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Numerical study of sandwich panel with a new bi-directional Load-Self-Cancelling (LSC) core under blast loading

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ABSTRACT

A new form of bi-directional Load-Self-Cancelling (LSC) sandwich panel is proposed in this paper. An array of square dome shaped steel sheet as core of the proposed sandwich panel is designed to cancel a certain amount of load during blast event owing to its arching geometry. The blast resistance and energy absorption capabilities of the sandwich panel are investigated numerically by using finite element analysis software LS-DYNA. The peak deflection of centre point on back face sheet, internal energy and peak boundary reaction forces are compared among monolithic plate, multi-arch uni-directional LSC structure, sphere dome structure and the proposed bi-directional LSC square dome sandwich panel. It is found that using the proposed bi-directional LSC square dome leads to 69%, 48% and 56% reduction in the out-of-plane boundary reaction force as compared to the flat plate, multi-arch panel and grid sphere panel, respectively. In addition, parametric studies of the influences of dome number, height, and layer material on the performances of the proposed bi-directional LSC sandwich panel subjected blast loads of different intensities are carried out to investigate the panel configuration on the effectiveness of its blast resistance and load-self-cancelling capability. The results demonstrate the superiority of the sandwich panel with the proposed bi-directional LSC core.

1. Introduction

Accidental explosion and terrorism activities have been increasing around the globe in recent years, and more than half of which were related to bombing attacks [1–3]. As a protection of life and infrastructure from bomb attack, blast resistant panels have been widely used across military, commercial and industrial applications [4–6]. Blast-resistant doors as an example of such panels are used at entrances of shelters and ammunition storage magazines. The traditional blast resistant doors are often designed as a solid panel of great weight which leads to poor operational performance and high costs [7]. The ideal characteristics of a blast resistant panel should be lightweight while capable of resisting blast loads.

Various blast resistant panels have been developed. Due to the lightweight and high energy absorption capability, different sandwich structures which consist of a relatively thick and lightweight core sandwiched by two thin skin layers, have been proposed to absorb energy in recent years [8]. The performances of sandwich structures with different forms, materials and topologies have been comprehensively reviewed [9–11]. Forms of sandwich structure core usually include honeycomb, corrugate, metallic foam, lattice and functionally graded core. Superior performance of sandwich structures under dynamic loading has been demonstrated via both numerical simulations and experimental tests [12–19]. Other forms of structures such as egg-box, negative Poisson's ratio, and continuously graded lattice structure were investigated for their energy absorption performance under dynamic loading [20–24]. Curved sandwich panel with aluminium foam as core also demonstrated superior performance over equivalent flat sandwich panel and solid plate against blast loading [25–28]. Most of the previous studies focused on the energy absorption and the deformation of the panel after blast, the investigations on blast load transferred to the supports were limited. In practice, supports of the structural panel also need be properly designed and protected because damage to the support may lead to the complete failure of the panel structure. In this regard, a uni-directional multi-arch panel was proposed [7,29]. This innovative design makes use of the unique property of arch structure form that transfers a certain amount of load applying onto the arch to the supports. In this case loads in the opposite directions at the intersections of adjacent arches would cancel each other, leading to reductions of the net loads to the supports of the structural panel. Both numerical simulations and experimental tests verified the effectiveness of the uni-directional multi-arch panel in resisting blast and impact loads [7,29]. However, some limitations of using this uni-directional panel were also identified. It cancels loads only in one

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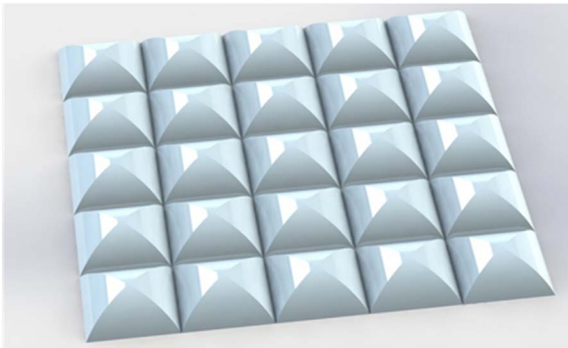

Fig. 1. Proposed square dome as core of bi-directional load-self-cancelling structure.

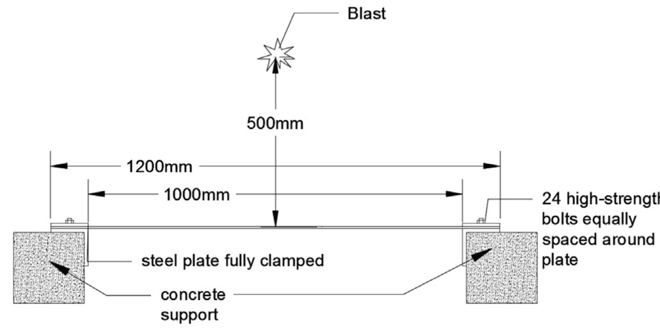

Fig. 2. Experimental setup of a steel plate subjected to blast load.

direction therefore its effectiveness in load-cancellation is effective in one direction only. Detailed discussions on the designs and performances of uni-directional multi-arch panels subjected to blast and impact loads can be found in the references [7,29,30].

To overcome the shortcomings of the uni-directional multi-arched panel, a bi-directional LSC sandwich structure is proposed in this study, the core consists of an array of two-axis-symmetric square domes as shown in Fig. 1. This new structural form is believed to have capability of cancelling load in both in-plane directions of the panel and therefore further reducing forces that would be transferred to the panel boundaries as compared to the uni-directional multi-arch panel. With the geometry similar to the proposed bi-directional LSC square dome structure, a modified structure named as "grid dome" is also numerically simulated in this study for comparison. It was originally proposed in [31], where the textile composite material and half sphere shape made it easy to deform and absorb energy. The grid of half spheres are placed with gaps between each other in the panel [31]. The array of grid sphere is modified and placed next to each other in this study to make it similar to the bi-directional LSC structure proposed in this study, since the load can be cancelled at the intersection points of the adjacent sphere domes as well. However, the adjacent grids of sphere domes are only point connected while the proposed square dome structure are connected with intersection lines, which allow more forces to be self-cancelled. Therefore, a superior LSC capacity is expected for the proposed square dome structure.

In this study, the effectiveness of this new form of LSC structure is numerically investigated and compared with an equivalent monolithic plate, and a uni-directional multi-arch structure [7] and a modified grid sphere dome structure [31]. Finite element software LS-DYNA 971 is employed in this study to calculate and analyse energy absorption, back plate centre deflection and boundary reaction forces of these structures under blast loading. The existing blast test data of a flat plate from other researchers is used to calibrate the numerical model. To validate the numerical model, the numerical results of dynamic response of the flat plate are compared with the existing experimental data. The calibrated numerical model is then used to perform numerical simulations of the proposed structure to evaluate its energy absorption capacity, blast load resistance capacity and boundary reaction forces. A series of parametric studies are also conducted to investigate the effectiveness of sandwich panels with different core configurations on their blast loading resistance capacities.

2. Numerical model calibration

Finite element software LS-DYNA 971 is used for numerical simulation in this study. As a widely applied FEA tool based on explicit numerical methods, LS-DYNA is dedicated to highly nonlinear, dynamic finite element analysis subjected to impact and blast loads. To calibrate the accuracy and reliability of the numerical model, a steel plate which was tested and numerically modelled by DSTO (Defence Science and Technology Organization) of Australia is adopted [32]. In year 2000, a series of blast tests were carried out to study structural response of a 5 mm thick mild steel plate. The charges of 250 g Pentolite (260 g TNT equivalent [7]) were applied with the alternating stand-off distance of 250 mm, 400 mm, 500 mm directly above the centre of the steel plate with dimension of 1200 mm by 1200 mm. The steel plates were bolted on to a 1000 mm by 1000 mm rigid steel frame with 24 equally spaced high-strength bolts. The steel frame was simply supported by concrete stands on four sides with some openings. The schematic diagram of experimental setup of the steel plate is shown in Fig. 2. Two Endevco 7255 A piezoelectric accelerometers, two PCB Piezotronic 109 A piezoelectric pressure gauges and a Novotechnik TI50 LVDT resistive displacement gauge were attached on the steel plate to record relevant data of the plate during and after the explosion. The test results are used to calibrate the numerical model in this study.

2.1. Element, mesh convergence test and boundary condition

The numerical model is constructed in Solidworks and LS-Prepost. The steel plate is modelled by using the fully integrated shell element to minimize hourglass energy in following simulations [33]. As an important factor for determining both the computational time and simulation accuracy, mesh size convergence tests are carried out with the element sizes of 20 mm, 10 mm, 5 mm, and 2.5 mm. Mesh convergence test results are shown and discussed in Section 2.4.

Boundary condition can be another critical factor for numerical simulation. In the model calibration and mesh convergence test, a simplified boundary condition for this steel plate subjected to blast loading is used to reduce computational time while representing the test conditions as closely as possible. In the simplified boundary condition, as shown in Fig. 3, 24 nodes are modelled as fully fixed to represent the 24 bolts that connected the steel plate and steel frame in the test, other nodes along the plate edges are constrained in three degrees of freedom, UZ, Rot X and Rot Y by using *BOUNDARY SPC SET. This simplified approach was also adopted in Chen and Hao [7], and showed relatively good agreement with the test data.

2.2. Material model used in LS-DYNA

The elastic-plastic material model *MAT 003 PLASTIC KINEMATIC is adopted for modelling the steel plate. This material model is commonly used for modelling metals with bi-linear elastic-plastic constitutive relationship and isotropic or kinematic hardening plasticity which is defined by a hardening parameter β. Here β equals to 1, representing isotropic hardening, is used. Material strain rate effect is also considered by applying Cowper-Symonds model in LS-DYNA which is defined by Eq. (1) [33].

$$\frac{\sigma_d}{\sigma_s} = 1+\left(\frac{\dot{\varepsilon}}{C}\right)^{\frac{1}{P}\text{EQ}} \tag{1}$$

where σ_d is the dynamic yield stress at plastic strain rate $\dot{\varepsilon}$, σ_s is the static