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Finite element analysis of the effect of an interphase on toughening of a particle reinforced polymer composite

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Abstract

A numerical method was used to study the interaction between a crack and the filler phase in a particle-reinforced polymer composite. The simulation was achieved by implementing a progressive damage-and-failure material model and element-removal technique through finite element analysis, providing a framework for the quantitative prediction of the deformation and fracture response of the composite. The effect of an interphase on composite toughness was also studied. Results show that a thin and high strength interphase results in efficient stress transfer between particle and matrix and causes the crack to deflect and propagate within the matrix. Alternatively, a thick and low strength interphase results in crack propagation within the interphase layer, and crack blunting. Further analysis of the effect of volume fraction and particle-particle interactions on fracture toughness as well as prediction of the fracture toughness can also be achieved within this framework.

Keywords

finite element analysis; particle reinforcement; interphase; fracture toughness

1. Introduction

Particle-reinforced polymer composites have been used as dental restorative materials for many years. High toughness of these composites is desired because it leads to better wear resistance and clinical performance [1]. However, the improvement of toughness due to the introduction of high modulus glass particles is inadequate. In some cases, the fracture toughness of the composite may be lower than that of the matrix material [2]. Earlier, it was shown that the mechanical properties of such composites are affected by the mechanical properties of the resin itself [3], and the properties, shape, size, volume fraction and distribution of the reinforcing particles [2,4–8]. In the cases of rubber-toughened [9,10] and UHMWPE particle-containing composites [7], toughness is indeed increased, but the loss in modulus, hardness or strength is appreciable, especially as the volume fraction of filler increases. Attempts have also been made to toughen composites by coating glass particles with rubber, but results are ambiguous; significant toughness increases could be achieved [11], but only within certain ranges of filler content[12].

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Theoretical predictions by Chan et al. implied that the fracture toughness of dental nanocomposites can be improved by a factor of 2–3 through a combination of enhanced interphase toughness by silanization, crack deflection, and crack bridging [13]. Ranade et al. incorporated a glass filler particle with a ductile and tough interphase (UHMWPE) into a BisGMA/TEGDMA matrix, and found that fracture toughness increased (38%), but modulus (25%) and strength (11%) decreased [2]. Other studies have shown that strong adhesion may reduce the fracture toughness of glass bead-filled epoxy composites [14]. Debnath et al. studied the relationship of different filler-matrix interfacial shear strengths on the flexural strength and toughness of BisGMA/TEGDMA composites reinforced by E-glass particles and found that a rubber interphase, whether bonded to the filler and matrix or not, did not improve toughness [15].

These experimental observations are somewhat inconsistent. In fact, the improvement of toughness in composites is the result of many factors, and several toughening mechanisms are involved during fracture including crack pinning, crack blunting, matrix/particle debonding, and crack deflection [6].

In previous numerical and analytical studies focused on toughening mechanisms, analyses were performed on the effects of filler particle properties, volume fraction, and interfacial bonding on composite elastic properties and fracture toughness. An axisymmetric finite element unit cell model contains a particle in the matrix (with or without an interphase) [4,10,13,16], while a representative volume element (RVE) unit cell model may contain a cluster of randomly distributed particles [17–20]. In the latter case, the influence of particle distribution on the stress intensity as well as on the final properties may be studied. While these models are able to address particle/matrix decohesion, they are not able to simulate crack deflection during crack propagation, principally because of the periodicity in the boundary conditions, which implies that damage (decohesion) occurs simultaneously throughout the microstructure.

The boundary element method (BEM) has been used to study the interaction between a crack and second phase particle in a discontinuously reinforced composite material. In this method, simulation is achieved using a “dual” boundary integral method, coupled with either a maximum energy release rate criterion or a maximum principal stress criterion for determining the direction of crack propagation [21–24]. Simulation of crack trajectories in the presence of one, two, or many randomly distributed particles yielded the finding that the crack trajectory is not substantially altered until the crack is near a particle [25]. Also, a pre-existing flaw at the particle/matrix interphase can attract the crack and substantially increase the energy release rate. BEM studies of crack propagation and interaction with a single or multiple inclusion(s) showed crack-tip shielding and amplification behavior [21]. Effects of modulus mismatch on crack growth and stress intensity behavior were also investigated. Knight et al. examined crack deflection/attraction mechanisms in a crack-particle interactions [26], finding that the constituent material properties (Poisson’s ratio) and spatial distribution have a significant effect on the localized stress distribution and energetics around the crack tip. However, due to the complexity of the mathematical formulations, difficulty with the treatment of singularities, as well as the lack of versatility of current boundary element codes present, the application of the BEM in studies of the fracture behavior of composites with complex microstructures is restricted.

In addition to BEM, analysis of crack-particle interactions and toughening mechanisms has also been carried out by FEM. Conventional FEM approaches such as the nodal release method and the re-meshing method require either a predefined crack path [27,28], or intense computation; they are inefficient for analysis of materials with second phases. Recently, the introduction of cohesive/decohesion element formulation into FEM provides a more

effective way to simulate crazing and crack propagation in materials. Several investigators developed and adopted this approach for interfacial failure simulation under either static or dynamic loading conditions. Hillerborg et al. applied cohesive element methods to analyze crack development in concrete [29], and it has also been used in the study of crazing and delamination of composites [30–34]. In this method, crack nucleation and extension, and thus the material strength and toughness, can all be characterized by the cohesive element and its traction-separation relationship. The loss of cohesion occurs when the elements start to progressively degrade, which leads to the formation of new traction-free crack surfaces. Thus, the near crack tip singularity can be considered in an efficient manner. An important advantage of this methodology for modeling fracture behavior is that macroscopic fracture criteria (e.g. $K_I = K_{IC}$) are not needed. Here, we will also use this approach to study the effect of the interphase material on crack propagation and toughness of the composite.

The material studied here is an E-glass particle reinforced BisGMA/TEGDMA resin matrix composite. The average diameter of the particles is 2.6 μm . In our complementary experimental studies, we provided a coating of ductile polymer (UHMWPE) on the glass particles in several different ways in order to both improve filler/matrix compatibility, and to introduce an energy-absorbing phase within the composite [2] to provide toughening for cracks propagating near filler particles. SEM images of fracture surfaces of various specimens as shown in Fig. 1 exhibit different fracture patterns of the composites. Without surface treatment, the glass particles do not bond to the resin matrix, and the fracture surface shows clean particle surfaces (Fig. 1(a)). Introduction of a silane (PE-silane) that bonded to the glass particle surface and was in its turn coated with UHMWPE that precipitated from solution somewhat improved particle/matrix bonding, and the surface shown in Fig. 1(b) indicates that the crack does not propagate purely along the particle-matrix interphase. Further improvement of particle-matrix compatibility, achieved by providing the precipitated UHMWPE with a methacrylate-bonding functionality, leads to the crack extending entirely within the matrix material, as shown in Fig. 1(c). These results indicate that the direction of crack propagation is affected by the interphase and in turn will affect the fracture toughness of the material [2].

The objective of this paper is to develop an engineering tool for the quantitative prediction of the deformation and fracture response of particle-reinforced polymer composites. Specifically, we wish to improve our understanding of the role of the interphase on the fracture toughness of glass particle reinforced composites.

2. Finite element model of crack tip deformation zone

Failure processes in particle-reinforced composites are related to the basic problem of a matrix crack interacting with second phase particles. Here, a small region in front of the crack tip was studied. Specifically, as shown in Fig. 2(a), a small (square) zone at the center of the 3-point bending specimen was selected as the area of interest; a detailed representation of this zone is shown in Fig. 2(b). This representative zone can be subdivided into two regions: the central deformation region and the outer surrounding region where the external load was applied. The outer region should be large enough so that boundary conditions do not interfere with the crack trajectory or the local crack driving force. The material in the surrounding region is assumed to be elastic with properties determined experimentally from specimens of a 0.3 volume fraction E-glass BisGMA/TEGDMA composite [2]. In the center region, a detailed representation of microstructure includes particle, matrix and interphase. Our current model considers a single particle, though it is possible to incorporate multiple particles within the deformation zone for other studies of crack-particle interactions. The finite element mesh used in our simulation is shown in Fig. 3 for (a) study zone unit cell and (b) central deformation zone, respectively.

The E-glass particle in the deformation region is modeled as purely elastic, with modulus and Poisson's ratio as listed in Table 1. The resin matrix material and the interphase material is modeled with a decohesion element formulation (progressive damage and failure material model) provided by ABAQUS [35]. There are two types of formulations: (a) traction-separation and (b) continuum-based models. The traction-separation formulation describes the mechanical behavior of the material by using the phenomenological relation between traction and interfacial separation. With increasing interfacial separation, the traction forces across the interphase reach a maximum, decrease, and vanish when complete decohesion occurs. Continuum-based models describe degradation behavior as a traction-separation formulation, and progressive damage and failure of materials is governed by the specific constitutive equations of the model. The latter formulation (i.e., the continuum based model) was used in our ABAQUS/Explicit analysis for crack propagation.

As shown in Fig. 4, the model used here includes an undamaged response, a damage initiation criterion and a damage evolution response. The undamaged material is modeled as an elastoplastic material model. Damage begins at the point marked $D = 0$ on Fig. 4 and initiation is based on an equivalent strain criterion. The criterion for damage initiation is met when the following condition is satisfied:

$$\omega_D = \int \frac{d\bar{\epsilon}^{pl}}{\bar{\epsilon}_0^{pl}} = 1 \quad (1)$$

where ω_D is a state variable that increases monotonically with plastic deformation; $\bar{\epsilon}_0^{pl}$ is the equivalent plastic strain, which is typically a function of stress triaxiality for ductile materials. A ductile damage initiation criterion was used in the simulation [36], in which the specific level of the damage initiation criterion is assumed to depend on stress triaxiality ($\bar{\epsilon}_0^{pl}(\eta)$). A low level of damage initiation strain is used in tensile conditions and a higher one in compressive cases. Essentially, the element does not fail in compression, but will degrade under tensile or shear stress conditions.

After damage initiation, the behavior of the materials is controlled by a damage evolution law. Damage manifests itself in reduction of the yield stress and elasticity (stiffness) [35]. ABAQUS/Explicit assumes that degradation of the stiffness associated with each active failure mechanism can be modeled using a scalar damage variable, D . As shown in Figure 4, beyond the damage initiation point, the solid curve represents the damaged stress-strain response, while the dashed curve is the response in the absence of damage. At any given time during the analysis, the stress tensor in the material is given by the scalar damage equation

$$\sigma = (1 - D)\bar{\sigma} \quad (2)$$

where D is the overall damage variable and $\bar{\sigma}$ is the stress that would exist in the material in the absence of damage.

The stiffness is given by:

$$E = (1 - D)E_0 \quad (3)$$

where, E_0 is the stiffness for undamaged material. The material loses its load-carrying capacity when $D = 1$. Based on the Hillerborg fracture energy approach [29], a material parameter, G_0 , the energy required to open a unit area of crack, can be used to control the softening response of the material after damage initiation. The G_0 value varies in the range of $0.05 - 0.1 \text{ Jm}^{-2}$ for polymer-filler interphase bonding fracture [37]. A value of 0.1 Jm^{-2}

was used in our simulation. The damage initiation strain ($\bar{\epsilon}_0^{pl}$) parameter as the function of stress triaxiality used in our model is listed in Table 2. Different strengths of the interphase material were simulated by adjusting material properties of undamaged interphase material. A comparison of stress-strain curves of undamaged materials for the polymer matrix as well as three different interphase materials (cases 1, 2 and 3, with yield strengths of 120%, 60% and 50% of the matrix material respectively) is presented in Fig. 5. The stress-strain curve for the matrix material was derived experimentally.

The boundary condition applied in the study zone is derived from a macroscopic 3-point bending simulation. We calculated the actual deformation gradient for a small square region in front of the crack tip during a 3-point bending simulation, then converted the deformation gradient in our microscopic unit cell simulation to a velocity boundary condition. As shown in Fig. 2(b), a gradient velocity boundary condition was applied on the representative zone with the highest velocity at the right corners and zero velocity at the left corners. A convergence study was carried out to ensure that the number of elements in the model was adequate. There are approximately 66000 nodes and 148000 elements in the final model with about 63000 nodes and 145000 elements in the center deformation region.

3. Results and discussion

The region surrounding the crack tip where the energy is predominantly dissipated is our special interest area. Fig. 6 shows the stress evolution as the crack propagates toward the embedded particle. The initial crack tip has a distance of $2r$ (r is the particle radius) away from the particle and the crack faces the center of the embedded particle in this case. A thin layer (2% of particle radius) of interphase material (stronger than the matrix material and with properties shown in Fig. 5) exists between the particle and matrix. Only those areas under high stress ($\sigma > 10$ MPa) are listed. As shown in Fig. 6, a stress concentration occurs at the crack tip only after the crack starts to propagate. Dissipation of energy by the creation of new surfaces relaxes stresses in regions other than at the crack tip. As deformation continues, the crack ‘senses’ the particle before making contact with it. The interphase material provides continuous stress transfer between matrix and particle, and stress increases rapidly inside the high modulus particle. As the crack approaches the particle, a large stress concentration area between crack tip and the particle is observed (Fig. 6 top right). Even though the maximum stress is observed at the particle surface, the crack does not grow in that direction. Instead, it propagates within the matrix material and is deflected around the particle. Once the crack starts to propagate forward again, the stress concentration in the area around the particle starts to decrease again (Fig. 6 bottom left). Once the crack passes the particle, it will continue to propagate within the matrix.

The crack has different trajectories when it faces a particle with different degrees of offset from the particle center (Fig. 7). The crack is bifurcated when it faces the particle center (Fig. 7 top left). If the crack approaches at an offset from the centerline of the particle, it is deflected. It is interesting to note that for $d=1.125r$, even though the initial crack trajectory is not facing the particle, the crack is still attracted by the particle as it approaches.

A comparison of the stress distribution gradients when the crack is very near the particle is shown in Fig 8. A crack facing the center of the particle has the most intense (here arbitrarily defined as the size of the zone in which the stress varies by $\pm 30\%$ of the matrix yield stress) interaction with the particle, which we interpret to indicate an effective crack shielding effect. As the crack propagation direction shifts away from the particle center, the existing particle has less effect on the crack propagation direction; the strongest indication is the reduction in the stress concentration area as shown in Fig. 8. The stress concentration for $d=1.125r$ in Fig 8 is caused by the high particle modulus, which makes the crack alter its

initial path and move towards the particle. As a result, crack propagation speed is reduced, leading to crack deflection.

It is well known that crack deflection by particles can lower the local crack-tip stress intensity factor and enhance crack growth resistance. The decrease of the energy release rate G is direct evidence of a decrease of the local stress intensity factor and therefore an increase of fracture toughness. Previous study has shown that when a crack approaches a stiffer phase, it may experience a ‘shielding’ effect, in which the energy release rate is reduced relative to the non-reinforced condition [25].

In our simulation, the energy release rate (G) is related to the work done by external forces and the change of total strain energy [38], i.e.

$$G = - \frac{d(U - W)}{da} \quad (4)$$

where W is the work done by the external forces, U is the total strain energy which includes elastic and plastic energies, and a is the crack area. Both W and U values can be obtained from ABAQUS. Fig. 9 illustrates the evolution of the normalized energy release rate, G/G^0 , as the crack propagates around the particle, where G^0 is the energy release rate when the crack propagates within the resin material only. The simulation results show that the energy release rate decreases as the crack approaches the particle. The largest decrease is in the case when the crack faces the center of the particle. The greater the degree of offset, the smaller the decrease in G . After the crack passes the particle, the nondimensional energy release rate returns back to normal. We also notice that in the case when the crack faces the particle center, the energy release rate continues to decrease after the crack passes around the particle. This is due to crack bifurcation as observed in Fig. 7. It is obvious that two cracks dissipate more energy than single crack.

In this study, special interest was focused on the effect of interphase material on the toughening mechanism of the composite. It was found that when the interphase material is stronger than the matrix, it permits good stress transfer between particle and matrix. In this situation, the crack propagates within the resin matrix, and crack deflection is the main toughening mechanism. However, the situation becomes complicated when the interphase material becomes weaker. In Fig. 10, we compared three thicknesses of the interphase material: 2%, 8%, and 12% of particle radius. The strength of the interphase material was lower than the resin matrix material (Fig. 5, case 2). The initial crack propagation direction shifted from the particle center by $0.375r$. As shown in Fig. 10(a), the layer of relatively weak interphase material still provided efficient stress transfer. Interphases with different thicknesses show similar stress distributions when the crack tip reaches the particle. Maximal stress concentrations were observed at the surface of the particle in all cases. However, the crack growth trajectories are different. As can be seen in Fig. 10(b), when the thickness of the interphase material is reduced, the crack still propagates within the matrix material and the crack deflection toughening mechanism is dominant. When the thickness of the interphase material reaches approximately 12% of particle radius, the crack will propagate within the interphase material. As a result, particle-matrix debonding occurs, and the crack-blunting toughening mechanism is activated. A comparison of energy release rates is shown in Fig. 11. At the beginning, as the crack approaches the particle, the evolution of energy release rate exhibits similar trends in all three cases. As the crack passes around the particle, the energy release rate in the thickest interphase case continues to decrease, while the energy release rate for the other two interphases reverts to the value for the pure matrix. This decrease of energy release rate is desired since it implies further energy dissipation.

Additional simulations were performed for interphases having thicknesses of 2%, 8%, and 12% of particle radius. An interphase material with a yield strength 50% of the matrix material was selected this time (Figure 5, case 3). Our results show that the crack-blunting toughening mechanism was triggered at a lower interphase thickness: the crack propagated within the interphase layer for thicknesses of 8% and 12% of particle radius. When crack-blunting occurs, a decrease of 10% in reaction forces in the vertical direction was observed as the yield strength of the interphase material decreased by 20% from that of case 2 indicating that crack-blunting is accompanied by a decrease in the strength of the unit cell. In another words, the increase of fracture toughness may lead to a decrease in strength of the composite. Our simulation results are consistent with our experimental data reported in [2].

4. Conclusions

Crack propagation and crack interaction with a second phase particle were simulated by a continuum-based decohesion finite element model. Our results show that crack deflection only occurs when the crack is near the reinforcing particle. The energy release rate decreases due to crack deflection.

The effect of interphase material on the toughening of the particle reinforced composite was also studied. Our results show that the existence of interphase material not only provides good stress transfer between particle and matrix, but also affects the crack propagation direction as the crack interacts with the particle. A combination of crack deflection and crack tip blunting toughening mechanisms was observed when the interphase material is more compliant than the matrix material and reaches a certain level of thickness. Weaker interphases lead to increased toughness, but decreases of strength are also observed. Therefore, a compliant and thicker interphase is desired to achieve maximum improvement in fracture toughness and strength. Our numerical approach provides a useful tool for designing new polymer composites with improved mechanical properties. Within the current framework, further studies such as the effect of particle-particle interactions and filler volume fraction can be easily achieved, and quantitative prediction of fracture toughness as well as other mechanical properties of particle-reinforced composite can also be obtained.

References

1. Truong VT, Cock DJ, Padmanathan N. Fatigue crack-propagation in posterior dental composites and prediction of clinical wear. *Journal of Applied Biomaterials*. 1990; 1(1):21–30.
2. Ranade RA, Ding J, Wunder SL, Baran GR. UHMWPE as interphase toughening agent in glass particle filled composites. *Composites Part A: Applied Science and Manufacturing*. 2006; 37(11): 2017–2028.
3. Kerby RE, Tiba A, Knobloch LA, Schricker SR, Tiba O. Fracture toughness of modified dental resin systems. *Journal of Oral Rehabilitation*. 2003; 30(8):780–784. [PubMed: 12880399]
4. Sun CJ, Wu W, Mahanti S, Sadeghipour K, Baran GR, Debnath S. Finite Element Analysis of Toughening for a Particle Reinforced Composite. *Polymer Composites*. 2006; 27(4):360–367.
5. Perek J, Pilliar RM. Fracture-toughness of composite acrylic bone cements. *Journal of Materials Science-Materials in Medicine*. 1992; 3(5):333–344.
6. Wetzel B, Rosso P, Hauptert F, Friedrich K. Epoxy nanocomposites - fracture and toughening mechanisms. *Engineering Fracture Mechanics*. 2006; 73:2375–2398.
7. Ranade RA, Wunder SL, Baran GR. Toughening of dimethacrylate resins by addition of ultra high molecular weight polyethylene (UHMWPE) particles. *Polymer*. 2006; 47(12):4318–4327.
8. Tohgo K, Fukuhara D, Hadano A. The influence of debonding damage on fracture toughness and crack-tip field in glass-particle-reinforced Nylon 66 composites. *Composites Science and Technology*. 2001; 61(8):1005–1016.

9. Hill RG. The role of microstructure on the fracture-toughness and fracture-behavior of rubber-reinforced acrylics. *Journal of Materials Science*. 1994; 29(11):3062–3070.
10. Guild FJ, Kinloch AJ. Modeling the properties of rubber-modified epoxy polymers. *Journal of Materials Science*. 1995; 30(7):1689–1697.
11. Amdouni N, Sautereau H, Gerard JF, Fernagut F, Coulon G, Lefebvre JM. Coated glass-beads epoxy composites - influence of the interlayer thickness on pre-yielding and fracture properties. *Journal of Materials Science*. 1990; 25(2B):1435–1443.
12. Lee J, Yee A. Micro-mechanical deformation mechanisms in the fracture of hybrid-particulate composites based on glass beads, rubber and epoxies. *Polymer Engineering and Science*. 2000; 40:2457–2470.
13. Chan KS, Lee YD, Nicoletta DP, Furman BR, Wellinghoff S, Rawls R. Improving fracture toughness of dental nanocomposites by interphase engineering and micromechanics. *Engineering Fracture Mechanics*. 2007; 74:1857–1871. [PubMed: 18670579]
14. Spanoudakis J, Young RJ. Crack-propagation in a glass particle-filled epoxy-resin .2 Effect of particle matrix adhesion. *Journal of Materials Science*. 1984; 19(2):487–496.
15. Debnath S, Ranade RA, Wunder SL, McCool J, Boberick K, Baran GR. Interphase effects on mechanical properties of particle-reinforced composites. *Dental Materials*. 2004; 20:677–686. [PubMed: 15236943]
16. Wu W, Sadeghipour K, Boberick K, Baran GR. Predictive modeling of elastic properties of particulate-reinforced composites. *Materials Science and Engineering A*. 2002; 332:362–370.
17. Sun CJ, Saffari P, Ranade RA, Sadeghipour K, Baran GR. Finite element analysis of elastic property bounds of a composite with randomly distributed particles. *Composites Part A: Applied Science and Manufacturing*. 2007; 38:80–86.
18. Sun CJ, Saffari P, Sadeghipour K, Baran GR. Effects of particle arrangement on stress concentrations in composites. *Materials Science and Engineering A*. 2005; 405:287–295.
19. Segurado J, Gonzalez C, LLorca J. A numerical investigation of the effect of particle clustering on the mechanical properties of composites. *Acta Materialia*. 2003; 51:2355–2369.
20. LLorca J, Segurado J. Three-dimensional multiparticle cell simulations of deformation and damage in sphere-reinforced composites. *Materials Science and Engineering A*. 2004; 365:267–274.
21. Ghobeity A, Deakin AS, Dryden JR. Thermal field around a partially debonded spherical particle. *International Journal of Heat and Mass Transfer*. 2007; 50(3–4):680–686.
22. Ayyar A, Chawla N. Microstructure-based modeling of crack growth in particle reinforced composites. *Composites Science and Technology*. 2006; 66(13):1980–1994.
23. Nandy M-O, Schmauder S, Kim B-N, Watanabe M, Kishi T. Simulation of crack propagation in alumina particle-dispersed SiC composites. *Journal of the European Ceramic Society*. 1999; 19(3): 329–334.
24. Kitey R, Phan AV, Tippur HV, Kaplan T. Modeling of crack growth through particulate clusters in brittle matrix by symmetric-Galerkin boundary element method International. *Journal of Fracture*. 2006; 141(1–2):11–25.
25. Bush MB. The interaction between a crack and a particle cluster. *International Journal of Fracture*. 1997; 88:215–232.
26. Knight MG, Wrobel LC, Henshall JL. Fracture response of fiber-reinforced materials with macro/microcrack damage using the boundary element technique. *International Journal of Fracture*. 2003; 121:163–182.
27. Kassam ZHA, Zhang RJ, Wang Z. Finite element simulation to investigate interaction between crack and particulate reinforcements in metal-matrix composites. *Materials Science and Engineering A*. 1995; 203(1–2):286–299.
28. Li R, Chudnovsky A. Energy analysis of crack interaction with an elastic inclusion International. *Journal of Fracture*. 1993; 63(3):247–261.
29. Hillerborg A, Modeer M, Petersson PE. Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements. *Cement and Concrete Research*. 1976; 6(6): 773–781.
30. Xu XP, Needleman A. Numerical simulations of fast crack growth in brittle solids. *Journal of the Mechanics and Physics of Solids*. 1994; 42(9):1397–1434.

31. Tjssens MGA, Van der Giessen E, Sluys LJ. Simulation of mode I crack growth in polymer by crazing. *International Journal of Solids and Structures*. 2000; 37(48–50):7307–7327.
32. Tjssens MGA, Van der Giessen E, Sluys LJ. Modeling of crazing using a cohesive surface methodology. *Mechanics of Materials*. 2000; 32:19–35.
33. Negre P, Steglich D, Brocks W. Crack Extension at an Interphase: Prediction of Fracture Toughness and Simulation of Crack Path Deviation. *International Journal of Fracture*. 2005; 134(3–4):209–229.
34. Gearing BP, Anand L. On modeling the deformation and fracture response of glassy polymers due to shear-yielding and crazing. *International Journal of Solids and Structures*. 2004; 41(11–12): 3125–3150.
35. ABAQUS, V6.6 user's manual and theory manual. 2006
36. Johnson GR, Cook WH. Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures. *Engineering Fracture Mechanics*. 1985; 21(1):31–48.
37. Kinloch AJ. The science of adhesion. *Journal of Materials Science*. 1980; 15(9):2141–2166.
38. Fan C, Ben Jar PY, Cheng RJJ. Prediction of energy release rates for crack growth using FEM-based energy derivative technique. *Engineering Fracture Mechanics*. 2007; 74:1243–1254.

Figure 1. SEM images of fracture surfaces of E-glass particle reinforced BisGMA/TEGDMA composites prepared using (a) as-received and cleaned 2.6μm glass beads; (b) UHMWPE coated/PE-silanated 2.6μm glass beads; and (c) Cl-MPS/OTS/UHMWPE coated/PE-silanated 2.6μm glass beads [2].

Figure 2.
Schematic representations of (a) 3-point bend specimen and (b) study zone.

Figure 3.
Finite element mesh design (a) Study zone; (b) Central deformation zone

Figure 4. Stress-Strain curves with progressive damage degradation used in the FEM simulation [35].

Figure 5.
Stress-strain curves for the undamaged matrix and interphase materials.

Figure 6.
 Von Mises stress evolution as the crack propagates around the particle (crack facing the particle center).

Figure 7.
Crack trajectory as a function of offset from particle center.

Figure 8.
Von Mises stress distributions when the crack has the most intense interaction with the particle.

Figure 9.
Nondimensional energy release rate as the crack interacts with the particle.

Figure 10.

(a) Von Mises stress distribution as the crack interacts with the particle; (b) crack trajectories.

Figure 11.
Nondimensional energy release rate as the crack interacts with the particle.

Table 1

Material properties of composite components [18]

Material	Young's modulus E (MPa)	Poisson's ratio
30% E-Glass reinforced composite	2800	0.35
BisGMA/TEGDMA resin matrix	1700	0.35
E-Glass particle	75000	0.24
Interphase material (Fig. 5 case 1)	3120	0.32
Interphase material (Fig. 5 case 2 and 3)	1700	0.32

Table 2

Damage initiation strain ($\bar{\epsilon}_0^{pl}$) as a function of triaxiality used in the simulation.

Triaxiality $\eta = p/q$	equivalent plastic strain $\bar{\epsilon}_0^{pl}$	Triaxiality $\eta = p/q$	equivalent plastic strain $\bar{\epsilon}_0^{pl}$	Triaxiality $\eta = p/q$	equivalent plastic strain $\bar{\epsilon}_0^{pl}$
-20.0	0.49545	0.0	0.02732	1.0	0.00496
-9.0	0.54169	0.05	0.02167	1.22	0.00452
-4.0	0.56350	0.11	0.01710	1.50	0.00415
-2.33	0.54497	0.17	0.01367	1.85	0.00384
-1.50	0.47809	0.25	0.01117	2.33	0.00357
-1.0	0.37621	0.33	0.00935	3.0	0.00333
-0.67	0.26666	0.43	0.00799	4.0	0.00312
-0.43	0.17177	0.54	0.00695	5.67	0.00294
-0.25	0.10063	0.67	0.00614	9.0	0.00278
-0.11	0.05349	0.82	0.00549	19.0	0.00263