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Experimental investigations and numerical simulations of multi-arch double-layered panels under uniform impulsive loadings

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ABSTRACT

A double-layered panel with a structural form of multi-arch-surface has recently been numerically demonstrated capable of absorbing considerable energy and mitigating the blast loading effects on structures. In this study, experimental tests were conducted to further verify the performance of multi-arch double-layered panels subjected to uniform impulsive loadings by using a pendulum impact test system at the University of Western Australia (UWA) Structural Lab. The uniform impulsive loadings were generated by pendulum striking on the surface of a fully confined airbag placed in front of the specimen. Specimens with various configurations were designed and tested to investigate the effects of different configurations, i.e. arch height, arch number, thickness and different loadings on the structural response to the uniform impulsive loads. Single-layered flat steel panels were also tested as control panel for comparison to study the efficiency of double-layered multi-arch panel in resisting impulsive loads. The experimental data including air pressure time history acting on the front arched layer, displacement time history at the center point on the back flat layer and strain history at some representative points on the back flat layer were recorded. The deformation modes of specimens are also identified and discussed. The experimental data show that the multi-arch panel with specific configuration performs better than the flat monolithic panel in resisting uniform impulsive loadings. Numerical models were also developed to simulate the experimental tests by using finite element codes Ls-Dyna. The predicted data from the numerical simulations were compared with the experimental results. A good agreement between the experimental and numerical results was achieved. The responses of peak boundary reaction forces were extracted from numerical results to further examine the effectiveness of multi-arch panels against uniform impulsive loadings. The validated numerical model can be used to conduct intensively numerical simulations to define the best performing multi-arch panel configurations for blast loading resistance.

1. Introduction

The protective structures are traditionally designed in heavy and solid way to increase their strength and inertial resistance, which results in high costs and poor operational performance. The ideal protective structures should be lightweight but capable of mitigating extreme loading effects on structural responses [1]. A multi-arch double-layered panel [2], as a new structural form, has been proposed to resist blast loadings. The advantage of using multi arches is that it can cancel out certain blast loads at the springing lines of two adjacent arches and therefore reduce the loads transferred to the inner flat layer and the panel boundary. This will provide better protection of inner layer and reduce the demand on support design. Its performance has been numerically demonstrated better than other forms of panels in resisting blast loads. To further verify the observations from numerical simulations [2], laboratory testing on the performance of the multi-arch double-layered panels subjected to intensive loadings was designed and carried out. This paper reports the testing results.

Lu and Yu [3] have briefly reviewed the impact test techniques such as pendulum, drop weight, inclined sled, gas guns, Split Hopkinson Pressure Bar (SPHB), explosives and electromagnetic acceleration etc that can simulate real impact events reasonably well. Radford et al. [4] introduced an experimental technique of using metal foam projectile to simulate intensive pressure pulses. The applied pressure mimics shock loading with peak pressures in the order of 100 MPa and loading time of 10 μs. The metal foam

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Table 1
Material properties of cold rolled stainless steel (grade SUS304) [22].

Property	Young's modulus	Poisson's ratio	Yield stress ($R_{p0.2}$)	Tangent modulus	Density
Value	190 GPa	0.3	270 MPa	470 MPa	8200 kg/m^3

Table 2
Specifications of all specimens.

Category	Name of specimens	Arch height (mm)	Arch number	Thickness (mm)	
				Arched layer	Flat layer
1st group (flat panels)	F0.9	–	–	–	T0.9
	F1.2 A	–	–	–	T1.2
	F1.2 B	–	–	–	T1.2
	F1.2 C	–	–	–	T1.2
2nd group (arch height)	S2-A5-h30	h30	A5	T0.55	T0.55
	S2-A5-h40	h40	A5	T0.55	T0.55
	S2-A5-h50	h50	A5	T0.55	T0.55
	S2-A5-h60	h60	A5	T0.55	T0.55
3rd group (arch number)	S3-A3-h50	h50	A3	T0.55	T0.55
	S3-A4-h50	h50	A4	T0.55	T0.55
	S3-A5-h50	h50	A5	T0.55	T0.55
	S3-A6-h50	h50	A6	T0.55	T0.55
4th group (thickness)	S4-T0.55+0.9	h50	A5	T0.55	T0.9
	S4-T0.9+0.55	h50	A5	T0.9	T0.55

projectile is a convenient experimental tool for the ranking of shock resistance of structures. A pendulum impact testing methodology was developed by Gabauer et al. [5] for the evaluation of two-post sections of strong post w-beam barrier. Yuen and Nurick [6] conducted the experimental and numerical investigations on the response of quadrangular stiffened plates subjected to uniform impulsive loadings. The uniform impulsive loadings were generated by using plastic explosive placed on polystyrene foam pad. The impulse was measured by means of ballistic pendulum system. Nurick et al. [7] experimentally investigated the behavior of a sandwich panel subjected to "uniform" loadings which were generated by detonating explosive and directing the blast through a tube towards the target. The deformation and tearing of uniformly blast-loaded plates were recorded.

Great efforts have been spent on the theoretical, experimental and numerical studies of panels subjected to impulsive loadings. Various deformation and failure modes of panels have been observed from experimental tests. Nurick and Martin [8,9] reviewed the theoretical predictions and experimental works on the deformation of thin plates subjected to impulsive loadings and provided a useful guideline for predicting deflections of impulsively loaded plates. When the displacement of plate reaches or exceeds the order of the plate thickness, the membrane forces are introduced to stiffen the structure, which reduce significantly the plate displacement. Jones et al. [10] undertook the experimental investigation to study the behavior of fully-clamped rectangular plates when subjected to uniformly distributed impulsive velocities. The maximum permanent deflections were observed from 0.2 to nearly seven times the corresponding plate thicknesses. Yu and Chen [11] theoretically predicted the final plate displacement, which coincided excellently with the corresponding experimental results for the displacement up to 5–10 times the plate thickness. Menkes and Opat [12] conducted a series of experimental tests by using sheet explosive applied to clamped beam with neoprene buffer. With the increase of impulsive loadings, they observed three failure modes which are Mode I (large inelastic deformation), Mode II (tensile tearing at or over the support) and Mode III (transverse shear failure at the support). Teeling-Smith and Nurick [13] carried out experimental study on the fully clamped circular plate subjected to uniform impulsive load. Olson et al. [14] investigated the failure of fully clamped square plate subjected to uniform impulsive load. Similar deformation and failure modes were also observed for both circular and square plates. Nurick et al. [15] observed necking and subsequent tearing at the boundary of clamped circular plates subjected to uniformly loaded air blasts. Mode I was further divided into Mode I (no visible necking at the boundary), Mode Ia (necking around part of the boundary) and Mode Ib (necking around the entire boundary). Nurick and Shave [16] reported the experimental results for clamped square plates subjected to impulsive loadings and subdivided Mode II into three phases: Mode II*(partial tearing at the boundary), Mode IIa (complete tearing with increasing mid-point displacement) and Mode IIb (complete tearing with decreasing mid-point displacement). Chen et al. [17] investigated experimentally and numerically the blast-resistant behaviors of arched RC blast door under single and multiple blast load. Full scale in-situ tests of an arch blast door subjected to single and multiple blasts were carried out in the latter study. Zhu et al. [18] and Shen et al. [19] conducted a large number of experiments to investigate the structural response of flat sandwich panels and curved sandwich panels subjected to blast loadings, respectively. The tests were conducted by using a ballistic pendulum system. They observed global large deflection and localized deformation patterns such as wrinkling, indenting and pitting failure on the face sheets after blast loads. Based on the experiments, corresponding numerical simulations were also carried out [20,21]. Numerical simulation

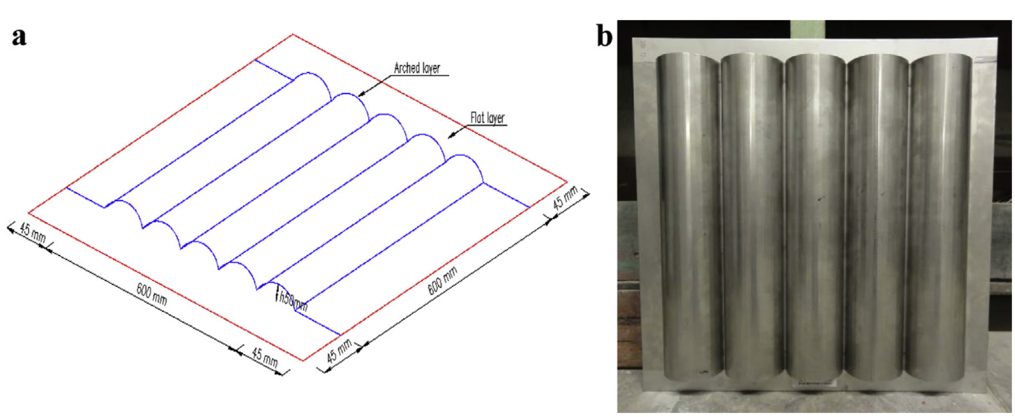

Fig. 1. (a) Schematic diagram of specimens S2-A5-h50; (b) Front view of specimen S2-A5-h50.