Full-scale tests of laminated glass windows subjected to blast loads

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Publication details
FULL-SCALE TESTS OF LAMINATED GLASS WINDOWS SUBJECTED TO BLAST LOADS

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ABSTRACT

Laminated glass panes are widely used for glazing windows to mitigate the hazard from ejecting glass fragments due to blast loads. In the common design analysis of structural responses to blast load, the glass windows are simplified as a single degree of freedom (SDOF) system. Popularly used design guides such as UFC and ASTM also suggest an equivalent SDOF analysis or equivalent static analysis. The accuracy of such simplified analyses has been continuously under debating. Recently, much effort has been directed towards understanding of the dynamic behaviour of glass material and interlayer polymer such as polyvinyl butyral (PVB). With the more sophisticated dynamic material properties, some numerical models of laminated glass have been developed to give more comprehensive and supposedly better predictions of glass structure performance under blast loading. In the current study, full-scale field blast tests were conducted to investigate the response of laminated glass windows to blast loadings. The test data are used to evaluate the accuracy of the available analysis and design methods in predicting the glass window responses. 1.5m × 1.2m laminated glass panels with different glass and interlayer thicknesses were tested. Glass pane deflections were monitored by mechanical linear variable displacement transducers (LVDT) and high-speed cameras. The responses of the tested windows are compared with the estimation of SDOF models and design standards. The reliability of these design analysis approaches is examined.

KEYWORDS

Laminated glass, field blast test, SDOF.

INTRODUCTION

Laminated glass has been proved to be one of the most direct and effective methods to reduce the risk of glass fragment injuries towards the residents in blast incidents. Laminated glass is normally made of two layers of glass panes laminated by a polymer interlayer. The aim of laminated glass is to prevent shattered glass splinters from ejecting towards residents. After glass cracking, the splinters will be held by the interlayer which deforms substantially as a continuous membrane to mitigate the blast energy.

Popular design standards such as UFC 3-340-02 (DoD, 2008) and Glazing Hazard Guide (SFE, 1997) by Security Facilities Executives (SFE) simplify the window structure to a SDOF system in analyzing its response to blast load. The equivalent load-mass factors and the resistance functions are obtained by analytical solution or from testing results. The accuracies of the predictions differ due to different
resistance functions and load-mass factors adopted. Besides these two standards, ASTM F2248 (in practice with E1300) (ASTM, 2009) and UFC 4-010-01 (DoD, 2003) are also facilitated with blast resistant window design. ASTM F2248 specifies an equivalent 3-sec design load with the assistant of ASTM E1300 to determine the thickness of laminated glass panel. UFC 4-010-01 does not provide any specific design guidelines but recommends referring to ASTM F2248. The accuracies of all the above standards in predicting the performance of laminated glass window need be checked.

Field blast tests on laminated glass windows have been conducted over the years. Kranzer et al. (Kranzer et al., 2005) tested 7.52mm laminated glass windows under small scale charges. No global window failure was observed due to the small scale blast loads. Hooper et al. (Hooper et al., 2012) conducted full-scale field blast tests on 7.52mm laminated panes. The tested panes were found to fail at silicone joints resulting in the whole pane ejecting into the testing room. There have been a number of other blast tests performed by various organizations, but most testing results are confidential and not assessable. Because the responses of laminated glass window to blast loads are highly nonlinear, the limited testing data cannot be extrapolated either. In practice, the design analysis is based mainly on simplified approaches, and sometimes detailed numerical simulations (Zhang, et al., 2013a, 2013b). The accuracy of these approaches needs to be further verified. Therefore, more tests are deemed necessary with various window sizes, glass thickness, and PVB interlayer thickness to better observe the response and failure modes of laminated glass windows, and also to verify the accuracy of the simplified approaches in predicting the glass window responses to blast loads.

In this study, full-scale field blast tests were carried out on laminated glass of different thickness. The responses of the laminated panes were monitored. The testing data were used to check the accuracy of predictions according to the design standards and SDOF models.

EXPERIMENT SETUP

Figure 1 depicts the testing site setup for the field blast test. A 3.4m x 3.2m x 2.0m (wide x depth x height) reinforced concrete (RC) testing cube with two individual cells was constructed to support the glass windows. In each test, two 1500mm x 1200mm laminated glass windows were fully clamped onto the front wall of the cube with 20mm thick heavy steel frames. 50mm bite depth was designed to clamp the panes firmly. Plastic strips were inserted into the gap between the inner and outer frames to avoid glass damage during installation.

Five laminated glass specimens were tested in three blast trials. In Test 1, two laminated panes with 3mm glass plies were tested in pair to evaluate the influence of PVB interlayer thickness (1.52mm vs 2.28mm). In Test 2, a laminated pane with 3mm thick glass plies and 1.52mm PVB interlayer was tested with another pane of the same interlayer but 6mm glass plies to check glass thickness effect. In test 3, a 7.52mm laminated glass pane (3mm glass, 1.52mm PVB, and 3mm glass) was tested with a monolithic tempered glass. The latter is not relevant to this study, thus not discussed. 10kg TNT explosives were detonated in front of the windows at different stand-off distances as listed in Table 1.
A pressure sensor was installed on the front wall of the RC cube. Two mechanical LVDTs were installed behind the glass panes to track their central displacement histories. The pressure and displacement data were captured using a NI portable data acquisition system at a frequency of 500kHz. Two high-speed cameras (Fastcam SA3 Photron®) were hidden behind steel bunkers positioned at the back of the RC cube to monitor the failure process of the laminated panes. The camera lens and exposure time were adjusted with balanced aperture. The high-speed cameras were filming at 2000Hz. The data transducers and the cameras were triggered by external wires glued to the charge, which were ignited by the detonation.

RESULTS AND ANALYSIS

Testing Results

Figure 4 shows the recorded pressure time histories. The histories are aligned to the instants when the shock fronts arrive at the front wall of the RC cube. It can be observed that the air pressure acting on the front wall rise instantaneously to peak pressures, then attenuate to ambient, which are followed by significant negative pressures. The measured reflected pressures are integrated along time to derive the reflected impulses. The resulted reflected impulses and recorded peak reflected pressures are listed in Table 1.
The recorded pane central deflection histories are presented in Figure 4. The probes of the mechanical LVDT transducers were glued to the pane centrals, which followed the movement of the panes. The deflection histories are abridged at the instant when probes debonded from the glass panes. As shown, the laminated glass panes deform gradually at the beginning due to the flexural rigidity of the un-cracked laminated glass pane. The deflection increased rapidly after glass plies cracked, implying a substantially reduced stiffness of the pane. Maximum deflections of 275mm and 280mm can be found at about 15ms for pane 1-1-1 and 1-1-2, respectively. The other two 7.52mm laminated panes (2-1-1 and 3-1-1) responded similarly. The maximum deflections of 326mm and 264mm were measured on these two laminated panes. The difference on deflection was mainly due to the magnitudes of blast loading. The 13.52mm laminated pane (2-1-2) responded similarly. But it moved faster due to larger flexural rigidity, and ended up with a smaller maximum central deflection of 220mm.

Table 1. Summary of recorded blast loads

<table>
<thead>
<tr>
<th>Test No.</th>
<th>W  (kg)</th>
<th>R  (m)</th>
<th>Pr (kPa)</th>
<th>Ir (kPa ms)</th>
<th>Pr (kPa)</th>
<th>Ir (kPa ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>10</td>
<td>121.1</td>
<td>395.0</td>
<td>-28.4</td>
<td>319.7</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>9</td>
<td>168.6</td>
<td>476.1</td>
<td>-35.8</td>
<td>543.5</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>12.3</td>
<td>82.2</td>
<td>413.3</td>
<td>-17.5</td>
<td>261.7</td>
</tr>
</tbody>
</table>

Despite of similar responses observed from pane central deflection histories, the snapshots of high-speed images recorded apparent different pane failure processes. As shown in Figure 5 for pane 2-1-1, glass cracked 2ms after the blast wave arrived. Glass broke severely with very dense cracks along the boundaries and coarse cracks at pane central. Significant deformation pulled the cracked laminated pane out of the frame at 30ms. Eventually, the pane failed perimetrally along its boundary and was totally pulled out of the frame during rebound. In comparison, the laminated pane with thicker glass plies responded differently. For pane 2-1-2, the glass cracked at a slightly earlier stage as the pane responded faster due to its larger flexural stiffness. The ultimate tensile strength of the thicker glass was reached at an earlier stage and at a lower deflection level. Cracks extended and numerous glass shards were formed but held by the PVB interlayer. The cracked laminated glass pane reached a maximum deflection at about 31ms and rebounded without being pulled out from the window frame. The cracked laminated pane was retained within the window frame without joint failure.

Figure 3 provides the failure images of the tested glass panes. As can be observed the glass plies of the laminated panes were all badly damaged. The 7.52mm glass pane (1-1-1) experienced severer damage
than the other 7.52mm pane due to the larger blast pressure. Pane 1-1-2 also suffered severe glass crack. Moreover, the cracked laminated pane was partially pulled out of the window frame along its left and bottom boundaries. The 7.52mm laminated glass pane (pane 2-1-1) had the worst damage with the entire pane being totally pulled out of the frame and fell on the ground. Pane 3-1-1 experienced relatively lower level damage with no sign of joint failure or interlayer rupture. The likelihood reason is the smaller blast pressure and also the cavity created by the rupture of the monolithic glass tested in pair resulted in blast wave diffraction.

Analysis and Discussions

Glass thickness influence

In test 2, a 7.52mm laminated pane (2-1-1) with 3mm thick glass ply and a 13.52mm pane (2-1-2) with 6mm glass ply were tested in pair with 10kg TNT explosive detonated at 10m stand-off distance. As shown on the recorded central deflection time histories in Figure 4, the thicker pane responded quickly due to its higher flexural stiffness. A peak deflection of 220mm was reached at about 7ms after blast wave arrived. In comparison, the thinner pane deformed slower but a larger maximum deflection of 326mm was induced at around 15ms. The difference was because the thicker glass pane had higher flexural stiffness and larger inertial resistance. Under the same blast loading it deformed less than a thinner glass pane. The 13.52mm laminated pane stayed in the window frame; while the 7.52mm pane was totally pulled out of the frame because of the significant deflection. The joint failure found on the thinner glass pane was likely due to the more significant pane deformation and central deflection, which led to the pulling out failure around its boundaries. The comparison indicates that a laminated pane made of thicker glass plies responds faster than a thinner pane. Due to higher flexural stiffness and larger inertial resistance, a thicker glass pane deforms less and is less easily being pulled out of its window frame, which therefore has higher blast loading resistance capacity.

Interlayer thickness

The interlayer thickness effect was examined through pane 1-1-1 (1.52mm PVB) and pane 1-1-2 (2.28mm PVB). The deflection time histories in Figure 4 show there is negligible difference on the responses of the two laminated panes. Despite having a thicker interlayer, a slightly larger maximum deflection (280mm) was recorded on the 8.28mm laminated pane. This resulted in the cracked laminated pane being partial pulled-out along the window boundaries (Figure 3).

Comparison with the design standards and SDOF methods

The measured responses of the three 7.52mm laminated glass panes (1-1-1, 2-1-1, and 3-1-1) are used to checked the accuracy of the design standards including UFC 3-340-02 and ASTM F2248. ASTM F2248 estimates pane deflection using nonlinear plate theory. The magnitude of pane deflection depends on the level of applied pressure and the equivalent effective thickness of the laminated pane. As shown in Figure 6, the maximum deflections estimated by ASTM F2248 are a lot lower than the measured deflections for all the three panes involved in the field blast tests. This is because ASTM standard greatly overestimates the stiffness of the laminated glass, especially for the post-crack phase. The simplification of using 3-second equivalent pressure to represent the effect of reflected blast pressure is not appropriate. The variation of using ASTM standard to estimate the laminated pane maximum deflection is enormous. In general, the maximum deflections estimated are only around 25% of the tested pane maximum deflections.

The predictions of UFC 3-340-02 employ a static resistance function as suggested by Cormie (Cormie et al., 2009) (Figure 2) and a constant load-mass factor of 0.65. As depicted in Figure 6, the UFC code better predicts the behaviour of the laminated glass windows than ASTM code, but the maximum pane deflection is still underestimated. For instance, when the laminated glass window is subjected to 121kPa peak pressure and 395kPa-ms impulse blast loading, the UFC standard well predicts the initial
response. A maximum deflection of 181mm is predicted at about 14ms and then rebounded; whereas in the field test the laminated pane continued to deform to about 275mm at its central before rebounding. A variation of about -34% is found between the predicted maximum deflection and the measured in the test. Likewise, 32% and 24% lower central deflections are predicted for pane 2-1-1 and 3-1-1 as compared to the testing data. This is probably because of the static resistance function adopted is not accurate enough. The implementation of a constant load-mass factor cannot properly represent the progressive crack of glass either. Also the relative slippage between laminated pane and window frame cannot be considered in the SDOF model either.

![Graphs showing deflection vs time for different panes](image)

CONCLUSIONS

In this study, field blast tests were carried out to investigate the response and blast resistance capacity of laminated glass windows. Significant window failure modes were found to be associated with the joint failure at the window frame. The recorded pressure and deflection data were used to check the accuracy of predictions according to the ASTM and UFC standards. Comparison indicates that ASTM underestimates the laminated glass pane response under blast loadings. UFC standard gives a more reliable estimation, but also underestimates the peak glass panel deflections. The influence of boundary conditions should be taken into consideration to provide better estimation of laminated glass window responses.

REFERENCES


