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Modelling the strengthening of glass using epoxy based coatings

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Abstract

Glass strength can be increased by applying epoxy based surface coatings. A number of models have been presented in the literature to explain the strengthening afforded by these coatings but until now there has been no clear evidence to definitively support one model over another. In this work, finite element models (FEM) of four-point bending test specimens have been developed. These models have been used to study the strength of cracked uncoated and surface coated specimens in order to identify the strengthening mechanism. The FEM results showed that full filling of the crack using epoxy coating is sufficient to heal the crack if the coating inside the crack is ideally glued to the crack surfaces. It is also shown that under these circumstances the coating modulus is relatively unimportant parameter. FEA results for partially filled cracks show that increasing the filled percentage increases the strengthening. Fractographic analysis of the 10 kg indented and coated samples showed that the fracture surfaces do not follow the median crack symmetric plane and that fracture started from another plane when coated properly, however the fracture surface of these samples still starts from the indentation site. On the other hand, fractographic analysis of the 1 kg indented and properly coated samples showed that the samples failed from their edges which indicate that the crack was overcome. The finite element results show that the diamond imprint resulting from the Vickers indentation play an important role in this type of fracture.

Keywords: Failure analysis; Fracture; Strength; Glass; FEA

1. Introduction

The strength of glass is usually controlled by surface flaws and therefore studies dealing with increasing the strength of glasses aim to negate or remove these surface cracks. The strength of glass can be temporarily increased by the removal of surface cracks by surface etching techniques; however subsequent handling results in the re-introduction of flaws.[1,2] Increases in glass strength can also be achieved by techniques such as thermal and chemical tempering that result in surface compressive stresses that have to be overcome before a crack can propagate, however these methodologies either cannot be applied or, as in the case of chemical tempering, are too expensive to apply to bulk container glass production.[3]

Alternatively glass strength can be increased by surface coatings. The surface coating layer may fill the pre-existing surface cracks or may protect the glass surface from further contact scratches. Strengthening of glass by surface coatings can be classified according to the material used. Either a coating material with mechanical properties matching those of the glass, such as inorganic sol–gel derived coatings (see, for example,[4]), or flexible polymeric coatings, often based on epoxy resin (see, for example,[5,6]) can be used. Polymeric coatings can be applied by spraying or dipping and as only moderate thermal treatments are required for these coatings, whereas high temperature treatments are required for sol–gel derived coatings, polymeric coatings are commercially preferable.

Several studies have attempted to explain how relatively flexible surface coatings can result in significant strength increases. It is generally accepted that penetration of the cracks by the coating is important but beyond this there is disagreement as to how this leads to strengthening. Hand et al.[7] studied the possible strengthening mechanisms for two related epoxy coating systems and they concluded that closure stresses arising from the thermal expansion mismatch between the coating in the cracks

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and glass could explain the increase in the strength of the coated specimens. On the other hand, Briard et al.[8] concluded that the increase in the strength of the coated glass resulted from elastic bridging of the two surfaces of the crack by the coating.

Fowkes et al.[9] also adopted an approach based on elastic bridging of the crack. For a (necessarily) simple geometry they obtained an explicit solution for the effect of filling a crack. The basis of their model was very similar to that introduced by Williams[10] for unfilled cracks. The results of Fowkes et al. showed that the effect of the filling material is to change the stress field singularity from $1/r^{1/2}$ to $1/r^{(1-\lambda)}$ where r is the distance from the crack tip and λ is the solution of the transcendental equation.[9]

$$\lambda \cot(\lambda\pi) = -\gamma_r \frac{(n_2+1)(n_1+1)}{4\pi(n_2-1)} \quad (1)$$

where $\gamma_r = G_2/(\varepsilon G_1)$, $2\pi\varepsilon$ is the crack angle, $n_i = (3-\nu_i)/(1+\nu_i)$ for plane stress or $n_i = 3 - 4\nu_i$ for plane strain, $i = 1, 2$ refers to the substrate and filling material respectively, and ν_i is the relevant Poisson's ratio. Fowkes et al. showed that effective repair occurs when $(1-\lambda) \to 1$ hence when $\gamma_r = G_2/(\varepsilon G_1) \geq 10$ the crack is effectively healed.

The aim of the current work was to try and resolve these conflicting pictures of the actual underlying strengthening mechanisms of epoxy coated glass by considering the failure of coated glass in a four point bending geometry. To this end a finite element model has been developed to model the behaviour of surface cracks coated with an epoxy based coating. The model is described and the results of the model are compared with experimental data also reported below.

2. Experimental

Glass microscope slides that had been sectioned into 2 halves, to give samples ~38 × 26 × 1.04 mm in size, were used for the experimental studies. In line with previous studies (see, for example, Hand et al.[11]) controlled defects were created in the centre of the glass slides using Vickers indentation. A CV model 4300-AAT Vickers hardness tester was used. Samples were indented using either a 1, 2.5, 5 or 10 kg load, which was applied for 10 s. The samples were left for a week after indentation to allow the sub-critical crack growth to saturate.[12,13] To remove any remaining residual stress some of the samples were annealed after one week. For annealing the samples were heated at 2 °C/min up to 560 °C, held 2 h and then cooled at 2 °C/min to room temperature.

The coating was prepared using liquid emulsifiable bisphenol-A/F (Huntsman, Araldite 340-2) water-based epoxy resin and a polyamidoamine (Huntsman, Ardur 340) hardener. A silane with glycidoxy functionality, Z6040 (Dow Corning), was incorporated in the coating.

To prepare the coating the silane was mixed with water, stirred with a magnetic follower and left for 2 h. The water–silane solution was added step by step to the epoxy–hardener mixture. After each step the water–silane and epoxy–hardener emulsion was mixed thoroughly until the final emulsion was formed. This emulsion was stirred for 10 min using a magnetic stirrer. Using this method, a uniform emulsion was obtained. During the current work, the percentage of epoxy to hardener was taken as 1:1.7 as recommended by Whittle.[13] Epoxy emulsion concentration (EC) is known to affect the filling of the crack; the emulsion viscosity increases with increasing EC and as a result penetration of the emulsion inside the crack becomes more difficult. Therefore several emulsion concentrations (EC) were examined during this study and these are detailed in Table 1.

Table 1
Emulsion compositions used to produce coatings.

Mixture concentration %	Epoxy (g)	Hardener (g)	Silane (g)	Water (g)
6.2	2.8	4.7	1.9	120
12.5	5.5	9.4	1.9	120
24	10.6	18.0	1.9	120
37.5	16.5	28.2	1.9	120
45	19.8	33.8	1.9	120
55	24.8	42.3	1.9	120

The fracture strengths of both coated and uncoated samples were measured using four-point bending on a Hounsfield model H100KS universal testing machine. A force transducer (model SM-100N-457) with capacity 1000 N was attached to Hounsfield testing machine to measure the applied load. The inner (l_i) and outer (l_o) loading spans were 6 and 20 mm and the loading rate was 0.5 mm/min. After fracture the failure stress was calculated using

$$\sigma_f = \frac{3F(l_o - l_i)}{2bh^2} \quad (2)$$

where F was the measured load at failure; h and b were the specimen thickness and specimen width (~1.04 mm and ~26 mm respectively) which were measured using vernier calipers. After fracture the crack depth was measured from the fracture surfaces using a Polyvar Met optical microscope. Axivision 4.7 was used to digitally capture the microscope images. For each test condition, 10 samples were tested.

3. Finite element modelling

Finite element (FE) models were created using ANSYS finite element software. The indented four-point bend test specimen has two planes of symmetry and this fact was used to reduce the size of the FE models. The crack geometry was modelled using two different two dimensional finite element models. The first is shown in Fig. 1, where a is the crack depth (usually taken to be 202 μm, the crack depth produced by the 10 kg indent), $a_t = 0.2$ a and t is the crack width. In this it was assumed that the crack sides are parallel for most of the crack depth. In the second case the approach of Fowkes et al.[9] was used. In this approach the crack is assumed to be wedge shaped rather than parallel sided. A constant crack wedge angle of $\theta = 0.2°$, calculated from the experimental results for a and t, was used. As described above in this model the effect of filling the crack is to change the stress field singularity from $1/r^{1/2}$ to $1/r^{(1-\lambda)}$ and the crack is fully healed when $\lambda \to 1$. Values of λ for a range of elastic moduli were obtained using this model.

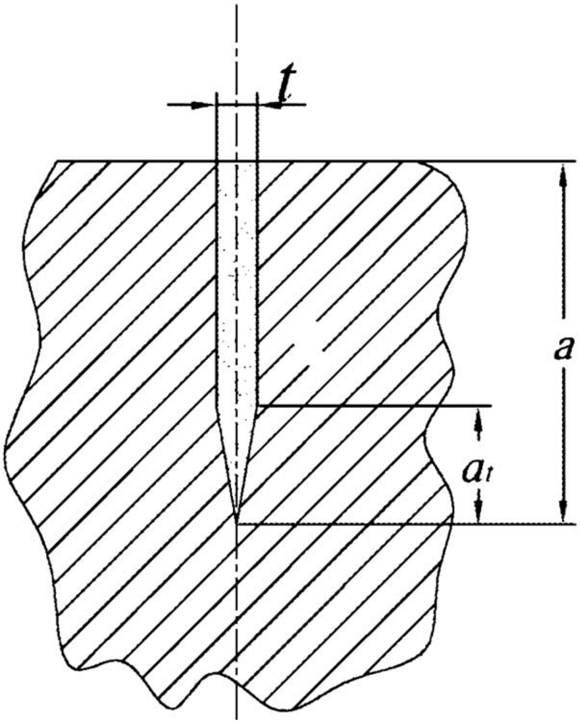

Fig. 1. Geometry of the crack in the two dimensional model.

It was assumed that the crack was equivalent to a through thickness edge crack and thus half a lengthwise cross section could be modelled with the symmetric boundary passing through the crack. In the current model the coating inside the crack was assumed to behave linearly elastically, and the interface bond between the epoxy and the crack faces was assumed to be perfect. Both fully filled and partially filled cracks were studied. In the fully filled crack case for the model shown in Fig. 2, 1% of the filling material was removed in the vicinity of the crack tip so as to retain the singularity field at the crack tip. In one of the full filling 2D models the presence of a surface coating layer was considered; the results of this part of the study showed that the surface coating layer has nearly no effect in results in terms of strengthening the glass in line with the previously reported experimental results of Verganelakis et al.[14] Hence, to simplify subsequent modelling the surface coating layer was removed and only the epoxy inside the crack was considered.

The mesh for both models was designed to give a very fine element size at the crack tip and to increase gradually towards the other side of the model (Fig. 2). The loading and the boundary conditions for both models were the same.

In the current model ANSYS PLANE82 elements, which have 8 nodes, were used to model the glass and the coating material; approximately 15,000 elements were used in forming the overall mesh. Both the glass and coating material were considered to behave in a linear elastic manner and the model was solved using linear elastic criteria. Although the coating is strictly viscoelastic, for the small strains considered here (the coating is constrained by the glass), following Matthewson[15] and Fowkes et al.[9] an elastic model is considered to be appropriate. The interface between the coating and the glass was considered to be perfectly bonded, i.e. the glass and coating elements shared the same nodes at the interface.

The shape of the controlled defect produced by Vickers indentation is a diamond impression with two perpendicular penny shaped cracks, known as median-radial cracks, as shown in Fig. 3. The median-radial crack is usually the main reason for fracture of cracked body. However, this may not be the case with coated samples. The results of the filled crack models show that the crack is almost healed as a result of filling the crack with epoxy as will be shown in the FE results and the experimental investigation show that the fracture plane of the coated samples could miss the median crack plane as will be shown in the experimental results. For this reason, the effect of the diamond indentation region on the strength of glass was also studied.

Therefore a 2D finite element model was created for the diamond imprint. In this model the presence of the median-radial crack was ignored for the reasons given above. The model was

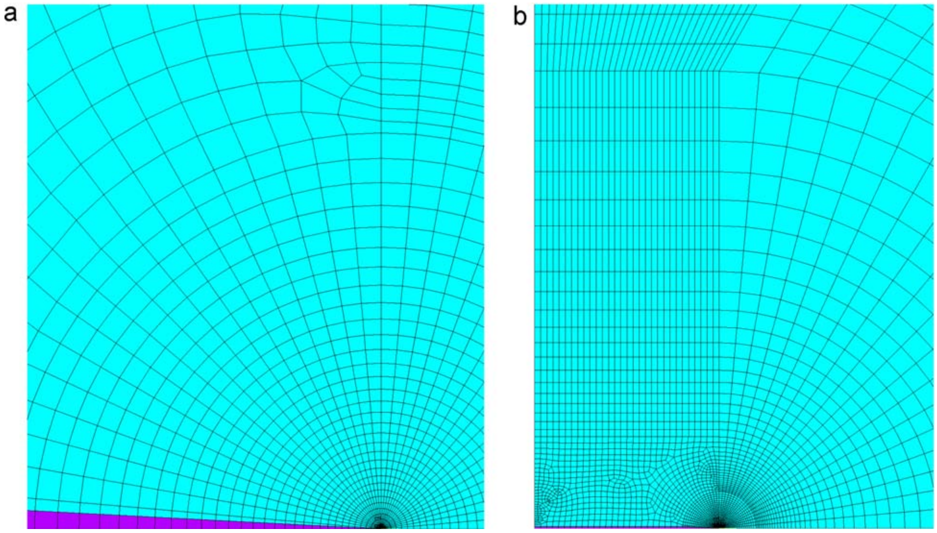

Fig. 2. FE mesh for model 1: (a) overall mesh and (b) enlargement of the near crack region.

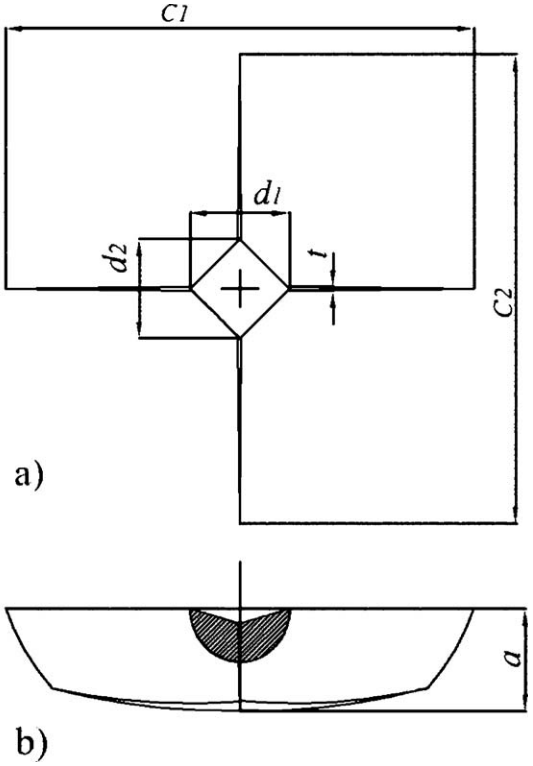

Fig. 3. Schematic diagram of Vickers indentation cracks: (a) plan view and (b) sectional view.

studied in the plan view of the sample with the applied load being simplified to uniaxial tension applied perpendicularly to one of the diagonals of the indent. This model is a simplified model compared with the real case, as the diamond shape is assumed to be extended through the specimen depth with the same dimension. Due to the symmetry of the model, it is sufficient to use one quarter of the model. The indentation impression shape was assumed to be a sharp diamond shape. Modelling of the diamond indentations resulting from 1, 2.5, 5 and 10 kg Vickers indentation was undertaken. Modelling of the Vickers diamond impression before and after filling with the epoxy coating was conducted.

The notch stress intensity factors were calculated using the stress extrapolation method.[16,17] The calculated results before and after filling with epoxy were compared to investigate the strengthening effect. The results of the different size notch models were also compared to investigate the effect of crack size on the values of the notch stress intensity factors.

4. Experimental results

Controlled defects were created using four different indentation loads. The created flaws were approximately semi-elliptical. The dimensions c_1, c_2, d_1 and d_2 were measured using an optical microscope. An average of 10 measurements were made for each dimension. The depths of the cracks (a) were measured using optical microscope by imaging the crack fracture surface. The width of the median crack (t) was measured by acquiring scanning electron microscope images for indented samples, see Fig. 3, and the median crack width was measured just ahead of the plastic deformation area. The measured crack dimensions are listed in Table 2.

Table 2
Measured Vickers indentation crack dimensions.

Indentation load	c (μm)	d (μm)	a (μm)	t (μm)
10 kg	886 ± 50	188 ± 12	202 ± 10	0.74 ± 0.29
5 kg	609 ± 24	131 ± 4	142 ± 9	0.54 ± 0.27
2.5 kg	431 ± 38	91 ± 3	96 ± 5	0.47 ± 0.1
1 kg	231 ± 22	56 ± 2	61 ± 3	0.28 ± 0.04

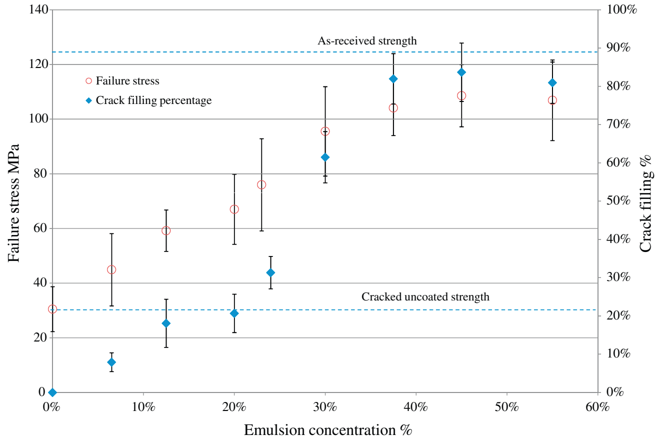

Fig. 4. Experimental failure stress and percentage crack filling versus coating concentration.

The 4-point bend strength of the as-received slides was 123 ± 13 MPa. The presence of a controlled defect resulting from a 10 kg Vicker's indentation reduced this strength to 30.4 ± 1.8 MPa.

Fig. 4 shows the effect of different ECs on the resultant failure stresses. An increase in failure stress with increasing EC can be seen up to an EC of 37%. The failure stress remained almost unchanged for an EC of 55%. Further increases in EC resulted in a decrease in the strength of the coated samples. From Fig. 4 we can conclude that an epoxy EC with approximately 45% is the best epoxy EC for strengthening cracked glass; this is approximately double the epoxy EC recommended by Whittle.[13] The average failure stress for the coated system of 108 ± 10 MPa is also higher than that recorded by Whittle (95 ± 15 MPa). The reasons for the difference between the current results and those of Whittle are not clear, but the differences suggest that more work is required to define the optimum coating conditions. Comparing the mean failure stress of the samples coated with the 44% EC emulsion with the mean failure stress of the as-received samples failure stress indicates that the coating has enabled approximately 90% of the as-received strength to be recovered despite the presence of a large (10 kg indent) controlled defect.

The effect of different controlled defect sizes on the strength of samples coated with a 45% epoxy EC is shown in Fig. 5. For the cracks created using a 1 kg and 2.5 kg Vickers indentation, the failure stress of the cracked coated samples was higher than the mean failure stress of the as-received glass samples indi-

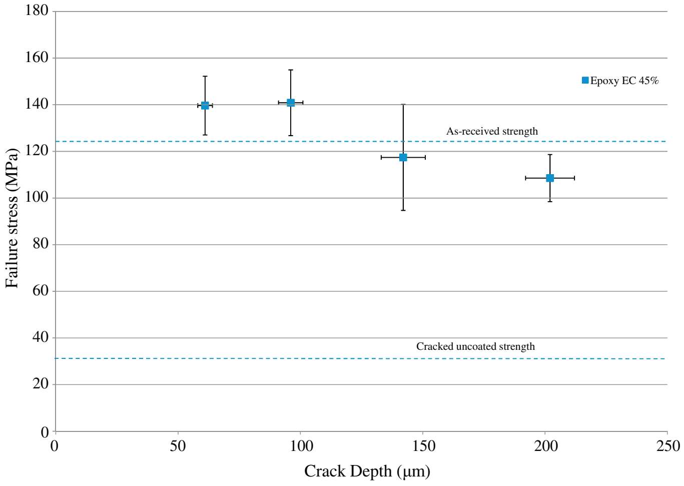

Fig. 5. Strengths of samples with different controlled defects coated with a 45% EC coating.

cating that the controlled defect had been overcome and that these small cracks had been completely healed using the water based epoxy coating. Fractographic analysis also showed that for the samples with 1 kg indents the indentation crack was not the fracture origin which again indicated that the epoxy coating had healed the indentation cracks these samples. For the 2.5 kg indented samples fractographic analysis indicated that 50% of the fracture origins were not at the indentation crack. In the case of the defects created by 5 and 10 kg Vickers indentations, the failure stress was lower than that of as-received glass and the fracture origin of most, but not all, of the coated samples was the indentation site.

5. FEA results

The effect of epoxy coating surface layer on the strengthening of glass was studied by using a crack filled model with a surface coating layer either 0 μm, 20 μm or 40 μm thick. The stress intensity factor results of these models are compared in Fig. 6. The applied load was constant in all curves and the maximum applied stress is 27.9 MPa (this corresponds to the failure stress of the uncoated samples), and the crack depth was 202 μm (corresponding to the crack size for the 10 kg indented samples). For all coating thicknesses nearly identical values of the stress intensity factor at the crack tip as a function of coating elastic modulus were obtained (see Fig. 6) indicating that the coating thickness has essentially no effect on the stress intensity factor at the crack tip. In line with experimental results reported by Fabes et al.[18] and Verganelakis et al.[14] it can be can concluded that the surface coating has a negligible effect on the strengthening of coated cracked glass.

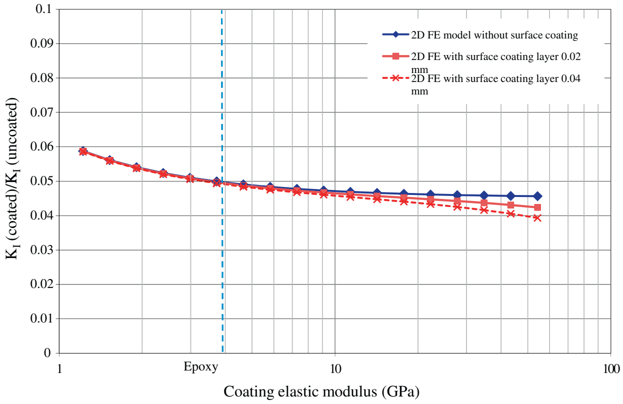

Fig. 6. K_I (coated)/K_I (uncoated) versus coating elastic modulus for crack of depth 0.202 mm and ideally filled with coating, with surface layer thicknesses $t = 0$, 0.02, 0.04 mm.

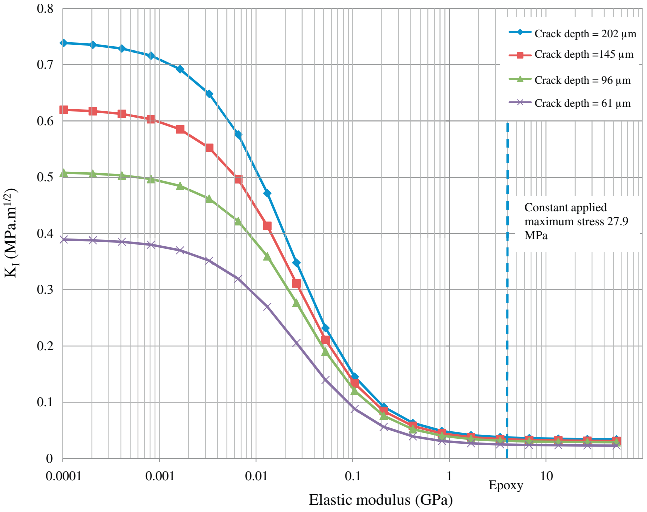

Fig. 7. Stress intensity factor (nodal displacement method) versus elastic modulus for crack filling coating and for four different crack depths for a wide range of elastic moduli values; the vertical dashed line is the elastic modulus of the epoxy coatings studied here.

Fig. 7 show the calculated results for perfect full filling of the crack as a function of coating elastic modulus and four different crack depths. Fig. 7 shows that when the coating has an un-realistically low elastic modulus the stress intensity factor value at the crack tip is almost the same as that for the uncoated glass and that for any realistic coating elastic modulus the stress intensity factor approaches 0.03 which indicates that the crack is almost healed. Whilst the expected value for K_I for a completely healed crack is zero as noted above in the current study 1% of the filling material in the vicinity of the crack was removed to maintain the singularity at the crack tip; thus a low non-zero value indicates crack healing.

Fig. 8 shows the results of λ calculated using the Fowkes et al. approach versus the filling material elastic moduli. It can be seen that a very low filling material elastic modulus approximates to the uncoated case and $\lambda \rightarrow 0.5$, i.e., the stress field singularity is $1/r^{1/2}$ and the stress field approaches that of cracked uncoated system. As the elastic modulus increases the value λ approaches 1, which means that there is no stress singularity at the crack tip and that the crack is healed. Fig. 8 shows that $\lambda = 0.997$ when the filling material elastic modulus equals that of epoxy. This again indicates that although the epoxy coating has a small elastic modulus compared with that of the glass, it is sufficient to repair the crack completely. A comparison of Figs. 7 and 8 indicates that both approaches similarly indicate that unless the coating modulus is unrealistically low the presence of a perfectly bonded coating will effectively heal the crack.

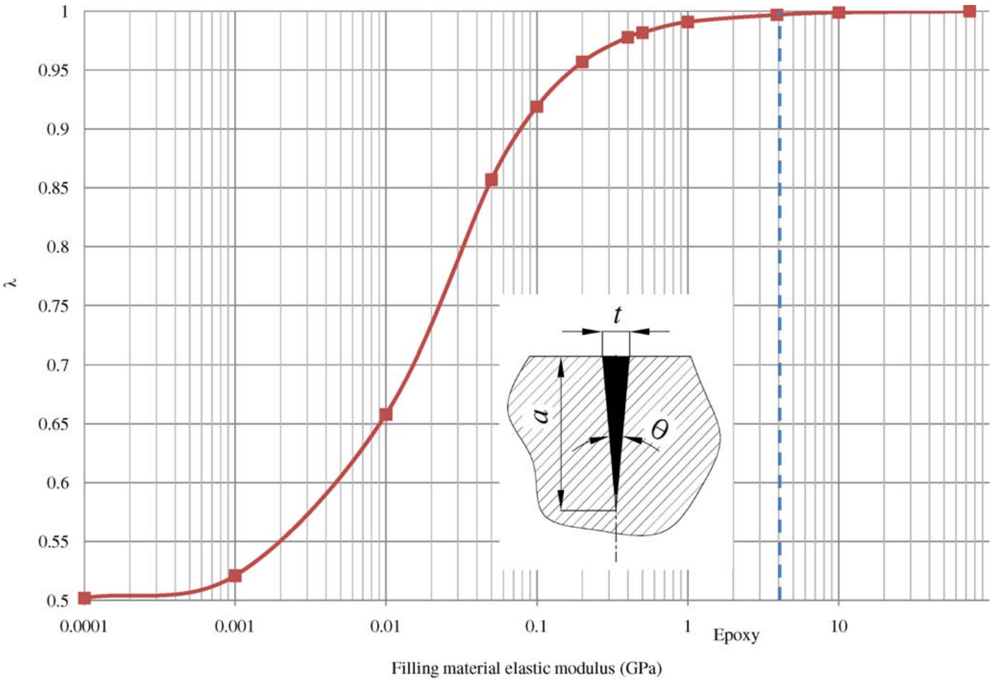

Fig. 8. The eigenvalue λ versus the filling material elastic modulus. This curve was plotted using the Fowkes et al.[9] solution. The cracked material is glass and different filling material was used. $\theta = 0.2$.

The results shown in Figs. 7 and 8 complement each other in the sense that the explicit model of Fowkes et al.[9] shows for a very simple geometry that the degree of singularity is changed at the crack tip by the presence of the coating in the crack, whereas the finite element results show, for a more realistic geometry that the stress intensity factor is reduced at the crack tip.

Observation of the fracture surfaces indicates that in many practical cases the crack is not fully filled. Thus the effect of partial filling of the crack was also studied. This study was done by gradually filling the crack from the glass surface with coating material and investigating its effect on stress intensity factor at the crack tip. Fig. 9 which shows the ratio of K_I (coated)/K_I

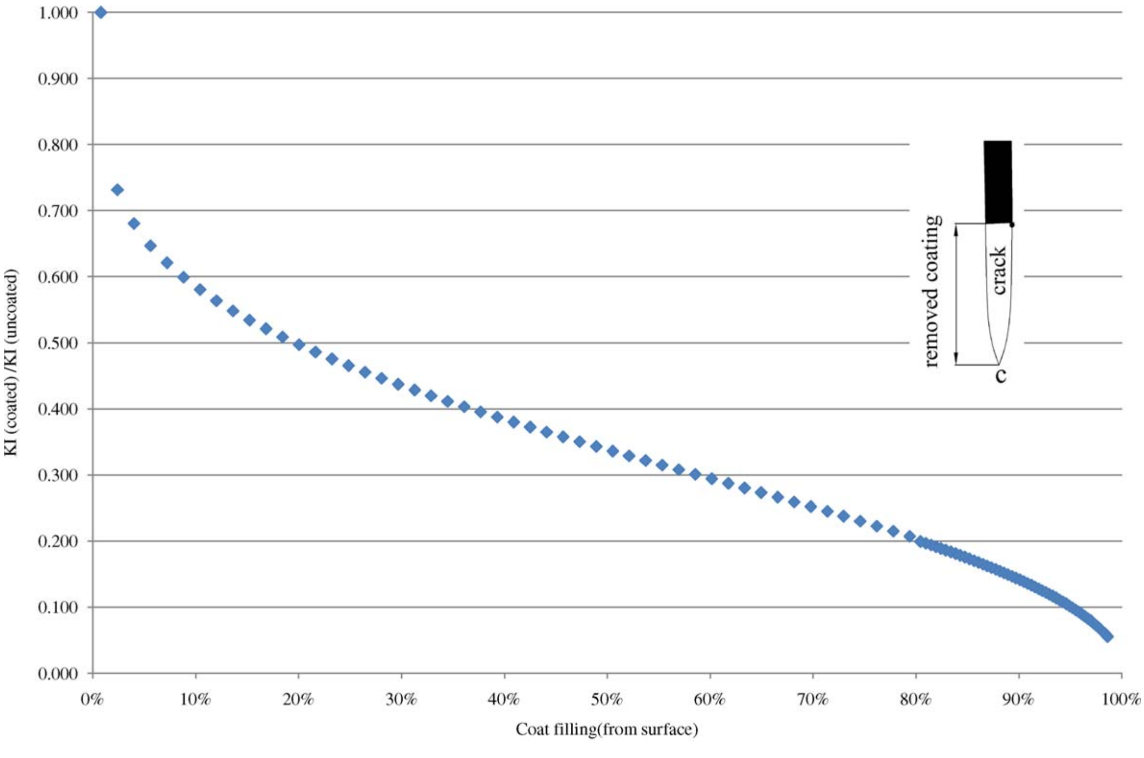

Fig. 9. The percentage of crack filling material (epoxy) from crack surface and towards the tip versus the ratio K_I (coated)/K_Ic (glass) at the crack tip.

Table 3
Results of the notch stress intensity factor.

Indentation load (kg)	Crack depth h (μm)	Notch dimension 2d (μm)	Notch K_I (uncoated) (MPa m^{446})[a]	Notch K_I (coated) (MPa m^{446})[a]	$\frac{K_I(\text{coated})}{K_I(\text{uncoated})}$
1	63	56	0.30	0.24	0.8
2.5	96	91	0.38	0.29	0.76
5	145	131	0.45	0.34	0.76
10	202	188	0.54	0.39	0.72

[a] See equation.[20]

(uncoated) versus the percentage crack depth filled by the coating indicates that the greater the extent of crack filling the lower the crack tip stress intensity factor and thus the greater the fracture stress. If 70% of the crack depth is filled K_I (coated)/K_{Ic} (uncoated) = 0.25. Thus for 70% crack filling this model suggests that the failure stress of coated samples would be increased by a factor of 4 as compared to the failure stress of uncoated samples which should be sufficient to recover the strength of the undamaged glass; i.e. if the coating is perfectly bonded full flaw filling is not required to recover the strength of the undamaged glass.

For the diamond shaped indent region the notch stress intensity factor was calculated at constant applied nominal stress of 100 MPa. The calculated values of the notch stress intensity factor for both filled and unfilled notches are listed in Table 3. The experimentally obtained dimensions of the diamond indent are given in Table 2.

Table 3 indicates that the notch stress intensity factor increases with indent size. It can also be seen that filling the notch with epoxy results in a decrease in the notch stress intensity factor of approximately 76%. On the other hand, these results indicates that although the coating results in an increase the stress required for fracture but the coating is not capable of fully healing a notch. Table 3 shows that the notch stress intensity factor for 1 kg indentation crack is 0.6 of the notch stress intensity factor for 10 kg indentation crack, i.e. for 10 kg indentation crack, if the notch stress intensity factor attains its critical value at an applied stress = 100 MPa, then the 1 kg indentation crack attains its critical notch stress intensity factor at an applied stress = 167 MPa.

6. Discussion

The experimental results showed that increasing the epoxy EC causes a steady increase in the fracture strength until the epoxy EC reaches the value of 37% as shown in Fig. 4. In this case the fracture strength is 105 ± 16 MPa which is approximately 85% of the average strength of as-received glass. From 37% to 55% epoxy ECs, fracture strength levels off and remains close to 107 MPa.

Fractographic analysis of the samples coated with different epoxy ECs showed that the percentage of epoxy which infiltrated into the median crack increased with the increase in the epoxy EC until the epoxy EC equalled 37% as shown in Fig. 4. The filling ratio corresponding to this epoxy EC is 82%. The average percentage of epoxy infiltrating the crack remained almost constant when the epoxy EC was changed from 37% to 55%. The change in the strength of the cracked and coated glass with the increase in the epoxy emulsion concentration followed the same trend as the change in the epoxy filling ratio with the increase in the epoxy EC. From these results, it can be concluded that the higher the percentage of crack infiltration by the coating, the higher the strength of the coated glass.

The finite element results for perfectly bonded coatings showed that there is a minimum value of the filling material elastic modulus for strengthening but for all realistic filling material elastic moduli (2 GPa to 74 GPa) there is no effect of coating modulus on the strengthening of glass (see Figs. 6 and 7).

The fractographic analysis showed that most of the coated and cracked samples using 10 kg indentation loads failed from the indentation site. Three types of fracture were recognized. In the first type, the fracture surface follows the median crack on both sides of the indentation site, in the second type the median crack follows the median crack symmetric plane only on one side of the indentation site and in the third type the fracture surface did not follow the median crack at all.

The third type of fracture was observed in approximately half of samples coated with epoxy EC of 30%. The corresponding epoxy filling ratio to this epoxy EC was 62 ± 7% (see Fig. 4). This type of fracture becomes dominant when the epoxy EC increases to 37.5%. The corresponding epoxy filling ratio to this epoxy EC was 82 ± 7%. In this type of fracture the coating which infiltrated into the median crack generated a closure stress over the median crack surfaces sufficient to close the median crack. As a result the fracture surface did not follow the median crack symmetric plane in most of these samples.

Fig. 10 shows that the experimental failure stress versus the percentage of the crack filling agrees with the two-dimensional partial finite element model results (filling from surface towards the crack tip) up to a crack filling ratio of 62%. Above a crack filling ratio of 62% the fracture stress calculated using FEA exceeds the experimental results. For complete filling of the crack, the finite element results showed that the crack is almost healed. The deviation of the finite element results from the experimental results is because failure from somewhere other than the large controlled damage site becomes more likely see also,[19] and indeed fractography showed that failure of these samples did not involve failure along the median crack (see Figs. 8 and 9), i.e. the dominant mode of fracture for these samples was fracture type three see Elsayed.[20] It should be noted however that fracture still initiates from the indentation site.[20] This is because although the epoxy coating is sufficient to heal the median crack, it is not sufficient to heal the diamond shape imprint. FEA showed that the effect of filling the diamond shape imprint with epoxy is to reduce the notch stress intensity factor levels to ≈76% of the

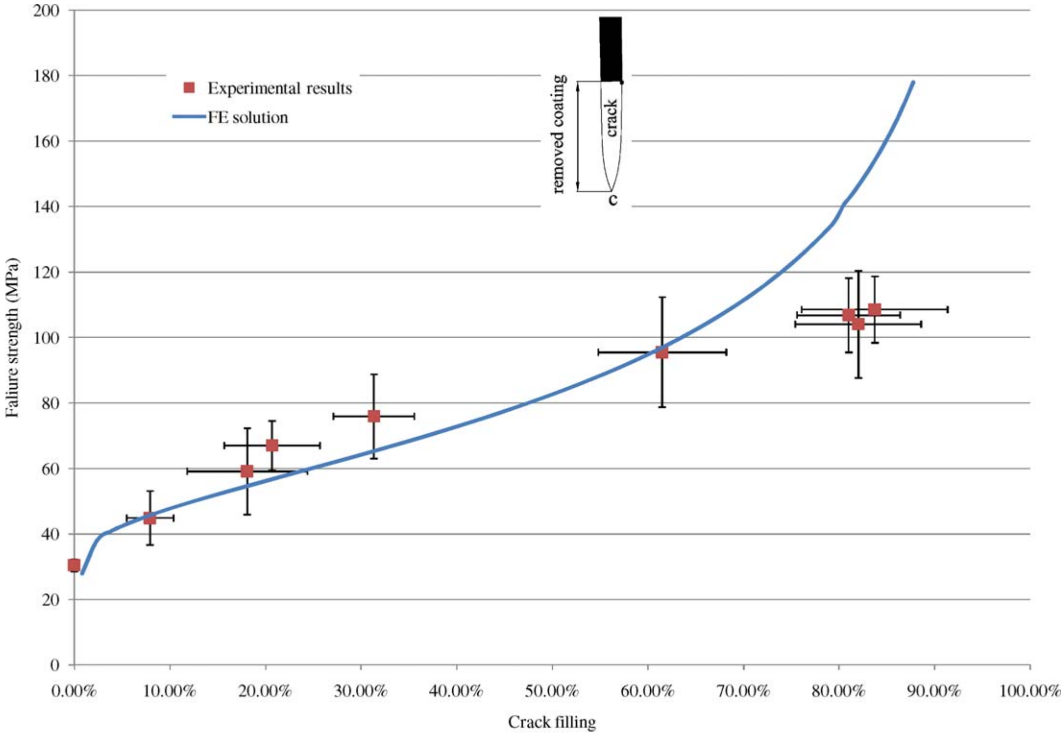

Fig. 10. The percentage of crack filling versus the failure stress using the experimental results and using the partial filling (fill from top to tip) two-dimensional finite element model results.

unfilled notch stress intensity factor. According to these results, while loading the coated samples, the notch stress intensity factor increases until reaching its critical value when a crack starts to grow from the diamond imprint notch. This may also explain why the FEA results for partial filling deviate from the experimental results at higher values of emulsion concentrations as shown in Fig. 10.

Fractography of samples with 1 kg and 2.5 kg indentation sites showed that more than half of these samples failed from edge defects and the fracture surface did not go through the indentation site. The average fracture stresses of these samples were higher than the average as-received fracture stress. Hence it can be concluded that for smaller indentation sites the epoxy coating can reduce the notch stress intensity factor to a lower enough value that failure initiates from a site other than the controlled damage site.

7. Conclusions

The FEA results show that for all realistic coating moduli the coating modulus has no effect on glass strengthening and that penetration of the coating into the crack is the important parameter. The results here were obtained for a model of 4 point bend testing and thus complement the analytic results of Fowkes et al.[9] for a very simple geometry which showed that coating penetration reduced the degree of singularity. Furthermore the FEA results showed that the effect of the surface coating layer thickness in strengthening of coated glass is negligible although it has an important role in protecting the surface of the coated glass.[20] The combined FEA and experimental results showed that greater filling of the crack by the coating is essential for greater strength increases. Hence the coating emulsion concentration has an important effect on the strengthening of glass as this affects the degree of coating penetration into the crack. The experimental and FE results of the current work showed that the filling material can heal the median cracks whatever its length, however the filling material cannot heal the large notches arising from indentation. The shape and size of the defect can therefore affect the percentage of strengthening achieved.

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