Modeling Transparent Armor Behaviors Subject to Projectile Impact

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ABSTRACT

Design and manufacturing of transparent armor have been historically carried out using experimental approaches. In this study, we use advanced computational modeling tools to perform virtual design evaluations of transparent armor systems under different projectile impact conditions. AHPCRC developed modeling software EPIC'06 [1] is used in predicting the penetration resistance of transparent armor systems. LaGrangian-based finite element analyses combined with particle dynamics are used to simulate the damage initiation and propagation process for the armor system under impact conditions. It is found that a 1-parameter single state model can be used to predict the impact penetration depth with relatively good accuracy, suggesting that the finely comminuted glass particles follow the behavior similar to a viscous fluid. Even though the intact strength of borosilicate and soda lime glass are different, the same fractured strength can be used for both glasses to capture the penetration depth.

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Introduction

The response of brittle solids to the impact loading of different projectiles has been a subject of considerable interest because of its significance to strength degradation and structural integrity of this important class of materials. It becomes particularly important in designing transparent armor materials because of the seemingly conflict goals of providing ballistic protection and maintaining vehicle weight and mobility. Design and manufacturing of transparent armor have been historically carried out using experimental approaches. This is because glass strength under tensile loading condition is controlled by surface flaws and therefore it is difficult to assess glass structural integrity using a deterministic analytical approach.

In order to examine penetration resistance of various glasses under ballistic impact condition, many researchers have conducted controlled impact experiments. For example, Behner et al. [2] measured failure front dynamics in borosilicate glass under gold rod impact and penetration. The dynamic failure wave front and rod penetration depth are measured simultaneously using high speed photography and flash X-rays. Nie et al. [3] measured the dynamic strength of borosilicate glass under combined compression and shear loading using Split-Hopkinson Pressure Bar (SHPB) technique. More recently, Bless and Chen [4] reported the experimental ballistic data for layered soda lime glass under the impact loading of a fragmentation simulated projectile (FSP). Even though penetration is limited in the top two glass layers, various damage patterns extends throughout every plate. With more experimental data becoming available, modeling activities are focused on finding the appropriate material constitutive model and the associated material parameters in modeling and predicting the impact resistance of glass. For example, Sun et al. [5] used a continuum damage mechanics (CDM)-based constitutive model to describe the initial failure and subsequent stiffness reduction of glass of the experiments carried out by Nie et al. [3]. A maximum shear stress-based damage evolution law was used in describing the glass damage process under combined compression/shear loading. With only two modeling parameters, reasonably good comparisons between the predicted and the experimentally measured failure maps have been obtained for various glass sample geometries under the impact strain rate of 250/sec. Under higher strain rate and higher confinement pressure, Johnson and Holmquist [6] examined the applicability of various constitutive models in EPIC'06 for the gold rod penetration experiments carried out by Behner et al. [2]. It was found that a 1-parameter single state model can be used to predict the penetration velocity as well as the hole profile and penetration depth with reasonably good accuracy.

In this study, we examine the applicability of the 1-paremeter single state model in EPIC'06 [1] in modeling the FSP penetration experiment reported by Bless and Chen [4] on layered soda lime transparent armor systems. Both monolithic glass and layered glass armor are examined with EPIC'06. Observations are then made on the predicted penetration depth and damaged glass strength for borosilicate and soda lime glass with different constitutive models. Directions for future research are also suggested.

Glass Constitutive Model Validation with FSP Single Shot Experiment

AHPCRC developed modeling software EPIC'06 [1] is used in this section to study the applicability of a simple 1-parameter single-state constitutive model to model the FSP penetration experiment reported by Bless and Chen [4]. LaGrangian-based finite element analyses combined with particle dynamics are used to simulate the damage initiation and propagation process for the soda lime glass under different impact conditions. The fractured material strength is modeled with only 1 parameter: constant equivalent stress of 570MPa as illustrated in Figure 1.

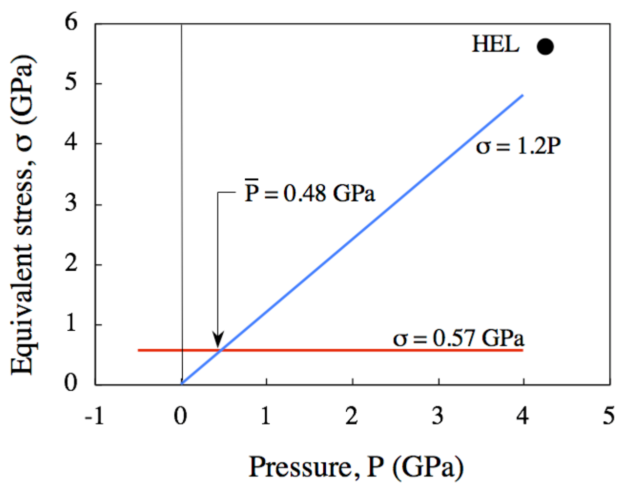


Figure 1. Single-state model for strength of fractured glass (replotted from Johnson and Holmquist [6])

At the first glance, this model may seem over simplified since it assumes that the fractured glass strength does not depend on confinement pressure or impact strain rate. From another perspective, this assumption may be physically sound since it describes an elastic-perfectly plastic behavior, i.e., viscous flow condition provided by the finely comminuted glass particles immediately in front of the projectile [7]. It should be mentioned that various other constitutive models have also been examined by Johnson and Holmquist [6] to simulate the gold rod penetration test on borosilicate [2], and that the simple 1-parameter model can predict the penetration velocity and depth with reasonably good accuracy. The value 570MPa is obtained by matching the gold rod penetration test data at V = 1600 m/s, see Figure 2 [2, 6].

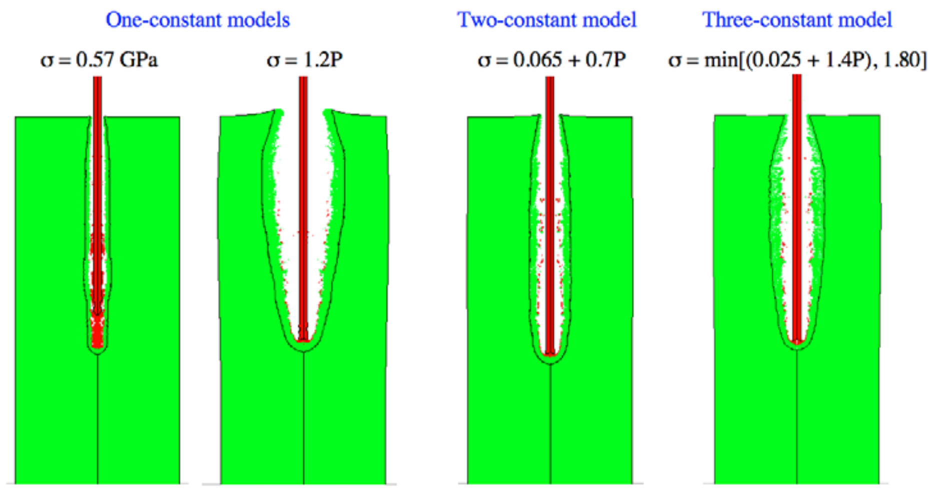


Figure 2. Predicted hole profiles of the single state model at t = 28 μs for V = 1600 m/s (replotted from Johnson and Holmquist [6])

The single-state 1-parameter glass model is next used in modeling the FSP penetration experiment reported by Bless and Chen [4] on <u>soda lime glass</u>. The target used in the experiment was made of seven layers of 30cm x 30cm soda lime glass of 7.6cm total thickness and two layers of polycarbonate of 12.7mm total thickness. The separate plates were assembled with polyurethane adhesive between the layers. A standard 12.7mm (50-caliber) fragment simulating projectile was shot into the glass layers at 1118m/s. The projectiles weigh 13.4g and are made of HRC30 steel [4]. The projectile was stopped in the second glass layer, with the total depth of penetration of 18.9mm. Figure 3 is a replot from Ref. 4 showing the different crack morphologies observed for the entire target.

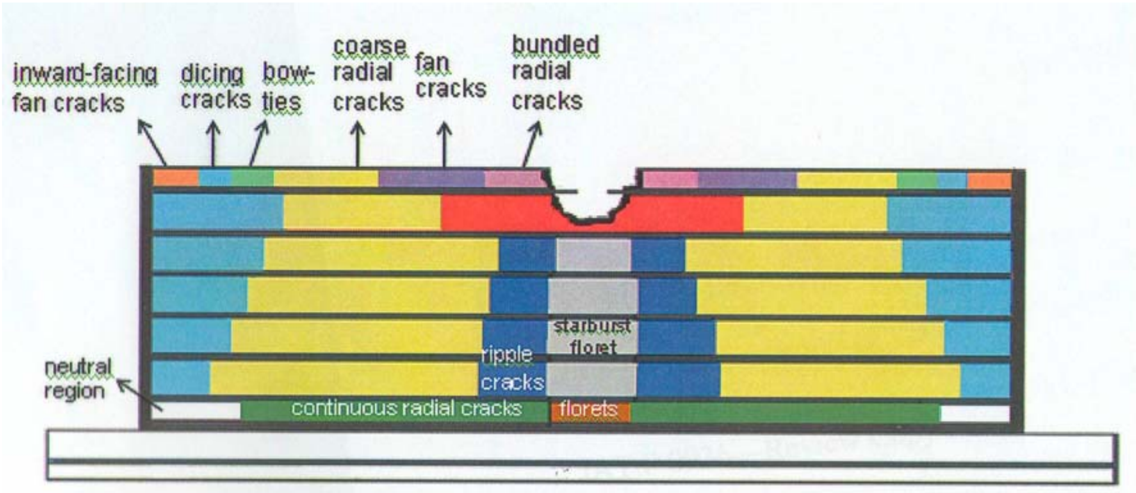
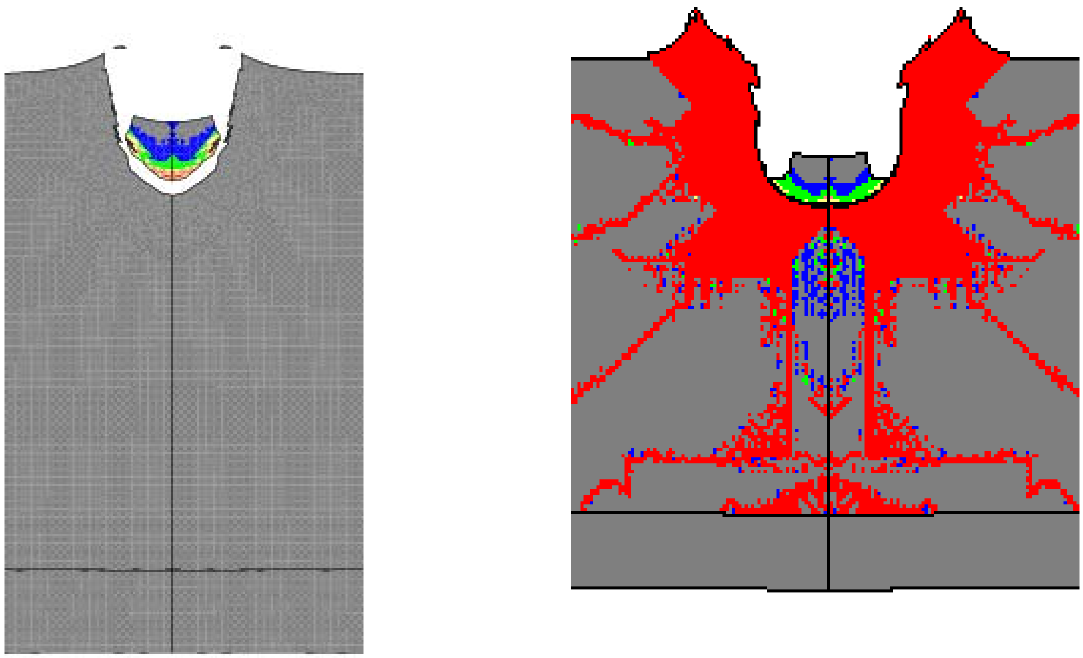


Figure 3. Damage map of complete target for the single shot FSP experiment (replot from Ref. 4)

Monolithic Glass Block

In EPIC'06 calculations, the following physical properties for soda lime glass are used: density = 2530kg/m^3, Young's modulus = 72GPa, Poisson's ratio = 0.25. The strength for fractured soda lime glass is assumed to be the same as those in Ref. 6 for the borosilicate glass: 570MPa. The single-state 1-parameter glass model is used. For the first round of calculation, a solid piece of 76mm thick soda lime glass target is used. Figure 4(a) shows the predicted impact region profile.

The predicted penetration depth is 18.39mm, slightly lower than the experimentally observed value of 18.9mm for bonded glass layers. For comparison purpose, the library brittle material model #82 for float glass in EPIC'06 is also used in modeling the monolithic glass target performance. The predicted damage zone is shown in Figure 4(b) and the penetration depth is 24.1mm, much higher than that of the 1-paramter model prediction.

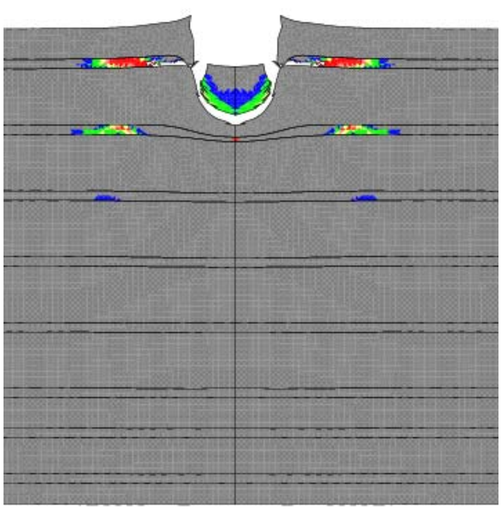


(a) 1-parameter prediction (b) Material #82 prediction
Figure 4. EPIC'06 predictions for monolithic glass armor

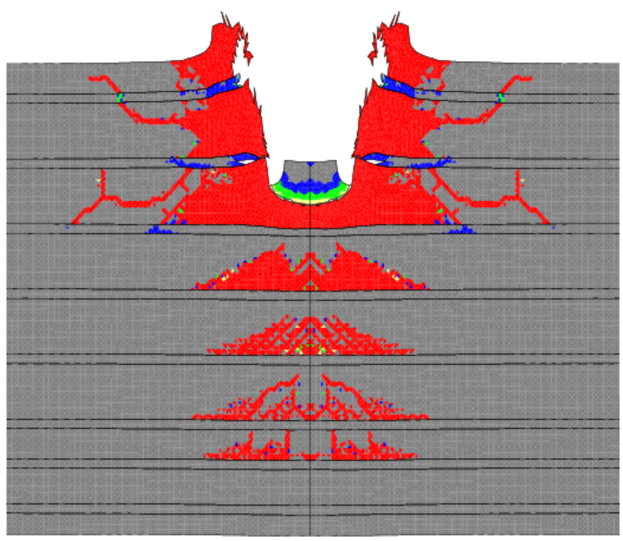
<u>Layered Glass Armor</u>

Next, the effects of the polyurethane adhesive layer on the impact resistance of layered armor are examined. The layering scheme used is consistent with that of Ref. 4. The polyurethane adhesive is modeled with EPIC library material #142 for polyvinyl butyral phenolic resin [1]. Again, both the 1-parameter JH-1 model and the library material model #82 are used in model the soda lime glass. Figure 5 shows the predicted impact zone for the two glass models. The predicted penetration depths are: 18.97mm for the 1-parameter model, and 27.38mm for the library material #82. For both glass models, the predicted total penetration depths for the layered armor are higher than their monolithic counterpart.

The results in Figures 4 and 5 also indicate that the predicted penetration depth with the simple 1-parameter model is very close to the experimentally measured penetration depth of 18.9mm for layered soda lime glass. It is interesting to note that even though the static indention tests indicate the strength of intact soda lime glass is about 25% higher than that of the intact borosilicate glass [8], the same fractured material strength of 570MPa can be used for both soda lime glass and borosilicate to accurately predict penetration depth. Similar observations have also been made in Refs. 5 and 9 where the same critical strength value of 600MPa was used for both borosilicate glass and soda lime glass with continuum damage mechanics formulation to predict low speed impact damage.



(a) 1-parameter prediction



(b) Material #82 prediction

Figure 5. EPIC'06 prediction for layered glass armor

Discussions and Conclusions

Results in Figures 4 and 5 also indicate that the library material #82 over predicts the penetration depth for both the monolithic and the layered target. With the simple, constant fracture strength model, EPIC'06 can predict the penetration depth of the layered glass armor with relatively good accuracy. This indicates that the comminuted glass particles at the tip of the projectile follow the material behavior of a perfectly plastic flow without any strain hardening, similar to that of a viscous fluid. Again, this behavior has been suggested by some researchers and is worth further exploration [7, 10].

It should be mentioned that the predicted damage zone is much more concentrated around the projectile, as oppose to the multiple other fracture mechanisms as shown and discussed by Bless and Chen [4]. The damages away from the projectile impact zone are due to the stress waves generated by the impact shock, and this is the fundamental difference between the impact behaviors of brittle armor and ductile armor: Ductile armor has single penetration point surrounded by material undergone considerable amount of plastic deformation; For brittle armor, in addition to the penetration crater and the finely comminuted zone immediately adjacent to it, there are large regions of damaged/fractured zone in the target with various crack morphologies. These different, discrete damaged zones will influence the multi-hit capability of the brittle armor systems in different degrees, therefore a comprehensive glass damage model that can predict all the damage mechanisms should be developed for the brittle armor systems. EPIC'06 with 1-parameter is sufficient in predicting the penetration depth and the damage around the impact crater, yet more development is needed to quantify and predict all the other damage mechanisms in brittle armor systems.

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