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MODELLING OF KEVLAR - AL ALLOYS AND FINITE ELEMENT SIMULATION OF MECHANICAL PROPERTIES

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ABSTRACT

In the field of defense and other highly secure places lot of impact are formed, at the time of the war lot of injuries are occurred due to the impact of the bullet and the gun shots. When Kevlar material is used as a Body Armor for the defense purpose and for the safety purpose at the time of the war enclosure, the problem facing here is when the impact is applied at a point the material deformation occurs and at a particular point and the deflection will be very high so that the human who is wearing the Kevlar as the body proof experience a heavy pain in the Armor. The Armor consists of Kevlar-Al alloys, these are the fibres present and the polymers are the resins and they combinely constitute Polymer Composites. Polymer Composites are formed as random or anisotropic fibre dispersions sheets with long fibres or woven fabrics. During the initial stage we investigated a bullet proof vest with various materials involved in it and several compositions of materials has been developed, but the major drawback here is when the deformation occurs it is creating only a point load here and the man who wears this armor feels the pain here. To overcome this, we model the polymeric fibre composites and finite element simulations of mechanical properties are experimented. Typical characterization and mechanical performance tests are available to investigate and optimize the composites. Finite element analysis (FEA) enables a theoretical approach to understanding of the structure-property relationships and confirmation of interpretation of measured properties. A displacement field is suited to identifying and quantifying stress intensities in local regions of the composite to determine parameters critical to the performance of the composites. A tensile stress gives a uniform deformation field that must be efficiently transferred to the fibers, creating stress concentrations at the fiber-matrix interfaces. This paper reviews the application of FEA to various composite types, stress situations and failure mechanisms. The FEA model design and simulation method are evaluated and compared.

Keywords: Kevlar, finite element analysis, polymeric fibre, composites, stress analysis.

Nomenclature

c	=	composite
d	=	diameter
E	=	Tensile Modulus
f	=	fibre
l	=	length
L	=	longitudinal spacing
S	=	lateral spacing
V	=	volume
π	=	pi
μm	=	micrometer

INTRODUCTION

Composites based upon thermoplastics such as polypropylenes, polyethylenes, poly (ethylene terephthalate), poly (butylene terephtahate), various polyamides, polystyrene and its copolymers with butadiene and acrylonitrile, poly (vinyl chloride) thermoplastic polyurethanes, thermoplastic elastomers and biopolyesters such as poly (lactic acid), poly (hydroxybutyrate) and its copolymers with hydroxyvaleric acid. Thermosetting polymers include epoxy resins, unsaturated polyesters, vinyl esters, epoxy-acrylates, polyurethanes, polyisocyanurates, polybismaleimides, polysiloxanes, formaldehyde based resins such as phenolic, melamine and urea, and many synthetic elastomers. Epoxy resins are the most commonly studied polymers using finite element methods and they are frequently cited as examples. Fibrous reinforcements include cellulosic fibres such as flax, hemp and others, glass fibres, carbon fibres, mineral fibres, synthetic fibres related to the matrix polymer. Table-1 shows common fibre reinforcements with brief comments. Short fibres are chosen for direct addition to a polymer in extrusion or injection moulding. Common short fibres are chopped glass and carbon fibres, wood flour and other plant derived cellulosic fibres. Nano-fibres are subject to much recent investigation and they are of increasing commercial importance, such as carbon nano-tubes, microcrystalline cellulose or nano-cellulose, boron nitride and alumina whiskers. The composites discussed mainly include fibres, however other fillers such a glass spheres and particulate or platelet shapes are studied using FEA since they can be represented in two- or three-dimensional models of polymer composites. Polymer can be included as another fibre or as a powder, that are subsequently melted to form a uniform matrix between and around fibres, as a plastisol (polymer dispersed in plasticiser) that is thermally gelled to form a solid matrix, or as a chain-extendable or cross-linking prepolymer. Sometimes a third component is included as an interphase surrounding the dispersed phase or when the layers of a laminate have different properties. A more complex model may include a density gradient within the matrix.

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Table-1. Fibres for reinforcement of polymer composites.

Fibre	Composition
Glass fibre	E-glass or S-glass
Carbon fibre	Graphite (formed by polymer pyrolysis)
Carbon nanotubes	Graphite cylinders
Kevlar	Poly (phenyleneterephthalamide)
Bastfibre (hemp, flax, rami)	Cellulose
Wood fibre or Flour	Cellulose
Nano-cellulose	Partially hydrolysed cellulose
Polymer fibre	Polypropylene, Polyamides, poly (ethylene terephthalate)
Mineral fibres	Rock wool, boron nitride, alumina

COMPOSITE PROPERTIES

Modulus that is orientation dependent and calculated as a volume fraction weighted mean of the matrix (polymer) and filler (fibre) in series or parallel (Equation (1)), where V = volumefraction, E = modulus, c = composite, f = fibre, m = matrix). An efficiency factor (g) is usually included to account for interfacial interaction and variables such as voids, in efficient dispersion of fibre bundles and variations in fibre alignments, etc (Equation (2)). The modulus can be measured using a universal test instrument in tensile mode (parallel with fibre orientation) that emphasises the properties of the fibres. An important observation for composite design is that the centre of the beam cross-section is relatively stressed free.

$$E_c = V_fE_f + V_mE_m = V_fE_f + (1-V_f)E_m \quad (1)$$

$$E_c = gV_fE_f + V_mE_m = gV_fE_f + (1-V_f)E_m \quad (2)$$

Where V_f can be calculated from the length (l) and diameter (d) of fibres and their longitudinal (L) and lateral (S) spacing in the composite.

$$V_f = \frac{\pi\, l\, d^2}{4\, L\, S^2} \quad (3)$$

(Equation (4) and Equation (5)) is a refinement that contains a geometric fitting parameter, A, where A = 2(l/d) for tensile configuration with E as the tensile modulus, and the aspect ratio (l/d) of length (l) and diameter (d). A numerical solution is obtained for Equation (4) and Equation (5) to model a composite modulus.

$$E_c = E_m(1+AB)V_f$$

$$(1-B)V_f \quad (4)$$

Where

$$B = E_f/E_m - 1/E_f/E_m + A \quad (5)$$

Fibre composites do not display yield strength, unlike the matrix thermoplastic, since fibre pull-out and fibre fracture occur intermittently until fracture. Progressive fragmentation of a composite is not well simulated by FEA since the composite structure must be changing to represent structural rupture. Simulation of modulus is made while the composite is still coherent. Measurement of composite mechanical properties provides an overall modulus without information on the contribution of components and variables within the structure. The hypothesis is that the model will behave the same as the real composite. If the hypothesis is correct then the behaviour of the composite will be well understood. If the hypothesis is incorrect them the model needs to be refined and further simulated until the data for the model and real composite converge. Three assumptions are made: (a). the fibre-matrix interface has perfect adhesion; (b). the fibre and matrix exhibit an elastic response to stress; (c). No axial load is transmitted through fibre ends.

COMPOSITE FIBRE STRESS DISTRIBUTIONS AND DEFORMATIONS ANALYSIS USING FEA

The modulus measured in shear mode emphasizes the matrix-fibre interface, while in flexure mode a combination of matrix and fibre modulus is measured, with the upper bended surface in tension and the lower surface in compression (Figure-1). The Von Mises stress contour diagram (Figure-1, lower image) shows a stress maximum at the fixture end and a compressive stress maximum in the lower centre surface. The same beam in three-point bend mode emphasizes the stress in the load region with compressive stress concentrated near the upper surface and tensile stress concentrated near the lower surface (Figure-2).

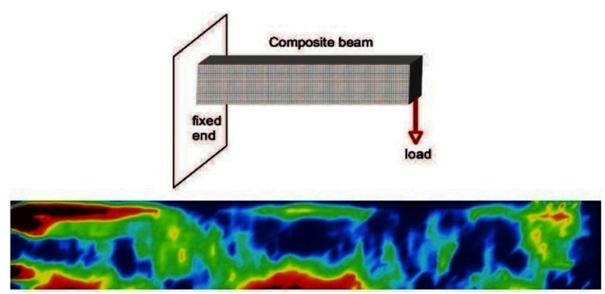

Figure-1. Supported composite beam with deforming end load (upper) and a Von Mises Stress contour plot showing the stress (lower).

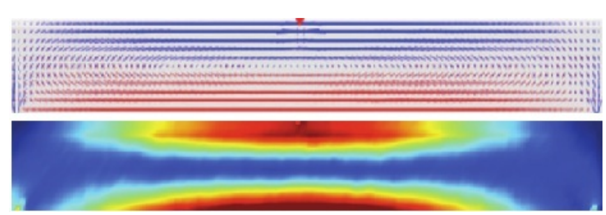

Figure-2. Beam under three-point bend stress showing compressive stress near upper surface and compressive stress near lower surface, stress distribution (upper image) and Von Misesstress contours (lower image).

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FEA requires a proposed model of the composite including the location of fibres within the matrix. The model can be validated by comparison with cross-sectional observation of the composite using optical or scanning electron microscopy. The model should correspond to the actual composite. Inclusion of interfacial interactions within the model is a hypothesis since the interfacial properties cannot be observed. A third phase of strongly adsorbed and immobilized polymer on the surface of fibres can be included to account for interactions (Figure-3, upper image). The modulus and volume or thickness of this interphase must be estimated as between that of the matrix and fibres. The interphase will be diffused into the continuum matrix. A gradient of modulus can be used instead of a discrete interphase (Chen and Liu, 2001). The nature of the gradient could be linear or non-linear (such as exponential) from the fibre modulus to the matrix modulus. Complex geometry models can be formulated to include various specimen shapes, fibre orientations, woven bundles, and even random voids. The complexity of the model will determine the lowest scale that can be analyzed while being representative of the whole composite (Vozkova, 2009). An example of a composite with an enlarged interphase is shown, where the simulation was an application of three-point bend stress (Figure-3, lower image). Complex stress fields are associated with the dispersed phase. This type of model is best studied by choice of a single particle or fibre when stresses associated with the interphase are to be considered. The concept has been applied to the visco-plastic matrix behaviour of metal composites that reveal similar mechanics to polymer based composites.

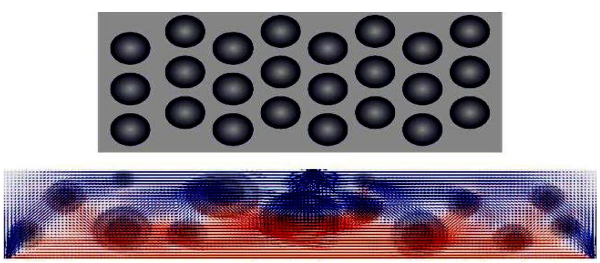

Figure-3. Fibre composite cross-section schematic showing interphase (darkened) around each fibre (upper) and the lower image shows stress distribution in similar model under three point bend stress.

The model is then tested by performing a simulation that is disturbing the model with stress and monitoring the evolution of the strain over time, or applying a strain and monitoring the stress over time. The evolution of the model with time is computed at each node of the finite elements. Application of stress or strain requires that part of the model be fixed. Typically for a beam one end will be fixed and the external stress or strain applied at the other end, for tensile or flexural (single cantilever bend) testing. Alternatively two ends can be fixed and the stress or strain applied in the centre, equivalent to a dual-cantilever bend. A three-point or four-point bend requires that the ends allow lateral movement or slippage, which is more complex to simulate in comparison to a real situation. The hypothesis is that the model will behave the same as the real composite. Unlike a model the real composite is likely to deviate from an ideal structure. Imperfections can be included as discrete entities such as voids, or as a general decrease in the model parameters analogous to an efficiency factor. The model is structurally similar to a polymer-fibre composite that can display a dimension dependent resonant frequency under modulated force mechanical testing.

COMPOSITE MORPHOLOGICAL STRUCTURES INVESTIGATED USING FEA

Important considerations for the design of composites that are assessed using FEA are: The bulk mechanical properties of the composite are determined by the modulus of each phase and their respective volume fractions. Consolidation of the composite is complete and the composite density is a volume fraction average of the component densities. Where consolidation is incomplete this can be represented by a density gradient across the thickness of the composite sheet. Fibre concentration and fibre diameter determine the distribution of fibres since a fixed volume fraction of fibres may be due to few of large diameter or many with small diameter, witha varying total fibre-matrix surface area. The fibre-matrix interface may be implicitly defined such that dewetting or voiding can occur, or be omitted so that the interface will remain intact. Fibre orientation can be included in the model but this will require a larger mesh size to generate sufficient distribution. Fibres are generally included in parallel orientation in models constructed since a random distribution is difficult to model unless the model is large (Figure-4). The surface versus bulk properties often vary in composites: there may be matrix rich or fibre rich surfaces, with density gradients from the surface to the bulk.

Figure-4. 3D Model of an oriented long fibre composite.

A 2D model similar to the fibre composite. The fibres are shown from an aligned view so in the 2D perspective they could be particles. Other similar composite models are shown later in this chapter where

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the fibres are aligned with the longitudinal axis of the beam. This view of fibre ends is best for observing the stress field throughout the composite and because stress transfer between matrix is better tested laterally for long fibres. In this case the stress is in three-point bend configuration pulling downwards from the right side, while the left side is fixed. The lower section of the beam is in compression, while the upper section is in tension. Some stress concentrations are visible between fibre ends. The regions of stress concentration are between fibres rather than in surface regions; compare with included fibres with and without fibres, where the stress concentrations emanate from along the surfaces. Stress concentrations between the fibres mean that fracture is likely to initiate at fibre-matrix surfaces or within the matrix between fibres. Strong interfacial bonding and a strengthened interphase will contribute most to a composite in this circumstance. Stresses in the compression zone along the lower part of the beam have concentrated where fibres ends are just a positioned downwards to the left, even though the model was constructed with the aim of randomising the fibre-end positions and diameters. The Von Mises stress plot is not shown because the colour shading obscured the circular fibres end.

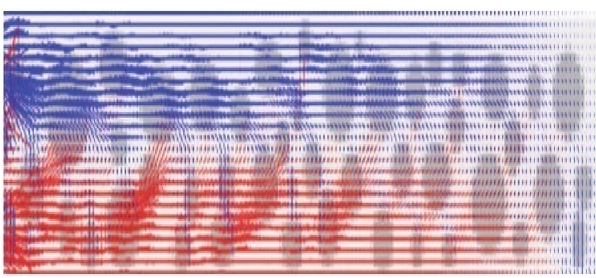

Figure-5. Composite beam viewed lateral to fibres, fixed on left with bending stress acting down from the right.

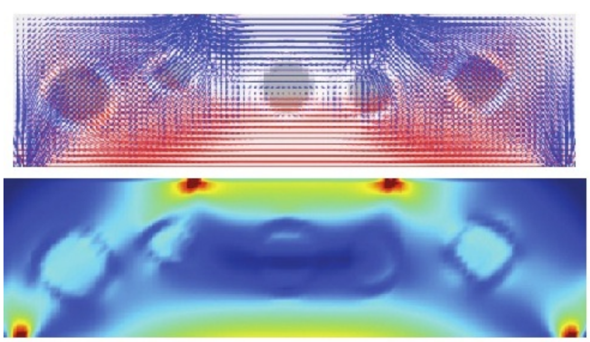

Figure-6. A simplified model of a polymer with a soft interphase surrounding each hard fibre particle under four-point stress, stress distribution diagram (upper) and Von Mises contour plot (lower).

A simplified model based on Figure-5, with fewer hard inclusions surrounded by soft interphase, is shown in Figure-6. The upper stress distribution diagram shows the compressive stresses passing from the application point through to the supported lower ends. The stress is not concentrated in the vicinity of the fibres, where the lighter shaded areas around each fibre is the soft phase. The lower central section of the beam is under a tensile stress situation. The lower Von Mises contour plot shows the stress reduced zones as darker areas around each fibre. A central stress free zones results from the four-point bend mode radiating stress away from the centre of the beam. Figure-7 shows the same model as Figure-6 with both ends fixed to represent a dual cantilever beam instead of a four-point bend configuration. The stress distribution in Figure-7 is similar though less intense than that of Figure-6 because some of the stress is redistributed as tensile stress emanating from the top corner fixtures. FEA depends upon the construction of a model to represent a material, such as a composite, and configuring the forces and constraints to best represent either a use situation or to reveal critical zones that are likely to cause performance problems. The contribution of an interphase has been evaluated using a variant of FEA called the advanced boundary element method to model fibre-reinforced composites with consideration of varying thickness boundary. Fisher and Brinson (Fisher and Brinson, 2001) have used the Mori-Tanaka model and its extension by Benveniste to study a three-phase composite with either separately dispersed fibre and soft interphase material, that may include voids, or where the fibres were enveloped by the soft interphase material. The Mori-Tanaka model was more effective in predicting the matrix dominated moduli of the composite. Physical aging was studied by using time and frequency shift factors for these thermorheologically complex materials, with frequency data being preferred. The 2D FEA results demonstrated the importance of the interphase in determining the overall shift rates of the composite. FEA was performed in 2D using a hexagonal array of inclusions with transverse hydrostatic and transverse shear superposition, to obtain the transverse Young's modulus and transverse shear complex moduli.

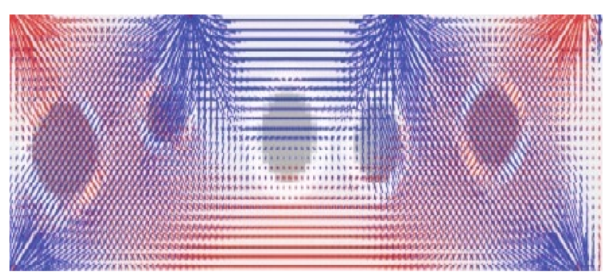

Figure-7. A four-point stressed dual cantilever simulation of a polymer with a soft interphase surrounding each hard fibre or particle shown as a stress distribution diagram.

A composite interphase model was constructed including glass beads, an interphase and polycarbonate matrix, with perfect bonding at each interface and the beads symmetry packed in a cubic array. The Young modulus, stress concentration and stress distribution were simulated. The interphase increased fracture toughness at

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the expense of elastic modulus, with these observations becoming larger with increase in interphase thickness. A suitable selection of filler content, interphase stiffness, thickness and Poisson ratio can reduce stress concentration with retention of composite modulus (Tsui, *et al*, 2001). Stress has been imparted in two orthogonal directions simultaneously on a cruciform shaped specimen (Lamkanfi, *et al*., 2010). The cruciform is applicable to real systems such as rotor blades. Strain was concentrated in the conjunction of the two stresses and concentrated in the corners rather than the centroid of the specimen. The numerical model was validated by experiments by means of a digital image correlation technique. Two- and three dimensional models were evaluated. An orthogonally stressed cruciform has been simulated independently (Figure-8) with a fixed point at the centre.

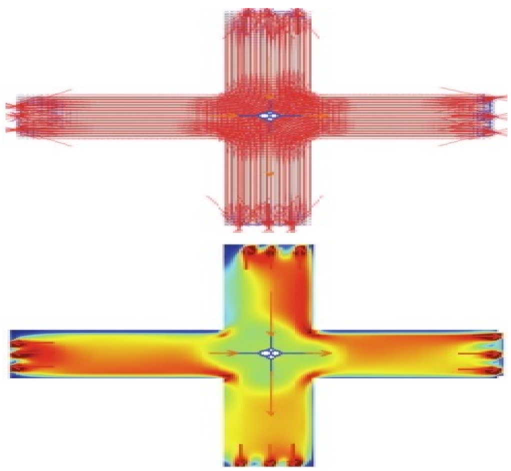

Figure-8. Cruciform with orthogonal stress, stress distribution (upper), Von Mises contour (lower).

The stress distribution (Figure-8, upper) shows the stresses concentrated in the central region near the corner. This is better depicted in the Von Mises contour plot where the darker shading passes from the arms around the centroid.

FINITE ELEMENT ANALYSIS COMPOSITE SIMULATIONS

Laminated composite structures

Damping of laminated carbon and glass fibre plastics is measured as the ratio of energy dissipated to the maximum strain energy stored per strain cycle. A finite damped element model including transverse shear has been used to measure and predict specific damping properties, mode shapes and natural frequencies of the composites (Lin *et al*., 1984). Analysis of laminated composites has been performed where the failure mode was delamination of the layers. When a weaker ply fails first, stress will be distributed to the remaining plies and the process will continue giving a progressive failure of the laminate. The modulus of the layers was anisotropic so the strength of the composite depended on the relative orientation of each layer within the overall laminate. Symmetric and anti-symmetric ply laminates with different numbers of layers were formed. Mechanical properties of a composite depend upon the geometry and aspect ratio of the fibres, while woven fibre composites are distinct from typical unidirectional long fibre composites. A woven fibre composite is usually prepared from multiple layers where the overall composite properties are the sum of the contribution layers. Flexural behaviour is a suitable way to characterize woven or unidirectional composites, since tensile force will be resisted by the modulus of only the continuous fibres. The layers of a woven composite can be divided into unit cells that are the smallest area in which the weave pattern is repeated (Figure-10). A composite model can be formed by adding units cells laterally and in the thickness direction to form a structure as required for the model.

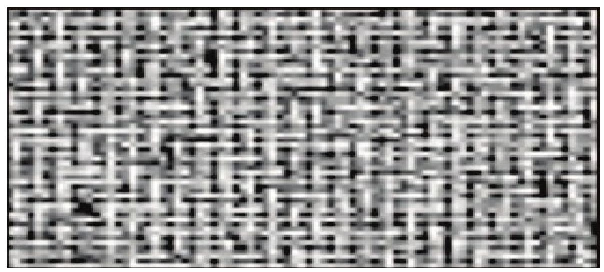

Figure-9. Standard cross ply woven fibre mat (KEVLAR).

A model of membrane layers of a laminated fibrous composite (analogous to Figure-11) addressed the particular issue of interlaminar shear stresses concentrating along an edge region.

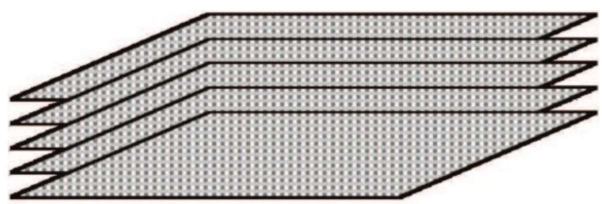

Figure-10. A multi layer woven fibre laminar composite (KEVLAR - AL LAYERS).

The laminated composite model shown in Figure-11 has stiffer surface layer where resistance to stress is most important and a softer central layer where stresses from deformation modes are least. In practice the central layer could be a foam or material with limited consolidation. Each of the layers is reinforced with the same type of fibres. The simulated was performed under four-point bending (upper image). A compressive stress concentration radiates from the application points to the two supported lower corners. A tensile stress is situated along the higher stiffness layer at the bottom. Stress transfer to fibres is visible throughout the laminated composite, but mainly as expected from regions of higher stress. A three-point dual cantilever simulation of the laminated composite is shown in Figure-11 (lower). The

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stress concentrations are more intense with tensile stress regions emanating from the upper corner fixtures and in two localised regions along the bottom layer. Stresses are greater in the stiffer matrix top and bottom layers and stresses are transferred to fibres throughout, though with increased intensity in the higher stress regions of the upper and lower layers of the laminate.

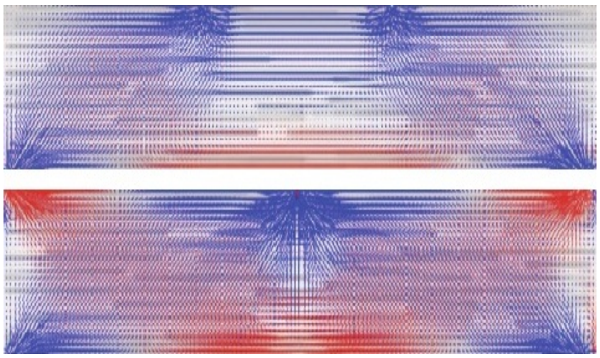

Figure-11. A model of a laminated fibre-reinforced composite with stiff surface layers (darker shading) and a central softer layer under four point bend (upper) and three-point dual cantilever (lower).

Anisotropy of thermoplastic composites

Orientations occur during processing operations such as extrusion and injection moulding. Fibrous and platelet fillers are orientated along the extrusion direction or along the more complex flow lines in injection moulds. This directional geometry of the fibres is normally welcome as maximum modulus and strength are required in the machine direction. These orientations simplify the preparation of finite element models and the simulation process. An anisotropic fibre composite is shown in Figure-12 (left) with the stress applied parallel to the fibres. The stress concentrations are low and concentration in regions where the fibreswere made shorter. When the stress was applied transverse to the fibres (right) the stress concentrations were much greater throughout since the lower modulus matrix carried more of the stress than the higher modulus fibres.

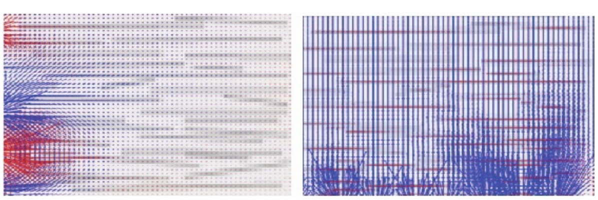

Figure-12. Anisotropic fibre composite showing stress distribution when stress was applied parallel to the fibres (left) and transverse to the fibres (right).

A three-dimensional finite element model was used to evaluate indentation of polypropylene-cellulose fibre composite to determine the elastic modulus and hardness FEA was conducted using a rigid flat cylindrical disk with a radius of 1 µm with Abaqus Indentation to 50 or 100 µm depth provided no difference in the unloading values. Analysis of the interphase region showed a 1 µm wide property transition zone, though this zone could not be isolated from the contributions of the adjacent polypropylene and cellulose fibre properties. An analogous model is shown in Figure-13 in 2D and the simulation was performed with stress applied to the hard round object while the soft material was supported along its base.

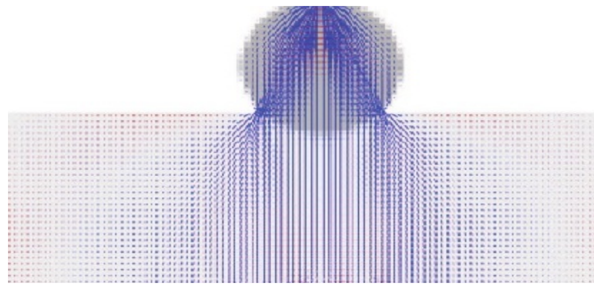

Figure-13. Stress distribution diagram for indentation of a soft material by a hard round object.

The stress diffuses from the application point with concentrations at the edge where the round object meets the soft material. Indentation by such a blunt object is not as critical as when a crack has been induced and the crack tip provides a focal point for stress concentration.

Fibre matrix interfacial adhesion

A rigorous composite model needs to give attention to explicit bonding between the matrix and fillers, which are often fibres, but may be platelets; spheres or irregular particles. Bonded joints provide the connecting system whereby stress is transferred from the relatively low modulus matrix resin to the supporting high modulus fillers.

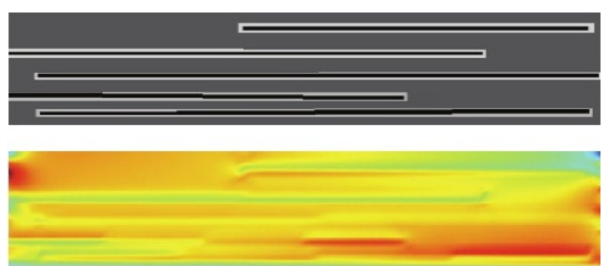

Figure-14. The model (upper) of composite with fibres with a weak interface, and after simulation showing Von Mises stress (lower).

A non-linear model was necessary to achieve accurate results relating a standard adhesion test experimental data with numerical data. Stresses concentrated at the interfaces at the longitudinal and transverse ends of an adhesive layer (Diaz, *et al*, 2010). Analyses and interpretation of adhesion strength needs to consider the viscoelastic nature of polymers, such that much energy in separating bonded interfaces is expended

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in the bulk polymer dueto viscoelastic processes converting stress energy into heat energy resulting from molecular segmental motion friction. The relationship between stress transfers, the elastic modulus and the mechanical properties depicted by a stress-strain analysis have been simulated by finite element analysis. Figure-17 shows a representative model of a fibre composite with a weak interface, represented by the lighter shading around each fibre. After simulation of a tensile stress the Von Misses stress distribution shows that stress has not been transferred to the fibres as well as in a composite with a strong fibre-matrix interface.

IMPACT DELAMINATION

Deformations on polymer composite

Laminar fibre-matrix composites are subject to failure by delamination under various loading modes and loading rates, including impact forces. The interface strength and deformation behaviour are critical laminate characteristics to be evaluated. Crack growth can be suitably initiated by including interlaminar cracks in the model. Bending, shear and mixed loading modes have been used in the failure simulations. An interface element wasuse to describe resistance to crack growth (Wisheart and Richardson, 1998).The resistance to impact has been investigated when composite laminates were subjected toan initial stress. A shear flexible plate composite model was impacted by a mass during the simulation. Finite element analysis was used to solve the contact force and the dynamic response of the composite plate. Barely visible impact damage was predicted using FEM of the larger scale structure.

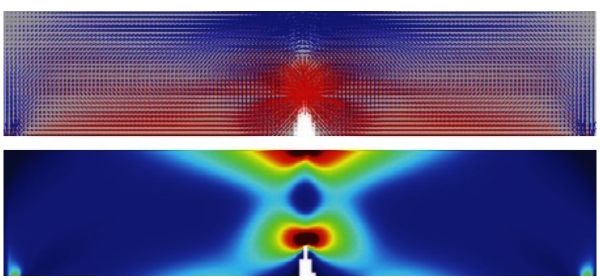

Figure-15. Stress concentration in a polymer with a crack induced in three point bend mode, stress distribution diagram (upper), Von Mises contour image (lower).

The method was validated using experimental data from carbon fibre epoxycomposites, and the approach was extended to glass fibre and Kevlar laminates. Low velocity impact damage to composite laminates results in complex cracking of matrix and fibre, and delamination. The complexity of the fractures makes prediction a difficult challenge, since the failure mechanisms are disperse. A FEA of post-impact damage zone with compression buckled delaminated fibres has been undertaken to assess the strength reducing mechanisms. Comparison of the FEM with laminates containing artificially induced damage has demonstrated consistency between prediction and observation. Damage mechanisms and mechanics of laminated composites due to low velocity impact has been evaluated (Hyung, *et al*, 1991). Prediction of damage development to failure in composites is important for assessment of applications. Progressive damage evaluation using FEA can predict potential damage that is often unobserved.

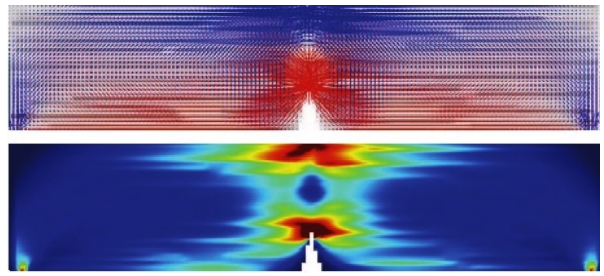

Figure-16. Stress concentration in a polymer composite with a crack, induced in three-point bend mode, stress distribution diagram (upper) and Von Mises contour image (lower).

Damage development in a polymer is accelerated by the presence of a crack as illustrated in Figure-15 where application of a stress in three-point bend mode has caused stress tensile concentration at the crack tip and compressive stress concentration at the point of stress application. The stress diagram (Figure-15, upper) shows the tensile stresses radiating from the crack tip, a situation that is likely to result in crack opening, growth and failure. The Von Mises contour representation (Figure-15, lower) emphasized the intensity of the stress concentrations. The same FEA simulation of a polymer composite with fibres parallel to the axis of the beam is shown in Figure-16. The stress concentrations are almost the same as in the plain polymer except that stress has been transferred to the fibres and can be seen to radiate away from the crack tip and application zone along the adjacent fibres. Transfer of stress to the fibres is more clearly seen in the stress distribution diagram (Figure-16, upper) where the fibres are the darker horizontal lines. The Von Mises contour plot show the stress transfer to fibres are the lighter streaks emanating laterally from the central stress zone. The resistance to impact has been investigated when composite laminates were subjected toan initial stress. A shear flexible plate composite model was impacted by a mass during the simulation.

Contribution of broken fibre and fibre pullout

Stress concentration at a broken fibre has been simulated by a model including a single brokenfibre surrounded by six equally spaced complete fibres in an epoxy resin, basedupon a fibre volume fraction of 0.6. The model and separately each component were simulated as a homogeneous, orthotropic material. The stress affected fibre length was half the ineffective broken fibre length. The contribution of fibre fracture or a fibre end is typically measured using the single fibre pull-out test. The matrix is fixed in position and a tensile force is applied to the fibre (Wong, *et al*., 2007). A 2D axisymmetric linear finite element model has been developed for fibre pull-out to meet the criteria: energy release rate for interface crack extension, large fibre aspect ratio, singular stress field at the crack tip, and interface crack initiation for short crack lengths. Interface crack initiation occurred under definite unstable mixed mode conditions, complicating the interpretation of the critical energy release rates. A model containing a region of broken fibres is shown in Figure-17. After simulation under a tensile stress the Von Mises stress contours show that most stress transfer to fibres occurs in the lower region where the fibre ends are overlapped. In the broken fibre (upper) region the stress intensities are low, particularly in the regions between breaks. A consequence is that the broken fibre region is not supporting its share of the stress, and the undamaged region has increased stress concentration that would be likely to cause further fibre breakage in a real situation. Fibre pullout is analogous in that low interfacial bonding will limit the stress that can be transferred to the fibres and the matrix will be more able to deform in the weakly bonded regions.

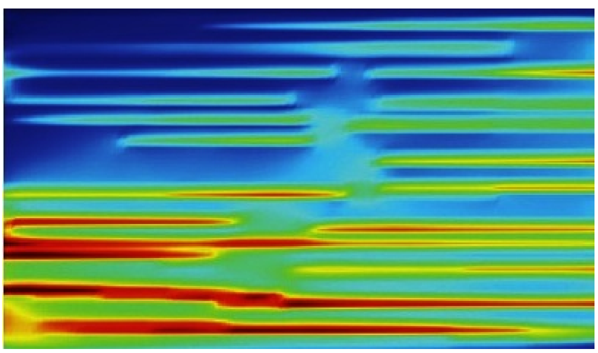

Figure-17. A fibre composite model including a region of broken fibres (top section) with mostly continuous or overlapping fibre (lower section).

Models for the debonding of a fibre embedded in a brittle matrix have been proposed and assessed. Some specific cases considered are: debonding with constant friction, debonding with Coulomb friction, and fibre pullout with constant friction. This method was based upon the use of a continuous distribution of dislocations in an integral equation formulation to replicate a crack. The study was confined to materials having a residual compressive stress across the fibre-matrix interface. Matrix dominated failure in polymer composites can be modelled by using cohesive zone interface elements. These elements have been shown to enable simulation of actual failure mechanisms that proceed via damage development through to failure. Cohesive zone elements accurately simulate delamination, in-plane failure of laminates, notch sensitivity impact fractures through to ultimate debonding failure.

CONCLUSIONS

Finite element analysis has provided an implicit means of modelling polymer composites, such as thermoset chopped fibre or woven fabric composites and laminates, thermoplastic- textile and dispersed chopped fibre composites that interpret the stress-strain behaviour in local regions compared with typical volume fraction continuum models. An FEA approach comprising model design, validation, optimization, simulation and analysis has been described. FEA applied to polymer composites has been reviewed and many examples demonstrated independently using a two-dimensional FEA program. The importance of stress transfer from matrix to fibre is emphasized by stress concentrations. The surface regions and inter-fibre matrix were identified as zones that supported most stress during deformation by bending since one surface is extended while the opposite surface is compressed. Consequently there is a requirement to have fibre rich regions near surfaces and complete compaction, which is readily achieved by a compression moulding process. The interior can be suitably partially compressed to create low density impact resistant composites. A tensile stress gives a uniform deformation field that must be efficiently transferred to the fibres, creating stress concentrations at the fibre-matrix interfaces.

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