5-b-27: LOCAL DAMAGE BASED MODELLING OF PROGRESSIVE CRACK PROPAGATION

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Abstract

Following the line of previous work ([1] and [2]), special local damage based rupture elements have been developed that predict the failure load in an elastic continuum and, further, are also capable of representing the process of failure initiation and propagation in the presence of plasticity. It has been shown that in the case of an elastic continuum this approach is an alternative to conventional LEFM techniques with the advantage of presenting progressive propagation and direct calculation of the failure load. Investigations have revealed that with elasto-plastic continuum, the unloading process cannot be controlled independently; it is also governed by the continuum conditions. The model has been verified through its application to a pre-cracked compact tension specimen model. The predicted failure loads are found to be in very good agreement with the experimental results obtained in the earlier research.

Introduction

Due to the extensive use of adhesive materials in structural bonding on one hand and the lack of a unified design tool for failure prediction in such structures on the other hand, the issue of development of material models and failure prediction techniques has received much interest in recent years. Related works on energy based modelling of crack propagation [3] and the use of crack bridging displacement controlled elements in modelling de-lamination in composites [4] can be found in the literature. Development of a local damage based approach to modelling crack propagation and predicting the corresponding failure load has been discussed. The suggested model has been assessed through the comparison of its prediction with the experimental results from previous tests carried out on pre-cracked compact tension specimens made from an epoxy adhesive.

Development of rupture elements

The load-displacement behaviour of the rupture elements is shown in Figure 1. The rupture elements are initially rigid-like and represent connectivity along the crack line. The system is then loaded in a quasi-static manner. Once the continuum reaches a critical state, the rupture elements are tripped (loose rigidity) and extend following one of the profiles outlined in figure 1. The line of elements along the crack line are sequentially tripped and released throughout this process. The load sustained by the system at this stage is referred to as the failure load. A convergence algorithm is used to prevent analysis instability at the turning points of the stiffness of the rupture elements (i.e. tripping and release)

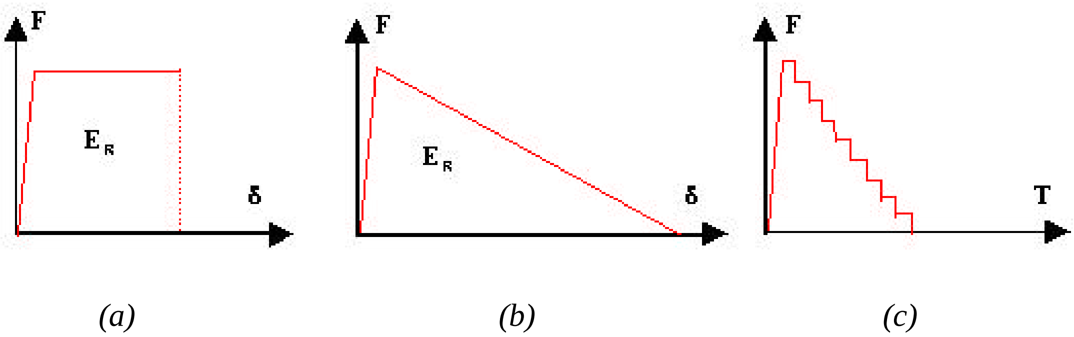


Fig. 1- Various loading-unloading schemes for rupture elements

- **Strain tripped rupture element with no unloading (type 1)**

This rupture element follows the load-displacement scheme of figure 1(a). The element's stiffness is set to zero when the critical continuum strain is reached. The rupture element will then continue to extend at a constant load, corresponding to the tripping condition. This represents crack opening but does not include unloading and release states. Using a series of rupture elements of this type along the crack line of a CT specimen model, an alternative solution to the conventional LEFM has been achieved. The area under the curve (E_R) represents the energy absorbed by these elements. The element definition is illustrated in figure 2.

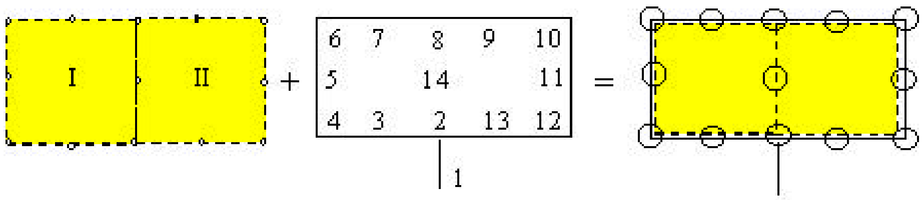


Fig. 2- Correlation of rupture elements (types 1 and 2) with the continuum elements

- **Strain tripped rupture element with energy based unloading (type 2)**

A direct representation of the process of crack propagation and failure prediction can be achieved by including unloading and release in the rupture element definition. The scheme of figure 1(b) absorbs a critical value of energy (E_R) during unloading. The element itself is quite similar to that of figure 2.

- **Strain tripped rupture element with time based unloading (type 3)**

Use of the previous types of rupture elements in modelling progressive crack propagation in an elasto-plastic continuum, generally results in a non-sequential release of the elements causing an irregular crack front opening profile. This phenomenon, referred to as "locking", is due to the dependence of the level of plastic deformation around the crack tip area on the loads acting on the rupture element. Studies indicate that the unloading curve may not be controlled independently in presence of plasticity. To overcome this problem a rupture element using the multi-step time based unloading profile as shown in figure 1(c) has been developed. This element uses an average strain based on nodal displacements to detect the tripping condition and has therefore a much simpler structure as shown in figure 3.

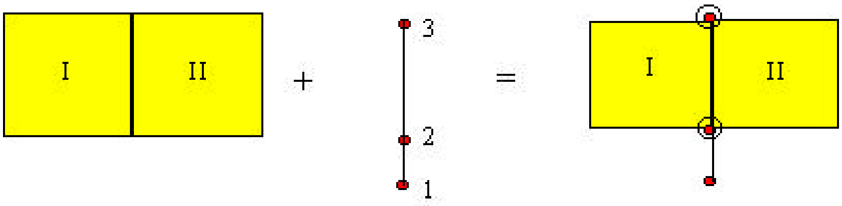


Fig. 3- Correlation of rupture element type 3 with the continuum elements

The continuum finite element model

The CT specimen model of an epoxy adhesive under mode I loading for which experimental data was obtained in previous research has been used in this work. The continuum is modelled using 8-node quadrilateral elements and a refined mesh has been applied to the crack tip area as shown in figure 4. The smallest element size is around 1.5 μm.

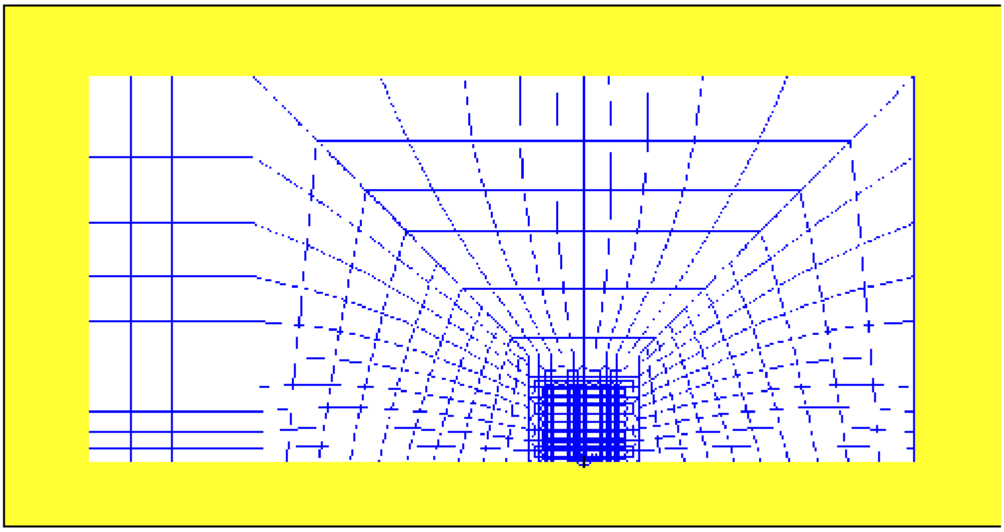


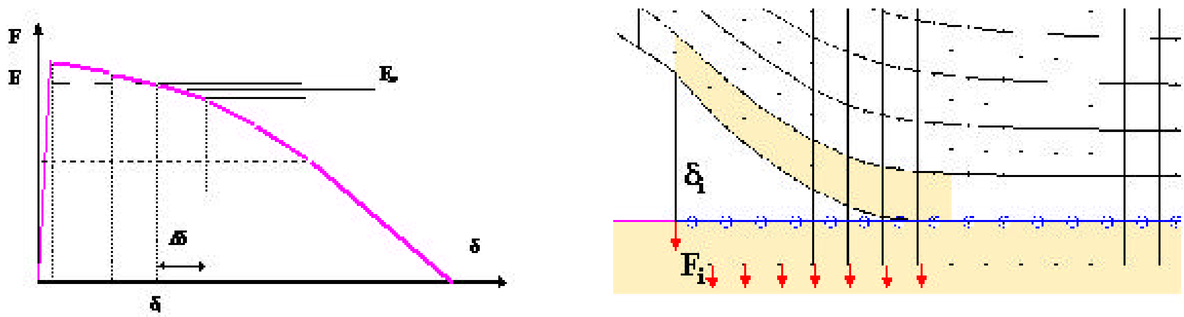
Fig. 4- CT finite element model (half of the specimen) with crack tip mesh refinement

Failure modelling in elastic continuum

The rupture elements of type 1 and 2 have been used to model crack propagation in the CT specimen described above. A series of the rupture elements, forming a line of crack bridging elements, have been integrated along the assumed crack line in the continuum model and non-linear finite element analysis has been performed. Figure 5 shows the formulation used to calculate the energy release rate from the results of the analysis of the model that uses rupture elements of type 1. The critical value (fracture energy) is compared with the result of LEFM crack closure technique in table 1. The good correlation validates the proposed solution. Using the rupture energy with the energy based unloading-release scheme (type 2), a direct prediction of the failure load has been achieved and the process of progressive crack propagation in the elastic continuum has been successfully presented as illustrated in figure 6.

scheme	No element, LEFM	Element (type 1)	Element (type 2)
Load, N	Virtual crack closure	Method Fig. 5	instability
64	143.01	144.11	143.64

Table 7.3- Comparison of G_{Ic} values from the developed technique of modelling crack propagation in elastic continuum with the conventional LEFM



$$G_I=2\{\Sigma(F_{av}\,\Delta\delta)\}/Lt, \quad F_{av}=(F_i+F_{i-1})/2, \quad \Delta\delta=\delta_{i-1}-\delta_i$$

Where L, t are element length and specimen thickness respectively

Fig. 5- Virtual rupture element extension technique for calculation of G_I from "no softening" elements

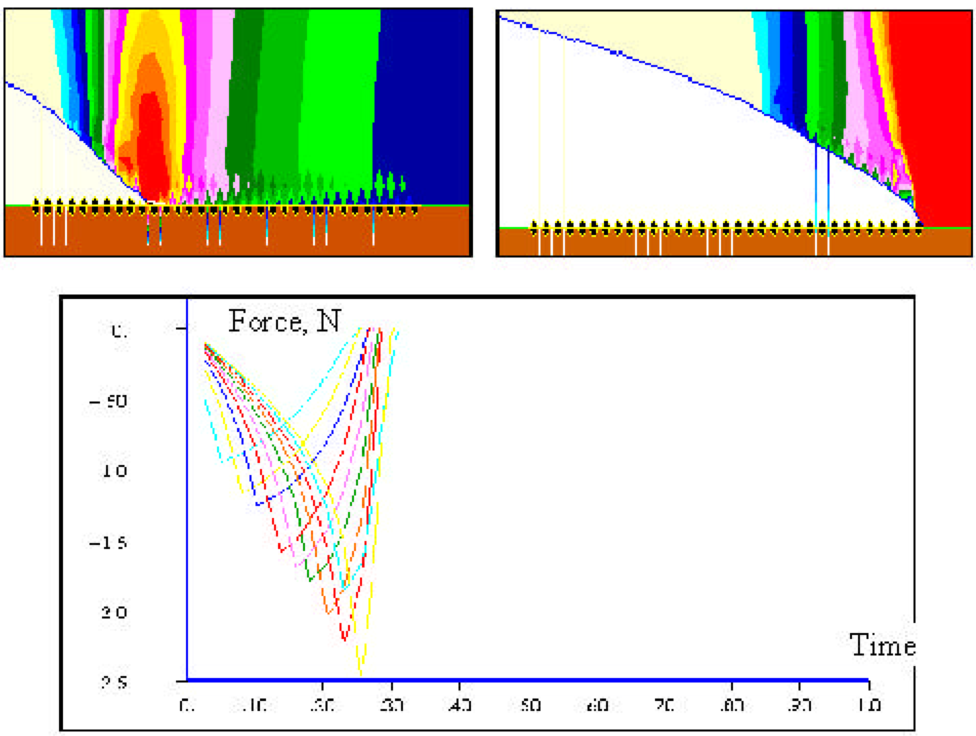


Fig. 6- Progressive crack propagation in elastic CT model using softening elements Top: formation of the process zone, Bottom: rupture elements' load history

Failure modelling in plastic continuum

Using rupture elements of type 3 the technique could provide promising results in failure prediction within an elasto-plastic continuum. An exponent Drucker-Prager model was used for this purpose. A physically justifiable presentation of progressive crack propagation was obtained as shown in figure 7.

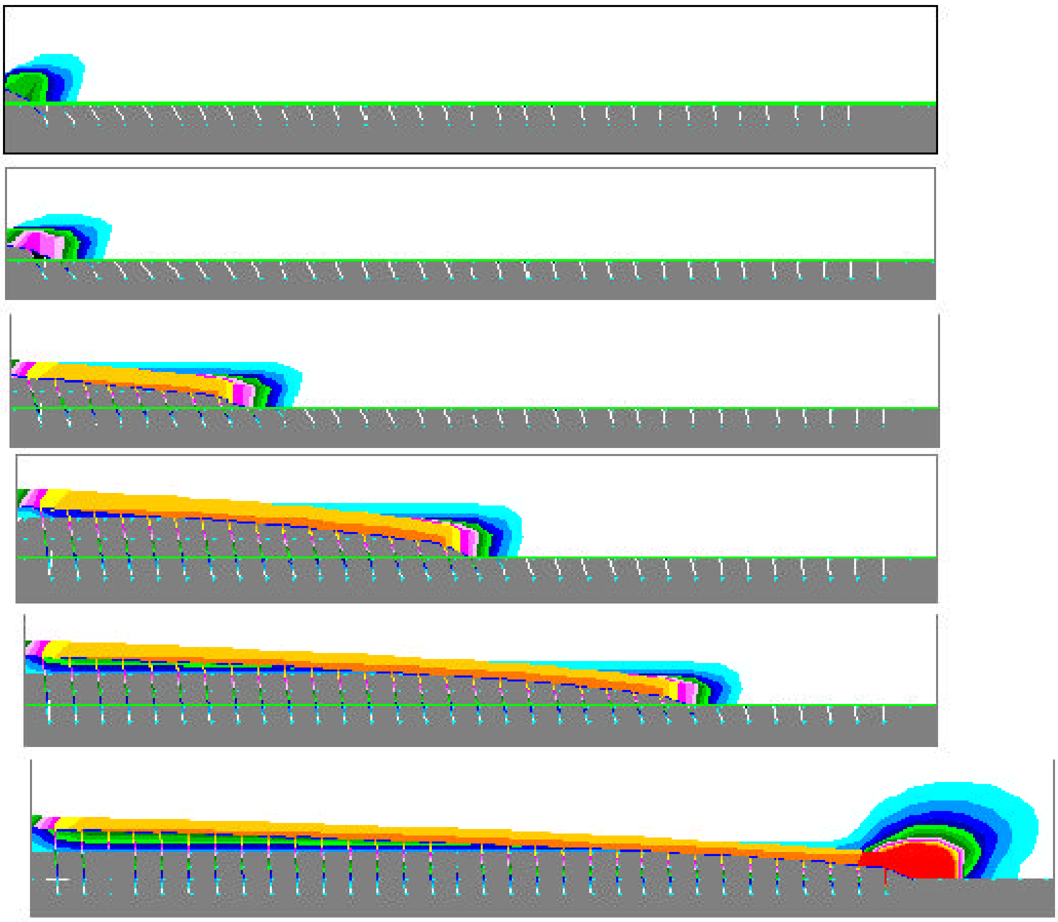


Fig. 7– Progressive crack propagation in CT model using rupture elements with time based unloading and exponent Drucker-Prager continuum material model

Concluding remarks

The strain tripped rupture element with no unloading included can be used a an alternative to the conventional LEFM when integrated into the elastic continuum.

Using the strain tripped rupture element with energy based unloading, it is possible to directly predict the failure load of a cracked elastic structure. This is an improvement to the application of LEFM as a post-processing design tool.

In the presence of plasticity, although the rupture elements of types 1 and 2 are capable of extending the plastic zone with the process zone, they do not provide a proper representation of the sequential opening of the crack front. This is referred to as the "locking" problem

Use of the rupture elements with time based unloading overcame the problem above. This rupture element was successfully applied to the cracked CT model and a physically justifiable representation of the crack propagation process was achieved

All the rupture elements introduced in this work are potentially applicable to the non-cracked problem as well as the cracked one. However the use of these rupture elements to address crack initiation is not discussed in this work and has been considered elsewhere ([5-6].

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