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Failure analysis of laminated glass panels subjected to blast loads

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ABSTRACT

This paper presents a rigorous and a reliable analytical procedure using finite element (FE) techniques to study the blast response of laminated glass (LG) panel and predict the failure of its components. The 1st principal stress (σ_{11}) is used as the failure criterion for glass and the von mises stress (σ_v) is used for the interlayer and sealant joints. The results from the FE analysis for mid-span deflection, energy absorption and the stresses at critical locations of glass, interlayer and structural sealant are presented in the paper. These results compared well with those obtained from a free field blast test reported in the literature. The tensile strength (T) of the glass has a significant influence on the behaviour of the LG panel and should be treated carefully in the analysis. The glass panes absorb about 80% of the blast energy for the treated blast load and this should be minimised in the design.

1. Introduction

Building facade forms the skin of a building and is the most vulnerable component in the building to blast loads. Glazed facades are often used in buildings for their architectural features and aesthetical aspects. Most of the buildings use 4–10 m high glazed facades in the ground floor lobby areas without any structural framework. These lower levels are the most vulnerable to near field blast events in which 80–90% of blast related injuries have been due to flying glazed fragments and facade pieces. If building facades disintegrate, direct blast pressure entering the building can cause injuries to occupants and damage to the building. Laminated glass (LG) panels, with a higher resistance to blast loads, are therefore used in buildings to minimise, if not eliminate the hazard from potential terrorist attacks.

LG consists of two or more glass panes permanently bonded with one or more polymer interlayers. Glass types such as annealed, heat strengthened and tempered are usually used in LG panels and polyvinyl butyral (PVB) is used as the interlayer material. Structural sealant joints are used to mount LG panels to the window frames. LG has two major advantages over normal glass encouraging its use in building facades designed to be blast resistant. One such advantage is that it avoids hazards due to flying glass fragments as the interlayer holds them after the glass brakes. Secondly, after the glass cracks the interlayer stretches and absorbs blast energy until it tears off. The fractured glass elements have some strength to provide stiffness when they are subjected to compression. The available strain energy at the post-crack phase of a LG panel is significantly higher than that at the pre-crack phase providing superior blast resistance compared to normal glass panels.

The standards such as American Society for Testing and Materials (ASTM) F 2248-09 [1] and Unified Facilities Criteria (UFC) 3-340-02 [2] are used for designing glazed facades to blast loads. However, both standards provide conservative design approaches based on simplified single degree of freedom analysis. The ASTM F 2248-09 standard does not account for the

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effects of interlayer in a LG while the UFC 3-340-02 standard is limited to design of monolithic thermally tempered glass. The UK Glazing Hazard Guide [3] provides a realistic approach for designing glazed facades to blast loads compared to the above standards. However, it is a highly confidential document which was established for only few window sizes available in the UK. An analytical procedure is therefore required for the vulnerability assessment and design of glazed facades with LG panels subjected to blast loads.

Numerical analysis with FE codes is a feasible method that has been widely used to investigate the behaviour of LG panels under blast loads. However, most of the existing research does not account for the fracture strength of glass as the glass elements or integration points are deleted when they exceed a predefined failure stress or a strain. In addition, there is limited research that modelled the silicone sealant joints in FE models. This paper presents a realistic approach in modelling LG panels using the LS-DYNA FE code and addressing the above limitations. Glass, interlayer and sealant joints are modelled with three dimensional (3D) solid elements, considering the supporting frame as a rigid base for simplicity. The material model used for glass accounts for the fracture strength of glass depending on its damage level. The results from FE analysis for stresses are used to predict the failure of different components in the LG panels. This paper therefore provides useful information to engineers for studying the blast response of LG panels and for their better design under a credible blast event.

2. Blast response of LG panels

Different techniques such as window films, window catching systems, LG panels and ballistic windows are commonly used in building facades designed to be blast resistant. However, the present study focuses on LG panels because they are energy absorptive and transfer less force to frame members and optimise the design of the entire facade system. Blast formulation, wave propagation and blast wave characteristics are described in the paper. The progressive failure of LG is then described in different phases.

2.1. Blast phenomenon

Blast or an explosion is a sudden release and transformation of potential energy into kinetic energy generating hot gases under a pressure up to 30 MPa and a temperature of about 3000–4000 °C [4]. High pressure gas travels at a high velocity (7000 m s^{-1}) away from the explosion source by creating shock waves [2]. Initially, the pressure of the shock front increases to a maximum overpressure and then decays as the shock wave expands away from the explosion source. After a short time, pressure behind the shock front drops below the ambient pressure by creating a partial vacuum. It creates high suction winds capable of carrying debris for long distances away from the explosion source.

Fig. 1 [5] illustrates a typical blast wave pressure–time profile at a point away from the explosive source. The air pressure at a particular point increases suddenly to a peak value, then decreases gradually and goes through a negative phase. This blast overpressure time profile can be mathematically represented by the Friedlander equation, as given by Eq. (1), where $p(t)$ is the instantaneous overpressure at time t, p_a is the atmosphere pressure, p_m is the peak pressure when $t = 0$, $p^0 = (p_m - p_a)$ is the peak overpressure at $t = 0$, t_d is the positive pressure duration and α is the decay factor.

$$p(t) = p^0(1 - t/t_d)e^{-\alpha t/td} \quad (1)$$

2.2. Failure of LG panels

Usually, LG panels are designed to fail by tearing of the interlayer rather than pulling out of the glass plates from the rebates. If the glass pulls out from the rebate or the frame members fail, the entire unit will be flung into the building causing a

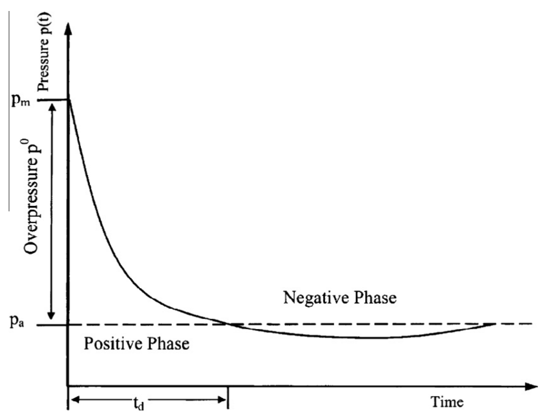

Fig. 1. Typical blast pressure–time history curve [5].