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Computational Analysis of Laminated Glass Panels Under Blast Loads: A Comparison Of Two Dimensional And Three Dimensional Modelling Approaches

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ABSTRACT

This paper illustrates the use of finite element (FE) technique to investigate the behaviour of laminated glass (LG) panels under blast loads. Two and three dimensional (2D and 3D) modelling approaches available in LS-DYNA FE code to model LG panels are presented. Results from the FE analysis for mid-span deflection and principal stresses compared well with those from large deflection plate theory. The FE models are further validated using the results from a free field blast test on a LG panel. It is evident that both 2D and 3D LG models predict the experimental results with reasonable accuracy. The 3D LG models give slightly more accurate results but require considerably more computational time compared to the 2D LG models.

KEYWORDS *- Blast load, Finite element modelling, Laminated glass, 2D shell elements, 3D solid elements*
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I. INTRODUCTION

Designing building facades to a credible blast load has become a major concern in most of the iconic buildings with the ever increasing terrorist attacks. Glazed facades are often used in buildings, especially at the lower levels for their architectural features and aesthetical aspects. Most of these facades stand about 4-10m height without any structural framework. However, it is evident from the past explosions that more than 80-90% of blast related injuries are due to flying glazed fragments and facade pieces. On the other hand, if the building facade disintegrates, blast pressure enters the building causing injuries to the occupants and even damage to the building. Laminated glass (LG) provides significant blast resistance compared to the normal glass and therefore used in buildings to minimise the hazard form potential terrorist attacks.

LG is made by bonding two or more glass panes with one or more elasto-plastic interlayers. PVB is the common interlayer material and glass types such as annealed, heat strengthened and tempered glass are used for the glass panes. LG panels are attached to the window frames using structural sealant joints where usually the rubber or silicone are used as sealant materials. LG is designed in a way that it fails by tearing the interlayer other than a failure at the supports. If the glass brakes in a LG panel the interlayer holds the glass fragments instead of forming free flying shards. The breakage of glass does not imply the failure of a LG panel as the available strain energy at the post-crack phase is significantly higher than that at the pre-crack phase.

The UK Glazing Hazard Guide [1], American Society for Testing and Materials (ASTM) F 2248-09 [2] and Unified Facilities Criteria (UFC) 3-340-02 [3] are three major standards used for designing glazed facades to blast loads. The UK Glazing Hazard Guide [1] provides a realistic approach for designing glazed facades by accounting the post-crack load carrying capacity of glass. However, it is a highly confidential document which was established for only few window sizes available in the UK. The ASTM F 2248-09 [2] neglects the effects of interlayer in the analysis while the UFC 3-340-02 [3] is limited to design of monolithic thermally tempered glass. All these standards are based on simplified single degree of freedom analysis and cannot be used to design large glazed facades used in typical buildings. Those limitations in the current standards emphasize the requirement of an analytical procedure to study the blast response of LG panels and for their design for a credible blast event.

Finite element (FE) analysis with computer codes is a feasible method to investigate the behaviour of LG panels under blast loads. Sophisticated FE models are required to investigate the influence of controlling parameters such as geometric and material properties of LG panels to enhance their blast resistance. On the other hand, simple FE models that provide results with reasonable accuracy are required to analyse the global behaviour of large LG panels used in existing buildings. This paper illustrates two modelling approaches available in LS-DYNA [4] FE code to analyse LG panels and provides information to address the above requirements. Research findings demonstrate that the 3D LG model provides more accurate results and enables to investigate the influence of controlling parameters and support conditions in LG panels. The 2D LG model on the other hand gives results with reasonable accuracy using less computational time and hence can be used to investigate the global behaviour of large LG panels.

II. FE MODELLING OF LG PANELS

LG panels have less thickness compared to the in-plane dimensions and therefore can be modelled with either 2D shell elements or 3D solid elements. FE codes with explicit capabilities such as LS-DYNA, ANSYS, ABAQUS and EUROPLEXUX have been used to investigate their behaviour under blast loads. This paper illustrates two modelling approaches based on 3D solid and 2D shell elements to analyse LG panels with LS-DYNA [4] FE code.

2.1 The 3D LG model

In the 3D LG model, the entire LG panel including the glass panes, interlayer and structural sealant joints are modelled with 3D solid elements. Fig. 1 shows the cross section of a typical 3D LG model indicating the glass and PVB solid elements through the thickness. The glass panes are modelled using material model 110 (MAT_HOLMQUIST_CERAMICS) while the PVB interlayer and the structural sealant joints are modelled using material model 24 (MAT_PIECEWISE_LINEAR_PLASTICITY). As was evidenced, the 3D LG models incorporating above material models give more accurate results but require considerably more computational time compared to the 2D LG models.

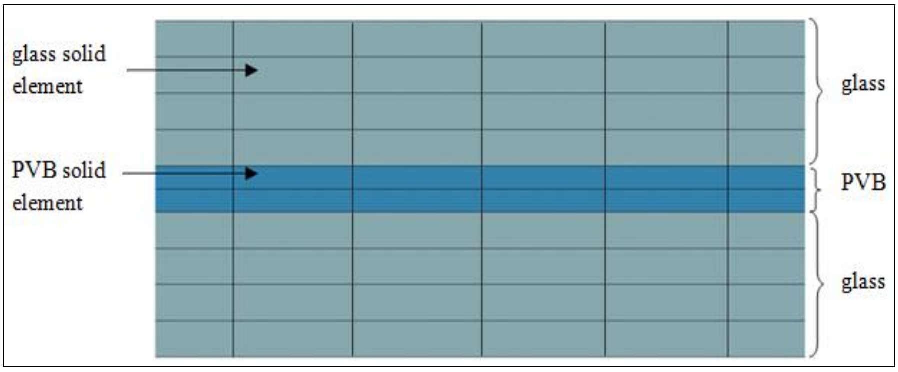

Fig. 1: Cross-section of a typical 3D LG model

The Johnson-Holmquist (JH-2) material model which has been widely used to model brittle materials subjected to high pressures, large strains and high strain rates, was implemented in LS-DYNA as material model 110. Cronin et al. [5] used the validation cases presented by Johnson and Holmquist [6] to explain the implementation and validation of the JH-2 model in LS-DYNA. This material model requires a set of mathematical equations, in which the material constants of glass under high strain rates were presented by Johnson and Holmquist [7]. Material model 110 provides a realistic approach to model glass as it takes into account the fractured strength of glass depending on the damage level. The maximum tensile strength or the maximum tensile hydrostatic pressure of glass (T) should be given carefully as it considerably influences the behaviour of a LG panel under blast loads. The authors have identified that the results from FE analysis agree well with those from experiments when the T of glass is varied around 60-65MPa for annealed glass. Material model 110 has been used to model glass panes for investigating the behaviour of LG panels under impact loads [8] and blast loads [9].

PVB, which is the common interlayer material, behaves as an elasto-plastic material under high strain rates occurring under blast loads. This behaviour can be implemented with LS-DYNA using material model 24 which allows defining arbitrary stress versus plastic strain curves for different strain rates. Wu et al. [8] used material model 24 to analyse LG windows under impact loads. It is used in this research to analyse LG windows under blast loads. The literature does not indicate any specific LS-DYNA material model to analyse structural sealant joints under high strain rate loads. This research therefore used the material model 24 to model sealant joints as it can implement the elasto-plastic behaviour of polymers.

2.2 The 2D LG model

The 2D LG model described in this paper uses material model 32 (MAT_LAMINATED_GLASS) to analyse LG panels under blast loads. It is implemented in LS-DYNA to model LG incorporating 2D shell elements, and has been previously used to analyse LG panels under blast loads [10, 11]. In material model 32, several integration points can be defined through the thickness of a shell element such that each integration point represents either glass or PVB interlayer. The cross section of a typical 2D LG model indicating the integration points representing glass and PVB is shown in Fig. 2. Material properties such as Young's modulus, Poisson's ratio, yield stress and plastic hardening modulus should be defined for both glass and interlayer. Material model 32 allows defining failure criteria for glass based on the failure strain where integration points are deleted if they exceed the failure strain.

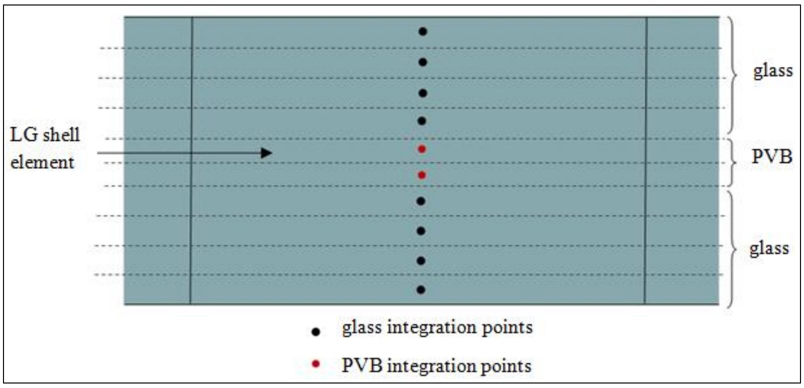

Fig. 2: Cross-section of a typical 2D LG model

The 2D LG model incorporating material model 32 has some limitations as described below. One of them is inability to define failure criteria for PVB as it is allowed to deform indefinitely without any failure strain. Material model 32 is unable to capture the fractured strength of glass as integration points are deleted if they exceed the failure strain. In the 2D LG model structural sealant joints are modelled with 3D solid elements using material model 24 similar to the 3D LG models. However, realistic support conditions cannot be modelled in the 2D LG models as the LG panels are modelled using 2D shell elements. However, 2D LG models have a major advantage over 3D LG models as they consume less computational time.

III. RESULTS AND DISCUSSION

Blast response of 3D and 2D LG models developed in this paper were compared with that from the theoretical models described by Wei et al. [12] based on small deflection and large deflection plate theories. The validation was started with the theoretical models to avoid the effects of sealant joints as they were developed for simply supported LG panels. The mid-span deflection and the principal stresses at the top and bottom glass surfaces obtained from the theoretical models are compared with those from the FE models. The free field blast test conducted by Kranzer et al. [13] was then used to further validate the FE models. The deflection-time history curves obtained from the experiments were compared with those from the FE models.

3.1 Validation with theoretical models

Wei et al. [12] presented the behaviour of a rectangular LG panel subjected to blast loading based on small deflection and large deflection plate theories. They considered a LG panel with 1.325m width, 1.325m height and 11.04mm thickness (4.76mm annealed glass + 1.52mm PVB + 4.76mm annealed glass) in their theoretical models. A simply supported LG panel subjected to a blast load with 6.9kPa peak positive over pressure and 7.7ms positive load duration (refer to Fig. 3) was considered in the analysis. The results of theoretical analysis for mid-san deflection and principal stresses at the top and bottom glass surfaces were used to validate the FE models.

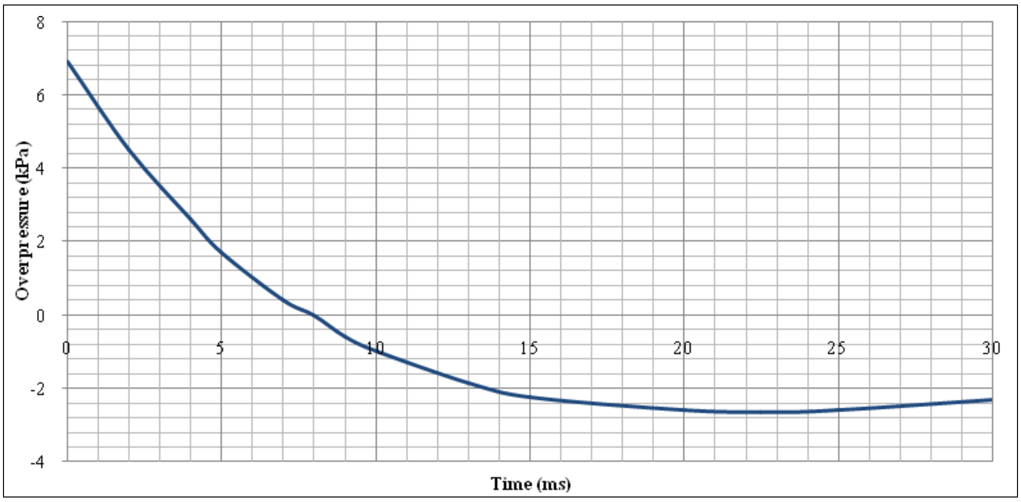

Fig. 3: Blast pressure time history curve used in the theoretical model

3.1.1 FE modelling

The FE analysis was carried out with LS-DYNA FE code using both 3D and 2D LG models. The blast load was assumed to be uniformly distributed over the front glass pane and one-quarter of the test panel was analysed by considering symmetry conditions. Ten solid elements (four for each glass pane and two for PVB) were used through the thickness of the 3D LG model. Shell elements with twelve integration points (five for each glass pane and two for PVB) through the thickness were used in the 2D LG model.

The material properties required in the analysis were obtained from the paper presented by Wei et al. [12] and are summarised in Table 1. The maximum tensile strength (T) of glass was varied between 60-70MPa in the 3D LG model and the yield strength of glass was varied between 70-80MPa in the 2D LG model. The Young's modulus of PVB was taken as 985Mpa in the FE analysis.

Table 1 Material properties of glass and PVB used in the analysis [12]

Material property	Glass	PVB
Density (ρ)	2500kg/m^3	1100kg/m^3
Young's modulus (E)	72GPa	985MPa
Poisson's ratio (Ʋ)	0.25	0.492

3.1.2 Comparison of results

Fig. 4 compares the deflection-time history curves obtained from the FE models with those predicted by the theoretical models used by Wei et al. [12] based on small and large deflection plate theories. According to small deflection plate theory, maximum deflection predicted at the first peak is about 6.28mm while it is about 13.52mm at the second peak. The corresponding values obtained from the large deflection plate theory are about 6.18mm and 12mm. The small deflection plate theory gives accurate results for small deflections where the deflection is less than the thickness of the plate. It does not predict the deflection at the second peak accurately as it is higher than 11mm which is the thickness of the plate.

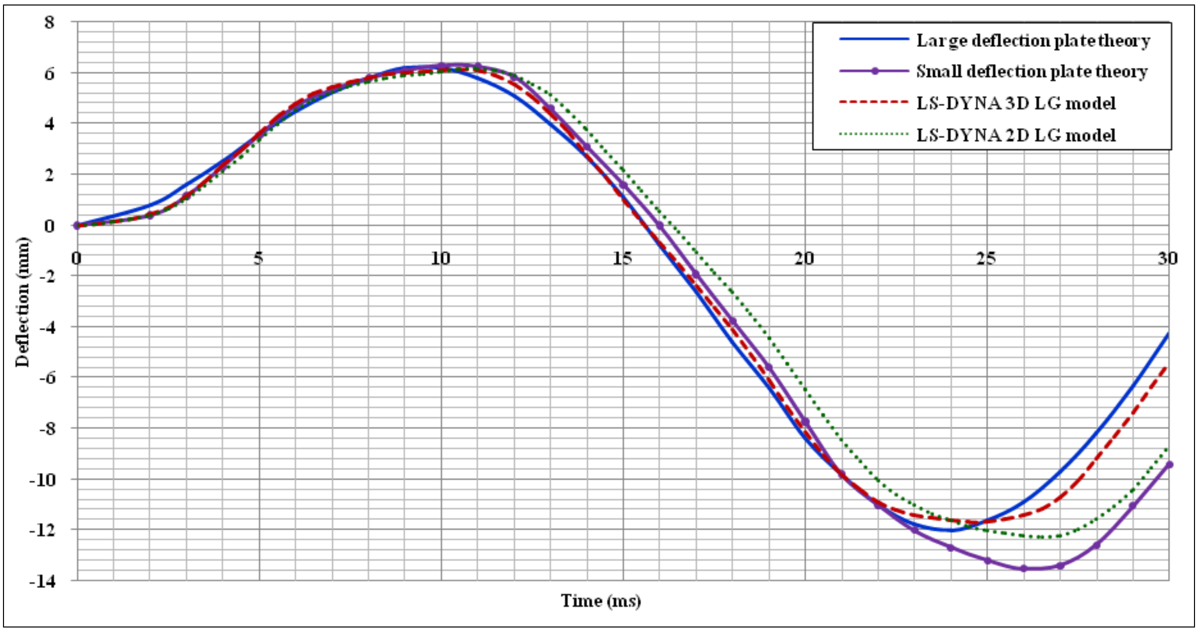

Fig. 4: Deflection vs. time at the centre of the panel (up to 30ms)

The results from FE analysis indicate that the tensile strength (T) of glass in the 3D LG model and the yield strength of glass in the 2D LG model have a negligible effect on the behaviour of the LG panel for the chosen blast load and hence those values were taken as 65Mpa and 80MPa respectively in the FE analysis. It is evident that the deflection-time history curve obtained from the 3D LG model closely agrees with the theoretical curve based on large deflection plate theory. The 3D LG model gives a maximum deflection of about 6.13mm at the first peak and 11.69mm at the second peak. The corresponding values obtained from the 2D LG model are about 6.17mm and 12.27mm. Overall, it can be said that deflection-time history curves obtained from the FE models agreed with the curves derived from the large deflection plate theory. It can also be noticed that the first peak of deflection occurs at the positive phase of the blast load while the second peak occurs at the negative phase. The maximum deflection at the second peak is about twice the maximum deflection at the first peak, and this might be due to the influence of the negative phase of the blast loading.

Fig. 5 compares the maximum principal stress variations at the centre of the bottom glass pane obtained from the FE analyses with the results predicted from the large deflection plate theory. According to large deflection plate theory, maximum principal stresses at the first and second peaks are about 20MPa and 29MPa respectively. Those values obtained from the 3D LG model are about 22.4MPa and 28.5MPa while those from the 2D LG model are about 21MPa and 26.5MPa respectively. The FE curves closely agree with the theoretical curve even though they do not show a smooth variation as the theoretical curve.

Fig. 6 compares the maximum principal stress variations at the centre of the top glass pane obtained from the FE analyses with the theoretical curve obtained from the large deflection plate theory. The maximum principal stresses obtained from the theoretical model at the first and second peaks are about 16.8MPa and 42MPa respectively. The 3D LG model gives them as 18.8MPa and 38.7MPa while those from the 2D LG model are about 17.5MPa and 38.9MPa respectively. By comparing the stresses at the both top and bottom glass surfaces it is clear that they have not exceeded the maximum tensile strength or the yield strength of glass assumed in the 3D and 2D LG models respectively.

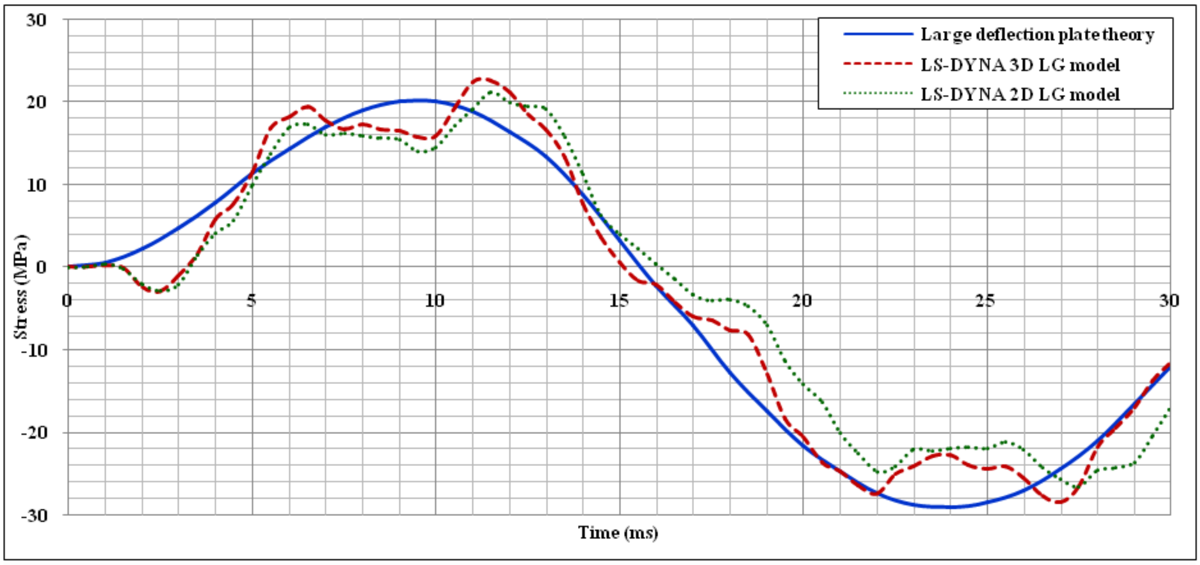

Fig. 5: Maximum principal stress vs. time at the centre of the bottom glass pane

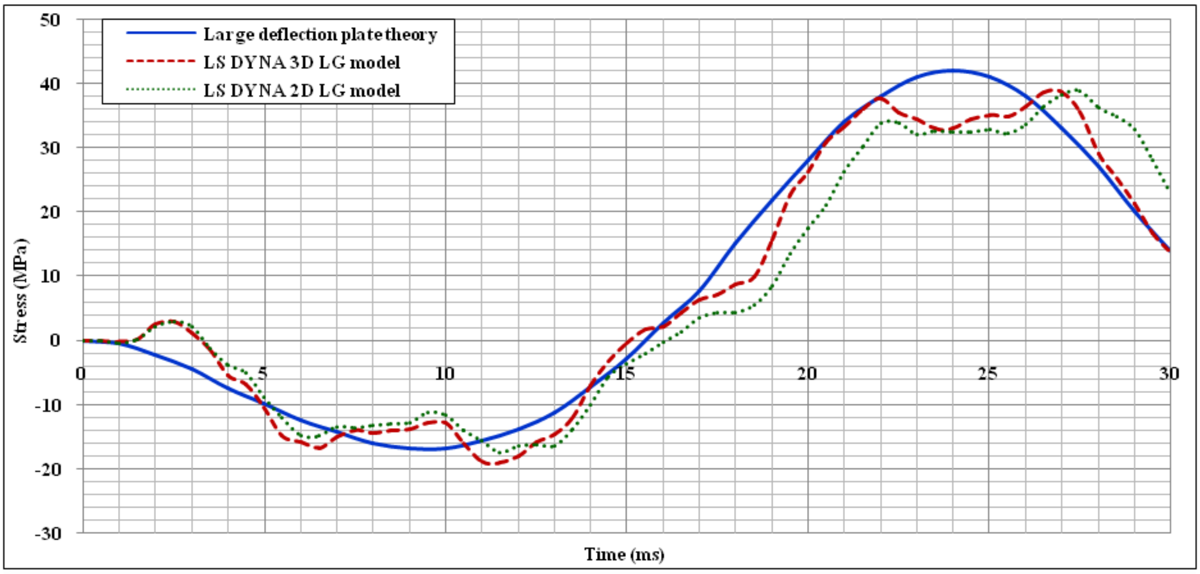

Fig. 5: Maximum principal stress vs. time at the centre of the top glass pane

Fig. 7 compares the deflection-time history variations of 3D and 2D LG models up to 100ms. Both FE models are identical up to first peak and then the 2D LG model slightly over predicts (about 0-15%) the maximum deflection from the second peak onwards. The period of the deflection-time history curve of the 3D LG model is about 30ms on average while it is about 31ms for the 2D LG model. It is clear that the FE models give similar results even though the 3D LG model is slightly stiffer than the 2D LG model.

The FE modelling and analyses were conducted using four parallel processors with the high performance computer facilities available at Queensland University of Technology (QUT). The 3D LG model consumed 28753s (about 8 hours) for the analysis up to 30ms while the 2D LG model consumed 2101s (about 35 minutes). The computational time of the 3D LG model is about 14 times that of 2D LG model. However, both FE models give similar results for mid-span deflection and the principal stresses at the top and bottom glass surfaces.

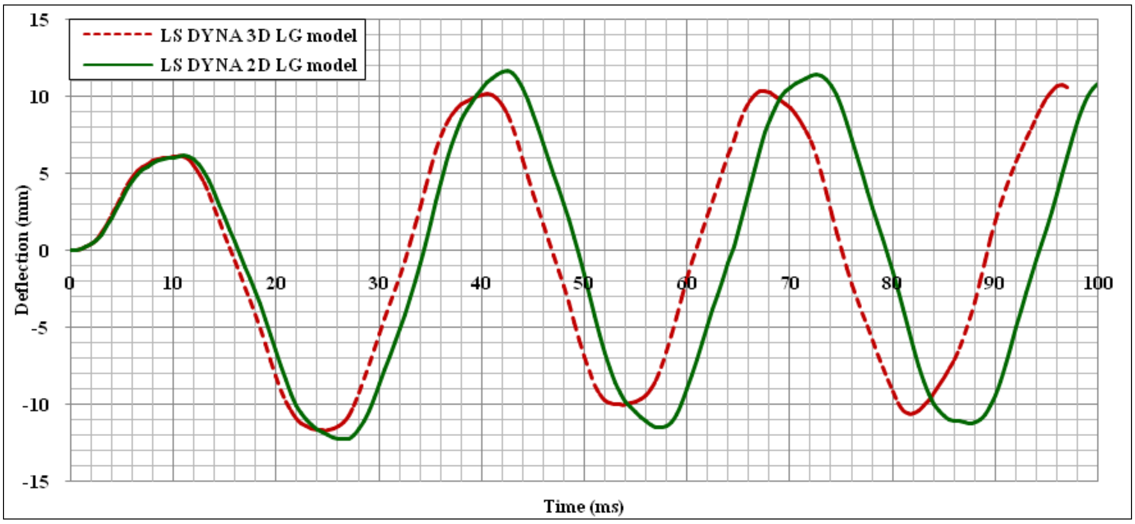

Fig. 7: Deflection vs. time at the centre of the panel (up to 100ms)

3.2 Validation with the results of experiment

Kranzer et al. [13] conducted experiments under blast loads on LG panels with 1.1m width, 0.9m height and 7.5mm thickness (3mm annealed glass + 1.52mm PVB + 3mm annealed glass). The results from one of them involving a free field blast test (test no FX014) was used to validate the FE models. Testing was conducted according to EN 13541:2001 [14] which states that the test piece should be clamped using rubber strips having about 50mm width and 4mm thickness. Fig. 8 illustrates the measured pressure-time history curve in the experiment, where the maximum positive blast pressure is about 108kPa while positive load duration is about 2ms [13].

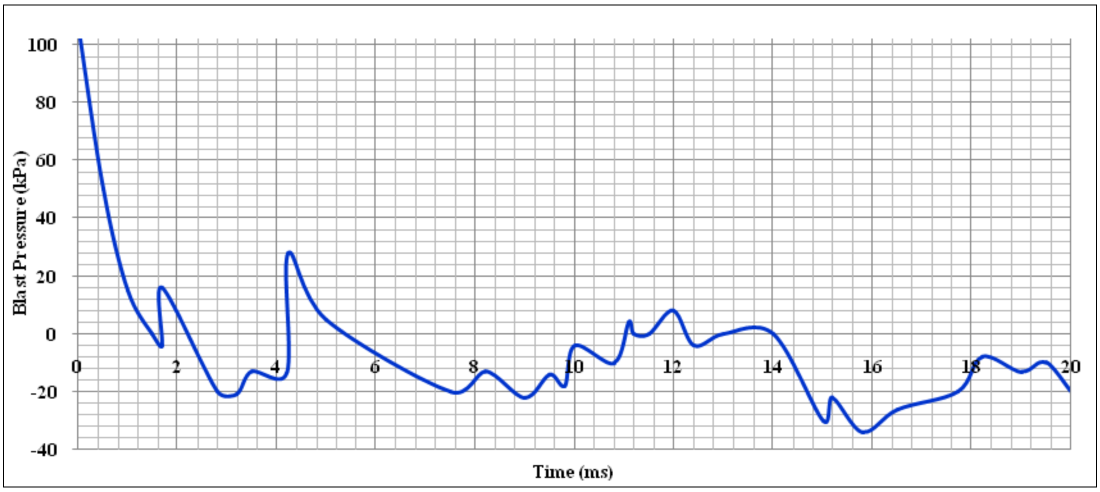

Fig. 8: Blast pressure-time history curve in the experiment

3.2.1 FE modelling

FE modelling was conducted with LS-DYNA FE code using both 3D and 2D LG models, which are shown in Fig. 9 and 10 respectively. Ten solid elements (four for each glass pane and two for PVB) were used through the thickness of the 3D LG model. Shell elements with ten integration points (four for each glass pane and two for PVB) through the thickness were used in the 2D LG model. In both FE models, rubber sealant joints were modelled using 3D solid elements. The blast load was assumed to be uniformly distributed over the entire front glass pane so that one-quarter of the test panel was analysed by considering symmetry conditions.

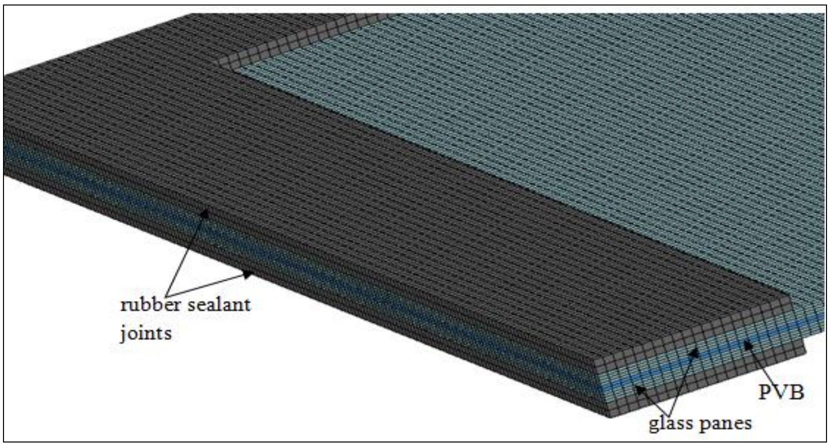

Fig. 9: View of the 3D LG model

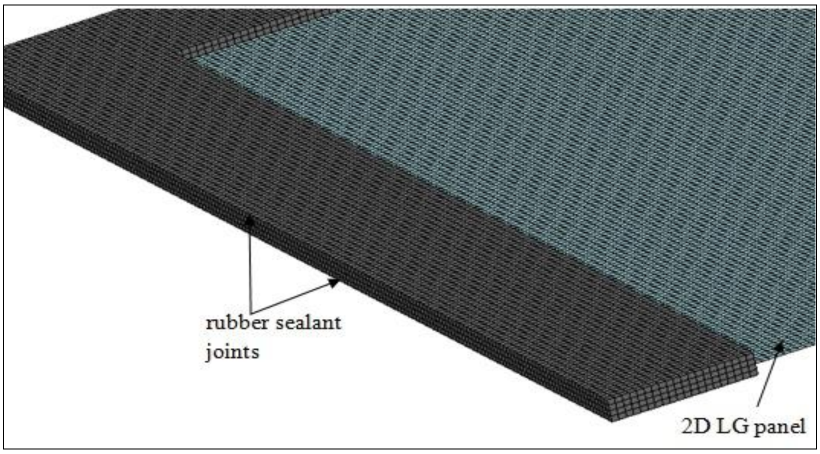

Fig. 10: View of the 2D LG model

The literature indicates that the dynamic breaking strength of annealed glass can be increased up to about 80MPa at high strain rates occurring under blast loads [15]. However, it can vary considerably from one point to the other as glass is not a homogeneous material. The presence of surface flaws and micro cracks [16] leads to the further reduction of the breaking strength of glass. In the 3D LG model maximum tensile strength of glass (T) was varied between 60-70MPa and in the 2D LG model yield strength of glass was varied between 70-80MPa to account the uncertainty of the breaking strength of glass.

PVB was analysed as an elasto-plastic material by taking the Young's modulus as 530MPa as indicated by Hooper et al. [15]. Kranzer et al. [13] mentioned that the hardness of the rubber strips should be about 50 IRHD in accordance with ISO 48 [17] where the corresponding Young's modulus should be about 2.3MPa. Table 2 summarises the material properties of glass, PVB and rubber sealant used in the FE analysis.

Table 2: Material properties of glass, PVB and rubber sealant used in the FE analysis

Material property	Glass	PVB	Rubber sealant
Density (ρ)	2500kg/m^3	1100kg/m^3	1100kg/m^3
Young's modulus (E)	72GPa	530MPa	2.3MPa (50 IRHD)
Poisson's ratio (U)	0.22	0.485	0.495

3.2.2 Comparison of results

Fig. 11 compares the deflection-time history curve observed in the experiment with those obtained from the 3D LG model under different tensile strengths (T) of glass. It is evident that the behaviour of the FE model is considerably influenced by the T of glass. The maximum deflection of about 15mm occurs at 3.7ms during the experiment. The results from the FE model closely agree with the experimental curve when T is set to 65MPa, at which the maximum deflection of 14.84mm (with an error of 1.1%) occurs at 3.5ms. The 3D LG model gives a maximum deflection of about 15.66mm (with an error of 4.4%) and 13.42mm (with an error of 10.5%) when T is taken as 63MPa and 70MPa respectively. In all cases, the deflections obtained from the FE models agree well with the experimental curve up to about 3ms, but under predict the deflection during the rebound.

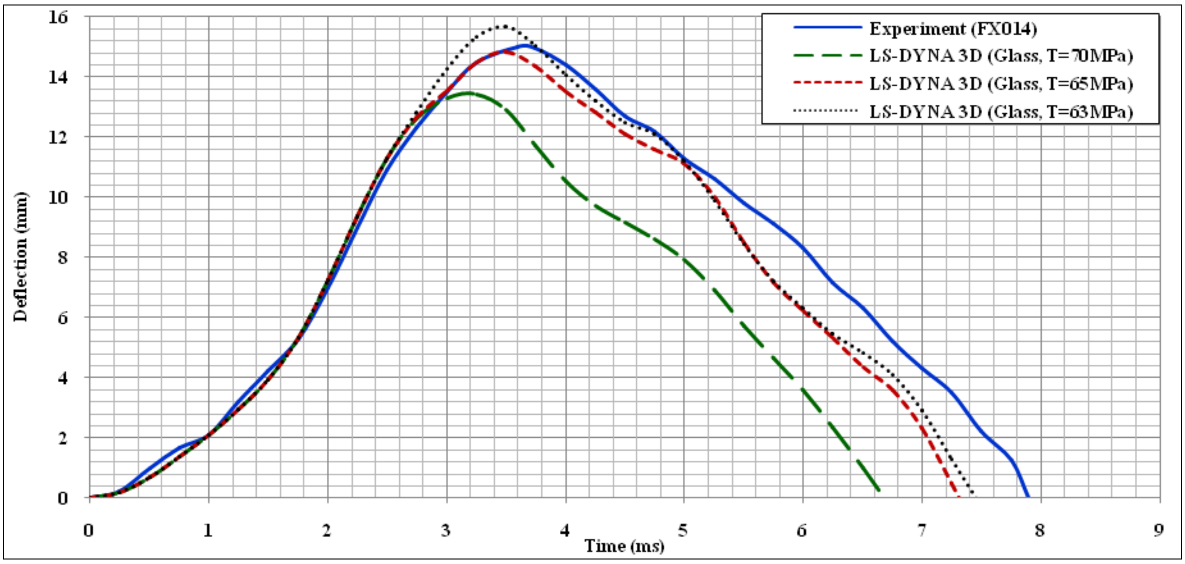

Fig. 11: Deflection vs. time at the centre of the panel for different tensile strengths (T) of glass in the 3D LG model

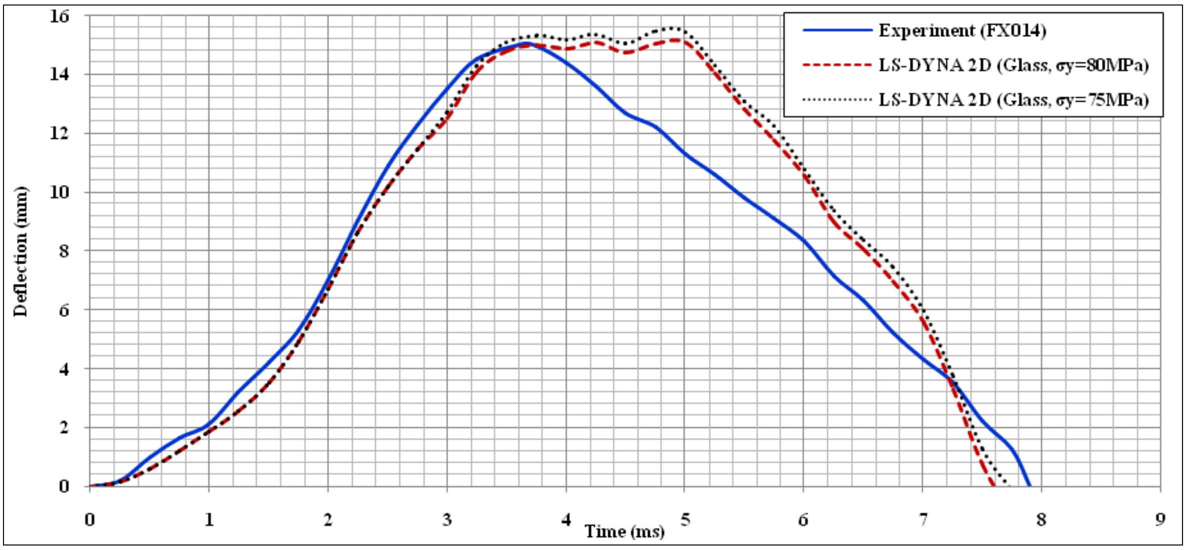

Fig. 12: Deflection vs. time at the centre of the panel for different yield strengths (σ_y) of glass in the 2D LG model

Fig. 12 shows the variation of mid-span deflection of the 2D LG model for different yield strengths (σ_y) of glass. The curves obtained from the FE models agree well with that from experiment up to about 3.5ms, but then over predict the deflection there after during the rebound. They vary around the maximum deflection from about 3.5ms to 5.0ms showing flat peaks unlike the smooth peak observed from the experiment. The maximum deflections obtained from the FE models are 15.08mm (with an error of 0.5%.) and 15.4mm (with an error of 2.7%.) when the σ_y is taken as 80MPa and 75Mpa respectively.

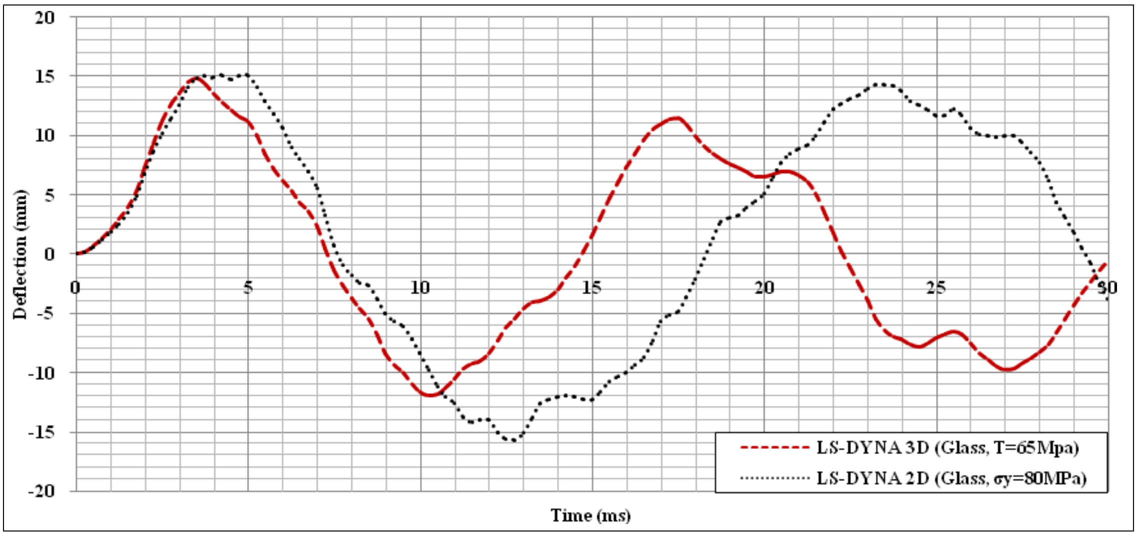

Fig.: 13 Deflection vs. time at the centre of the panel (up to 30ms)

Fig.13 compares the deflection-time history curves obtained from the 3D and 2D LG models whose results agreed best with the experimental results. The 3D LG model obtains its maximum deflection of about 14.84mm during the first peak and then the peak deflection reduces showing 12 and 11.5mm deflections during the second and third peaks respectively. The 2D LG model gives about 15.08mm deflection during the first peak, shows its maximum deflection of about 15.7mm during the second peak and then the peak deflection reduces to about 14.3mm during the third peak. It is clear that the 3D LG model is much more stiffer than the 2D LG model and their average time periods are about 15 and 19ms respectively.

The FE modelling and analyses were conducted using four parallel processors with the high performance computer facilities available at Queensland University of Technology (QUT). The computational times required by the FE models for analysis up to 8ms are compared. The 3D LG model required 11901s (or approximately 3 hours and 18 minutes), which is significantly higher than the 575s (or approximately 9.5 minutes) required by the 2D LG model. It is evident that the 3D LG model consumes about 20 times computational time compared to the 2D LG model for the chosen loading conditions and the analysis time.

IV. CONCLUSIONS

This paper compares two modelling approaches incorporating 3D solid and 2D shell elements to model LG panels under blast loads with LS-DYNA FE code. In the 3D LG model material model 110 (MAT_HOLMQUIST_CERAMICS) is used to model glass and material model 24 (MAT_PIECEWISE_LINEAR_PLASTICITY) is used to model the interlayer. Material model 32 (MAT_LAMINATED GLASS) is used to model the entire LG panel in the 2D model. Structural sealant joints are modelled with solid elements using material model 24 in both 3D and 2D LG models.

Firstly, a simply supported LG panel without sealant joints were used for the validation. The 3D and 2D LG models gave similar results for mid-span deflection and the principal stress at the top and bottom glass surfaces, and these results agreed well with those from the theoretical model presented by Wei et al. [12] based on large deflection plate theory. When the FE models were analysed up to 100ms, the 2D LG model over predicted the maximum deflections slightly from the second peak onwards. The results of FE analysis indicated that the 3D LG model was slightly stiffer than the 2D LG model. Secondly, the free field blast test conducted by Kranzer et al. [13] was used to validate the FE models. The results obtained for mid-span deflection from the 3D and 2D LG models agreed well with the experimental results. The behaviour of the 3D LG model was sensitive to the maximum tensile strength of glass while the 2D LG model was sensitive to the yield strength of glass. Results from both FE models agreed well with the experimental results when those values were set as 65MPa and 80MPa respectively. The deflection-time history curves extended up to 30ms indicated that both 3D and 2D LG models are identical up to first peak and then the 3D LG model becomes significantly stiffer than the 2D LG model. This might be due to the inability of modelling real support conditions or capturing the fractured strength of glass in the 2D LG model. Overall, it can be said that both 3D and 2D LG models are able to model the behaviour of LG panels under blast loads. However, it was evident that the results from the 2D LG model are more accurate under low-level blast loading where glass is subjected to less damage as seen when validating the theoretical models. It has been shown that the 3D LG models consume considerable computational time compared to the 2D LG models. Small LG panels with height and width less than 1.5m were used for the validation. However, facades in buildings can be high as 3-10m and wide as 2-3m. Modelling such building facades can be very tedious with 3D solid elements considering the significant increase in the computational time. The 2D LG models can therefore be used to model the global behaviour of large facade systems.

The 2D LG models have some limitations such as inability to define failure criteria for interlayer and account the fractured strength of glass. The 2D LG models do not facilitate the modelling of real support conditions as the LG panels are modelled using 2D shell elements. The authors therefore suggest the use of 3D LG models to investigate the influence of controlling parameters such as material and geometric properties of different facade components and the support conditions. Once the correct model has been identified, 2D models can be used to study the blast response under different loading scenarios.

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