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Influence of the negative phase and support flexibility on the blast response of laminated glass panels

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HIGHLIGHTS

- Effects of negative phase on blast response of laminated glass (LG).
- Negative phase has less impact on LG panel with rigid supports.
- Negative phase has high impact on LG panel with flexible supports.
- Flexible supports absorb large amount of blast energy and reduce that of sealants.

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ABSTRACT

This paper presents a comprehensive numerical procedure to treat the blast response of laminated glass (LG) panels and investigates the effects of two important parameters: the negative phase of the blast loading and support flexibility on the blast performance of LG. The influence of the negative phase is examined on the blast response of LG panels fixed to rigid and flexible supports. Findings indicate that the negative phase has negligible impact on the centre deflection, energy absorption and the support reactions of LG panels with rigid supports while it has significant impact on those with flexible supports. The support flexibility is varied by changing the cross-section dimensions of the steel cables used with the flexible supports. Results show that blast performance of flexible facades can be further improved by using steel cables with smaller cross-sections as they increase the energy absorption while reducing reaction forces at the steel cables. Flexible supports seem to delay the failure of LG panels which are more likely to fail after dissipation of the blast pressure and hence reduce the injuries occurring from direct blast pressure and the broken glass fragments. The new information generated in this paper will therefore encourage engineers to come up with innovative flexible façade systems which will minimise the hazards from potential near field explosions.

1. Introduction

Designing building facades to a credible blast load has become an important consideration with the ever increasing number of terrorist attacks. Glazed facades with monolithic annealed glass are often used in buildings, especially at the lower levels for visual exposure, aesthetics, opacity and environmental compatibility. Under near field explosions, these facades can be subjected to extensive damage causing various injuries to the occupants. Fig. 1 illustrates two of the major bomb attacks that occurred and highlights the damage they caused to the external façade systems [1,2]. 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 façade disintegrates, blast pressure enters the building causing injuries to the occupants and even damage to the building. Previous research investigated action effects on a structural frame by assuming that the building facade will disintegrate in a blast event [1,3]. However, building facades could be designed for a credible blast load to minimize, if not eliminate hazards due to flying and falling glass shards and pressure related injuries. The credible blast load is the designed blast load for a given glazed panel causing its failure with the expected hazard level.

Building facades fabricated with laminated glass (LG) provide significant blast resistance compared to monolithic annealed glass used in most buildings. LG consists of two or more glass plies permanently bonded with one or more polymer interlayers. Annealed and heat strengthened glass types are usually used in LG while polyvinyl butyral (PVB) is the common interlayer material [4]. LG

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(a) Bomb attack on Murrah Federal Building in Oklahoma, USA, 1995 [1]

(b) Bomb attack on Government and media buildings in Oslo, Norway, 2011 [2]

Fig. 1. Damage to the glazed facades from major bomb attacks.

panels are fixed to the window frames using structural sealant joints where silicone sealants are mostly used in blast resistant glazing. LG has two major advantageous over monolithic annealed glass used in most buildings. When LG fractures, glass fragments adhere to the interlayer avoiding free flying shards which have been the major cause of injuries with monolithic annealed glass. Furthermore, even after glass cracks, the interlayer deforms by absorbing blast energy where the post-crack load carrying capacity of LG is considerably higher than that at the pre-crack phase [5]. Building facades with LG will therefore minimise if not eliminate the hazard from effects of uncontrolled explosions. The influence of interlayer properties on the blast response of LG has been studied in a previous paper [6].

This paper presents a comprehensive numerical procedure to study the blast response of LG panels by accounting for the support flexibility using the LS-DYNA explicit finite element (FE) code [7]. Previous research studied the blast response of LG panels by assuming that the sealant joints are fixed to a rigid base by neglecting the deformation in the frame for simplicity [8–10]. This could be a conservative approach as the flexible supports could absorb the blast energy and minimise the damage to the glazing. Research has been carried out to study the blast response of LG fixed to flexible cable nets with point supported spider connections [11,12]. A similar study is required for LG panels fixed with window frames along the edges as they will have a better blast performance compared to those with point supported connections. This is because, it is believed that LG should be properly fixed to a window frame along the four edges to achieve the best performance as it is usually designed to fail by tearing of the interlayer to maximise the energy absorption.

This paper therefore investigates the blast response a LG panel fixed to a window frame along the edges with structural sealant joints by accounting for different support conditions. Fully framed LG panels are fixed to rigid supports and also to flexible supports with steel cables to compare their performances under different blast loads. Most of the previous research simplified the blast load by considering only the positive phase and assumed that the negative phase will have a negligible impact on the blast response of building facades [8–10]. Existing design standards for blast resistant glazing such as American Society for Testing and Materials (ASTM) F 2248-09 [13], Unified Facilities Criteria (UFC) 4-010-01 [14] and UFC 3-340-02 [15] do not account for the effects of negative phase of the blast loading or the support flexibility and hence the effects of these important parameters are studied in this paper. Results from the FE analysis indicate that the negative phase has significant impact on the blast response of LG panels with flexible supports while it has less impact on those with rigid supports. Furthermore, LG panels with flexible supports have better blast performance compared to those with rigid supports. The new information generated in this paper will therefore contribute towards safer and more economical design of the entire façade system including window glazing, frames and supporting structures for the effects of near field explosions.

2. Background

This section provides some background information on the blast phenomenon and the methods of estimating blast related parameters. The different types of glazed facades and supporting structures used in existing buildings are then discussed. Finally, commonly used flexible façade systems such as cable net facades are briefly discussed in this section.

2.1. Explosion and blast phenomenon

Blast or an explosion is a sudden release and transformation of potential energy into kinetic energy with the production of gas under high pressure and temperature. A typical blast overpressure time-history curve at a point away from the explosive source is illustrated in Fig. 2 [16]. Initially, the blast overpressure increases to a peak value, then decreases gradually and goes through a negative phase. The Friedlander equation which is generally used to express the blast overpressure variation is given by Eq. (1) [17], where $P(t)$ is the instantaneous overpressure at time t, P_{amb} is the ambient pressure, P_{max} is the peak pressure when $t = 0$, $P_{op} = (P_{max} - P_{amb})$ is the peak overpressure at $t = 0$, t_0 is the positive pressure duration and b is the decay factor.

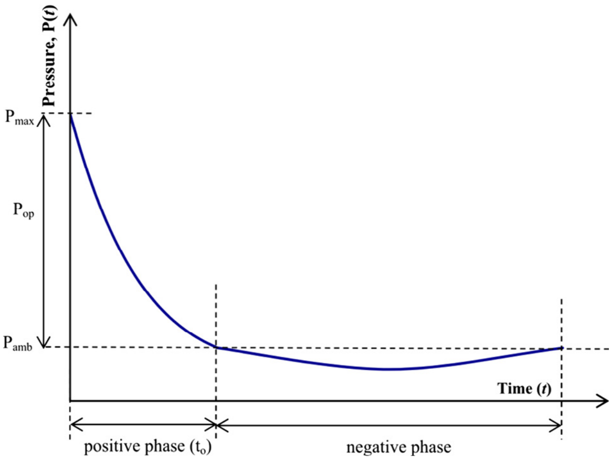

Fig. 2. Blast overpressure-time history variation for a typical blast load [16].