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# Gradual Fracture of Layers in Laminated Glass Plates under Low-Velocity Impact

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## Abstract

Multi-layer laminated glass is a composite that consists of glass layers connected with interlayers, typically made of polymers. The softer interlayer maintains transparency, provides damping of vibrations and connects glass shards after fracture, thus improving the post-fracture resistance and thereby maintaining the structural integrity. This study investigates the responses of such a composite to the consecutive, gradually increasing low-velocity hard body impacts using a computational-experimental research program. This is essential for a deeper understanding of the gradual fracture process of glass layers in a multi-layer composition. It will be beneficial in setting a direction for future studies devoted to the examination of the composition effect on the impact resistance of a laminated glass and for the design of new protective glass panels. The industry-standard annealed float glass plates laminated with a polyvinyl butyral (PVB) were selected, representing the most common material combination of the structural laminated glass. Motivated by the sacrificial-glass-ply concept and the key role of the middle glass layer, we designed the thicknesses of both external glass layers to be thinner, whereas the inner glass layers were slightly thicker. To investigate the gradual fracture process of glass layers, contact forces, velocities at selected points of the laminated glass plates, failure times, and fracture patterns were closely examined.

**Keywords:** laminated glass, PVB interlayer, low velocity impact, fracture, pendulum impact machine, LS-DYNA.

# 1 Introduction

Laminated glass is a multi-layer composite that consists of glass layers connected with an interlayer made typically of polymers. The softer interlayer damps vibrations and connects glass shards after fracture, thus improves the post-fracture resistance and thereby maintains the structural integrity. To improve the post-fracture performance of laminated glass, sacrificial-glass-ply design is often promoted [1,2,3]. The idea of this concept is that one glass layer is allowed to fracture to dissipate impact energy, whereas the rest is preserved to sustain further loads. The design of a suitable laminated glass composition is a current topic. It has been shown in [4] that three-layer samples may offer better impact resistance than five-layer or seven-layer laminated glass of the same overall thickness under certain conditions. But the results in [2] indicate that the intact middle glass layer in a three-glass-ply laminate unit was crucial to sustain impact and dynamic stiffness at a post-fracture stage. Moreover, the lack of data on the dynamic performance of fractured laminated glass panels at different breakage stages has recently been mentioned in [2]. This study tries to narrow this gap and investigates the impact resistance and gradual fracture process of two different designs of the multi-layer laminated glass. Numerical models are also included to support and supplement the experimental data. The onset of fracture is best characterised for most brittle materials (including glass) by a Rankine criterion [5]. In that case, a crack initiates when the principal stress in tension reaches the critical value. However, after the contact of the impactor with the glass, the calculated stresses of the finite elements in the contact zone are much higher than the commonly used critical values [6]. If the Rankine criterion is used, these elements fail immediately, and the cracks develop. This does not correspond to the experimental observation that the glass failure is preceded by elastic deformations for a longer period. Therefore, the enhancement of the Rankine criterion by a nonlocal approach was recommended in [6] by introducing the concept of critical energy. In this approach, the element, although violating the Rankine failure criterion, fails not until the internal energy in its surroundings exceeds the assumed critical energy. However, the method recommended for the determination of model parameters is complex and expensive [6] and has to be adjusted retrospectively depending on the impact position and the laminated glass setup [7]. In this contribution, we therefore introduce an alternative approach.

# 2 Methods

The response of a multi-layer laminated glass to a low-velocity impact was studied using a computational-experimental research program.

The test set-up involved a pendulum impact machine [8] and freely hanged specimens. The impactor was made of steel and had a cylindrical body and a hemispherical nose with a radius of 100mm. The total weight of the impactor was 48.7kg. Its initial release height was 5cm and was gradually increased by 5cm with each test. The specimens were suspended on thin steel strings to eliminate the effect of structural supports and to allow for more accurate validation of numerical models. The length of thin steel strings was adapted to locate the centre of the specimen at the bottom return point of the impactor trajectory. Non-destructive and destructive impact tests were carried out on laminated glass units, where two different geometries were selected for the experimental campaign, i.e., 5-layer laminated glass (5LG) containing three glass plies and two PVB interlayers and 7-layer laminated glass (7LG) made from four glass plies connected with three PVB interlayers. Motivated by the sacrificial-glass-ply concept [3] and the key role of the middle glass layer [2], we designed the laminates with thinner external glass layers compare to inner glass layers. Four accelerometers were attached to the specimen: at the corner, the middle of the horizontal and vertical edge, and the quarter of the horizontal edge. One accelerometer was attached to the impactor.

The models were developed using general-purpose finite element code LS-DYNA originally developed for analysing the dynamic response of structures. Only a quarter of the laminated glass plate and the impactor were meshed, taking advantage of the symmetrical geometry to reduce computational cost and model complexity. A small part of the tip of an impactor was considered flat to avoid excessive stress concentrations at the midpoint of the glass. The glass panels were discretised with triangular shell elements to allow for a more random distribution of cracks. The polymer interlayers were discretised with fully integrated solid elements. A rigid material model with increased density was used for the impactor permitting to model the impactor nose only so further reduce the computational cost. A viscoelastic generalised Maxwell model approximated the time/temperature-dependent response of a polymer foil, combined with the Williams-Landel-Ferry shift parameters. A smeared fixed crack model [9] with the previously mentioned nonlocal failure criterion [6] was adopted for the glass.

## 3 Results

The data measured by the accelerometer on the impactor was filtered by the low-pass filter type CFC 1000 and multiplied by the weight of the impactor to obtain the time-dependent contact force [10]. Forces calculated at the contact interface were extracted from the simulation. The numerically derived contact forces match the experimental ones very well, see Figure 1. Similar agreement was achieved for all the specimens examined. The comparison of contact forces acting on different samples proves that the contact forces were consistent not only for non-destructive tests, but very similar evolutions developed also for the same scheme of fractured layers. The 7LG-samples resisted mostly higher contact forces than the 5LG-samples. For both types of laminated glass, the scatter of the breakage forces is substantial due to the stochastic nature of tensile strength of glass. The peaks of contact forces leading to the breakage of a glass layer were not always higher than the largest forces observed during the previous less powerful impact events. This observation may indicate that some naked-eye invisible damage occurred during the previous contacts and/or the initial micro-flaws grew during previous impacts and caused the subsequent failure [1].

Figure 2 shows examples of fracture patterns. If the impacted layer fractured first, the cracks were mostly localised around the impact point and spread only occasionally towards edges. Otherwise, cracks spread quickly on the outer non-impacted surface and reached the edges within less than 0.4ms. The crack patterns partly differed for the samples where glass layers fractured consecutively in the direction from the non-impacted surface to the impacted one. The major changes in crack patterns occurred when the first glass layer(s) fractured. Further, the growth of cracks under consecutive impacts was small until the fracture of the next glass layer. This suggests that the density of cracks is given by the initial power of the impact leading to fracture, because additional impacts did not change the density of cracks significantly. All glass layers did not generally fracture at one impact event, so the cracks did not completely propagate across the layers.

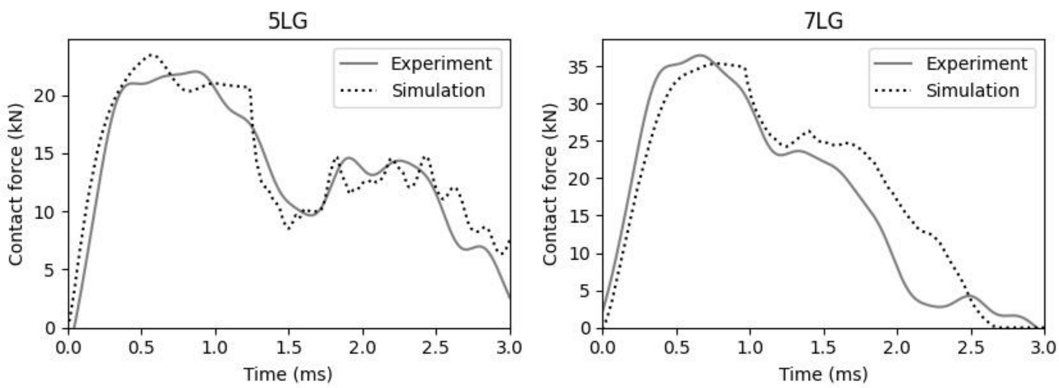


Figure 1: The contact forces derived for samples 5LG and 7LG subjected to 16 and 8, respectively, consecutively increasing impacts.

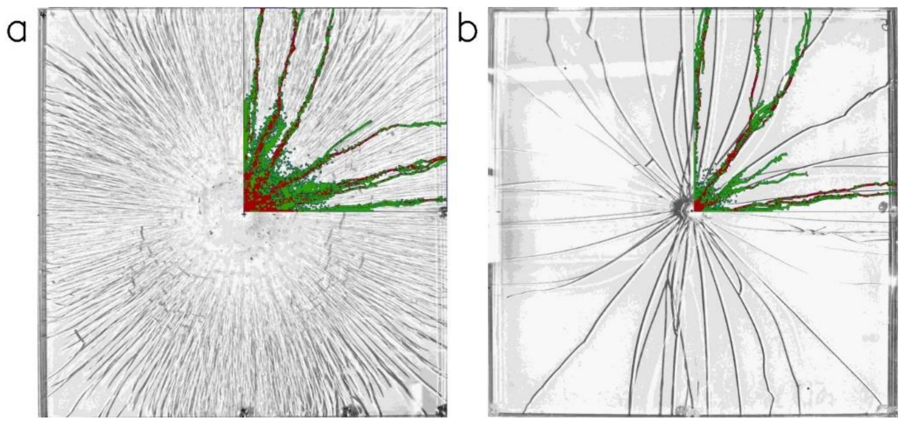


Figure 2: The fracture patterns developed in 5LG (a) and 7LG (b) after 16 and 10, respectively, consecutively increasing impacts.

## 4 Conclusions and Contributions

This study investigated the responses of multi-layer laminated glass plates to the gradually increasing low-velocity impact loading using a computational-experimental research program. This is essential for a deeper understanding of the gradual fracture process of glass layers in a multi-layer composition. The following inferences can be drawn from the study:

1) Experimental data for multi-layer laminated glass plates with two different geometries were compared.
2) Good consistency for the experimentally measured non-destructive responses of impacted laminated glass samples and good agreement with the calculated results, demonstrated in terms of velocities and contact forces, proved the repeatability of the experiments and the consistency of the acquired data.
3) The results indicated that specimens with one or more fractured layers were in many cases able to resist similar or even higher contact forces compare to those initiating the fracture of intact laminates.
4) The damage of laminated glass samples initiated in the back glass layer for 5LG-samples or in one of the outer glass layers for 7LG-samples. However, the subsequent sequence of fracture of the remaining glass layers differed.
5) Despite the large scatter of breakage forces, the post-critical vibrations of partially fractured samples exhibited similar first natural frequencies. The PVB interlayers provided a stiff shear connection between glass layers during the impact; the frequencies of laminated glass samples were mostly higher than those of monolithic glass plates with their thicknesses corresponding to the overall nominal thicknesses of unfractured glass layers.
6) Two of three input parameters of the nonlocal failure criterion, i.e. critical energy and critical radius, can be identified using the failure time of the glass layer. In this study, the failure time was identified as the time when the contact force of the unfratured and fractured glass layer begins to differ. The remaining parameter, i.e. the critical tensile stress, can be adjusted by fitting a numerical softening branch of the contact force to the measured one.

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# References

[1] P. Foraboschi, “Hybrid laminated-glass plate: Design and assessment”, in “Composite Structures”, 106, 250–263, 2013. doi:10.1016/j.compstruct.2013.05.041

[2] X. Wang, J. Yang, W.T.A. Chong, P. Qiao, S. Peng, X. Huang, “Post-fracture performance of laminated glass panels under consecutive hard body impacts”, in “Composite Structures”, 254, 112777, 2020. doi:10.1016/j.compstruct.2020.112777

[3] N.D. Kaiser, R.A. Behr, J.E. Minor, L.R. Dharani, F. Ji, P.A. Kremer, “Impact Resistance of Laminated Glass Using Sacrificial Ply Design Concept”, in “Journal of Architectural Engineering”, 6, 24–34, 2000. doi:10.1061/(ASCE)1076-0431(2000)6:1(24)

[4] F.W. Flocker, R.L. Dharani, “Low Velocity Impact Resistance of Laminated Architectural Glass”, in “Journal of Architectural Engineering”, 4, 12–17, 1998. doi:10.1061/(ASCE)1076-0431(1998)4:1(12)

[5] J. Pelfrene, J. Kuntsche, S. Van Dam, W. Van Paepegem, J. Schneider, “Critical assessment of the post-breakage performance of blast loaded laminated glazing: Experiments and simulations”, in “International Journal of Impact Engineering”, 88, 61–71, 2016. doi:10.1016/j.ijimpeng.2015.09.008
[6] T. Pyttel, H. Liebertz, J. Cai, “Failure criterion for laminated glass under impact loading and its application in finite element simulation”, in “International Journal of Impact Engineering”, 38, 252–263, 2011. doi:10.1016/j.ijimpeng.2010.10.035
[7] C. Alter, S. Kolling, J. Schneider, “An enhanced non–local failure criterion for laminated glass under low velocity impact”, in “International Journal of Impact Engineering”, 109, 342–353, 2017. doi:10.1016/j.ijimpeng.2017.07.014
[8] P. Máca, J. Zatloukal, R. Sovják, “Design of a novel horizontal impact machine for testing of concrete specimens”, in “WIT Transactions on the Built Environment”, 141, 149–158, 2014. doi:10.2495/SUSI140131
[9] A. Hillerborg, M. Modeer, P.E. Petersson, “Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements”, in “Cement and Concrete Research”, 6, 773–782, 1976. doi:10.1016/0008-8846(76)90007-7
[10] A. Zemanová, P. Hála, P. Konrád, T. Janda, R. Hlůžek, “The influence of interlayer properties on the response of laminated glass to low-velocity hard-object impact”, in “International Journal of Impact Engineering”, 159, 104036, 2022. doi:10.1016/j.ijimpeng.2021.104036