Engineering Structures 123 (2016) 155–165

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Dynamic response of double skin façades under blast loads

Chao Ding [a,*], Tuan Ngo [a], Priyan Mendis [a], Raymond Lumantarna [b], Marc Zobec [b]

[a] Department of Infrastructure Engineering, The University of Melbourne, Parkville, VIC 3010, Australia
[b] Permasteelisa Group, 13–15 Governor Macquarie Drive, Chipping Norton, NSW 2170, Australia

ARTICLE INFO

Article history:
Received 12 January 2015
Revised 24 May 2016
Accepted 30 May 2016
Available online 10 June 2016

Keywords:
Blast
Double skin façades (DSF)
LS-DYNA simulation
Coupled 2DOF approach
Structural responses

ABSTRACT

Blast loads pose devastating threats on façade systems. Fragments from glass façades can cause injuries or even fatalities. Double skin façades (DSF) are becoming increasingly popular in modern façade construction practices due to their energy efficiency. In addition, DSF exhibit a higher blast resistance capacity compared to single layer (monolithic) façades. The Unified Facilities Criteria (UFC) 3-340-02 (2008) provides approaches to assess blast performance of monolithic glass panels. However, due to the complex interactions between DSF panels and the air within the cavity, current codes are insufficient to address the blast responses of DSF. This paper presents analytical approaches to obtain maximum deformations (centre) of the DSF panels subjected to blast pressures. A blast trial was described in this paper for validating the blast pressure simulation in LS-DYNA. The dynamic response of the monolithic panes simulated by LS-DYNA was then validated against the single degree of freedom (SDOF) approach. The key theoretical backgrounds of the analytical model are the two degree of freedom (2DOF) approach and adiabatic process. Based on those two theories, a coupled 2DOF analysis was then proposed, since it combined the analysis of the two panes and the air cavity between them. Blast responses of DSF in the elastic regime using the coupled 2DOF approach conformed well to the validated LS-DYNA simulation results. By comparing the results from the coupled 2DOF approach and UFC 3-340-02, it was found that UFC is over-conservative. Therefore, in terms of engineering applications, the analytical model provides an efficient and accurate approach to assess the blast responses of DSF in the linear-elastic regime.

1. Introduction

Common forms of terrorist threat, such as bombs, have evolved in both scope and scale [1,2]. These explosions are aimed at destroying structures and killing people. Important assets, such as landmark buildings and government facilities, are often the primary targets of these explosions. In most circumstances, the target structures would suffer catastrophic damages. In addition, injuries and loss of lives associated with this structural damage are enormous. Consequently, due to this increasing concern, there is now a greater focus on protective aspects of structures.

The current trend in building design, especially for high-rise buildings as a city's landmark, suggests that glazing façade components cover up to 70% of the external surface of a structure [3]. Compared with other façade materials, glazing is the most vulnerable part [4]. Hence, in a blast event, the glazing component would always suffer the most destructive damage. Flying glass fragments are problematic when the glazing is not adequately designed. In the case of an explosion, especially close to modern glass buildings, the flying glass fragments could cause more than 80% of the human injuries [5]. The shattered glass fragments are forced inside or outside the building with a high velocity, causing severe injuries to both building occupants and pedestrians outside. Furthermore, the following blast waves will also intrude inside the building, resulting in even further injury to the occupants. This highlights the importance of an established approach to assess blast resistance performance of a façade system [6]. The dynamic behaviour of glazing systems under impulsive loading, such as blast, still poses a great challenge for engineers [7].

The normal approach in façade design guidelines requires the façade system to resist mild hazards, such as wind and occasional impact, where the magnitude is significantly smaller than that of blast loading. This approach means that there might be a failure of the façade system when it is exposed to blast loading. Therefore, it is necessary to incorporate blast design guidelines in design codes in order to fulfil a range of façade protection functions, especially for the design of critical buildings such as embassy and government office buildings, which are considered at high risk and would require special attention to counteract blast attacks. Guidelines such as UFC 3-340-02 [8], only specify the design of monolithic glazing panels under blast loading. However, sometimes

* Corresponding author.
E-mail address: elvisdchao@gmail.com (C. Ding).

http://dx.doi.org/10.1016/j.engstruct.2016.05.051
0141-0296/

the monolithic glazing panel will be very thick in order to resist a certain type of blast loading. This results in higher manufacture and construction costs, which may not be economically viable for the consideration of a low probability event (e.g. blast).

Double skin façades (DSF) are becoming increasingly popular in façade construction practice due to their sustainability features, such as thermal comfort optimisation, good ventilation, energy efficiency in cold seasons, good daylight performance, external noise and wind protection, and high-tech image [9–12]. In addition, recent studies show that DSF exhibit enhanced blast performance compared with monolithic façade systems. Laminated glass can be used as the external skin to significantly dissipate blast energy [13] through the breakage of glass piles and large deformation of the polymer interlayer [4]. Even if the external skin breaks, the internal skin can act as a second protective layer to block the shattered glazing pieces and blast waves. This will greatly enhance the protection of building occupants from blast-related injuries. Therefore, DSF are an ideal selection for façade applications, in terms of both sustainability and safety aspects.

Despite the significant advantages of DSF, there still lacks a design code that directly addresses its blast performance. Current codes (e.g. AS 1288 [14], ASTM E 1300-04 [15] and ASTM F 2248-12 [16]) that specify the design of insulating glass units (IGU) are inadequate to address the performance of DSF under blast loading [17]. The limitations of these codes are:

- Only IGU are addressed rather than DSF. The air gap distance between two panes of IGU is normally less than 16 mm [18]. However, the cavity distance between two panels of DSF can range from 20 cm to 2 m [19]. The difference of cavity gap can result in significant variations in load distributions [20].
- The load transferred to an individual panel of IGU is determined based on the thickness of the panel, without taking the cavity air into account.

This paper attempts to establish an analytical approach to evaluate the blast responses of DSF. Section 2 aims to validate the numerical model against experimental investigations and an SDOF approach. This validated numerical model is then the basis for the validation of the 2DOF approach in Sections 3–5.

2. Experimental program and FE validation

2.1. Experimental program

This published experiment is aimed at the validation and calibration of the numerical model. An analogical DSF under blast loading was tested in a joint collaboration between the University of Melbourne and the Permasteelisa Group [21].

In this test, steel panels were used as the DSF panels to minimise uncertainties due to the statistical strength variability of glass [29]. A ventilated DSF compartment was set up. The cavity of the compartment had the following dimensions: 1 m width × 3 m height × 0.25 m depth. The detailed schematic drawings are shown in Fig. 1.

The external steel panel mounted for the DSF had a height of 2.3 m, a thickness of 10 mm and a width of 1 m, as shown in Fig. 1. The detailed set-up of the experimental work could be found in the published work [21]. A concrete block with a width of 1 m, height of 3.1 m and thickness of 0.5 m was used to support the DSF to resist blast loading [21]. The internal panel of the analogical DSF was represented by the surface of the concrete block. Therefore, the internal panel of the DSF can be taken as a fixed structure for analysis, since the deformation of the above concrete block can be neglected when subjected to this level of blast loading.

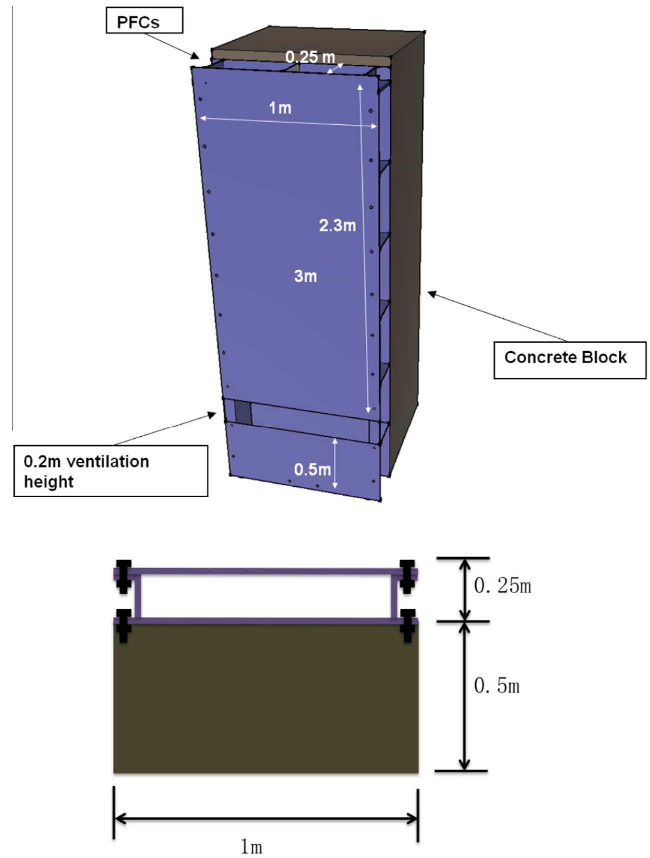

Fig. 1. Schematic drawing of tested analogical DSF and concrete block.

Fig. 2 shows the on-site experimental works.

Three pressure transducers (PCB Series 102B) were mounted on the internal panel (concrete block) of the tested DSF to measure the cavity pressure history, as shown in Fig. 3.

The recording frequency of the PCB Series 102B pressure transducers is 1000 kHz. Therefore, during the trial, data at the gauges was recorded at intervals of 1 μs.

Another two side-on pressure gauges were placed at a height of 1.2 m and at stand-off distances of 42 m and 47 m in order to measure the incident pressure histories. All the pressure data will be used in the next section to validate the accuracy of the LS-DYNA numerical simulation.

The general layout of the blast test setup is shown in Fig. 4. The description of the explosives can be found in [21]. A charge weight equivalent to 250 kg of TNT was used for the test. The stand-off distance between the explosive charge and the tested DSF was 52 m [21].

The results obtained from the three pressure transducers were averaged to obtain more accurate data, which will be presented in the next section.

2.2. FE validation against experimental work

The FE software LS-DYNA was used to simulate the above experimental set-up, process of detonation, blast wave transmission and blast-structure interaction. The explosive was represented by a sphere of pressurised gas at high pressure after ignition of the charge. The density of a typical TNT explosive is 1630 kg/m^3, and the detonation velocity is 6930 m/s [22]. Each simulation model consists of two phases: a two-dimensional (2D) analysis and a subsequent three-dimensional (3D) analysis. The function of a two-dimensional (2D) analysis is to effectively and accurately calculate blast wave transmission. An Arbitrary Lagrangian-Eulerian