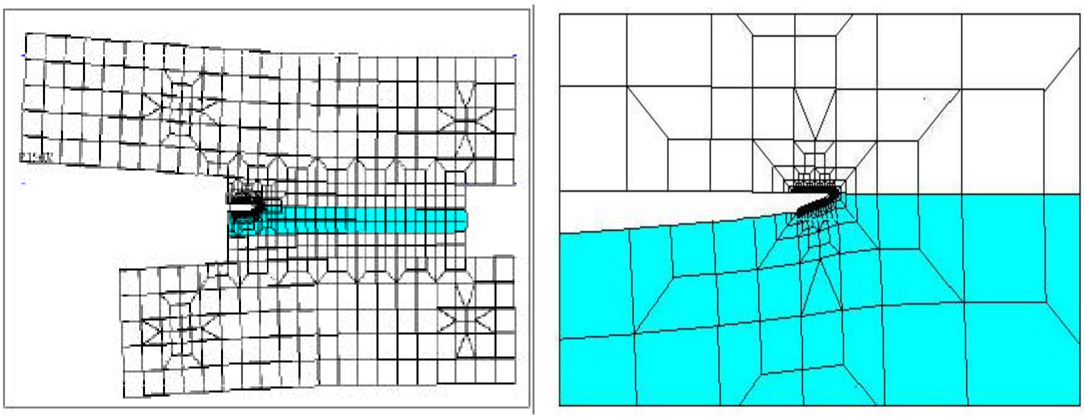


Figure 5- Deformed cleavage finite element model showing the adhesive layer and the propagated crack along the interface, whole model and the crack tip area at 3 mm

Mode-I Analyses

To calibrate the tripping strain, a number of analyses using different tripping strains were performed and the failure predictions were compared with the experimental failure load. Using the calibrated values of tripping strain, finite element analyses were performed of the cleavage model with rupture elements incorporated along the crack line. The analyses were repeated for a number locally refined crack tip locations corresponding to a range of crack lengths from 0.0 to 3.0 mm. Mode-I predicted failure loads were obtained. Results, showing the variation of the normalised (based on experimental failure load for mode-I non-cracked specimen) experimental and predicted failure load with the crack length, are plotted in Figure 6.

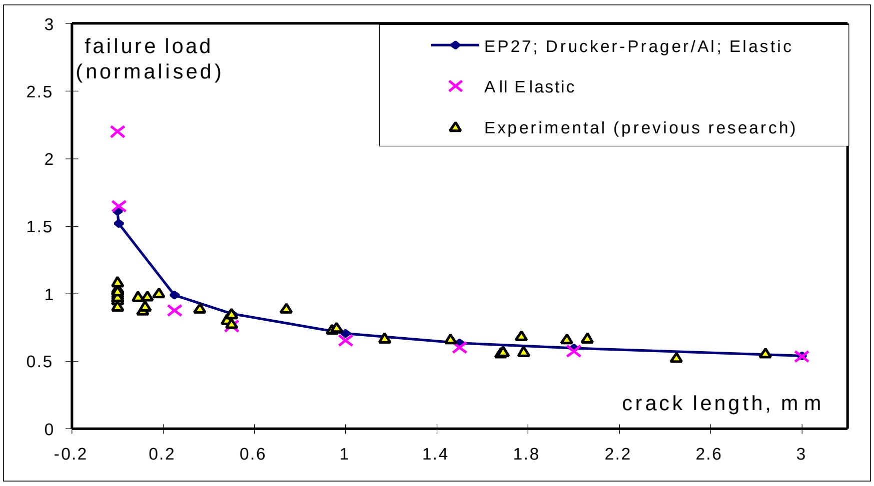


Figure 6– Mode-I results for failure load in cleavage test specimen at different crack lengths based on different continuum models compared with the experimental data

Mixed-Mode Analyses

Similar analyses were used to validate the modelling technique for failure prediction under mixed mode loading. The cleavage mesh with the localised refinement, described earlier in this chapter, was used for all mixed mode analyses. The calibrated tripping strain used for mode-I failure prediction was applied. The results appear to be in good agreement with the experimental results corresponding to the mixed mode loading as shown in Figure 7. This is a remarkable achievement as it suggests that in a plastic continuum the average strain level, in the direction perpendicular to the crack, dominates the condition of propagation of the crack regardless of the loading mode, provided that the appropriate material model is used.

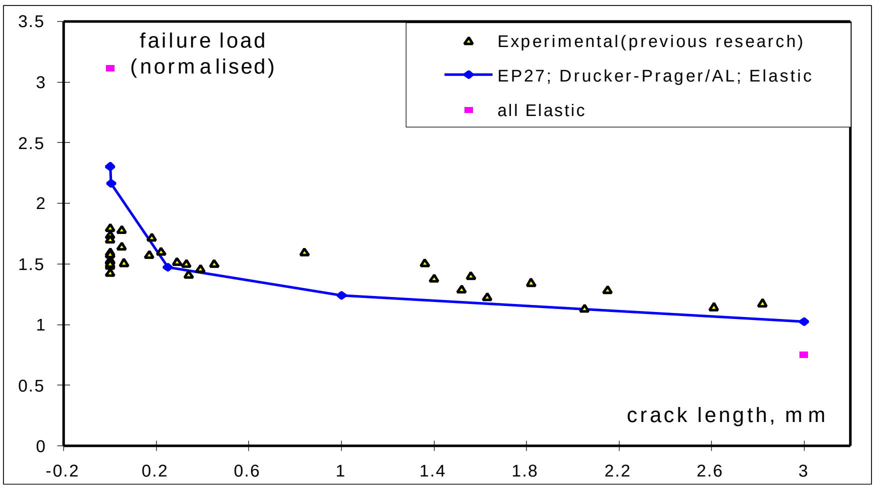


Figure 7– Mixed mode results for the failure load in cleavage test specimen at different crack lengths compared with the experimental data

Concluding Remarks

A failure prediction technique that uses a local damage based rupture element was extensively assessed through the integration of these elements along the crack line of a cleavage model. Continuum plasticity was included and both cracked and non-cracked configurations under mode-I and mixed mode loading were analysed.

Using this technique consistent rupturing energies were obtained although the unloading process of rupture elements was not controlled from the energy point of view. Thus progressive crack propagation in plastic continuum was successfully represented. The failure prediction based on this rupture element was significantly improved by using a more realistic continuum material model. This sort of prediction accuracy cannot be obtained when using an elastic continuum.

Good failure prediction for all loading modes was achieved using a single failure criterion. Thus the failure prediction technique was found to be mode independent. This is a noteworthy and important achievement

The use of the modelling technique applied to both mode-I and mixed mode loading in plastic continuum would suggest this approach as a promising method in achieving a framework for predicting failure initiation and propagation in generalised continuum.

References

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[3] Hadidimoud S, Crocombe AD and Richardson G, WCARP 1, pp 219-222, Germany, 1998

[4] Hadidimoud S, Crocombe AD and Richardson G, EURADH 2000, France, 2000

[5] Xie M and Gerstle WH, J Eng Mech, 121-12, pp 1349-1358, 1995

Aknowledgement

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