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Dynamic response of spherical sandwich shells with metallic foam core under external air blast loading – Numerical simulation

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ABSTRACT

The dynamic response of spherical sandwich shells with aluminum face sheets and aluminum foam core under external air blast loadings were investigated numerically by employing the LS-DYNA. To calibrate the numerical model, the experiments of cylindrical sandwich shells were modeled. And the numerical results have a good agreement with the experiment data. The calibrated numerical model was used to simulate the dynamic response of spherical sandwich shells subjected to the external air blast loadings. It is found that the spherical sandwich shells have a better performance than that of the cylindrical sandwich shells in resisting the blast loadings. The structural dynamic response process has been divided into three specific stages and the deformation modes have been classified and discussed systematically. According to parametric studies, it is concluded that with the decrease of radius of curvature, increase of the thickness of foam core and face sheets and decrease of blast intensity, the blast-resistance is increasing obviously; keeping the thickness summation of front and back face sheet almost constant, a big thickness of front face sheet will improve the blast-resistance performance. These simulations findings can guide well the theoretical study and optimal design of spherical sandwich structures subjected to external blast loading.

1. Introduction

Sandwich panels are made up of two stiff, strong shins separated by a lightweight core. The separation of the shins by the core increases the moment of inertia of the panel with little increase in weight, producing an efficient structure for resisting bending and buckling loads [1]. Additionally, good energy absorption can be achieved by employment of sandwich components: energy is dissipated by bending, stretching and fracture of the skins and by localized crushing of the core [2]. The cores, commonly, are made of balsa-wood, foamed polymers, glue-bonded aluminum or Nomex(paper)honeycombs. Using mental foams as cores can overcome the deficiencies which existed in the common cores – cannot be used much above room temperature, and their properties are moisture-dependent [3]. Therefore, sandwich structures with metal faces sheets and metal foam cores show advantages over other sandwich constructures under intensive impulse loading such as blast and impact [4]. The studies of the structural response of these sandwich structures with metal face sheets and metal foam core have been conducted experimentally [5,6], theoretically [7–11] and numerically [12,13].

The curved panels are much stronger and stiffer than other structural forms and they generally have better performance under various loadings because they can support the external loads effectively by virtue of their spatial curvature. Combination of the advantages for both the shell and sandwich structures is of great importance for its applications [14,15]. Some analytical models were developed to predict dynamic response of cylindrical sandwich shells including the buckling problem [16,17], nonlinear sandwich shell theory [18], effect of blast loading [19,20], and energy absorption [21]. Shen et al. [15] investigated the curved sandwich panels under blast loading experimentally, which perform better than equivalent solid counterpart and a flat sandwich plate. And a new deformation mode (global wrinkling) has been observed in the experiment. Xie et al. [22] conducted experiments on deformation and failure of clamped shallow sandwich arches with foam core subjected to projectile impact. And it is found that the traveling plastic hinge seems a dominant factor for significant difference of deformation modes in dynamic and quasi-static loading. Jing et al. [23–27] examined the effects of geometrical configurations and impulse loading on the deformation/failure of cylindrical sandwich shells with aluminum foam cores subjected

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to air blasting and projectile impact loading, experimentally and numerically. And it is found that the deformation modes are sensitive to the blast loading intensity and geometric configuration. In addition, the shear failure for the foam core and interfacial failure between foam core and face sheets were observed in the experiments under projectile impact loading, which was also observed in the numerical investigation under projectile impact loading.

Unlike the stress in cylinder shells, the stress of in spherical shells is distributed homogeneously because of central symmetry of their geometries and loadings. Under the same wall thickness, spherical shells show excellent bearing capacity [28]. At present, spherical shells are mainly applied in the storage of all kinds of gas, as the one end of capsule shell structures such as submarines, fuel tanks and coal mine refuge chambers, as the nuclear reactor containments designed to resist any external or internal blast load and as the roof coverings and domes to resist external pressure. And the dynamic response of spherical shells has been investigated extensively [29–31].

According to the aforementioned topics, spherical shell combined with sandwich structures may be have a better performance of resistance to the blast and impact loading than cylindrical sandwich shells. Li et al. [28] conducted the numerical investigate on the dynamic response of metallic spherical sandwich shells with graded aluminum foam cores under internal blast loading and obtained a better resistance to internal blast loading.

However, the investigations on the dynamic responses of spherical sandwich shells subjected to external blast loading have not yet reported. Therefore, the present research is concerned with the blast resistance of spherical sandwich shells with an aluminum foam core and aluminum face sheets under external blast loading, representing an extension of the previous works on cylindrical such panels. The commercial software Ls-Dyna 971 was applied to investigate the dynamic responses of metallic spherical sandwich shells under external air blast loading. To calibrate the accuracy of the numerical model, the numerical results of a series of cylindrical sandwich shells were compared with the experimental results recorded by Shen et al. [15]. The calibrated models were then employed to perform the simulations of the spherical sandwich shells. And the numerical results demonstrate that the spherical sandwich shells outperforms the cylindrical sandwich shells in resisting blast loading. The structural response processes and deformation modes of the spherical sandwich shells have been discussed in this study. In addition, parametric studies were carried out to investigate the effects of shell geometrical configurations and blast loading on the capacities of resisting blast and absorbing energy. Details are presented in the following sections.

2. Numerical model calibrations

The numerical model was made by using commercial software Ls-Dyna 971 [32]. A nonlinear, explicit finite element numerical method was used in this software. Reliable numerical predictions of structural response to blast load have been proven [23,24,26]. So the numerical simulation of the responses of the spherical sandwich shells with metallic foam cores under blast loading was carried out by this software.

To validate the accuracy and reliability of the numerical model in this software, a cylindrical sandwich shells with aluminum foam cores tested by Shen et al. [15] was used to calibrate the model. A total of 33 explosion tests were conducted in the experiments. They were divided into three groups for parametric studies with respect to different charges, face sheets and core thicknesses. Two radius of shells (300 mm and 600 mm), three face-sheet thicknesses (0.5 mm, 1.0 mm and 1.6 mm) and three thickness of aluminum foam core (10 mm, 20 mm and 30 mm) were utilized. There were 16 bolts between matching cylindrical solid steel frames for clamping the each of the cylindrical sandwich shells and the frames were bolted onto the front face of the pendulum as shown in Fig. 1 [15]. The impulse on shell and clamping, deflection history at the center point on the back face sheet and strain history at four points on the back face sheet were measured by the pendulum, laser displacement transducer and strain gauges, respectively [15]. Selected test datas were used to calibrate the numerical model made in Ls-Dyna in this study.

2.1. Element, mesh, boundary conditions and contact modeling

Since the sandwich shells and clamped frames is symmetric about x–z and x–y planes, only a quarter of the shells and frames was modeled, as shown in Fig. 2. The numerical models have been built by using commercial software ANSYS and Ls-Prepost. After performing a mesh convergence analysis, a feature mesh size of 2 mm was determined to be optimal for both the shell and solid elements, which balanced the numerical stability requirement, the accuracy of the FEA results and the computational efficiency. The sandwich shell sheets were modeled by Belyschko-Tasy four-node shell elements [33], while foam core and clamping frames were modeled by eight-node solid elements.

In this numerical simulation, two approaches of boundary conditions were considered about for the bolts used in the experiments to clamp the sandwich shells. The first approach (B.C.1) is to more closely represent the testing conditions, so the nodal constraints were used at positions of bolts on the top face of front clamping frame and bottom face of back clamping frame as showed in Fig. 2. The second approach (B.C.2) is the equivalent of the first approach. The surface constraint was used on the peripheral of top face of front clamping frame, as showed in Fig. 3, instead of nodal constraints at positions of bolts.

The *CONTACT AUTOMATIC SURFACE TO SURFACE TIEBREAK model was adopted to account for the bond connection between the face-sheets and the foam core. The tiebreak failure criterion has normal and shear components [32]:

$$\left(\frac{|\sigma_n|}{NFLS}\right)^2 + \left(\frac{|\sigma_s|}{SFLS}\right)^2 \geqslant 1 \quad (1)$$

where σ_n is the normal stress; σ_s is the shear stress; NFLS and SFLS are the normal and shear failure stress, respectively, and listed in Table 1.

To prevent the penetration between face sheets and core, the contact between them was defined by using *CONTACT AUTOMATIC SINGLE SURFACE with a contact static and a dynamic

Fig. 1. A photograph of the experiment settings.