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PREDICTION OF DUCTILE CRACK GROWTH IN POLYETHYLENE USING MEASURED TRACTION – SEPARATION CURVES

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ABSTRACT

An accurate prediction of ductile fracture employing a cohesive zone modelling approach depends critically on the choice of the cohesive law used to characterise the material in the crack tip damage zone. A successful new method for direct experimental measurement of this law in tough pipe grade polyethylene has been described recently. Results indicate significant and quantifiable effects of rate and geometrical constraint on the measured cohesive zone parameters: energy of separation and cohesive strength. Here we present a cohesive zone model within the finite volume method to predict crack initiation and propagation history in a tough PE80 type pipe grade polyethylene. A family of experimentally measured rate dependent traction curves is used as a means of establishing the local fracture process. Model predictions indicate that the cohesive zone parameters are not constant but change with both time and position along the crack path depending on the prevailing rate and degree of constraint. By accounting for rate and constraint effects in this manner it should be possible to maintain perceptible physical validity in the representation of the behaviour of the crack tip process region, something not always apparent in many existing cohesive zone models.

KEYWORDS

Crazing, Polyethylene, Cohesive zone model, Ductile crack growth

INTRODUCTION

Conventional fracture mechanics methods are unable to achieve meaningful predictions of ductile crack growth in present-day high strength steels or tough engineering polymers. This is because for these materials, the choice of a single characterising fracture parameter such as a unique stress intensity factor or energy release rate is often a wholly inadequate representation of the material behaviour. The introduction of a material specific process zone ahead of the crack tip appears to provide a means of overcoming this limitation. Cohesive zone models utilise some form of traction – separation law to describe the material degradation and load carrying capacity due to local deformation within the zone. Using this approach it becomes possible to segregate the local work of fracture from general plasticity within the continuum and thus to predict the global fracture response from a description of the local microstructural behaviour.

Medium density polyethylene may exhibit different modes of fracture, such as rapid crack propagation or slow crack growth, depending upon the prevailing loading rates and temperature. Both rapid crack propagation and slow crack growth are believed to be associated with the formation of a craze ahead of the crack tip. During slow crack growth large scale deformation does not occur, but rather the damage is highly localised. It is this fact that allows the postulation of a thin layer of material, in the most simple case along a prescribed single crack path with an associated cohesive law, to be used for the prediction of crack growth under low rates of loading. General applications of the cohesive zone model include modelling of ductile fracture under quasi-static loading [1] and the analysis of dynamic fracture problems [2,3]. It is increasingly becoming clear, however, that for such models to retain physical reality the cohesive zone parameters must be updated with time, allowing for local mechanisms such as rate dependent hardening and softening or variations in constraint along the crack path to be taken into account in the quantification of the local work of fracture [4,5,6,7]. Pandya and Williams have reported a scheme to measure the cohesive zone law as a function of rate and constraint [8,9] in a range of polyethylenes. These measurements were used for the numerical prediction of crack growth in a rate independent analysis using the finite volume method, which showed reasonable comparison with the measured macroscopic load behaviour [10]. Here we include rate dependence in this numerical scheme by incorporating a family of measured traction – separation curves into the model.

MEASUREMENT OF COHESIVE LAW

The techniques used in the measurement of cohesive zone parameters in tough polyethylene have been described in detail elsewhere [8,9]. In summary, rectangular bars were cut from pressed sheet of dimensions of 16 x 16 x 100 mm and circumferential notches were introduced by rotating the specimen in a lathe so as to produce a highly constrained circular ligament within a square section bar. The specimens were then tested in tension on a screw driven Instron. As the damage is confined within this ligament it is possible to measure the localised traction – separation behaviour of a given material over a range of applied rates. Both notch depth, which affects the degree of constraint, and the applied displacement rate have an effect on the measured law as indicated in Figure 1.

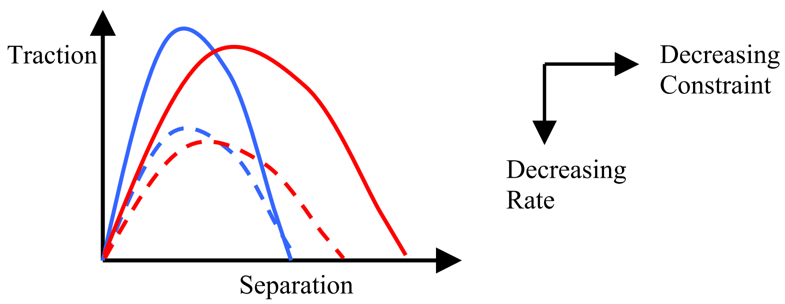

Figure 1: Schematic illustration of the effect of changes in constraint and rate on the measured cohesive law

METHODOLOGY

Results are presented for a pipe grade polyethylene, with a density of 940 kgm^{-3} and a Poisson's ratio of 0.3. A three point bend geometry was modelled within the finite volume method using a 2D plane strain analysis. A cohesive law was used to describe the local separation along a prescribed crack path while the surrounding bulk was treated as elastic-plastic using incremental J2 flow theory. Numerical simulations were performed at an applied displacement rate of 0.1 mm/min and the predicted load – time traces compared to experimental measurements. The boundary conditions for the model are shown in Figure 2. Boundaries 1, 2, 3 and 5 were traction free while the prescribed traction – separation law was applied to boundary 4 along a single layer of cells. The specimen was assumed to be supported on a friction free roller. Making use of geometrical symmetry only half the specimen was modelled.

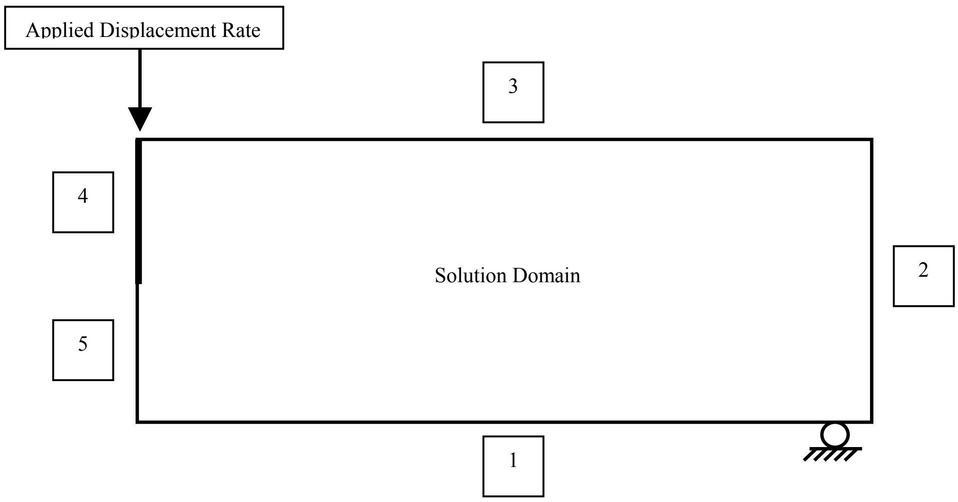

Figure 2: Boundary conditions for the three point bend geometry

Both a single rate and rate dependent analysis was performed. In the first case the initial crack tip opening rate in the three point bend geometry was estimated as 0.006 mm/min and a traction - separation curve measured at that rate in a deep notched, high constraint geometry was used as the cohesive law for all cells along the crack path. In the second case a family of traction - separation curves measured over a range of displacement rates was incorporated into the numerical method. A fully implicit updating procedure was employed to determine the holding traction for each cell by calculating the values of cell displacement and displacement rates via a two way iteration process within each time step. Mesh sensitivity studies were performed and indicated that convergence in the predicted load was achieved for a cell size of 0.1 x 0.1 mm corresponding to a total of 112 cells along the prescribed crack path.

RESULTS

Single Rate Analysis

Traction – separation curves at 0.006 mm/min and 0.004 mm/min were used to perform a single rate analysis and the load – time predictions were compared to the experimentally measured result as shown in Figure 3.

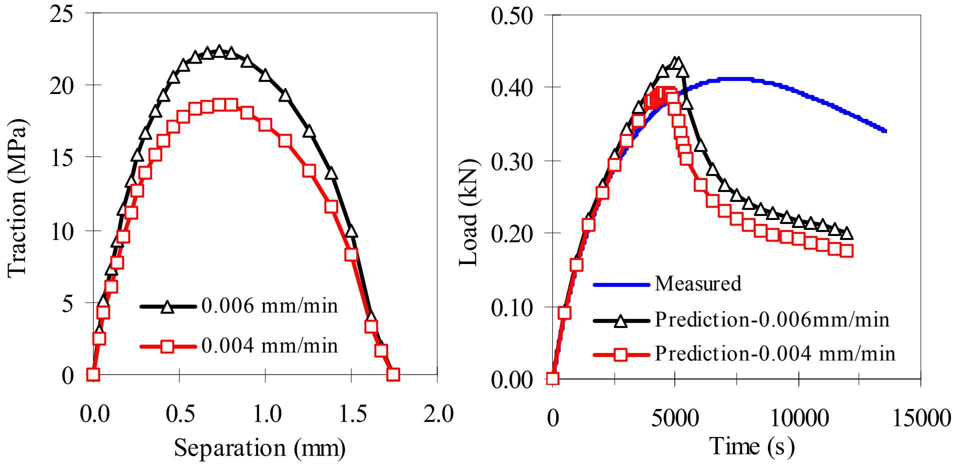

Figure 3: Load – time predictions using a fixed constraint, single rate cohesive law

Figure 3 shows that with a fixed constraint, single rate fracture criterion it is possible to accurately predict the initial part of the load – time curve and the onset of crack initiation. However, the load falling region of the experimental result is not adequately predicted by this method. It is also clear, comparing the two results, that the predicted peak load is directly dependent on the magnitude of the cohesive strength. Cell opening rates and holding tractions for the single rate analysis of 0.006 mm/min were computed at different positions along the prescribed crack path and are shown in Figure 4.

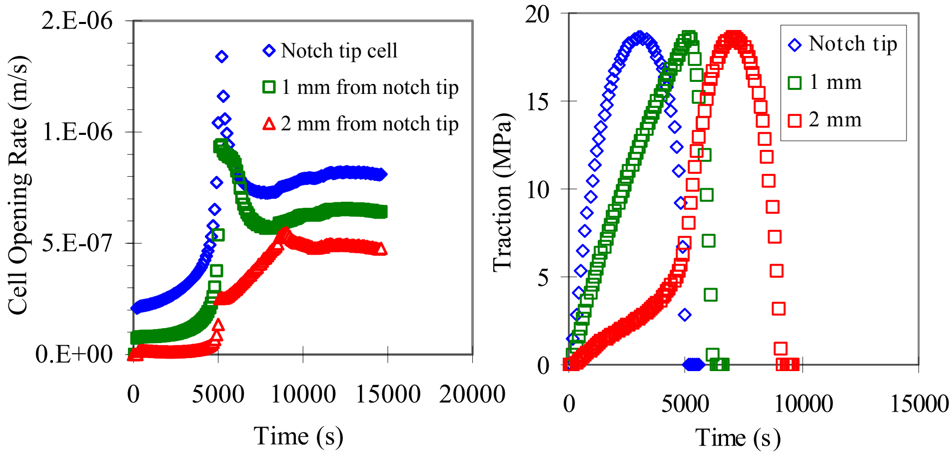

Figure 4: Cell opening rates and holding tractions as a function of time using a fixed constraint, single rate cohesive law

Figure 4 shows that cell opening rates change considerably with both time for a given cell and with position along the crack path, suggesting the need for rate dependence to be incorporated into the analysis.

Rate Dependent Analysis

A family of rate dependent curves was generated by measuring the traction – separation law in a high constraint geometry over a range of displacement rates. Indications from experimental studies on low constraint geometries had suggested that the main effect of a reduction in constraint was to increase the break separation values of the measured curve. On this basis a set of equivalent low constraint traction curves was postulated from the measured high constraint curves. Figure 5 shows a family of both high and low constraint curves along with the associated cohesive law for the notch tip cell, which emerged as a prediction from the model in each case rather than having to be prescribed in advance. For both set of curves, the predicted notch tip holding traction for a given displacement and displacement rate was determined by interpolating between the curves using the method outlined earlier. The predicted rate dependent cohesive law is seen to deviate substantially from the single rate curve of 0.006 mm/min shown earlier in Figure 3, particularly in the decohesive region where cell opening rates changed rapidly.

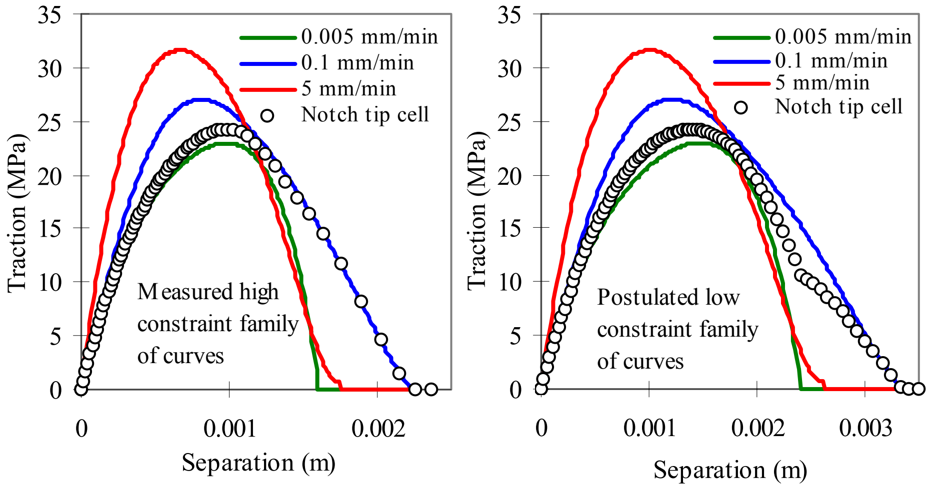

Figure 5: Prediction of the local work of fracture at the notch tip using a family of rate dependent high and low constraint traction curves

The predicted load – time response for the different models discussed above is shown in Figure 6.

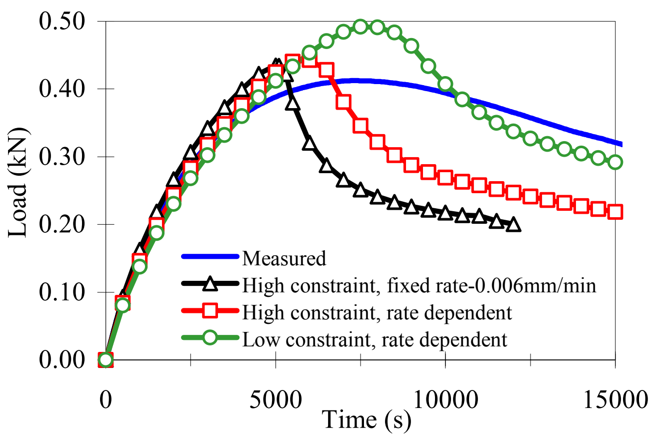

Figure 6: Load – time predictions for different local fracture criteria

Figure 6 indicates the need for constraint variations to be included in the choice of cohesive law, perhaps in a similar manner to the incorporation of rate dependence outlined above. While the high constraint, rate dependent analysis in Figure 6 improves the prediction of crack initiation, it cannot accurately predict global softening, where it is believed that the effect of different prevailing constraint factors along the crack path is not adequately modelled by a fixed constraint cohesive law. The prediction achieved using the family of low constraint curves matches the global softening behaviour more closely but over predicts the global energy dissipated prior to the initiation of crack growth. It seems, therefore, that neither rate or constraint dependence of the cohesive law can be prescribed in advance and that the time dependence of both must be incorporated into the analysis.

CONCLUSIONS

A physically based cohesive zone model was described using experimentally measured rate and constraint dependent traction – separation curves to establish a local cohesive law. Introduction of rate dependence in the choice of the cohesive law improved the prediction of crack initiation but was unable to adequately describe the global softening behaviour. It was suggested that it may be necessary to monitor and update the choice of holding traction at any point in time and position along the crack path in terms of variations in constraint as well as rate. This indicates that the cohesive law cannot be considered to remain constant with crack growth and that a single set of parameters are not sufficient to characterise rate dependent fracture in tough engineering polyethylenes.

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