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A numerical method for predicting the deformation of crazed laminated windows under blast loading

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ABSTRACT

The design of laminated glazing for blast resistance is significantly complicated by the post-crack behaviour of glass layers. In this research, a novel numerical method based on a semi-analytical energy model is proposed for the post-crack behaviour of crazed panes. To achieve this, the non-homogenous glass cracks patterns observed in literature experimental and analytical work was taken into consideration. It was assumed that, after the glass crazing, further deformations would occur in the cracked edge areas, whilst the central window surface would remain largely undeformed. Therefore, different internal work expressions were formulated for each zone and were then combined in the overall model. The resulting differential equation was then solved numerically. The results obtained were compared with data from four experimental full-scale blast tests for validation. Three of these blast tests (Tests 1–3) were presented previously (Hooper et al., 2012) on 1.5 × 1.2 m laminated glazing samples made up with two 3 mm glass layers and a central 1.52 mm PVB membrane, using a 15 and 30 kg charge masses (TNT equivalent) at 13–16 m stand-off. The fourth blast test (Test 4) was conducted on a larger 3.6 × 2.0 m pane of 13.52 mm thickness, using a 100 kg charge mass (TNT equivalent) at a 17 m stand-off. All blast tests employed the Digital Image Correlation (DIC) technique to obtain 3D out-of-plane deflections and strains.

The proposed analytical method reproduced the experimental deflection profiles, with the best estimates obtained for the more severe loading cases. Reaction forces were also compared with experimental estimates. The predictive ability of the proposed method could permit more accurate designs to be produced rapidly, improving structures resistance to such loadings.

1. Introduction

The blast resistance of glazing is an important consideration when designing against explosions. Monolithic annealed glass panes produce dangerous shards due to the inherent low fracture toughness of the material. Fragments are propelled both inside and outside the building space and can cause significant injuries and damage. After fracture, residual blast pressures are able to penetrate the building envelope, causing further injuries to occupants and equipment.

Laminated glazing, comprising layers of glass and Polyvinyl Butyral (PVB) membranes, is significantly more resilient to blast loads [1]. After the glass layers craze, the glass fragments remain bonded to the polymer membrane, which need to be retained in the frame. The PVB membrane can then deform significantly, absorbing large amounts of energy and preventing blast pressures from entering the interior.

The behaviour of the crazed pane is complex to model in detail. To gain understanding of the laminated material, several experimental studies have been performed on glazing panels subject to shock loading, either with blast tests [2–9] and in shock tubes [10]. The results of such tests have been used recently by many researchers to validate finite element analyses (FEA) of both impact and blast loading [2,3,11–17]. Whilst these models are often able to predict the behaviour of the system, their use requires significant specialist knowledge and computer time.

Analytical solutions instead can produce relatively rapid results, though they cannot account for the same variety of situations as FEA

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models. A commonly used analysis method is given by single degree of freedom approximations. These can use constants derived either empirically or from first principles to estimate the windows behaviour and therefore produce structural designs [1,18]. This approach is currently used for the design of elements, as it can produce accurate data based on extensive tests databases [1]. Some authors [19–22] proposed instead more detailed analytical models, as these could be used to predict additional aspects of the glazing behaviour. Wei and Dharani [23] employed Von Karman large deflection theory to simulate the deformation of window panes. The authors used their results to also calculate the probability of window failures and the likely crack locations [24]. In this analysis the authors used a single cosine function to represent the deflected shape of the window. Their work was expanded by Del Linz et al. [25] employing a higher order deflection function and comparing the analytical results with DIC recorded data. The research used three sets of blast test data (Tests 1–3) and showed that the analytical technique considered could accurately predict deflections before the glass failure and likely crack concentrations in the failed panels, as well as the reaction forces imposed on the supporting structures. It therefore could provide additional details on the structural behaviour compared with previous approaches, using potentially a smaller number of initial assumptions.

The condition of a glazed pane after it has crazed is more complex than before the glass failure. The crazed pane material is no longer homogenous as its properties are likely to depend on the density and orientation of the cracks. As shown experimentally [4] and through the pre-crack solutions mentioned above [25], in cases where the blast pressures deform the glass impulsively, the crack pattern tends to be denser along bands corresponding to the higher bending stresses in the pane at the points of initial fracture. This influences the deformation which follows, especially in the case of stronger blast excitations. A significant change in the panes curvature occurs at these higher crack density locations throughout the glass deformation history. This effect is indicated by the arrows in Fig. 1 for Test 3, where a clear change in curvature is visible approximately 1/3 of the distance from the edge to the centre of the pane. Fig. 2 shows the locations of the surface cuts plotted in Fig. 1 and in subsequent figures. In all cases the shortest pane side was assumed to be aligned with the x-axis.

Whilst the detailed physical characteristics of the systems are different, the presence of these lines of high curvature highlight a similarity with the plastic large deflection of plates commonly analysed with yield line theory [26]. This analysis is based on equating the external work performed by the loads to the internal energy stored in the system, which is localised at a series of failure yield lines. For laminated glass panes, the energy absorbing capacity due to out-of-plane bending of the cracked glass is close to zero, therefore a different energy absorption method needs to be assumed. As the deflections of the system cannot be assumed to be small, the membrane forces acting on the pane will be significant and represent a possible mechanism for the development of internal energy. Therefore, whilst in other applications the internal work is calculated using the increase of rotation angle at the yield lines and a plastic bending capacity, in this case the elongation of the membranes was considered. As mentioned above, the glass cracks were shown to be concentrated along the edges of the panes in the blasts tests considered in previous studies. Therefore, for this research, it was assumed that the material deformations due to the membrane forces would also be concentrated in these areas, which would be limited by the window supports and the lines of high curvature highlighted in Fig. 1. The behaviour of such cracked glass was assumed to be similar to that measured by Hooper et al. [4]. A differential equation solution for the systems of interest was derived equating the external energies applied by the blast to the internal membrane energy caused by the deformation of these highly cracked areas, respecting the assumptions of the behaviour described above.

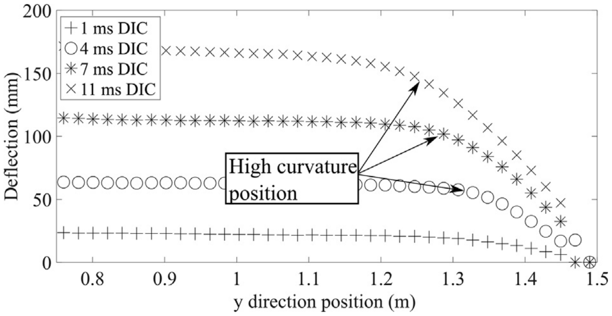

Fig. 1. Deformation along a centre line of the window in Test 3 (adapted from [4]).

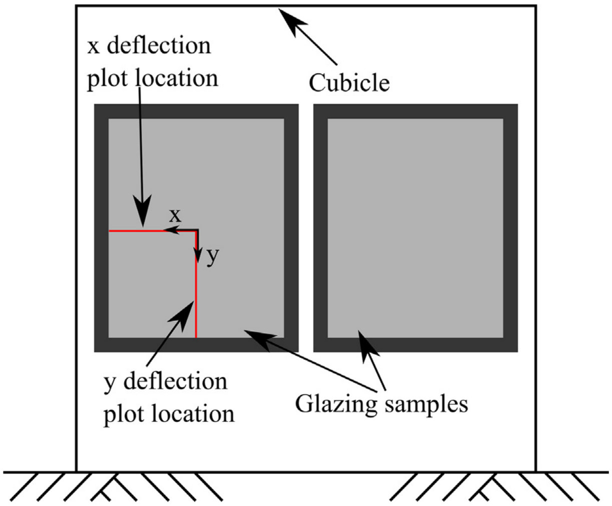

Fig. 2. Cuts locations used in the data presentation.

To validate the proposed analytical methods using data comprising different pane dimensions and aspect ratios, data from four blast tests were used. Three of these (Tests 1–3) were obtained from Hooper et al. [4] and have been used previously to validate the pre-crack analytical solution [25]. Additionally, the results from a further test (Test 4) conducted by Hooper are presented here and compared with both pre-crack and post-crack analytical solutions [27]. The glazing pane used for Test 4 was 3.6 m × 2.0 m. The glass make-up was given by two 6 mm glass layers interlayered with a 1.52 mm PVB layer.

The analytical solution for the post-crack behaviour was therefore compared with the experimental data from four tests. An estimate of the reactions based on the model results was also produced for the first three tests so as to compare these results with those produced from experimental data [28]. Due to possible uncertainties in the derivation of the loading function, a small sensitivity study was also conducted to assess the influence of the fitting paramaters.

The aim of this work was to provide a more flexible tool for designers, which could provide additional details, such as the entire deformation history and reactions forces calculated in this work, compared with previously used design methods. Additionally, as per the single degree of freedom approach, calculations would be relatively rapid, therefore offering a useful tool for the practical design of these structures.

2. Method

2.1. Experimental program

The evaluation procedures for all four tests were very similar. Tests 1–3 have been described in Hooper et al. [4]. They were conducted on 1.5 × 1.2 m laminated glazing samples made up with two 3 mm glass layers and a central 1.52 mm PVB membrane. The blast loading was a