Engineering Structures 151 (2017) 459–471

Contents lists available at ScienceDirect

Engineering Structures

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

Numerical investigation of the response of I-core sandwich panels subjected to combined blast and fragment loading

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ARTICLE INFO

Article history:
Received 8 January 2017
Revised 9 August 2017
Accepted 14 August 2017

Keywords:
Sandwich structure
Blast loading
Combined loading
Failure mode
Energy absorption

ABSTRACT

The LS-DYNA software was employed to investigate the dynamic response of I-core sandwich panels under combined blast and fragment loading. The combined blast loading was simulated by placing pre-fabricated fragments at the bottom surface of bare explosive. To facilitate evaluating the synergistic effect under combined blast loading, the resistance of sandwich panels under bare blast loading was also assessed. The results demonstrated that the damage caused by combined blast loading was more severe than that by bare blast loading. The roles of charge mass, face-sheet configuration and core configuration on the deformation/failure behavior and energy absorption characteristics of panels were analyzed and discussed in detail. Under combined blast loading, the panels exhibited a perforation and tearing failure mode accompanied by structural fragments from failed front face. The charge mass is relevant to whether the residual momentum of fragments is large enough to penetrate the back face. The face-sheet configuration that had thick front face and thin back face was favorable in mitigating the damage response. The core configuration with dense core webs provided more assistance in preventing the appearance of failure pattern with a large connected region. The face-sheet configuration and core configuration have negligible influence on the total energy absorption, but they would redistribute the energy dissipation among each panel component. Furthermore, the comparisons of blast resistance between sandwich panels and conventional monolithic counterparts were made. It turned out that the sandwich panels experienced lower level damage failure on back face but dissipated similar energy relative to equivalent solid plates.

1. Introduction

Sandwich structures are well known for their interesting properties, such as lightweight, high specific strength, high specific stiffness, and high specific mechanical energy absorption. Those properties can be improved and tailored into specific needs by varying mass combination and distribution. This contributes to their comprehensive potential application in protective structures [1–6]. With the rapid development of various precision guided weapons, the possible damage suffered by structures from contact and close-in non-contact explosions is the serious concern for protecting construction designers. Blast wave and high-speed fragments created by regular warhead explosion almost simultaneously impact structures. Under such circumstances, the synergistic effects of these two destructive loadings should be taken into account when evaluating the performance of protective structure [7].

A number of researches have been done on the combined effects of blast and fragment loading against protective structures. Li et al. [8] performed combined experimental and numerical investigation into the deformation and damage characteristics of steel solid plates under synergetic effects of blast and fragment loading. Results revealed that the penetrability of fragment cluster is the key factor to induce a visible penetration hole in the central region of plate. Ranwaha and Yuen [9] carried out an experimental study to test the damage alleviation of cellular materials under the impact of blast-induced fragments. Various cellular materials were employed as energy absorbers. Moreover, the effects of nominal thickness and layer arrangement of cellular materials, as well as the size and speed of blast-induced fragment were evaluated in detail. As common candidate for protective structure, the concrete structures have also drawn increasing attention on their resistance to combined blast loading [10]. Through impact tests, Sohel et al. [11] evaluated the resistance of steel–concrete-steel sandwich slabs against large mass projectile/fragment impact. Based on the test results, a validated analytical expression was derived to predict the global response under impact load, which can be very

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http://dx.doi.org/10.1016/j.engstruct.2017.08.039
0141-0296/

helpful for assessing the impact performance of composite sandwich panels. Nyström and Gylltoft [12] proposed a numerical method to study the effects of combined blast and fragment loading on response of reinforced concrete structures. In their simulations, the synergistic effect was artificially decoupled into blast loading and fragment loading. The difference in arrival time between blast wave and fragments was estimated using a single-degree-of-freedom (SDOF) method. The energy loss during the process of swelling and fragmenting the casing, and accelerating the fragments was neglected, so it is likely to overestimate the damage effect of combined loading. Also, a set of experiments and numerical analyses were carried out to examine how the blast and fragment impacts influence the concrete blocks [13]. Results showed that the damage from blast wave and fragment impacting is localized on the surface of the impact zone. Analyses indicated that an alternative way for designers to evaluate such synergistic effect is to separate the loads from the blast wave and fragment impacts. In order to take the damage effect from fragment impacts into account, the target structure could be modeled as a pre-damaged structure with penetration holes or decreased effective dimensions, and the impulse from the fragment impacts could be added to that of blast wave. Rakvåg et al. [14] idealized the perforations as pre-formed holes of generalized shapes in target steel plates, and subsequently applied controlled pressure pulses on the plates, aiming at giving insight into the combined effects of pressure and fragment loading. However, this methodology is only applicable to the situation wherein fragments strike and perforate the flexible target before pressure load arrives. Børvik et al. [15] used a discrete particle approach to simulate the combined effects of blast and sand impact loading on steel plates. Good quantitative agreement between the experimental and predicted deformation response of the plates was obtained. This is a very promising practice and application in simulating the combined effects of blast and sand impact loading.

Though there are plentiful literatures regarding the dynamic response of sandwich panels subjected to blast loading, they usually focused on the blast loading from bare charge [2,16–20]. Zhang et al. [2,18] conducted a series of parameter studies on the dynamic response of corrugated core sandwich panels subjected to air blast loading. The failure modes of corrugated core sandwich panels were systematically analyzed and classified. Combining experiment and numerical simulation, Li et al. [19] also investigated the deformation process and failure modes of trapezoidal corrugated sandwich panels under air blast loading. By means of experimental testing, Zhu et al. [20] obtained various failure patterns of honeycomb sandwich panels under air blast loadings. The property of core is critical to the performance of panel. Corrugated and honeycomb cores were categorized as hard while I-cores were categorized as soft for certain dimensions and aspect ratios, and the best blast performance overall had been found for the soft-core designs [21]. To evaluate the performance of I-core sandwich panels subjected to underwater loading, Mori et al. [22] carried out experimental study using a water shock tube experimental apparatus. In addition, a few studies with respect to I-core sandwich structures have been done in terms of stress assessment [23], buckling strength [24,25] and load-carrying behavior [26]. Since comparable documentations and experiments about the sandwich structures under combined loading are seldom available, further efforts should be inspired to enrich the studies in this field.

This paper mainly aims to improve the understanding of synergistic effects of blast and fragment loading. Simulations were conducted on the dynamic response of I-core sandwich panels under bare blast loading and combined loading. The roles of charge mass, face-sheet configuration and core configuration on the failure patterns and energy absorption mechanism of sandwich panels were analyzed in detail. Furthermore, the deformation mode and energy absorption were also compared with that of equivalent monolithic plates for better assessment on the damage resistance of sandwich panels.

2. Numerical simulation particulars

2.1. Geometric modelling

The object of study here, an I-core sandwich panel, is schematically shown in Fig. 1. The sandwich panel has a square frame comprising of a front face sheet, "I" shaped cores and a back face sheet. The geometric parameters identified in Fig. 1 are as follows: the panel side length (b), front face sheet thickness (t_f) and back face sheet thickness (t_b), core web thickness (t_c), core height (H_c) and unit cell width (b_c). All of the sandwich panels in present work have identical side length $b = 400$ mm, and the total number of unit cell is determined by the ratio of b to b_c. The remaining parameters for the cases considered here are listed in Table 1. The geometric parameters of equivalent monolithic plates are listed in Table 2. According to the dimensions of I-core sandwich panels, the thickness of monolithic plates was set to 7.4 mm under the constraints of identical mass and same in-plane size.

The explosive charges in simulations are cylindrical shaped TNT and are placed over the panel along the centerline. Three different charge masses (W) of 35 g, 74 g and 157 g were used. Generally, the fragments produced by metal casing attached to the charge surface are most destructive, and those whose normal direction orients toward target are the key members to destroy structures. Therefore, a group of pre-fabricated cuboid fragments were positioned on the bottom surface of explosive to consider the synergistic effects of blast and fragment. Each single fragment has the dimensions of 6 mm × 6 mm × 3 mm and weighs around 1.92 g. The pre-fabricated fragments need to fully cover the bottom surface of explosive. So, the quantity (n) of fragments can be figured out after giving the dimension of explosive in radial direction. For the charge mass of 35 g, the dimensions in diameter (d) and length (L) are $d = 48$ mm, $L = 12$ mm, then the quantity of pre-fabricated fragment is set as 81 according to the diameter. To study the effect of charge mass, the diameter and amount of fragment of 74 g charge are same as that of 35 g, while the length is increased to 25 mm. Furthermore, in order to study the effect of fragment quantity, the length of 157 g charge is same as that of 74 g, while the diameter and quantity of fragment are increased to 70 mm and 169, respectively. Fig. 2 shows the in-plane arrangements of fragment for charges with different radial dimension. Stand-off distance was defined as the distance from the bottom surface of

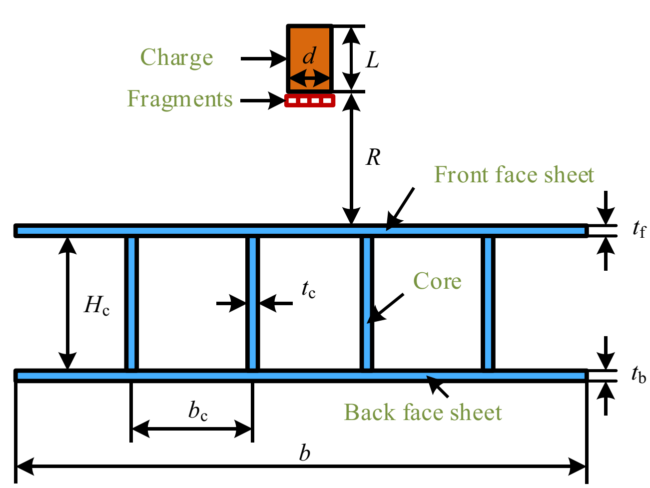

Fig. 1. Sketch of cross-section of geometry model (5 unit cells).