

MODELLING THE EFFECT OF A DISCRETE INTERPHASE ON THE FRAGMENTATION PROCESS IN POLYMER MATRIX COMPOSITES.

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SUMMARY

A 2 dimensional axisymmetric finite element model has been developed which investigates the effect of a fibre fracture and the subsequent stress redistribution to different interphase and matrix combinations. Three purely elastic and two elasto-plastic components were defined and used in various combinations to create five model matrix / interphase systems. A purely elastic matrix or interphase was shown to develop strain in the resultant fibre fragments exponentially. Inclusion of an elasto-plastic matrix or interphase lead to a linear strain transfer where yielding occurred and an increased stress transfer length. The inclusion of an interphase with different properties to the matrix and fibre highlighted the possibility of tailoring fibre coatings and matrices to give better strength or toughness or impact performance by altering the stress transfer or positively affected length following fibre fracture.

KEYWORDS: Interphase, Finite Element Method, Fragmentation, Plasticity,

INTRODUCTION

The single fibre fragmentation test is an established method for examining the micromechanics of the fibre-matrix interface in composite materials. However, the test is dependent upon data reduction schemes for quantitative results, which are inherently based on a number of micromechanical models. The original studies of Cox [1] and Kelly-Tyson [2] still form the basis of most models even though the fundamental assumptions are not observed in practice. The Cox analysis described all constituents as elastic, whilst the latter was developed for metal matrix systems where matrix yield occurs, although it was subsequently adapted to a debonded fibre. For fragmentation studies the matrix is invariably elasto-plastic in nature.

Tripathi *et al* [3], included the elasto-plastic nature of the resin into a finite element model, through the inclusion of a digitised true stress/ strain curve. The results showed that inelastic deformation of the matrix (originating at the fibre-end stress concentration) in the form of yield and cold draw, significantly affected the stress transferred to a short fibre. This idea led to the proposal that the Cumulative Stress Transfer Function (CSTF) could be employed for the quantitative analysis of the fragmentation test.

The problem is further complicated by the presence of an interphase region around the fibre. Interphases are inevitably present because of the sizing resins on the fibres used in composite manufacture. Thus, an additional layer of material with unknown properties may exist.

Previous studies have shown that such a layer also has a significant effect on the load transfer to a reinforcing fibre [4].

A finite element model based on a fully embedded fragment which excluded end bonding has been shown to overestimate the effect of a discrete interphase on the stress transfer process [5]. Therefore, it is essential to include a fibre-break in the model. This paper describes a finite element study of a broken fragment surrounded by a discrete interphase in a matrix of various properties.

EXPERIMENTAL

Finite Element Model.

A two dimensional axisymmetric finite element model has been generated which analyses the effect of a single fibre break on the stress state in a continuous fibre. The model is a 2 dimensional axisymmetric representation of 3 concentric cylinders, one each for fibre, interphase and matrix. The model is further simplified by symmetry.

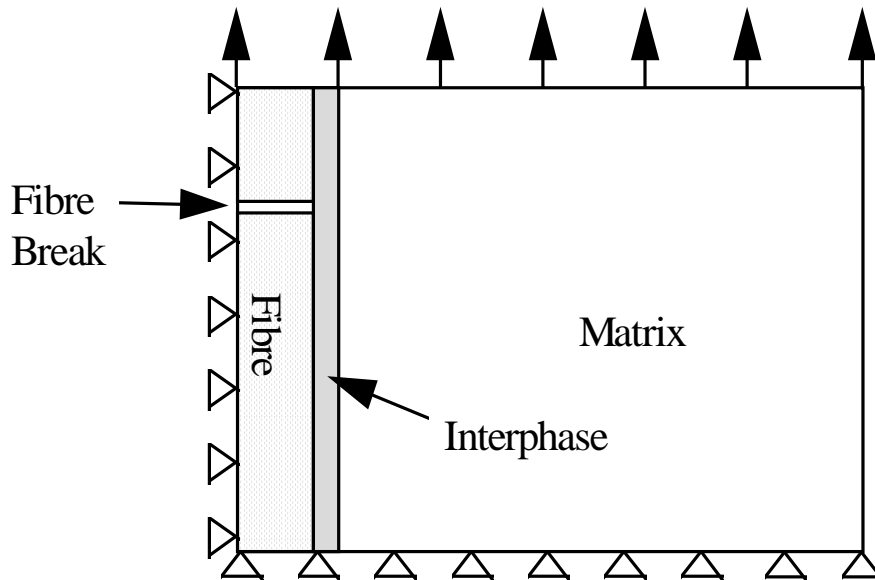


Figure 1. Schematic representation of model.

The model was constrained on the bottom edge in the axial direction and on the left hand side in the transverse direction, for symmetry. To model a fracture event, a strain of 1% was applied to the top edge of the model, and the analysis carried out. Subsequently a row of elements in the fibre was selected and 'killed'. The action of element death effectively reduces the stiffness matrix of the selected elements to a near zero value, so the model behaves as if there is a gap in the fibre. The analysis was then continued to investigate the fibre fracture and stress redistribution events.

The geometry was chosen to represent a fibre in bulk resin, with an appropriate interphase layer. The resin thickness was chosen such that the stress at the free edge, furthest from the fibre, was only 1% of the maximum stress achieved anywhere else in the model, hence edge effects could be ignored. The fibre radius is 3.5 units, the interphase 0.7 units and the matrix 44 units. The current study considered only the results obtained for a fibre break occurring at 1% applied strain. At this load, fragmentation does not generally occur in practice, but the

model allows a comparison of how different matrix/ interphase systems respond to a break in the fibre.

The fibre break was induced asymmetrically into the model, so that the two resultant fibre fragments differ in length. This enabled a direct comparison with previous data from a short fibre fragment model with identical geometry [4].

The FEA model generation, meshing and solution were carried out using ANSYS 5.4 software [6]. 2D 1st order structural solid elements (type Plane 42) were used for the majority of the model with 2nd order 8 noded structural solid elements (type plane 82) directly around the fracture site, where significant deformation was expected. The model comprised 10965 elements and 11232 nodes. The FEA mesh was graduated to incorporate computational effort into the region directly adjacent to the fibre break and within the interphase, with less emphasis on the bulk matrix where fewer stress events take place.

Materials

Five model materials, based on the properties of resins used in composites manufacture [7] were chosen for the investigation of the stress redistribution on fibre fracture in different matrix/ interphase combinations. The materials were denoted by the following combination of letters, the first indicates the nature of the material as elastic (E) or plastic (P), and the second, the modulus and yield strength as high (H), medium (M) or low (L). These were:

- i) PM, a ductile material with medium modulus and yield strength.
- ii) PL, a ductile material with low modulus and yield strength.
- iii) EH, an elastic material with high modulus.
- iv) EM, an elastic material with the same medium modulus as PH.
- v) EL, an elastic material with the same low modulus as PM.

The fibre was modelled as glass. Properties of all the model constituents used are listed in Table 1.

Table 1. Properties of all constituents used in the analyses.

| Property | Glass Fibre | PM | PL | EH | EM | EL |
|--|--------------------|-------------|-------------|----------------|-------------|-------------|
| E (GPa) | 76 | 3.22 | 2.56 | 5.67 | 3.22 | 2.56 |
| Poisson's ratio | 0.25 | 0.36 | 0.369 | 0.31 | 0.36 | 0.369 |
| Tensile yield strength (MPa) | - | 59.9 | 40.8 | - | - | - |
| Tensile yield strain (%) | - | 3.62 | 2.88 | - | - | - |
| Cold draw strength (MPa) | - | 49.5 | 31.7 | - | - | - |
| Density (g/cm³) | 2.5 | 1.3 | 1.3 | 1.27 | 1.3 | 1.3 |
| Resins on which properties are based. | Glass | Epoxy Resin | Epoxy Resin | Phenolic Resin | Epoxy Resin | Epoxy Resin |

Different matrix/ interphase systems were designated using two sets of letters, thus system PM-EH consists of a PM matrix with an EH interphase, for example.

The results of these model systems were investigated by comparing the tensile strain profiles in the fibre centre (TSFC) before and after the fibre fracture. The stress transfer length (the length of fibre required to return the majority of strain to the fibre following fracture) has also been computed.

RESULTS AND DISCUSSION

The model was run 9 times to analyse the following matrix/ interphase systems; EH/EH, EH/PM, PM/EH, PM/PM, EM/EM, EL/EL, PM/PM, PL/PM and Glass fibre/glass. In all the systems, the tensile strain in the fibre centre (TSFC) prior to the fibre fracture was equal to the applied strain because the model represented a perfectly bonded continuous filament. When a fibre break was induced, a large proportion of the fibre-stress was redistributed into the adjacent interphase and matrix. The energy dissipated by fibre fracture can be calculated by comparing the area under the TSFC curves before and after fibre fracture. The volume (or area in a 2D model) of interphase and matrix affected is a function of the properties of the components, as shown by the differing profiles in Figures 2-4. The break site in the model is asymmetric, so the resulting fragments have different lengths. Since the rate of strain development is constant for a given combination of matrix and interphase, the attained strain is less in the shorter fragment. At the break, the value of TSFC falls to almost zero. The small residual strain at the break can be attributed to a very small contribution from the 'killed' elements, which still have some stiffness despite the introduction of a stiffness multiplier of 1×10^{-6} and because the solution is averaged between nodes. This is apparent as data points that occur above the fibre break site in the Figures 2-4.

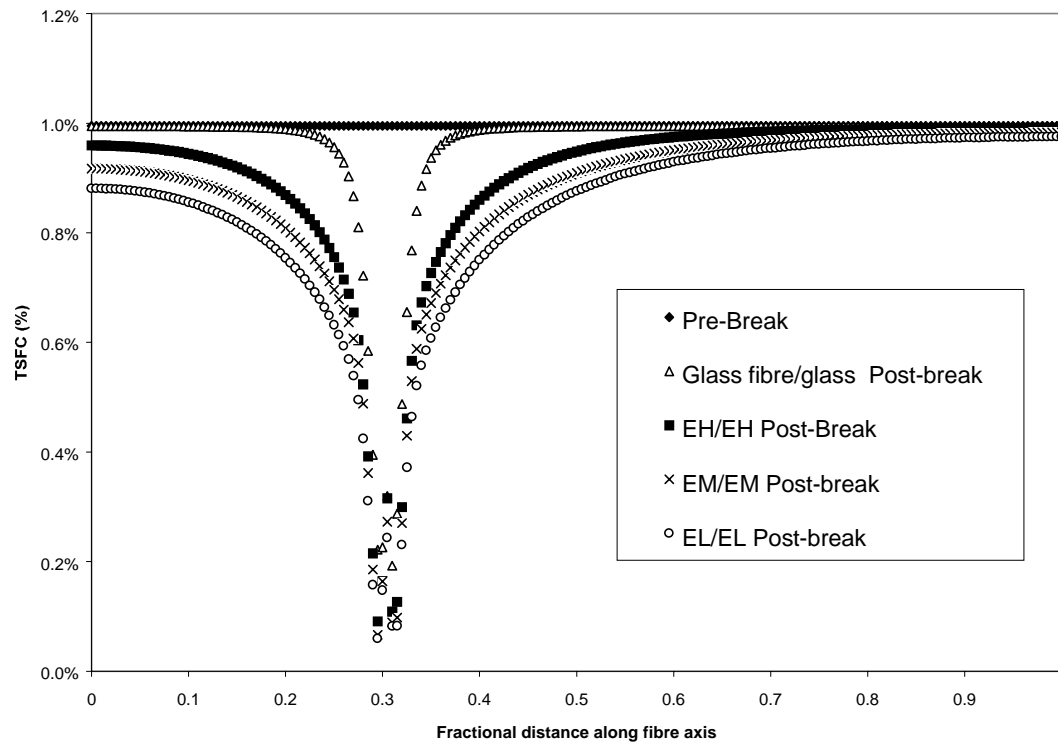


Figure 2. Pre and post-break TSFC profiles for the EH/EH, EM, EL and all glass fibre systems.

After fibre-fracture, the shape of the TSFC profiles is determined by the volume of material over which the energy previously stored in the fibre is redistributed. For a given level of strain

energy, a stiff material will require less deformation for it to disperse, hence a smaller volume will be perturbed. Therefore the strain transfer to the fibre will be more rapid in a stiffer material, resulting in a shorter stress transfer length.

Figure 2 shows a comparison of 4 purely elastic systems in the absence of an interphase. Here, strain is developed exponentially in the fibre fragments up to a plateau level, with the rate of strain development increasing with matrix stiffness. As the stiffness of the matrix surrounding the fibre is reduced, the stress transfer length increases showing more extensive deformation of the matrix. The resultant strain development profile for the fragment is characterised by a lower gradient over the transfer length.

Predicting the affected volume is made more complex by the elasto-plastic nature of the interphases and matrices since plastic deformation can occur. Inclusion of the true elasto-plastic properties of the resin materials has a significant effect on the post-break stress redistribution. In Figure 3, a comparison of the elasto-plastic (PM/ PM) and equivalent elastic (EM/EM) systems shows that the inclusion of plasticity significantly alters the TSFC profiles in the fragments. The EM/EM system shows an exponential increase in strain because it is purely elastic, whereas the PM/PM system shows an initially linear rate of strain development. The linear region occurs because of yielding and cold drawing in the elasto-plastic resin matrix. Linear strain development only occurs in the region where the material has yielded, elsewhere strain development occurs exponentially, as in the purely elastic systems.

Yielding of any constituent leads to a greater volume of material being influenced and deformed by the stress redistribution, hence the stress transfer length is increased.

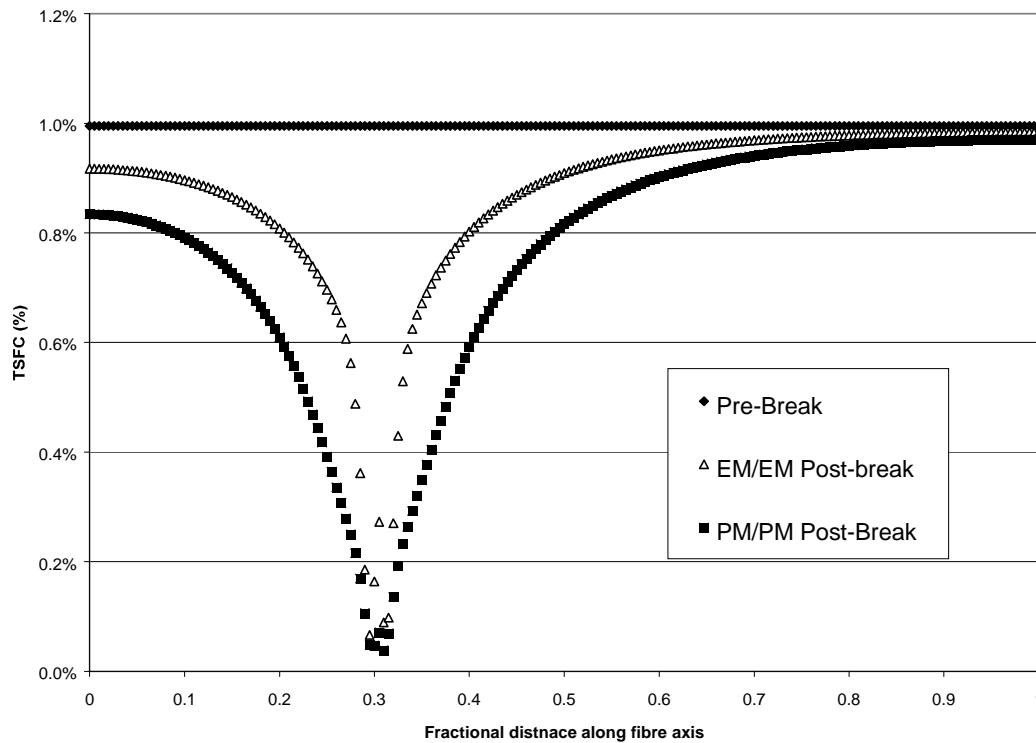


Figure 3. Pre and post-break TSFC profiles for the PM/PM and EM/EM systems.

The incorporation of an interphase layer with properties different from the fibre and matrix will further modify the volume of material affected. The effect of incorporating an interphase is shown in Figure 4. Comparing PM/PM with PM/EH and EH/EH shows how the interphase

elasticity affects the stress transfer. Examining the PM/PM and PL/PM and EH/PM allows the matrix and interphase plasticity to be studied.

In the PM/PM system, the strain in the fragments develops initially in a linear manner because of yielding in the elasto-plastic constituents, and exponentially where yielding does not occur. The inclusion of a stiff elastic interphase layer (PM/EH) means that when the fibre breaks, the energy redistribution occurs largely within the interphase with little effect on the matrix so that the TSFC profile is very similar to that for the EH/EH system. Hence the PM/EH system has a much shorter stress transfer length compared to that for the PM/PM system.

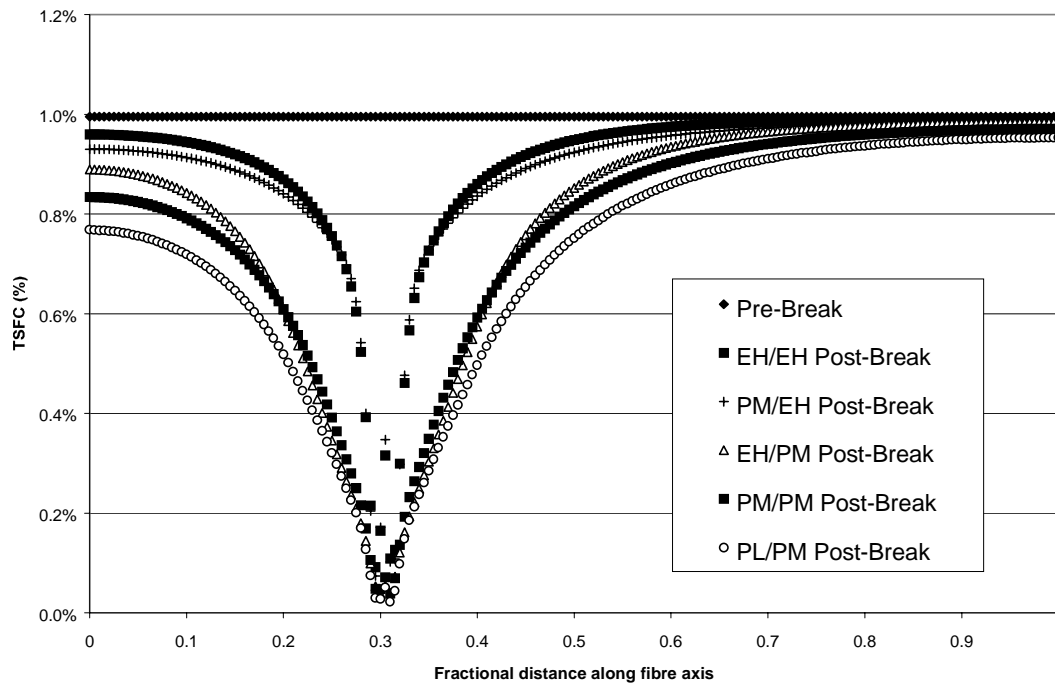


Figure 4. Pre and post-break TSFC profiles for the EH/EH, EH/PM, PM/PM, PM/EH and PL/PM systems.

The TSFC profiles do however exhibit some dependence on matrix properties, illustrated by a comparison of the PM/PM and PL/PM systems. Here the softer PL matrix exhibits a larger transfer length which is associated with deformation of the matrix. This is because the interphase layer has insufficient modulus to absorb the energy placed into it by the fibre-break, elastically.

With the purely elastic EH/EH system, strain develops exponentially in the fragments after fracture. However, in the presence of a medium modulus elasto-plastic interphase (EH/PM), extensive plastic deformation occurs within the interphase, resulting in an initially linear strain development profile and an increased stress transfer length. The profile is shown in Figure 4 to be similar to that for the PM/PM system, indicating that at this thickness of interphase its properties are more important than those of the matrix in controlling the reintroduction of stress into the fragment.

The effect of matrix plasticity and modulus on the TSFC profiles is dependent upon the properties of the interphase and its thickness. Thus, a thin/ high modulus interphase layer will be able to absorb the same quantity of energy as a thick/ low modulus interphase. Hence, there

will be an optimum interphase thickness for a given material at a specified applied strain for the matrix properties to have a significant effect on the stress transfer function. In the EH/PM and PM/EH systems the interphase thickness must be near its optimum since the matrix properties do not have a large influence on the TSFC profile. However, for PL/PM the interphase thickness is insufficient to compensate for the low modulus of the matrix.

These examples show how the interphase and matrix properties could be tailored to provide a composite with greater strength or fracture toughness. With a high modulus interphase layer, the energy of fibre fracture can be contained within this region thereby shielding the matrix from plastic deformation. In this way, the stress transfer or positively affected length is kept short. However, with a low modulus elasto-plastic interphase the energy will be dissipated over a large volume of material with a high degree of deformation in the matrix and interphase, resulting in a much greater stress transfer or positively affected length.

A high modulus matrix with an elasto-plastic interphase surrounding a fibre (EH/PM) could be analogous to high volume fraction composites where the constraint provided by the stiffer EH matrix in the current model is caused by neighbouring fibres in the full composite. Thus, extensive matrix yielding near a fibre break within a high fibre volume fraction composite should be anticipated. This prediction is currently being investigated.

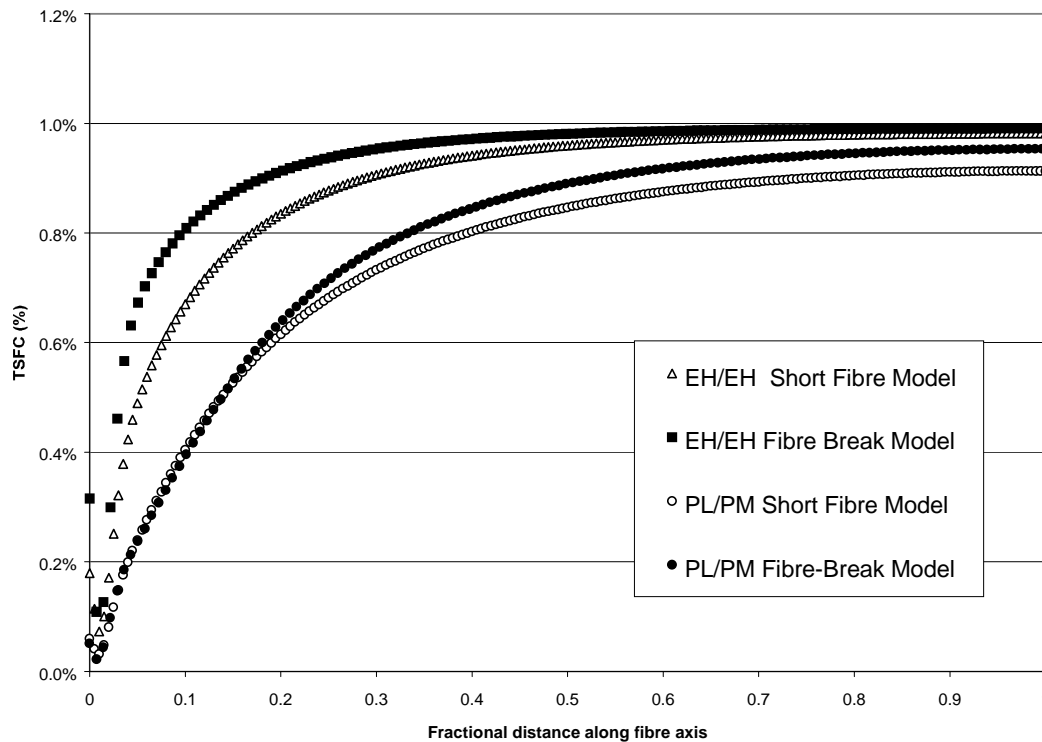


Figure 5. Comparison of TSFC profiles generated by fibre-break model (this work) and the fully embedded short fibre model with a low modulus region to reduce end-bonding [5].

In a previous paper [5] we described an axisymmetric FE model in which the effect of end-bonding (invariably present with a fully embedded fibre) was removed by including a region of very low modulus (0.001GPa) at the fibre-end, to simulate a fibre-break. We now compare the effect of an interphase of differing properties on the stress transferred to the fibre calculated from both models. Figure 5 shows that for a purely elastic case (EH/EH) the rate of stress transfer differs but full loading of the fibre still occurs. However, with the elasto-plastic PL/PM system, the fragment in the fibre-break model reaches a significantly higher maximum

strain. These discrepancies arise because load is transferred differently in each model. In the current fibre-break model, load is transferred from the fibre to the matrix during fibre fracture, whereas in the short fibre model, load is transferred from the matrix to the fibre. The alleviation of end-bonding in this case leads to an increase in the shear stresses present at the matrix/interphase and particularly the interphase/ fibre boundaries.

The rates of strain transfer over the transfer length for the PL/PM system, calculated from the two models are in agreement because yielding of the matrix and interphase controls the process. However, the volume of material perturbed is greater in the short fibre model leading to a lower maximum strain. In the purely elastic system (EH/EH), the rates of strain transfer are similar as they are governed by the modulus of the material.

The fibre-break model would appear to provide a more representative strain transfer regime for simulating fragmentation. However, strain transfer due to subsequent loading of a previously created fragment has not been considered here, so the fully embedded short fibre model may be applicable in this case.

CONCLUSIONS

The nature of the TSFC profile following fibre fracture depends on the volume of material involved in the stress redistribution. A stiffer material will be deformed less at a given amount of strain energy so that the stress transfer length is shorter. The stress transfer length is reduced with increasing matrix and/or interphase stiffness.

In a two phase fibre/ matrix system with a purely elastic matrix exponential strain development within the fractured fibre or fragment is exponential with the rate of strain transfer directly proportional to its modulus. The inclusion of plasticity into the matrix suppresses strain transfer because yielding and cold drawing occurs. Hence the linear strain development produces a longer stress transfer or positively affected length.

The inclusion of an interphase modifies the strain profile in the fragment. When purely elastic, the stress transfer or positively affected length in a given matrix is increased by reduction in its modulus. When it is elasto-plastic, the stress transfer or positively affected length in a given matrix is increased by reducing its modulus and/ or shear yield strength.

There is an optimum interphase thickness for a defined material and applied load, at which the properties of the matrix do not significantly affect the stress transfer or positively affected length. The optimum thickness increases with a decrease in interphase stiffness/ yield strength but increases with applied load.

Energy absorption within the composite on fibre-fracture can be tailored: In a high modulus matrix, a short stress transfer length is required to reintroduce the stress into the fibre. Thus, the probability of a stress concentration at the fibre-end leading to brittle fracture is enhanced. In the presence of a more ductile interphase, energy absorption can alleviate the stress concentration and provide composites with high fracture toughness or impact strength.

A finite element model representing an embedded short fibre without end-bonding has been shown to misrepresent the stress build up in the fragmentation process.

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