# MODELLING OF GLASS EXPOSED TO BLAST LOADING: STOCHASTIC FRACTURE INITIATION AND NODE SPLITTING

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ABSTRACT
In terms of mechanical behaviour, glass plates are known for their stochastic fracture initiation followed by rapid crack propagation. As structural components, glass plates exhibit linear elastic behaviour until fracture initiation. Due to microscopic surface cracks, often referred to as surface flaws, the fracture initiation behaviour varies from specimen to specimen. After fracture initiation, cracks propagate from the initiation point at speeds of approximately 1,500 m/s. These phenomena are challenging to model numerically, requiring stochastic models for fracture initiation and robust fracture models for crack propagation. In this study, we combine the glass strength prediction model for predicting fracture initiation with node splitting to propagate the resulting cracks. To evaluate the performance of this modelling approach, we compare numerical predictions with experimental data from blast-loaded monolithic and laminated glass plates.
*Keywords: glass, GSPM, node splitting, blast loading.*

## 1 INTRODUCTION

Glass is a material known for its excellent transparent properties, widely used in building facades and vehicles. In the event of an explosion close to a building or vehicle, the glass plates typically form the first protective shell of either the building or the vehicle. To serve as an effective protective shell, the glass plate must absorb as much energy as possible. Unfortunately, glass is a brittle material with stochastic fracture behaviour. Thus, the protective capabilities of the glass plate in terms of energy absorption are minor and uncertain.

Protective windows are typically constructed from a type of composite called laminated safety glass, which typically consists of two layers of glass plates and a polyvinyl butyral (PVB) interlayer. This composition offers significant advantages in energy absorption, reduced injuries during explosions and preventing burglary. While a single glass layer is prone to total failure upon cracking, laminated glass offers a fail-safe structure because the PVB interlayer maintains the integrity of the glass layers after initial failure. In the event of a window fracture, the PVB interlayer holds the glass fragments together, transforming the window from a laminated composite to a glass-reinforced polymer.

Understanding the structural behaviour of laminated glass is crucial, particularly in scenarios involving blast loading. The structural behaviour transitions through several phases: starting with the linear, elastic behaviour of the glass layers, progressing through the sequential failure of the glass layers, and culminating with the deformation and potential failure of the PVB interlayer. An important step in increasing this understanding is to model the glass plate fracture process in a sufficiently realistic manner in terms of both fracture initiation and crack propagation. Several strength prediction models with focus on the fracture initiation of glass have been introduced to reduce the glass strength uncertainties.

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Rudshaug et al. [1] proposed the glass strength prediction model (GSPM), a strength prediction model based on the generation of microscopical surface flaws from the production process of float glass. The GSPM is integrated into the finite element solver LS-DYNA in the material model *MAT_GLASS_SPM in version R16 [2].

Conventional crack propagation modelling typically involves either element erosion or stiffness degradation to represent the crack path, which smears out the crack width over the element size, slowing down the crack speed. In this study, we combine the GSPM for predicting fracture initiation with the node splitting features in the Impetus Solver to propagate the resulting cracks [3]. To evaluate the performance of this modelling approach, we compare numerical predictions with experimental data from blast-loaded monolithic and laminated glass plates [4]–[8].

## 2 GLASS STRENGTH PREDICTION MODEL

The GSPM is a tool designed to predict fracture initiation in glass plates, integrating linear elastic fracture mechanics (LEFM) and sub-critical crack growth (SCG) through a Monte Carlo simulation framework [1]. The in-situ version of the model is integrated with finite element (FE) solvers. This integration enables real-time calculation of failure distribution during simulations, leveraging the stochastic nature of glass fracture to allow users to select specific flaw maps for failure initiation. The model provides insights into the variability of fracture initiation, offering valuable information on the repeatability of the scenarios under study.

A key feature of the GSPM is its capability to generate representative artificial flaw maps on glass surfaces. These maps include a variety of flaws characterized by their shape, depth, orientation, and location, which are critical for predicting fracture strength. The model tracks the sub-critical crack growth of each flaw based on environmental conditions and loading history, focusing specifically on mode I loading.

During the FE simulation, the GSPM generates a fracture initiation distribution from the representative sample of flaw maps, ranked from weakest to strongest. This allows users to select a flaw map to initiate failure, thereby determining the strength of the glass specimen. The model predicts scatter in fracture initiation location and timing, which provides an indication of the repeatability of the case studied. A small scatter suggests consistent strength for the given load case and geometry, enhancing the model’s applicability in various design scenarios.

### 2.1 Implementation into the Impetus Solver

The GSPM is available as a standard material model in LS-DYNA R16, with the keyword *MAT_GLASS_SPM [1], [2]. In the LS-DYNA implementation, the GSPM predicts the fracture initiation location and timing, and activates the crack propagation features available in the glass material model *MAT_GLASS. The implementation is based on glass plates modelled with shell elements, where the outer integration points in the plate surface normal directions are located on the plate surfaces. The crack propagation features of *MAT_GLASS involve either element erosion or stiffness degradation to represent the crack path, smearing out the crack width over the element size.

An alternative way of representing the crack path is to use a node splitting technique, where the crack is represented by splitting the nodes at the element borders. The Impetus Solver is an explicit finite element solver that offers node splitting features [3]. However, it does not support deformable shell elements. For this reason, we must make some alterations in the way the glass plate surfaces are identified. The Impetus Solver offers cubic 3D elements, as illustrated in Fig. 1, where the outer integration points are close to the element surfaces. To determine which integration points that are associated with the two surfaces of a glass plate, we compare the normal vector of the three element surfaces, $n_1$, $n_2$ and $n_3$, related to each corner integration point to the normal vectors of the glass surfaces, $n_{surf}$ (see Fig. 2). Further, we use the midpoints of the element surfaces associated with the glass surfaces as potential flaw locations for the generated flaw maps. The surface stress values, $\sigma_1$ and $\sigma_2$, used in the GSPM are estimated based on the mean stress values of the outermost integration point layers, $\sigma_{1,i}$ and $\sigma_{2,i}$, associated with the glass plate surfaces (see Fig. 3). We assume a linear stress distribution over the thickness and extrapolate the stress as presented in eqns (1)–(4):

$$\sigma_m = \frac{\sigma_{1,i}+\sigma_{2,i}}{2}, \tag{1}$$

$$\sigma_b = \frac{\sigma_{1,i} - \sigma_{2,i}}{2} \cdot \frac{l}{l_i}, \tag{2}$$

$$\sigma_1 = \sigma_m + \sigma_b, \tag{3}$$

$$\sigma_2 = \sigma_m - \sigma_b. \tag{4}$$

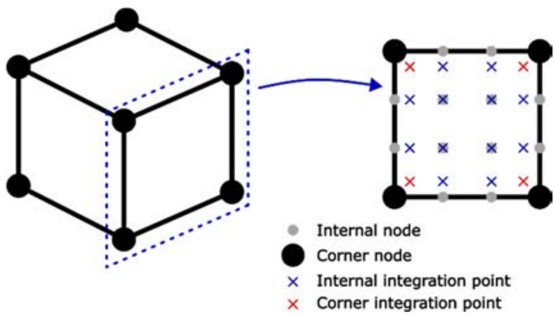



Figure 1: Illustration of a cubic 3D element showing nodes and integration points.

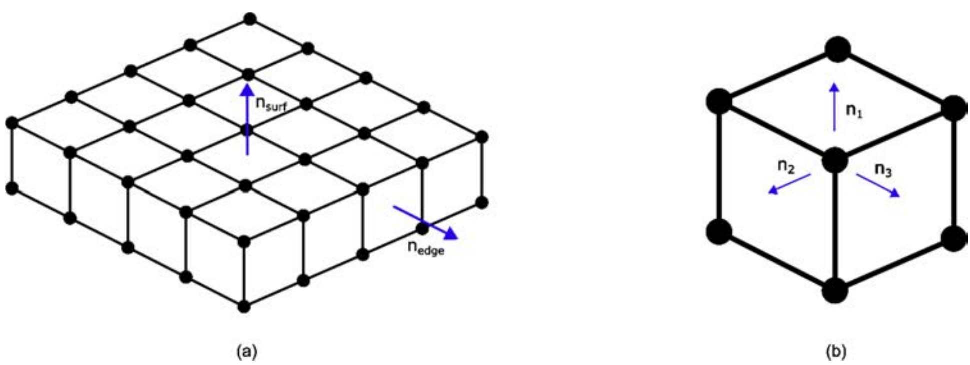



Figure 2: Illustration of the glass surface normal, $n_{surf}$, and edge normal, $n_{edge}$ (a), and the element surface normal, $n_1$, $n_2$, and $n_3$, related to a corner integration point (b).

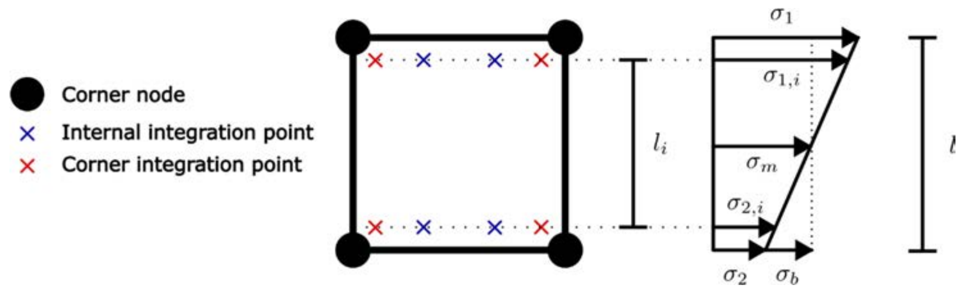



Figure 3: Illustration of the surface stress estimation used in the implementation. $\sigma_1$ and $\sigma_2$ represent the mean surface stress at surface 1 and 2 and $l$ the plate thickness. $\sigma_{1,i}$ and $\sigma_{2,i}$ represent the mean stress at the integration point layer associated with the surface. $l_i$ is the distance between the integration point layers. $\sigma_m$ and $\sigma_b$ denote the membrane and bending stress, respectively.

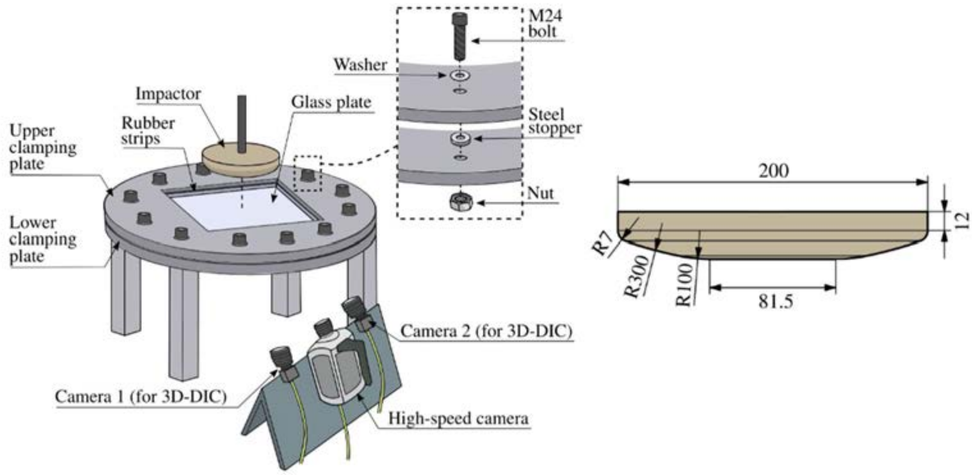
When the GSPM predicts fracture initiation, we initiate crack propagation from the specified element at the predicted timing. To model the fracture initiation, we split the nodes of the surface closest to the integration point where fracture initiation is predicted. Further, to initiate a sufficient number of crack paths in addition to the first fracture, we include the option to initiate fracture with a stress-based criterion relative to the predicted critical stress from the GSPM, $\sigma_{cr,GSPM}$. The stress-based criterion is controlled with the scaling parameter $\gamma > 0$, where the critical stress is set to $\gamma \cdot \sigma_{cr,GSPM}$ after the first fracture. After fracture initiation, the crack propagation process is modelled using the brittle damage model available in the Impetus Solver, *PROP_DAMAGE_BRITTLE, with the parameters presented in Table 1. In this study, the critical stress, $\sigma_s$, in *PROP_DAMAGE_BRITTLE is set to a high value to ensure that fracture initiates only from the GSPM.

Table 1: Input parameters for *PROP_DAMAGE_BRITTLE. $t_s$ and $\alpha_s$ are taken from [4].

| $\boldsymbol{\sigma_s}$ | $\mathbf{K_c}$ | $\boldsymbol{t_s}$ | $\boldsymbol{\alpha_s}$ |
|---|---|---|---|
| MPa | MPa mm$^{1/2}$ | s | – |
| 200 | 23.7 | 2.0e-7 | 0.5 |

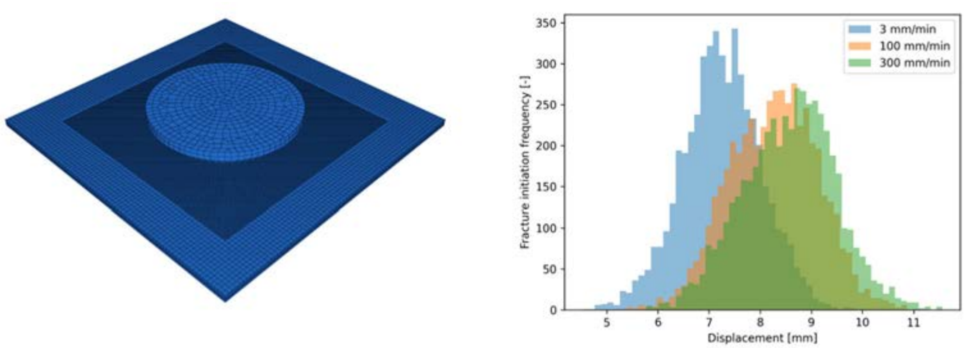
### 2.1.1 Validation

To validate the implementation of the GSPM into the user material interface of the Impetus Solver before coupling it to the brittle damage model, we use the experimental study on monolithic glass plates subjected to quasi-static punch loading performed by Osnes et al. [5]. The experimental study consisted of three test series with 30 monolithic glass plates in each. A wooden impactor provided the loading with loading rates of 3 mm/min, 100 mm/min and 300 mm/min. The in-plane plate dimensions were 400 mm × 400 mm and the thickness was 1.8 mm. An overview of the experimental setup and impactor dimensions are shown in Fig. 4. We model the setup in a similar way as presented by Osnes et al. [4] with cubic elements and use the GSPM parameters calibrated by Rudshaug et al. [1] for supplier 2. Both the wooden impactor and the rubber strips are modelled as linear elastic materials without any fracture models, while the glass plate is modelled as a linear elastic material with the GSPM. The failure percentile parameter, $P_f$, of the GSPM is set larger than one to not initiate fracture. Fig. 5 presents the discretized numerical model and the resulting strength predictions. To avoid a spurious penalty on the crack propagation paths in the diagonal direction of the elements and increase the number of possible crack paths in the glass plate, we use pentahedron elements as illustrated in comparison to the hexahedral element discretization in Fig. 6 for all glass plates in this study. The strength predictions for the three loading rates are consistent with what was found by Rudshaug et al. [1] and the experimental results of Osnes et al. [5].




(a) (b)

Figure 4: (a) Overview of the experimental setup; and (b) Dimensions of the wooden impactor. *(Source: Adopted from [5].)*




**(a)** **(b)**

Figure 5: (a) The numerical model of the quasi-static punch tests showing the element discretization; and (b) The resulting strength predictions from the GSPM.

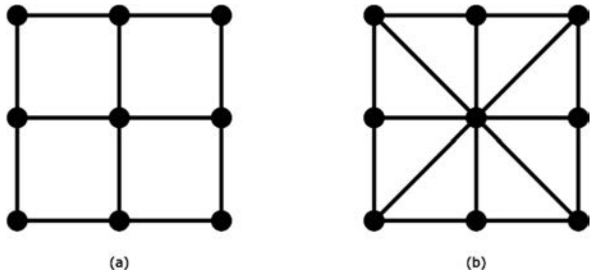



Figure 6: In-plane illustration of a hexahedral (a) compared to a pentahedral (b) discretization.

## 3 MONOLITHIC GLASS PLATES EXPOSED TO BLAST LOADING

Osnes et al. [6] and Brekken and Ingier [8] performed twelve experiments on monolithic glass plates of in-plane dimensions 400 mm × 400 mm and thickness 3.8 mm exposed to blast loading with three peak overpressures, ~50 kPa, ~60 kPa and ~70 kPa. In this study, we focus on the glass plates that were exposed to the ~70 kPa peak pressure blast loading. An overview of the experimental setup is illustrated in Fig. 7. We model the setup in a similar way as presented by Osnes et al. [4] with cubic pentahedron elements and use the GSPM parameters calibrated by Rudshaug et al. [1] for supplier 1.

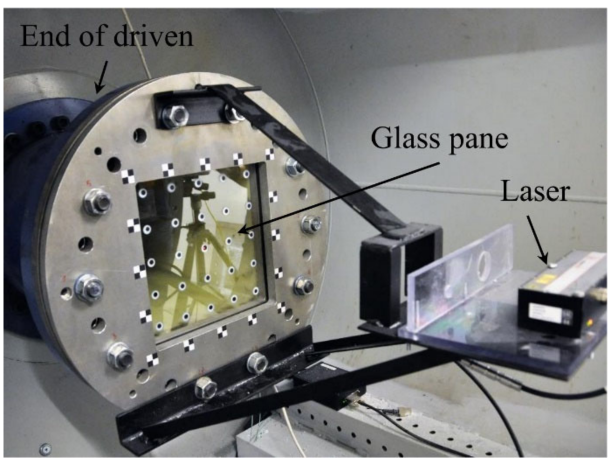



Figure 7: Overview of the experimental setup for the blast loaded glass plates. *(Source: Adopted from [8].)*

The failure percentile parameter, $P_f$, of the GSPM is set to 0.05 to initiate fracture for the virtual glass plate representing the strength at the 5% point of the weak tail of the predicted strength distribution. The critical stress after the first fracture is set to 50% of the predicted critical stress, i.e., $\gamma = 0.5$. Fig. 8 presents the predicted crack pattern compared to an experimental crack pattern. We note that the predicted crack pattern displays multiple features also seen experimentally with radial cracks propagating from the centre and circumferential cracks near the boundaries.

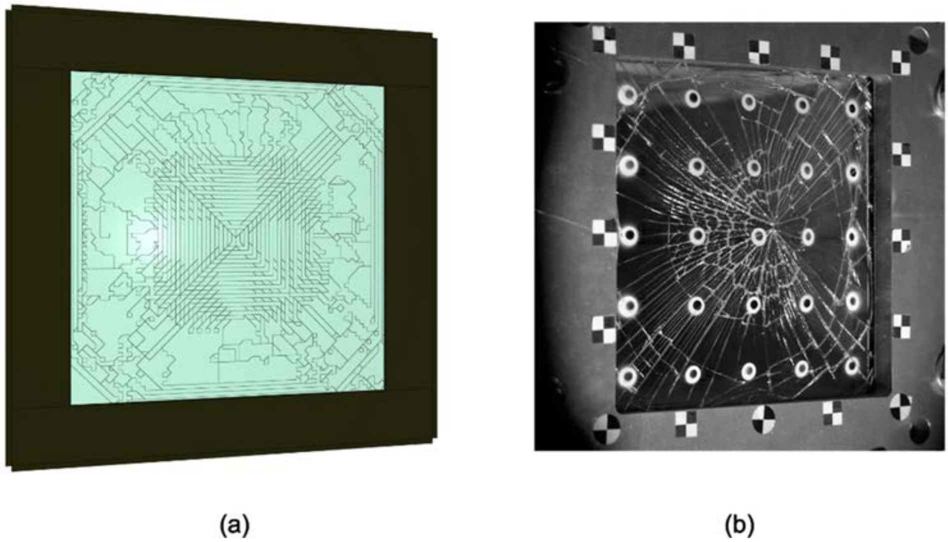



Figure 8: The predicted crack pattern with $P_f = 0.05$ (a) compared to an experimental crack pattern adopted from [7] (b).

## 4 LAMINATED GLASS PLATES EXPOSED TO BLAST LOADING

Osnes et al. [4] performed fifteen experiments on single-layered laminated glass plates consisting of two 3.8 mm thick glass plates and one 1.52 mm thick PVB interlayer. The in-plane plate dimensions were 400 mm × 400 mm. The single-layered laminated glass plates were exposed to blast loading in the same way as the previously discussed monolithic glass plates, with five peak overpressures, ~170 kPa, ~200 kPa, ~215 kPa, ~238 kPa and ~255 kPa. In this study, we focus on the four laminated glass plates that were exposed to the ~238 kPa peak pressure blast loading. For these laminated glass plates, fracture initiated in both glass layers around the centre of the plate. We model the setup in a similar way as presented by Osnes et al. [4] with cubic pentahedron elements and use the GSPM parameters calibrated by Rudshaug et al. [1] for supplier 1.

The failure percentile parameter, $P_f$, of the GSPM is set to 0.05 for the outer glass layer and 0.1 for the inner layer. The critical stress after first fracture is set to 50% of the predicted critical stress, i.e., $\gamma = 0.5$. Fig. 9 presents the predicted crack pattern compared to the experimental crack pattern for the outer layer. Also here, we note that the characteristics of the predicted crack pattern resemble what is seen experimentally, with higher crack density at the centre and corners including many radial cracks.

## 5 SUMMARY

We implemented the GSPM into the user material framework of the Impetus Solver, which offers higher order elements and node splitting features. To activate the crack propagation features with the node splitting technique, GSPM is coupled to the brittle damage model available in the Impetus Solver, *PROP_DAMAGE_BRITTLE. The implementation was validated using experimental data from three test series including monolithic glass plates subjected to quasi-static punch loading and monolithic and laminated glass plates exposed to blast loading. Overall, the predictions from the implemented framework compared well to the experimental data.

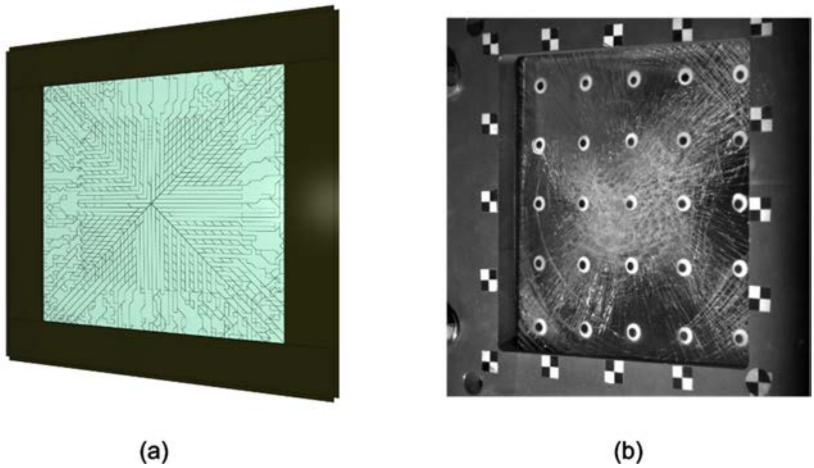


Figure 9: The predicted crack pattern with $P_f = 0.05$ for the outer glass layer and $P_f = 0.1$ for the inner glass layer (a) compared to an experimental crack pattern adopted from [4] (b).

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