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Experimental and numerical study of aluminum foam-cored sandwich tubes subjected to internal air blast

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A B S T R A C T

The blast response of aluminum foam-cored sandwich tubes that were subjected to internal air blast was investigated experimentally and numerically. Blast experiments were performed to capture the fundamental deformation, the maximum deflection of the inner face-sheet (MDIF), and the maximum deflection of the outer face-sheet (MDOF). A special MDOF (SMDOF) can be achieved by normalizing the MDOF with respect to the corresponding face-sheet radius and tube mass. Results confirm that the SMDOF of sandwich tubes is moderately sensitive to the core relative density, internal diameter, core thickness, and explosive charge. The finite element (FE) model was constructed using the Voronoi algorithm. After verifying the FE model, numerical studies were conducted to investigate the deformation process of sandwich tubes, the densification of double-layer cores, and the effects of core arrangement and face-sheet thickness on blast resistance. The SMDOF is influenced by the inner and outer face-sheets, whereas the special energy absorption (SEA) is mainly affected by the inner face-sheet.

1. Introduction

Foams, a new class of ultra-light materials, can absorb a large amount of kinetic energy because of their ability to undergo large deformation at a nearly constant plateau stress [1–3]. Foam-cored sandwich structures have received increasing attention because of their excellent property of withstanding blast loading, and have been extensively used in marine and other military applications [4–8]. The remarkable performances of sandwich structures depend on the innovative geometrical design of the foam core [8–11].

Furthermore, traditional blast-resistant devices perform with low efficiency and heavy weight [12,13]. Lightweight and improved blast-resistant containment vessels have become popular with the increase in terrorism [14]. The sandwich tube has been considered a novel structural design that can enhance blast-resistant vessels to contain explosive materials, and protect persons or equipment from internal explosion [15–17]. The foam-cored sandwich tube has better energy absorption (EA) capability than the monolithic blast-resistant tube because the sandwich structures can undergo extreme plastic deformation at an almost constant plateau stress [18–20].

The dynamic response of sandwich tubes received increasing attention over the last decade. Shen et al. [21] studied the dynamic response of sandwich tubes that were subjected to internal blast loading using experimental, numerical, and analytical methods. They concluded that sandwich tubes exhibit superior blast resistance compared with monolithic tubes with the same mass. Liu et al. [14] investigated the dynamic response and blast resistance of graded foam-cored sandwich tubes using the LS-DYNA software. They affirmed that sandwich tubes with thin inner face-sheets are superior to those with thick inner face-sheets. Moreover, they confirmed that the tube with a negative core configuration has the best blast resistance. Karagiozova et al. [12] proposed an analytical model for partially confined sandwich tubes to investigate the foam-crushing process and the outer face-sheet deflection. More recently, Liang et al. [22] used the FE model constructed using the random Voronoi algorithm to simulate the deformation process of sandwich tubes under internal blast loading, and investigated the effects of explosive charge, the face-sheet and core thicknesses, and core gradient on blast resistance. They verified that plastic dissipation and outer face-sheet deflection are two conflicting objectives in the evaluation of blast resistance.

Studies on the dynamic response of sandwich tubes subjected to internal air-blast is limited because of the complex stress status caused by the multiple pressure reflections in sandwich tubes [23]. Although several investigations have been conducted, the

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underlying mechanism of the internal blast response of sandwich tubes has not been thoroughly understood and thus further investigation is necessary. In the present study, experimental and numerical studies were performed on aluminum foam-cored sandwich tubes that were subjected to air-blast loading. Initially, blast experiments were conducted to capture the fundamental deformation, the maximum deflection of the inner face-sheet (MDIF), and the maximum deflection of the outer face-sheet (MDOF). Subsequently, the effects of parameters, such as core relative density, internal diameter, core thickness, and explosive charge, on the MDOF were discussed. Then, the Voronoi algorithm was employed to create the FE model, which was validated by the experimental results. Finally, the FE results were utilized to investigate the deformation process of sandwich tubes, the densification of double-layer cores, and the effect of core arrangement and face-sheet thickness on blast resistance.

2. Experimental procedure

The sandwich tubes used in this study were produced with steel face-sheets and closed aluminum foam cores (Fig. 1). The face-sheet was cut from a commercial AISI 1045 steel tube. The foam core was cut from 100-mm thick foam panels by an electro-discharge machine to minimize the damage to the cell edges. The core was annealed at 393 K for 1 h to relieve the residual stresses in the foams during manufacturing. Three foams (F1, F2, and F3) were used in the experiments with corresponding relative densities of 0.11, 0.16, and 0.27, respectively.

A sketch of the experimental setup is shown in Fig. 2. The experimental results were served as a validation basis for the subsequent simulation model. The height of the tube was fixed at 100 mm. The thickness of face-sheets was 1.5 mm. Table 1 presents the dimensions of the specimens and explosive charges. An aluminized explosive, JHL, was used in the blast experiments. The cylindrical explosive charge was held at the center of the sandwich tube using iron wires and detonated at its apex with a detonator. The length to radius ratio of the charge was equal to that of the internal face-sheet. The sandwich tube was supported by plastic

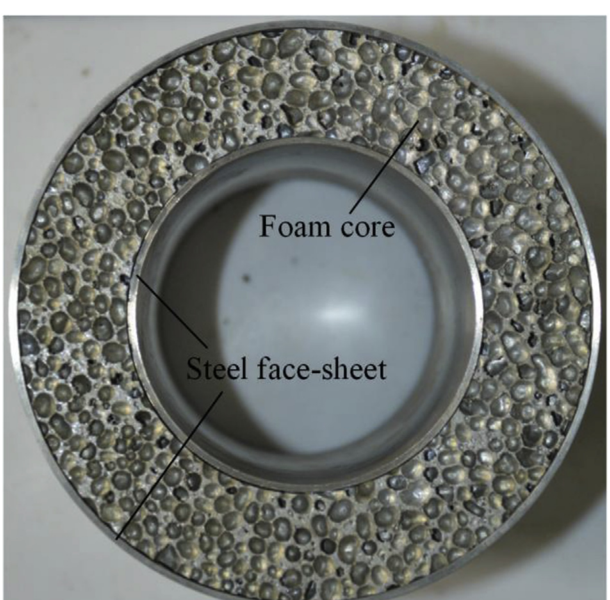

Fig. 1. The sandwich tube consisting with steel face-sheets and closed aluminum foam core.

foams to reduce the influence of the reflected waves from the ground. The purpose of this setup is to minimize the end effects influence on the specimen. Each test was repeated twice.

3. Experimental results and discussion

Table 3 shows that the tube specimens can be divided into four cases. Case 1 has different core densities (Groups T1, T3, and T5; Groups T2, T4, and T6; or Groups T7, T8, and T9). Case 2 has the same core thickness and density but different inner dimensions (Groups T2 and T7; Groups T4 and T8; or Groups T6 and T9). Case 3 has the same internal diameter but different core thicknesses (Groups T3 and T11; or Groups T4 and T12). Case 4 has the same tube but different explosive masses (Groups T1 and T2; Groups T3 and T4; Groups T5 and T6; or Groups T10, T11, and T12). Table 2 presents the deformation patterns, the MDIF, and the MDOF. Possible slippages between face-sheets and cores may appear because of the free contact between parts.

To compare the maximum deflection of the tubes at equal masses, the MDOF was normalized with respect to the corresponding face-sheet radius and tube mass. The normalized maximum outer face-sheet deflection, called special MDOF (SMDOF), was used to evaluate the blast resistance performance. Fig. 3 plots the SMDOF of the tube specimens with different cases. Fig. 3(a) depicts the SMDOF of the tubes with different core densities. The low-density-cored specimen exhibited a SMDOF of 0.39 kg^{-1} when the internal diameter was 64 mm, whereas the high-density-cored specimen exhibited 0.363 kg^{-1}, indicating a slight decrease. A similar tendency was observed when the internal diameter was 96 mm. The core density had a slight influence on the SMDOF. Fig. 3(b) shows that the SMDOF of the tubes with a small internal diameter is higher than that of the specimens with a large internal diameter. As the internal diameter of the specimen increased from 64 mm to 96 mm, the SMDOF decreased by 89.3% at a relative density of 0.11. As the blast pressure decayed exponentially in air, the large internal diameter led to low incident blast pulse on the internal face-sheet. Fig. 3(c) indicates that as the thickness of the core increased from 10 mm to 20 mm, the specimen's MDOF decreased by 94.9% at an explosive charge of 9.6 g and by 69.4% at an explosive charge of 14.1 g. An increase in core thickness was beneficial for decreasing the SMDOF at equivalent tube masses, and the rate of decrease was low when the charge was high. Fig. 3(d) illustrates that the SMDOF increases with the explosive charge. The SMDOF of the tubes at a charge of 14.1 g was approximately 58.4%–92.3% higher than that of the tubes at a charge of 9.6 g.

4. Numerical simulation

4.1. FE model

FE analysis was carried out to elucidate the deformation process of the maximum radial deflection cross-section of sandwich tubes. The foam core was constructed using the 2D Voronoi algorithm. The FE model was generated by the MATLAB software [24]. Fig. 4 shows that the foam-generating process using the Voronoi algorithm can be divided into four stages [25–27]. First, N nuclei are randomly generated in a given area A based on the principle that the minimum distance between any two nuclei is larger than a given distance δ_{min}. Fig. 4(a) shows that the given area in this paper is a cylindrical region. Second, these nuclei are copied to the surrounding regions by translation, thereby keeping a periodic boundary condition [Fig. 4(b)]. Third, the Delaunay triangulation and the Voronoi diagram are generated when the translation points close to a nucleus are connected to one another. Fig. 4(c) shows the