Modelling Laminated Glass in LS-DYNA under Extreme Loading Conditions

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1 Introduction

In the event of an explosion in a populated urban area, fragmentation from glass is a significant contributor to human injury. The mitigation of glass fragmentation hazards is well-established through the use of laminated glass featuring a polymer interlayer, such as DuPont Sentry Glass Plus (SGP) or polyvinyl butyral (PVB). These interlayers work by exploiting the inherent viscoelastic and adhesive properties of the polymer, providing a mechanism to dissipate the energy of the blast through work done in deformation of the interlayer while retaining fragments of broken glass. This behaviour is fundamental to limit the projection of fragments of otherwise brittle glass, thereby reducing or eliminating highly hazardous secondary fragmentation associated with glazing.

As a result, laminated glass has been designed to withstand substantial blast loadings, absorbing and dissipating the energy from the blast wave through cracking and deformation. This pane deflection can result in substantial load transfer to the window framing system, resulting in a dynamic in-plane and out-of-plane loading scenario that requires adequate restraint in order to avoid total pane failure. Whilst the benefits of laminated glass have been utilized for decades in blast hazard mitigation, relatively few analytical models exist that are capable of capturing the complex mechanics of the pane and frame loading under the high strain-rate conditions observed in blast events.

This research paper presents recent activities by Arup to develop a methodology that has been demonstrated to be effective in replicating both lab (specimen) and full-scale arena test results of single pane laminated glass response to blast scenarios in LS-DYNA. In further development, *MAT_280 is used to investigate the effects of residual glass strength post cracking on the model's validation.

2 Laminated Safety Glass

Laminated glass or Laminated Safety Glass (LSG) incorporates a PVB interlayer into a composite layup. This construction combines the durability and transparency of glass with a ductile and highly elastic PVB interlayer. LSG is extensively used in both the automotive industry and built environment due to its enhanced impact resistance and ability to retain the sharp glass fragments from an otherwise brittle failure mode, which often results in hazardous fragmentation. Within protective design for the built environment, LSG is often used to meet two objectives of protection [1]:

1. Maintaining the building envelope, and;
2. Minimising flying debris.

Following fracture of the glass, LSG is able to withstand substantial deflections prior to failure by rupture or tearing at supports, thereby limiting the ingress of the debris beyond the façade and providing an adhesive surface that retains glass fragments. The protective performance of LSG is dependent on several factors that interact throughout its response under blast including the material thickness, glass heat-treatment, pane support conditions, interlayer mechanical properties, and adhesion level – the bond between the interlayer and the glass itself.

3 Model Parameters

The authors have previously developed and characterised a laminated glass pane to a blast test using solid elements to represent the glass. In this approach, the individual parts of a laminated glass pane were correlated to test data including the PVB, adhesion between the PVB and the glass and the glass pane in LS-DYNA [3]. Then the model has been compared to a full-scale blast test and demonstrated peak magnitudes for displacement within 10% of the test [2]. An elastic material with an erosion criteria was used to represent the glass and crack growth in the pane, which had the undesirable effect of

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removing the residual strength that cracked laminates exhibit during a blast test. In the following sections, the authors summarise the parameters used for PVB and Adhesion based on the work completed previously and then present the new full pane models using *MAT_280 to demonstrate how the residual strength of glass affects the shape of deformation and the mid-span displacement throughout the response of the glass.

3.1 PVB

The PVB is meshed using hexahedron 8 node solid elements with an element formulation of -1 (fully integrated S/R solid elements). To represent the hyperelastic and viscoelastic parts of the PVB *MAT_77H is used.

*MAT_77H uses a six-term polynomial to fit the hyperelastic part of the material, which is shown in equation 1.

$$W(J_1, J_2, J) = \sum_{p,q=0}^{n} C_{pq}(J_1 - 3)^p (J_2 - 3)^q + W_H(J) \quad (1)$$

This material card also has the option to include a Prony series that represents the viscoelastic parts of the material. The Prony series in LS-DYNA is detailed below:

$$g(t) = \alpha_0 + \sum_{m=1}^{N} \alpha_m e^{-\beta t} \quad (2)$$

Given by,

$$g(t) = \sum_{i=1}^{n} G_i^{-\beta_i t} \quad (3)$$

The material is effectively a Maxwell fluid that consists of dampers and springs in series; G_i represents shear moduli and β_i are the decay constants. The material coefficients used to fit the material curves in the simulation are listed in Table 1 for the hyperelastic part and Table 2 for the viscoelastic part.

Table 1: Hyperelastic material model parameters used for the PVB

Parameter	**Value**
C_{10}	0.94
C_{01}	2.06
C_{11}	-0.23
C_{20}	0.404
C_{02}	0.0182
C_{30}	-0.0063

Table 2: Prony Series Parameters for PVB

B (1/s)	$\boldsymbol{G_i(MPa)}$
9080	684.5
10	3.0
11	4.78
2000	0.3

3.2 Adhesion

Adhesion is modelled as cohesive elements with an 8-noded 4-point cohesive element. To accurately represent the cohesive element delamination behaviour, a material that utilises a bilinear traction separation law for both the tangential and normal directions is used. A representation of the traction separation law is shown in Figure 1 and the properties are provided in Table 3.

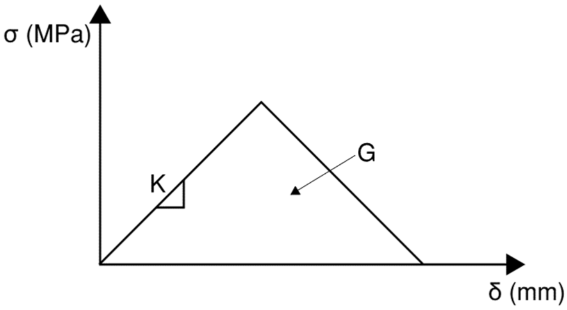

Fig.1: Traction Separation Law used to describe adhesion of PVB interlayers

Table 3: Summary of Cohesive Material Properties

Cohesive Elements	Bi-Linear Traction Separation	*MAT_186 COHESIVE_GENERAL	σ =1.8MPa G =3000 J/m^2

4 Full Pane Assessment

Using the PVB and adhesion material characterisation as described, a comparison to full-scale blast testing was completed. Hooper [4] carried out a series of live arena blast tests adopting laminated glass with a PVB interlayer for a range of charge sizes and standoff distances. The test setup adopted by Hooper [4] is presented in Figure 2. Panes of 1.2m by 1.5m were supported along all four edges using single sided structural silicone bonded to a steel subframe.

This test arrangement was replicated in LS-DYNA. The test scenario simulated was a 30kg TNT equivalent charge at a 16 meter standoff distance, corresponding to Hooper's Test 3. Blast loads for the simulation were derived from pressure time-history data gathered from gauges measuring reflected pressure at the same 16 meter standoff during the Hooper test. This ensured high fidelity in reproducing the test conditions for simulating the blast load on the glass, which is important for making relevant comparisons between the test and simulation results.

Two element types to represent the glass material were tested in the simulation. In the first assessment, the glass was modelled using solid elements, with a linear elastic material card (see Table 4), and in the second assessment the glass was modelled using thick shells with a material card that distinguishes between damage in compression and tension (see Table 5).

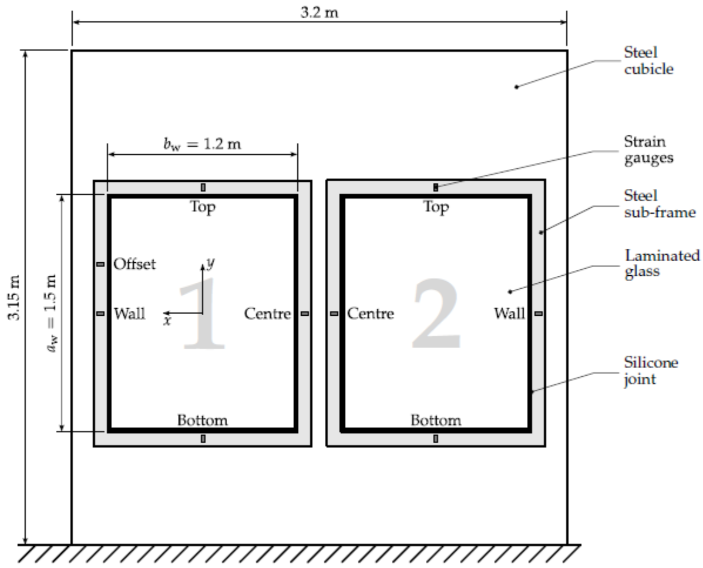

Fig.2: Full pane test setup completed by Hooper [4]

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4.1 Solid Element Method

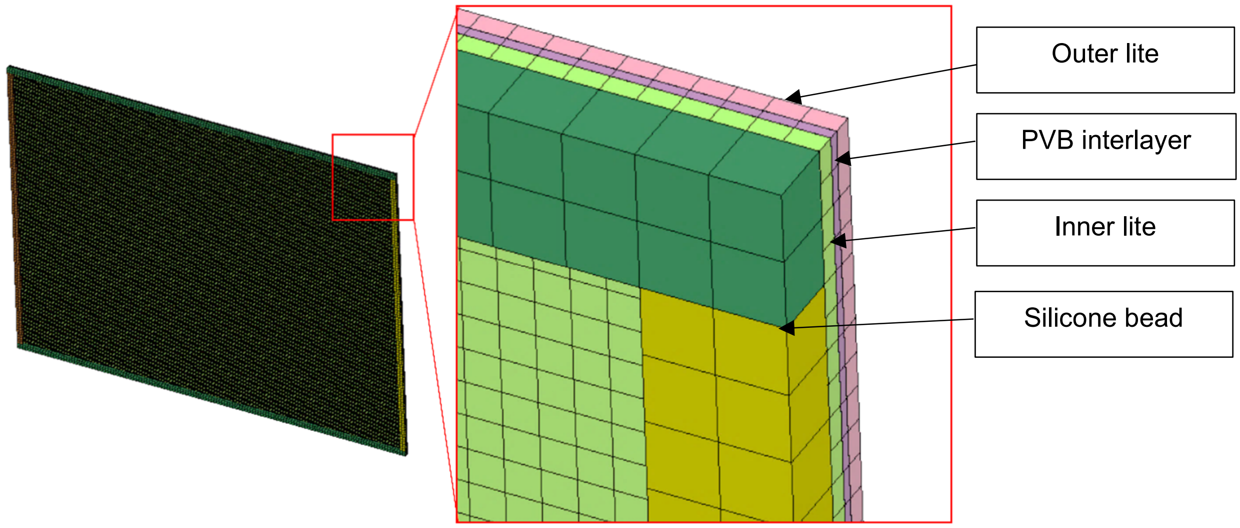

Fig.3: Full Pane Simulation Model - 5mm element size

The simulation model that was developed to represent a full pane is shown in Figure 3. The inner lite, PVB interlayer and outer lite were all modelled using fully integrated 8-noded quadratic elements with 5mm x 5mm edge lengths. The adhesion elements were modelled using the same mesh density, however, with 0.01mm through-thickness. The structural silicone joint was also modelled using quadratic elements but utilized greater element size. For the purposes of this investigation, the structural silicone bite was assumed to be of sufficient depth that it would not fail during loading. It is included to simulate the flexibility of the glass edge support rather than any explicit failure mechanism. As such, the connection between the inner lite and silicone was modelled using tied contact.

Additionally, one dimensional discrete beams with zero stiffness, mass and damping properties were applied down the centreline of the pane to allow easier visualisation of the pane shape during loading. Blast loading of the pane was replicated using a *LOAD_SEGMENT_SET approach to the external face of the outer lite. This allowed the pressure time-history curves measured during the physical experimentation to be applied directly in the simulation. Element erosion was used to simulate crack growth for the glass panes. This erosion criterion was based on element peak stress of 80MPa, corresponding to the dynamic breaking strength of annealed glass. Table 4 summarizes the material cards employed in the model.

Table 4: Summary of the glass material used in the solid element method

Material	Material Card	Summary of Parameters
Glass	MAT_1	$E = 70GPa, \rho = 2500/m^3, \nu = 0.22$

Figure 4 illustrates the deformed shape of the solid element method that was observed from the simulation of the laminate when subjected to the replicated full test blast impulse. Both the elastic and plastic response of the system can be observed, with glass failure denoted by the removal of the elements from the pane.

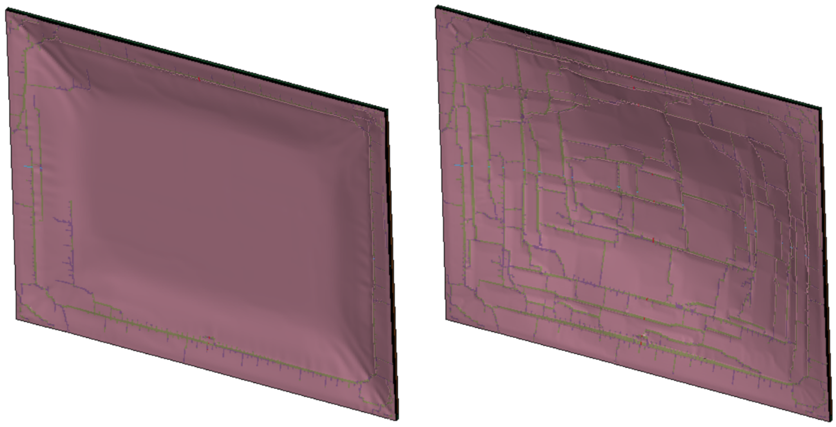

Fig.4: Full pane deformed shape at 5ms and 15ms respectively

Figure 5 offers a visual comparison of both the simulation and Hooper's physical test results. While the comparison of deformed shape is difficult to display, reasonable replication of the failure condition can be observed between the two tests. Inner lite failure and delamination is observed in both, occurring approximately at midway of the long edge.

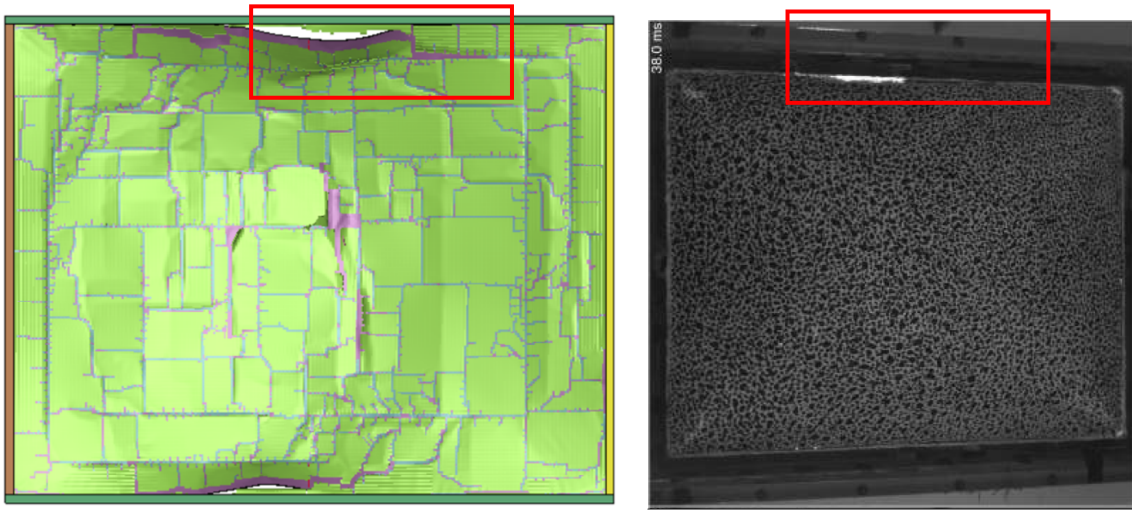

Fig.5: Full pane deformed shape at maximum inward deflection (note time stamp in video is based on detonation time)

4.2 Thick Shell Elements (*MAT_280)

To investigate newer modelling methods, a glass model that separates the damage into compression and tension was employed in the second simulation approach. The inner lite and outer lite were modelled using thick shell elements utilizing *MAT_280 with a softening approach. The simulation model that was developed to replicate the full pane testing is consistent with the model in Figure 3 but featuring the thick shells rather than solid elements to model the glass. The PVB interlayer was modelled using fully integrated 8-noded quadratic elements with 5mm x 5mm edge lengths.

Table 5 lists the parameters utilised for the glass material card. Element deletion was not implemented in the model as the glass does have minor residual capacity that is important to the post failure performance, particularly with respect to the deformed shape of the panel. The softening values applied to the model are 0.2 of the elastic stiffness after failure and 0.15 for the stress in case of failure; therefore the elastic stiffness at failure is reduced to 20% and the failure stress is reduced to 15% of its capacity. The Rankine stress criterion was used, where the principal stresses are bound by the tensile strength (*ft*) and compressive strength (*fc*). In the development of cracks for *MAT_280, a crack occurs perpendicular to the maximum principal stress direction as soon as tensile failure occurs.

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*Table 5: Material properties for annealed glass (*MAT_280_GLASS)*

	Tensile Force *ft*	Compression Force *fc*	Stiffness after failure	Softening factor compression
Value	80 MPa	1000 MPa	0.2	0.15

The adhesion elements were modelled using the same mesh density as the glass, however with 0.01mm through-thickness with a cohesive element formulation. The adhesion elements were also modelled using 8-noded solid elements. The structural silicone joint was also modelled using quadratic elements but utilized a greater element size.

Additionally, plotel elements with zero stiffness, mass and damping properties were applied down the centerline of the pane to allow easier visualization of the pane shape during loading and to track displacement. Blast loading of the pane was replicated using a *LOAD_SEGMENT approach to the external face of the outer lite. This allowed the pressure time history curves measured during the physical experimentation to be applied directly to the face of the pane.

Figure 6 illustrates the deformed shape that was observed from the simulation of the laminate when subjected to the replicated full test blast load. The deformed shape is displayed at a response time of 5ms and 15ms on the left and right of the figure, respectively.

Fig.6: Full pane deformed shape at 5ms and 15ms respectively

Figure 7 offers a visual comparison of both the thick shell element method and Hooper's physical test results. Similar to the previous modelling methodology, inner lite failure and delamination is observed in both, occurring approximately at midway of the long edge.

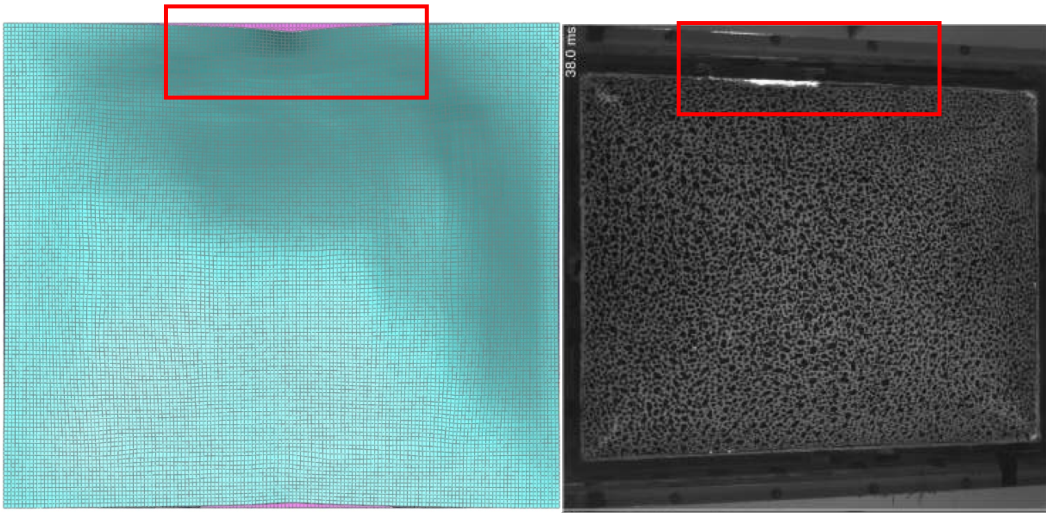

Fig.7: Full pane deformed shape at maximum inward deflection (note time stamp in video is based on detonation time)

A comparison between the crack pattern of the glass pane witnessed post-test and the output in the simulation displays a heavily cracked laminate in both the simulation and the test (Figure 8).

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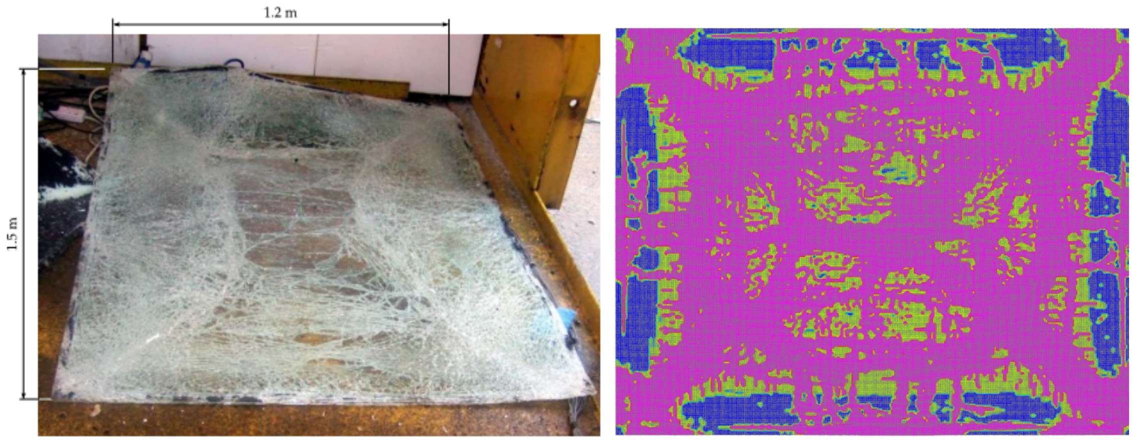

Fig.8: Comparison of crack pattern between test and simulation

5 Summary

A full-scale blast test was modelled using two different methods to represent the glass. The first method used solid elements and an elastic material property with an element erosion criterion based on the failure stress to represent the cracks that occur in the glass. The second method used thick shells with a material card that separates the damage based on compression and tension. The thick shell method provides a more representative bathtub shape, which is found to occur in the experiment as per the displacement curve captured in Hooper [4].

Figure 9 presents a comparison of the deformed shape of the panel from both the physical testing and the two glass methods employed. As is demonstrated the thick shell method illustrates a more parabolic shape than the solid element method. However, the solid element method achieves a much closer displacement to the test compared with the thickshell method which overestimates the displacement by approximately 8%.

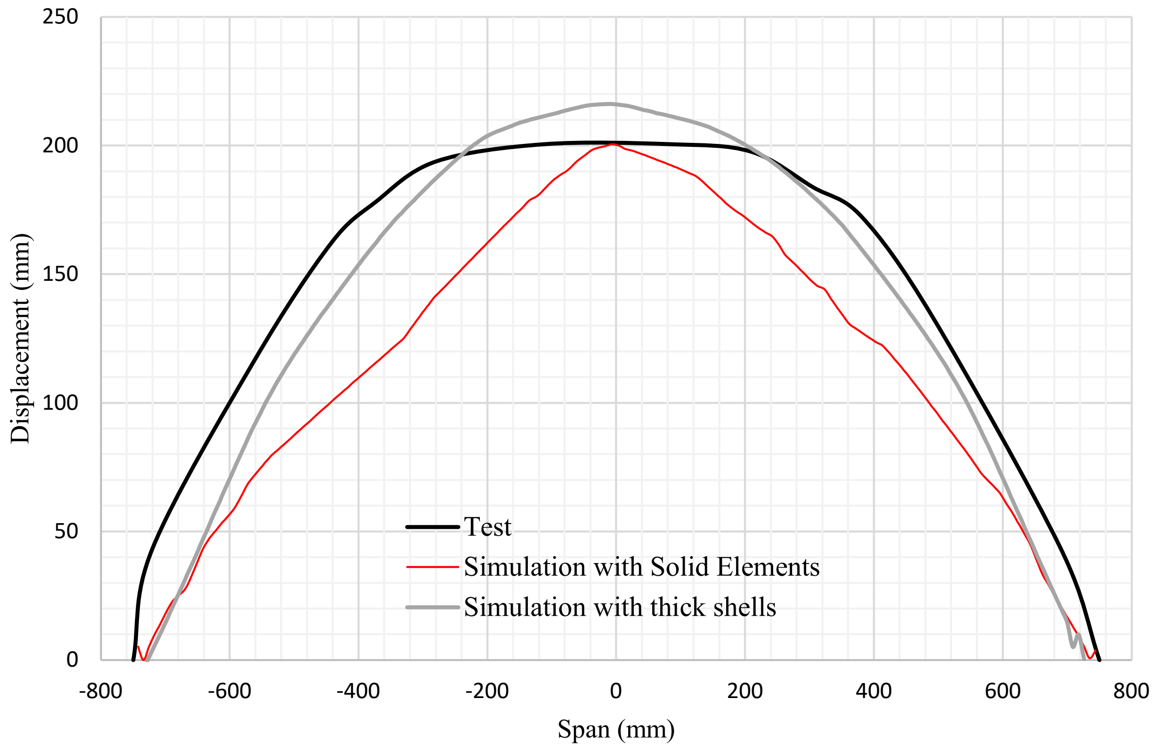

Fig.9: Comparison of deformed shape for physical test and simulation (30kg at 16m)

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Both methods demonstrate reasonable correlation to the full pane test both in terms of the progressive displacement of the pane and overall deflected shape. Moreover, both methods accurately predict the failure mechanism of the laminated glass observed during this test, placing failure in the correct location on the pane. Comparison of the forces within the simulated glass pane and reactions at the supports are also similar between the two methodologies.

Despite these similar results, a major difference was observed in the overall run times of the model; the thick shell method reduces computation time by 75% in comparison to the solid element method. As a result, the time required to solve the thick shell method is comparable with most single degree of freedom (SDOF) methods. While SDOF methods remain faster, these simulations overcome a number of significant shortcomings in SDOF methods. For example, it is difficult and uncommon to characterize the behaviour of irregular pane shapes using SDOF methods. However, these simulation approaches can be robustly applied to odd panel shapes and a variety of edge support conditions. Additionally, many SDOF models for laminated glass feature relatively simplistic material models for the glass and, more importantly, the PVB. Brittle failure in glass and a bilinear elastic-plastic material model for PVB are not uncommon. While this may be acceptable to capture the inward excursion of the pane as a single point, it is difficult to robustly correlate the reactions generated from these material models to the forces observed in trials. Furthermore, the treatment of the pane via the independent material models of its component parts overlooks the most significant and beneficial feature of LSG: its behaviour as a composite material.

Perhaps one of the most exciting developments arising from both of these modelling methodologies are related to the ability to robustly assess the response of cracked LSG as a composite material. In particular, the pane response displays the interaction between adhesion of glass to interlayer and the stretching of the interlayer itself. This interaction between adhesion and deformation is fundamental to derive the benefits of LSG under blast loading and to avoid designs that fail prematurely. It is correspondingly fundamental for accurate simulation and prediction of protective capability for laminated glass.

6 References

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[3] Livermore Software Technology Corporation (2018) LS-DYNA Material Manual, Livermore California, USA

[4] P. Hooper, "Blast Performance of Silicone Bonded Laminated Glass, PHD Thesis (2011)

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