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Use of a local damage model to determine rupture

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Abstract

A finite element based local damage model has been developed which simulates the process of crack initiation/propagation using a line of crack-bridging energy absorbing elements in the form of special non-linear springs. Plastic deformation in the surrounding continuum has been accounted for in this model. The effect of the near crack tip traction forces on the stress/strain distribution along the crack line for elastic and elasto-plastic continuum response is also investigated.

1 Introduction

Local damage based modelling approaches in the form of energy based (i.e. Xie and Gerstle, 1995) and strength based cohesive crack models as well as the crack-bridging approach have received much interest as promising techniques to model the process of rupture. Following their previous works, Tvergaard and Hutchinson (1996) have used a cohesive zone model to characterise the fracture process in which the effect of the crack tip by plastic straining is incorporated. Cohesive zone type interface models have also been presented by Needleman (1992). A crack bridging element approach on the other hand has been used by Cui and Wisnom (1993) to model delamination in composites and followed by the work of Wisnom (1996) in which an interface user element has been developed to model the interfacial region between the linear elastic composite plies. Stress-relative displacement relations representing localised yielding which occurs at a certain stress level are used to characterise the infinitely thin resin rich layer between the composite plies. Failure is represented by a critical displacement. In this paper the energy controlled rupture model proposed by Crocombe et al. (1995) in the form of a bilinear spring element which represents failure in linear elastic continuum has been followed. A series of non-linear spring elements are defined in the form of user subroutines to run with ABAQUS finite element code. The main objective is to account for plasticity in the continuum and to model failure based on rupture energy represented in the form of the energy absorbed by the user defined spring elements.

2 FEA

A series of 2-D finite element analyses is performed using both the non-linear spring elements available in ABAQUS element library and the user-defined elements. A compact tension (CT) specimen has been used with a refined mesh along the crack line. Due to symmetry only half of the specimen is modelled. Both elastic (e) and elastic-perfectly plastic (ep) continua have been modelled. Both have a tensile modulus of 2600 MPa and the latter has a flow stress of 47 MPa.

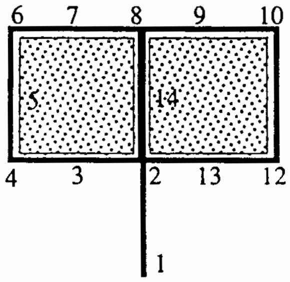
3 Stress-tripped rupture element

Initially a simple 2-node bilinear ABAQUS spring element (SP2) was defined. This damage element is activated at a given level of stress (i.e. a certain spring force) which remains constant. A line of these elements along the assumed crack line were linked between the corner nodes of the continuum elements and the ground nodes. In the case of 8-node quadrilateral elements, displacements of the mid point nodes on the crack line were constrained using linear multi-point constraint equations. The main limitation of this element was that it could not be linked to a level of plastic deformation in the continuum and thus only a linear elastic continuum could be modelled correctly. When used in a CT specimen this model provided results that correlated excellently with Linear Elastic Fracture Mechanics (Table 1). The results were almost independent of the stress level at which the springs were activated. Two values of 53.3 and 80 MPa (tripping forces of 0.5, 0.75 N) were used to provide results. Once the tip element was tripped it could produce the energy release rate for the applied load. In fact as long as the continuum plasticity is not included this model works as an alternative to the Crack Closure Technique. This model was also run with elastic-perfectly plastic material model using a tripping force of 0.85 N and the value of spring energy divided by the continuum element area was compared with those obtained from virtual crack closure technique to confirm that the user model is working properly although these result do not present any physical concept. Based on the applied load (60 N) and the tripping force the damage zone size was estimated as 0.05 and 0.0234 mm for linear elastic and 0.0172 mm for elasto-plastic model.

4 User defined strain-tripped rupture element

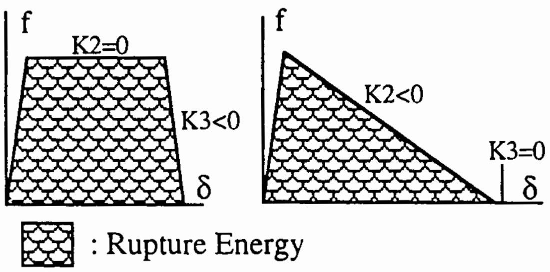
- **Overview**

To enable the element to be compatible with plasticity in the continuum elements a special element was developed which could be activated at a specified level of continuum plasticity. These are tripped based on continuum strains and have been analysed in combination with different elasto-plastic continuum models. User element "SP814" is a 14-node special non-linear spring element having 13 nodes coincident with the two continuum 8-node elements to which it is linked and one ground node (fig. 1-b). The element changes state from K_1 (initial stiffness, nearly rigid compared with the continuum) to K_2 (either zero or negative stiffness as shown in fig. 2) at a specified strain level in the continuum. The element is finally released when a critical level of energy is absorbed by the spring. The final stiffness (K_3) is either a high negative value (fig. 2-a) or zero (fig. 2-b). The rupture displacement is determined using the critical energy and the spring force at the tripping strain. Using this model, rupture may always commence at a consistent level of plastic deformation and the energy absorbed by the user element may present only the separation energy as an inherent material parameter.



SP814

Fig.1- User element



(a) (b)

Fig.2- Force-Displacement relations

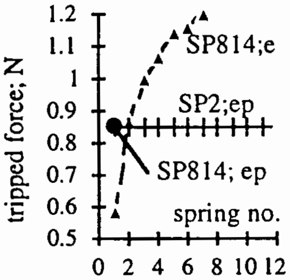


Fig.3- Spring forces when tripped

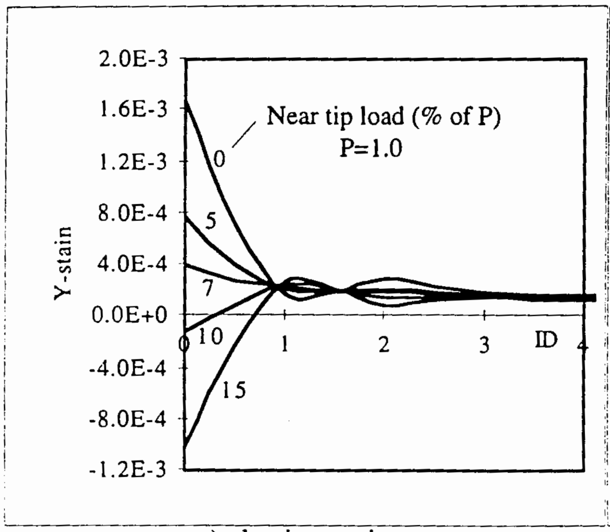
- **Strain controlled rupture with zero softening**

Initially an analysis of the CT specimen with an elastic continuum was undertaken with a tripping strain of 1.7%. The result for the spring element energy shown in Table 1 is not entirely consistent with the LEFM and stress tripped elements as the energy absorbed during unloading has not been calculated explicitly but has been approximated in the same way as the stress tripped elements and this is not exactly correct. It should be emphasised however that once the continuum non-linearity is included in the analysis only the strain controlled elements are expected to present rupture correctly and to produce the same critical damage parameters for all analysed configurations.

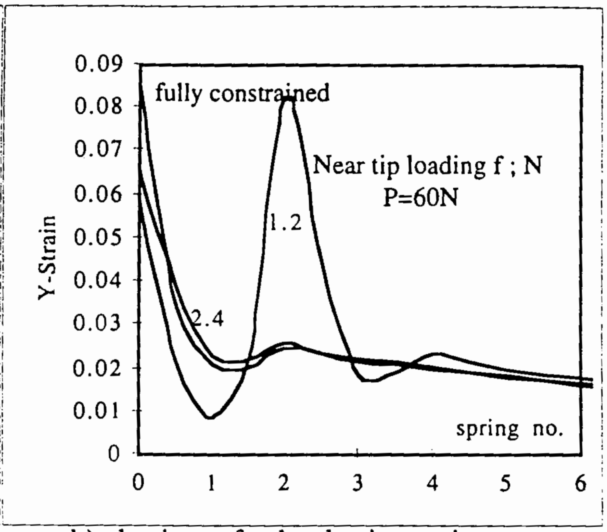
Analysis of the CT specimen model using these elements in conjunction with elasto-plastic material behaviour resulted in a fluctuating strain field around the crack tip area after the first element (or the first few elements depending on the tripping strain) was tripped. This prevented some of the elements along the crack line from reaching the specified tripping strain. In consequence this changed the order in which these elements were tripped. This was not noted in the linear elastic continuum analysis. The tripping strain used in this analysis was adjusted to provide comparable results with those of the stress controlled elements. The corresponding strain (2.7%) at the tripping force (0.85 N) of the tip element (stress tripped) was used as the tripping strain. A typical failure load of 60 N applied to the CT specimen model resulted in tripping of the tip spring only (this load had tripped 11 stress controlled elements at 0.85 N). A much higher load was required to trip further elements. This is due to the increasing tripping forces of the strain controlled elements along the crack line as shown in fig. 3 for elastic continuum (SP814-e). A parametric study on the effect of the near crack tip traction on the stress/strain distribution along the assumed crack extension line was performed to investigate this effect. The high dependence of stress/strain field on the level of these traction forces was confirmed. This effect is shown in figs. 4-a and 4-b. In the case of elastic continuum with zero load ahead of the crack tip, the strain field takes the normal singular distribution. As traction increases the strains pass through the zero singularity point (i.e. Dugdale). Further increase results in a compressive singular field. However there is no significant fluctuation of strains in this case (Fig. 4-a). In the case of elastic -perfectly plastic continuum a number of near tip nodal constraints are replaced with different levels of uniform traction. This resulted in significant fluctuation in the strain field. As the traction approaches the initial reactions at the constrained nodes the strain distribution approaches the normal state (Fig. 4-b).

P=60N	LEFM Crack closure	Stress tripped rupture element	Strain tripped rupture element
Gc (Jm-2)	126.6	126.2	97.3

Table 1- Energy release rate at failure load for a CT specimen with elastic continuum



a) elastic continuum



b) elastic-perfectly plastic continuum

Fig. 4- Effect of near tip traction forces on stain distribution along the crack line (near tip forces (f_i) based on uniform stress distribution)

5 Future work and conclusion

Due to the high dependence of the strain field on the near tip traction which affected the tripping process, the initial force-displacement relation for the spring elements (fig. 2-a) was replaced by that of Fig. 2-b in which spring softening occurs as soon as the element is tripped. At the current stage the model is subjected to some minor problems in releasing the spring after the critical energy level is absorbed. These are mainly routine and once they are sorted the element will model rupture based on critical damage parameter(s) (i.e. the rupture energy and the tripping level of plasticity). The future work includes adjusting these parameters to fit best with the rupture process and to provide reasonable results for different configurations of loading and geometry. Different available material models including Von Mises and Drucker-Prager will also be examined to evaluate the validity of the proposed model.

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