The collapse response of web-core sandwich panels partially filled with metallic foams under drop-weight impact

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Abstract. Thin-walled web-core sandwich structures are widely applied due to their weight specific mechanical performance. When subjected to a transverse load, the sandwich structures are apt to undergo local deformation which would considerably decrease the cross-sectional height and their global load resistance, especially under a concentrated load. In the paper, a novel method is proposed only to fill the upper compressive region of the web-core sandwich panels other than the whole cross section with metallic foams, which would effectively restrain the local deformation at the cost of slight increase of the structural total mass. The collapse response of web-core sandwich panels with four different reinforcing configurations under drop-weight impact is investigated using ABAQUS code. The numerical results show that the two empty panels without foam filler have a close valley force and the foam filler significantly improves the structural load-carrying capacity after the initial elastic peak force. Moreover, it is noticeable that the partially filled panel suggested here demonstrates the similar load resistance to the fully filled one and much more weigh specific energy-absorbing performance than the other three sandwich panels.

1. Introduction
Light-weight sandwich structures with web-cores are generally applied in some engineering fields such as watercrafts and aircrafts due to their concise configuration and high load-carrying performance. The most common web-core constructions consist of two face-sheet spaced by some webs which are perpendicular to the face plates. The two face sheets were considered mainly to carry bending moment as well as the vertical webs to resist shear force when subjected to a transverse load. Romanoff et al. [1-5] conducted an extensive investigation of bending elastic response of web-core sandwich constructions analytically and numerically. The bending response of a web-core sandwich beam, divided into local and global components, was analyzed based on the plane frame method to predict the deflection and stress distributions of the face plates [1]. Then, a stress analysis method was proposed to gain the deflection, bending moment and shear force by transforming the web-core sandwich beam into an equivalent homogenous sandwich beam [2]. The similar equivalent transforming method as the web-core sandwich beam mentioned above was used to determine the bending response of web-core sandwich plates [3]. In addition, shear stiffness of the laser-welded T-joints in web-core sandwich structures was measured experimentally, based on which the shear stiffness of the sandwich structure was calculated [4]. The deflection and stresses of the laser-welded web-core sandwich plates under patch loading were predicted by combining the global bending and local response using sandwich and basic plate theory, respectively [5]. Jiang et al. [6] conducted three-point bending tests to examine the strength of the laser welded web-core steel sandwich plate, which
demonstrated that the weld width significantly affects the structural failure mode. Furthermore, the influence of geometrical parameters, including the thickness of the face plate, the spacing and height of the webs, on the stiffness of the sandwich constructions was analyzed [7]. Sun et al. [8] carried out a detailed three-point bending test on the bending performance of laser-welded web-core sandwich plates.

When the webs are inclined, not perpendicular to the face plates, the web core would transform into trapezoidal corrugated one. Chang et al. [9] presented a closed-form solution for the linear bending behavior of a corrugated-core sandwich panel by reducing the 3D sandwich panel to an equivalent 2D orthotropic thick plate. Kazemahvazi and Zenkert [10] developed an analytical model for the compressive and shear behavior of corrugated all-composite sandwich structures, where the inclined web cores also are made of sandwich structures.

When subjected to bending moment, thin-walled structures generally undergo inward deformation in the compressive region which would considerably decrease the height of the cross section and the structural bending resistance, especially under a concentrated load. An effective strategy to restrain the local deformation is filling lightweight material into the thin-walled constructions. Briscoe et al. [11] presented a shear buckling model for the foam-filled web-core sandwich panels based on a Pasternak foundation model. Zangani et al. [12] studied the failure behavior of web-core sandwich panels filled with phenolic foam by the finite element analysis of three-point bending tests, which revealed that the foam filler effectively restricts the buckling tendency of the corrugated webs. Moreover, the energy-absorbing performance of the sandwich structures under drop-weight impact was investigated, and the contribution of the different components of the panels was studied [13].

Considering the local deformation mainly occurs in the compressive region, a novel reinforcing strategy for the thin-walled sandwich constructions, only filling the compressive region with lightweight material, is suggested in this paper. The collapse of web-core sandwich panels partially filled with metallic foams under drop-weight impact is simulated by the ABAQUS code. The varying characteristic of the load-displacement curves and weight specific energy absorption are mainly focused on to highlight their advantage over other cross-sectional configurations.

2. Structural design
In practical engineering application, thin-walled web-core sandwich panels are popular due to their weight specific load-carrying capacity. Four cross sections of web-core sandwich panels with identical global width, height and walled thickness are presented, where the webs are evenly spaced, as shown in Figure 1. For simplicity, the height of DE and DF panels is also evenly spaced by the horizontal reinforcing web, and the SF panel is fully filled with metallic foams, while the DF one only filled in the upper half region.

![Figure 1. The four cross sections of web-core sandwich panels presented here: SE, DE denote the single-layer and double-layer empty panels, respectively; SF, DF denote the single-layer and double-layer foam-filled panels, respectively.](image-url)
3. Numerical tests

Drop-weight impact is a frequently accidental case, which would bring about considerable local and global deformation in the thin-wall sandwich panels. Rectangular web-core sandwich panels with the above four cross sections impacted by a rigid sphere at the center and simply-supported one-way by two rigid cylinders are simulated to explore their impact resistance, see Figure 2.

![Figure 2](image)

Figure 2. The numerical tests for the case of DF panel.

In the finite element models, the height of the structures \( h \) is set as 0.1m, the size of the other geometric parameters is listed in Table 1. Considering the symmetry of the tests, a half model is established to reduce the solving time.

| Width \( b \) | Spacing \( d \) | Thickness \( t \) | Length \( L \) | Span \( s \) | Sphere \( R_1 \) | Cylinder \( R_2 \) |
|---|---|---|---|---|---|---|
| 6\( h \) | \( h \) | 0.02\( h \) | 20\( h \) | 16\( h \) | 0.5\( h \) | 0.5\( h \) |
| =0.6 | 0.1 | 0.002 | 2.0 | 1.6 | 0.05 | 0.05 |

Note: \( d \) is the vertical web spacing, \( t \) walled thickness, \( L \) the total length of the sandwich panels, \( s \) the spanning distance between the two cylindrical bearings, \( R_1 \) the radius of the spherical drop-weight, \( R_2 \) the radius of the two cylindrical bearings.

4. Finite element models

In the present models, the spherical drop-weight and the two cylindrical bearings are modeled employing Analytical Rigid which would not deform all the time. The thin-walled panels including the face plates and webs are constructed using 3D deformable Shell, while the foam filler using 3D deformable Solid.

The material of the thin walls including the face plates and reinforcing webs, is considered to be an elastic-plastic metal with density \( \rho_s=7.8 \times 10^3 \text{kg/m}^3 \), elastic modulus \( E_s=200 \text{GPa} \), Poisson’s ratio \( \nu=0.3 \) and flow stress \( \sigma_{0,s}=600 \text{MPa} \). The matrix material of the filled metallic foam is assumed to be the same as the face plates and webs. The properties of the metallic foams were considered to be functions of the relative density and the matrix material properties, and Santosa et al. [14] summarized the existing relations as follows: relative density \( \bar{\rho} = \rho_f/\rho_s \), elastic modulus \( E_f = E_s \bar{\rho}^{2/3} \), plateau stress \( \sigma_p = \sigma_{0,s} \bar{\rho}^{3/2} \), initial densification strain \( \varepsilon_D^{\text{Initial}} = 1 - 1.4\bar{\rho} \) and full densification strain \( \varepsilon_D^{\text{Full}} = 1 - \bar{\rho} \), where the symbols \( \rho_f, \rho_s \) represent the density of the metallic foam and its matrix material, respectively. The case for the density \( \bar{\rho} = 0.05 \) is chosen in present models. In the material library of the ABAQUS software, there is a material model named Crushable Foam well suitable for the metallic foams, and it is noted that the above nominal stains should be transformed into their corresponding true ones.
The Dynamic, Explicit procedure with time period 2s is employed to model the present quasi-static response, and the spherical drop-weight impacts the sandwich panels by the displacement 0.1m leading to an average velocity 0.05m/s.

The General Contact method is used to simulated all the possible contact action with frictionless tangential behavior and hard normal behavior. The midspan cross section of the sandwich panels is added symmetric boundary, and the cylindrical bearing is fully fixed without any displacement.

Considering that the structural deformation mainly occurs in the zone under the drop weight, the thin-walled face plates and webs within the length 0.3m across the midspan cross-section is meshed finer with global size 0.005m, and the other region 0.02m. In the same way, the foam filler is meshed in the two regions with global size 0.01m and 0.05m, respectively.

5. Results and discussions

The reaction forces of the drop-weight during impacting the four different web-core sandwich panels are shown in Figure 3. It can be observed that the empty panels without foam filler including SE and DE panels demonstrate a similar load-resisting tendency after the initial peak force in a certain loading process, which ascends after achieving a minimum value, and thereupon the DE panel displays much higher load resistance than the SE one. According to Alien’s findings [15], the bending moment per unit width of the thin-walled sandwich structures $M$ mainly provide by the spaced face plates can be estimated by

$$M = \sigma_b t (h - t)$$

where the symbol $\sigma_b$ is the maximum skin stress.

Adding the horizontal web to the DE panel approximatively located in the neutral surface mainly aims to restrain cross-sectional flattening and keep its height, which pays little contribution to the bending resistance. The height-decrease of the webs, numbered from the left to right of the cross section, is displayed in Figure 4. It can be seen that the web height of SE and DE panels decreases close to each other before the loading displacement up to 0.06m, afterwards the height of the third web W3 of SE panel drops more noticeably. It is surprising that the height of the fourth web W4 of DE panel decrease much more than that of SE panel, which would lead to the decrease of bending moment. The difference of the load resistance between SE and DE panels is perhaps caused by the horizontal reinforcing web, which would pay more contribution to the global bending resistance with the flattening of the cross section and the movement of the neutral surface.
In addition, Figure 3 reveals that the two panes filled with metallic foam, i.e. SF and DF panels, which don’t have a valley force after the initial elastic stage, exhibit more distinct load-resisting tendency from the two empty ones. It is reasonable to conclude that the foam filler plays a significant role in restraining the cross-sectional flattening at the cost of slight increase of structural weight. Furthermore, the reaction forces of the SF and DF panels develop well close to each other except at the later stage, which could provide a good explanation that the foam filler in the compress region plays more important role in restricting the cross-sectional inward deformation.

![Figure 4](image)

**Figure 4.** The decrease of the vertical web-height of SE and DE panels: the webs is numbered from the left to right of the cross section W1, W2, …, W7, i.e. W4 denotes the middle web.

![Figure 5](image)

**Figure 5.** The weight specific energy absorption of the four different cross-sectional panels normalized by that of the SE panel.

The weight specific energy absorption $SEA$ is a key factor in some engineering, which is defined by the energy absorption divided by the structural total mass $m$, i.e. $SEA=E/m$. Based on the principle of energy conservation, the energy absorption $E$ can be calculated by integrating load force with the displacement, i.e. $E = \int Pd\delta$. The total mass of the web-core sandwich panels filled with metallic foams can be derived from

$$m = \rho_s A_s L + \rho_f A_f L = (t l_s + \bar{\rho} A_f)\rho_s L$$  \hspace{1cm} (2)
where \( A_c, A_f \) are the total cross-sectional area of the thin-walled components and that of the foam filler, respectively, and \( l_s \) is the total cross-sectional length of the thin-walled components with the same thickness \( t \). Let \( A_c = l_s + \frac{1}{t} A_f \), and the formulation of the mass becomes \( m = A_c \rho_s L \). Because the two terms \( \rho_s, L \) are entirely identical for the four structures presented here, the structural total mass would be dominated by the one \( A_c \), which is called characteristic mass here. For simplicity, the characteristic mass \( A_c \) is used to calculate the specific energy absorption, i.e. \( SEA = E/A_c \). The numerical results of \( SEA \) for the four sandwich structures are plotted in Figure 5, which are normalized by that of SE panel for comparison. It is evidently found that the \( SEA \) of the DF panel is the largest one, which is about 1.4 times that of the SE panel. Of course, this relation is obtained based on the case presented here, and it would perhaps be much better if the geometrical or material factors of the DF panel are optimized.

6. Conclusions
Thin-walled sandwich structures are liable to undergo local inward deformation, which would considerably decrease the cross-sectional height and the structural global load resistance. In the paper, one-way simply-supported web-core sandwich panels with four different cross-sectional configurations impacted by a rigid spherical drop-weight is investigated using ABAQUS code. The numerical results reveal that the thin-walled sandwich structures filled with light-weight foams can efficiently restrict the inward deformation and keep the structural global load-carrying capacity at the cost of slight increase of the structural mass, especially only partially filled in the compressive region of the cross section. The load vs. displacement curves of the empty web-core sandwich panels without the foam filler have a valley force after the initial elastic peak one, while the foam filler significantly improves the load resistance without the valley force. The partially filled web-core sandwich panel with metallic foam exhibits a well close tendency to the fully filled one, which well illustrates the reasonability of partially filling the structures only in the compressive region. The \( SEA \) of the partially filled sandwich panel is much larger than that of the general single-layer empty one in terms as far as the case presented here. Of course, it may be more excellent if the geometric or material factors of the partially filled sandwich panel is optimized.

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