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Graded effects of metallic foam cores for spherical sandwich shells subjected to close-in underwater explosion

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ABSTRACT

A fluid model is developed and used in combination with Abaqus/Explicit to investigate the effects of graded foam cores on the loading of a sandwich spherical shell subject to underwater explosion from the inner side, after having validated the modeling technique by reproducing results by other authors. Based on the relation between the core strength and the stiffness of the outer face sheet (OFS), four different situations are considered to discuss the graded effects. It is demonstrated that for the case of relatively strong cores and the OFS with low stiffness or soft cores and the OFS with high stiffness, the core arrangement of low/medium/high (relative density from the inside to the outside) has the best performance to shock loadings which is a consequence of the effects of the fluid–structure interaction and the energy absorption capability; on the other hand, for the case of intermediate core strengths and stiffness of the OFS where the pulling-back force due to the stretching of the OFS is close to the core strength, the configuration of high/medium/low has the best performance due to its higher energy absorption efficiency of the foam and lower transmitted stress.

1. Introduction

Cellular materials, including honeycombs [1,2], foams [3–7], truss lattices [8,9], etc, are well known to mitigate shock loadings, owing to their excellent energy absorption capability. The typical stress–strain curves of the cellular materials exhibit three regions: linear elasticity (usually less than 5%), plateau and densification. The material can undergo large compressive deformations and dissipate considerable amounts of shock energy with a relatively low transmitted force during the plateau phase. However, the stress transmitted to the protected structures will increase steeply if the material comes into the densification phase. The optimum energy-absorbing structures are required to absorb shock energy while keeping the transmitted force to the protected structure below a limited value [10] which is generally the plateau stress of the cellular materials. For the cellular material with a particular density, the plateau stress is a unique value and the material is only efficient on the shock mitigation over this limited value. In order to widen the range of the limited stress levels and improve the energy absorption capability, functionally graded materials are adopted by combining a larger range of densities.

In the past few years, graded cellular materials have attracted more and more researchers' interests since their properties can be designed and controlled, and they have shown a great potential for the shock resistance compared with the traditional uniform structures. Previous investigations mainly focus on the dynamic behaviors of graded/layered structures under contact loads and the blast resistance ability against air blast. These studies can be divided into two categories according to the dimension of the problem: one-dimensional (1D) graded cellular materials and two/three dimensional sandwich beams/shells/plates with graded cellular cores.

For the former, a great number of studies have been conducted to compare the shock resistance capability of the 1D graded cellular materials with their equivalent counterparts, including graded honeycombs [11–13], graded metal hollow sphere foams [14–17], graded foam materials [18–25], etc. The main research methods involve FE simulations [11–13,16,17,25], experimental studies [15] and analytical models [14,18–24]. Although the cellular topologies and research methods are various, they obtained the similar results and we summarize them as follows. Their results indicate that whether the graded cellular materials can outperform their equivalent counterparts depends on two factors: the density arrangement of cellular materials and the intensity of impact/blast loadings. Generally speaking, there are two typical density arrangements, i.e. the 'hardest' layer serving as the first impacted layer and the 'weakest' layer being in contact with the protected structures (positive density arrangement) and vice versa (negative density arrangement). For the positive density arrangement, the hardest layer

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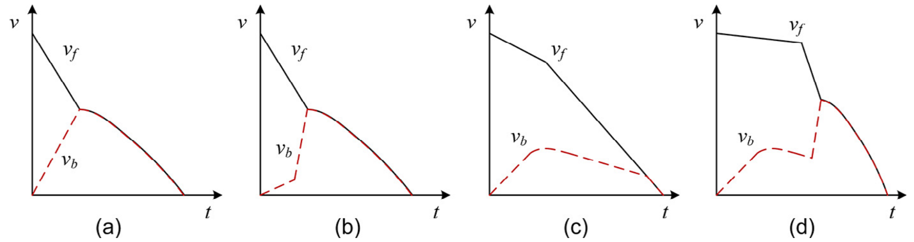

(a) (b) (c) (d)

Fig. 1. The four regimes of behaviors of the sandwich beam. Sketches of typical velocity profiles in (a) Regime A, (b) Regime B, (c) Regime C, and (d) Regime D [27].

and the weakest layer deform simultaneously and the transmitted stress is determined by the weakest layer before the full densification. For the negative density arrangement, the cellular material deforms progressively from the weakest layer to the hardest layer and the transmitted stress is determined by the material being crushed. Therefore, the positive density arrangement is a winning strategy when subjected to the low impulsive loads, since it can absorb all the energy with a lower transmitted stress to the protected structures. However, under the high intensity impulsive loads, the negative density arrangement has relatively higher energy absorption capabilities but transmits larger stresses to the protected structures.

The impact behaviors of graded two/three dimensional sandwich beams/shells/plates are related to the intensity of impulsive loads, the material and geometry parameters of the front and back face sheets, and the properties of the density arranged cellular cores, which are more complex than the 1D cellular materials. Previous studies have constructed various maps to show the regimes of behaviors of the sandwich structures with single-layer cores. Liang et al. [26] investigated the response of metallic sandwich panels to water blast and elucidated two inherently different regimes: “strong core” and “soft core”. Tilbrook et al. [27] further redefined the regimes of behaviors of sandwich beams into four types of response, according to the velocity responses of the front and back face sheets, as shown in Fig. 1. The possible cases of the four regimes are given as follows. Regime A: strong cores and the back face sheet with low stiffness where the core strength can deform the back face sheet easily; Regime B: soft cores and the back face sheet with high stiffness where the back face sheet cannot have plastic deformations through only the compression of the core strength; Regime C and D: intermediate core strengths and stiffness of the back face sheet where the pulling-back force due to the bending and stretching of the back face sheet is close to the core strength. The difference between Regime C and D may attribute to loading conditions. For Regime C, the load is relatively small, and for Regime D, the load is relatively high to fully densify the core.

There are also many studies to explore the impact responses of the sandwich structures with graded cores. Wang et al. [28] and Gardner et al. [29,30] investigated the blast performance of functionally graded sandwich composite beams by shock tube experiments. The results indicated that the graded sandwich beams with the ‘weakest’ layer being placed at the impinged end outperform the case that the ‘harder’ layer serves as the first impacted layer [28]. Additionally, increasing the number of the graded layers can enhance the shock resistance ability of such structures. The air blast resistances of sandwich plates [31], cylindrical shells [32] and spherical shells [33] with graded cores are studied numerically. It is demonstrated that the shells/panels with the densities of the graded cores decreasing from the impinged side to the distal side possess smaller deflection and superior blast resistance.

Although there are extensive studies discussing the graded effects of cores for the sandwich beams/plates/shells, their studies focused on the optimal designs by arranging the density of the cores with the relation between the core strength and the pulling-back force of the back face sheet fixed. Their conclusions on the graded effects are probably not comprehensive and only valid in one specific situation. Additionally, the loading condition of close-in underwater explosions is seldom studied. Different from the load of impacts or air blasts, the load of underwater explosions is dependent on the properties of the sandwich structures and also the back face boundary conditions. The effects of fluid–structure interactions and explosive bubble are still needed to be revealed when studying the sandwich beams/plates/shells, to provide an insight into near-field underwater explosion protections. Therefore, the present work reveals the graded effects in a more comprehensive way by studying the shock resistance of the spherical sandwich shells with graded metallic foam cores under close-in underwater explosions. A numerical solver that couples the Runge–Kutta Discontinuous Galerkin (RKDG) method [34,35], the Finite element method (FEM) [36] and the Modified Ghost Fluid method (MGFM) [37,38] is used to consider the interactions of the explosion bubble, water, deformable structures and cavitation. Four computational cases are designed corresponding to the four regimes in reference 27 which include the general response types of the sandwich structures to shock loadings. The graded effects of the foam cores are discussed in each regime by comparing three configurations (relative density from the inside to the outside of the spherical shells: low/medium/high, high/medium/low, medium/medium/medium). The remainder of this paper is organized as follows. In Section 2 and Section 3, the numerical solver is introduced and validated. The computational model addressing the geometry and the material properties is presented in Section 4. In Section 5, we discuss the fluid behaviors and the graded effects of the foam cores in the four regimes. Finally, concluding remarks are given in Section 6.

2. The numerical solver

The initial state of underwater explosion simulations is usually defined at the moment when a high-pressure gas bubble is formed after the completion of the detonation process. The initial gas bubble has the same volume and internal energy as the original explosive in water. Therefore, the computational model includes explosive gas, water and the spherical sandwich shells with metallic foam cores, as shown in Fig. 2(a). Correspondingly, the numerical solver includes a spherically symmetric Eulerian compressible fluid solver, an axisymmetric Lagrangian solid solver and coupling techniques which account for the explosion bubble and the compressible fluid, the deformable structures, and the nonlinear interactions of the gas–water–structure system, respectively. The proposed numerical solver can significantly reduce the computational time since the elements of the water are restricted to 1D. In this section, we proceed to briefly introduce the fluid solver, the solid solver and their coupling techniques.