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In-plane compression response of wire-woven metal cored sandwich panels

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ABSTRACT

This article presents the buckling behaviors of two types of WBK (Wire-woven Bulk Kagome) cored sandwich panels subjected to in-plane compression. Classical theories are introduced, and the experimental and numerical results are presented. The effects of several design parameters are analyzed. For both types, the peak loads were governed by macroplastic buckling. Low shear modulus and strength of the WBK core substantially influenced the buckling behaviors of the sandwich panels before and after their peaks. A small initial deflection greatly decreased the resistance against buckling of the sandwich panels with thinner cores, as confirmed by a two-stage FEA (Finite Element Analysis) and the analytic solution accounting for eccentricity.

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1. Introduction

Since Sypeck and Wadley in 2001 introduced a new kind of cellular metal 'textile core' [1], a number of techniques have been developed to fabricate cellular metals using metallic wires. The new types of cellular metals were named 'wire-woven metals' by the authors. Because a wire is a good mother material offering high strength without defects and is easy to form into truss-like structures, wire-woven metals technology is expected to have advantages over previous techniques that have been used to fabricate cellular metals, such as investment casting and metal foaming. We developed WBK, which stands for Wire-woven Bulk Kagome, a few years ago [2]. WBK is a wire-woven metal composed of helically formed wires arranged in parallel in six different directions evenly distributed in space, inherently having a 3D structure like a Kagome truss [3], whereas the textile core has a layered structure with 2D plain-woven wire meshes. The mechanical properties of WBK under compression or shear loading were investigated to show that its strength is much higher than those of conventional cellular metals and even comparable to those expected for use in the ideal Kagome truss structures composed of straight struts and frictionless joints [2,4–6]. Also, WBK was evaluated to determine its performance as a core material for sandwich panels and the optimal design methodology of WBK-cored sandwich panels was studied to obtain its maximum bending strength for a given weight or the least weight for a given bending load [7,8]. However, the buckling behavior of WBK-cored sandwich panels against in-plane compression has never been investigated.

Honeycomb-cored sandwiches are widely used in light weight structures. Their mechanical properties, engineering design and even fabrication methods are well documented. In addition, the buckling behaviors of honeycomb-cored sandwiches have been studied extensively. A honeycomb core has strength and stiffness under shear comparable to those under compression. Consequently, a honeycomb core in a sandwich is not likely to be sheared under buckling load. Also, the size of the cells is generally too small to allow dimpling to occur on the face sheets. Instead, the sandwich often buckles due to face wrinkling induced by the poor strength at the adhesive bond between the honeycomb core and the face sheets [9].

Recently, Bart-Smith and her colleagues investigated the buckling behaviors of metallic sandwich panels with 2D and 3D truss cores [10–12]. The cores were metallurgically well bonded with the face sheets and debonding never occurred in their studies. However, their sandwich panels were vulnerable to elastic or plastic face wrinkling because the truss cores were single-layered, having joint intervals which were comparable to the core heights.

WBK is inherently a multi-layered structure with small cells, and the intersections among wires and the contacts between the WBK core and face sheets are brazed to form strong joints. However, the shear strength and, especially, the stiffness of WBK are not as high as those of honeycomb cores or single-layered truss cores [7,13]. Consequently, the WBK-cored sandwich panels subjected to buckling loads are expected to behave differently from the sandwich panels with other cores. Recently, we investigated the feasibility of application of WBK-cored sandwich panels in

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shipbuilding [14]. As a part of the results, this article presents their buckling behaviors. Classical theories are introduced, and experimental and numerical results are presented. The effects of aspect ratio, strength and stiffness of the WBK core, the constraint of the core near the ends, and eccentricity on the resistance of the sandwich panels against buckling and post-buckling behavior are evaluated.

2. Theory

If a sandwich panel is composed of metallic thin face sheets and a thick WBK core of metallic wires, and the intersections among the wires and the contacts between the WBK core and the face sheets are well brazed, the panel subjected to in-plane compression may fail in various modes, as shown in Fig. 1. Fig. 1(a) depicts macroelastic buckling. According to Euler's formula, the critical load, P_{cr}^E, is given as a function of the length, L, and the bending stiffness, D, as follows:

$$P_{cr}^E = k^2\frac{\pi^2 D}{L^2}, \quad \text{where } D \approx E_f\frac{bt_fh^2}{2(1-\nu_f^2)}, \tag{1}$$

where k denotes the constraint at the both ends of the sandwich panel, $k = 1$ or 2 for rotation free or fixed ends, respectively. E_f and ν_f are the Young's modulus and Poisson's ratio of the face sheets, respectively. b, h and t_f are the width, distance between the centroids of the upper and lower face sheets, and thickness of the face sheets. If the shear stiffness of the core, A_cG_c, is so low as to be comparable to P_{cr}^E, the sandwich panel will buckle with core shear deformation, as shown in Fig. 1(b). Then, the critical load for macroelastic buckling is modified as follows [15]:

$$P_{cr}^S = P_{cr}^E\frac{1}{1+\frac{P_{cr}^E}{A_cG_c}}. \tag{2}$$

If the stress in the face sheets reaches the yield strength of the face material before macroelastic buckling occurs, the sandwich panel will fail by macroplastic buckling, and the critical load is given by:

$$P_{cr}^P = A_f\sigma_f^o = \frac{4t_fb\sigma^o}{\sqrt{3}}, \tag{3}$$

where σ^o and σ_f^o are the yield strength of the mother material of the face sheets and that modified by the factor, $\frac{2}{\sqrt{3}}$, which is introduced under the assumption of plane strain condition [10].

Because the sandwich panel has the thin face sheets and a high bending modulus due to the thick core, the panel may fail by local buckling of the face sheets such as face wrinkling or face dimpling, as shown in Fig. 1(c) and (d). According to Allen [15], the critical load corresponding to face wrinkling is given by:

$$P_{cr}^W = A_f\sigma_f^W = 2t_fb \times 0.58\,(E_fE_c^2)^{\frac{1}{3}}. \tag{4}$$

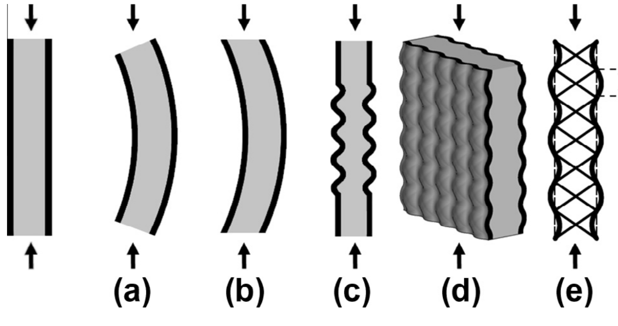

Fig. 1. Modes of buckling of sandwich panels subjected to in-plane compression.

And, according to Wicks and Hutchinson [16], the critical load corresponding to face dimpling is given by:

$$P_{cr}^D = A_f\sigma_f^D = 2t_fb \times 0.255\frac{\pi^2E_f}{1-\nu_f^2}\left(\frac{t_f}{\text{cell size}}\right)^2. \tag{5}$$

Because the WBK core is bonded with the face sheets by copper brazing of sufficient strength, the core is never expected to be bond from the face sheets during in-plane compression. Hence, the possibility of dimpling due to face-core debonding, which is often observed in honeycomb-cored composite sandwiches, is ruled out.

3. Experiments

3.1. Specimen preparation

The mother material used to fabricate both WBK cores and face sheets was low carbon mild steel. Zinc plated steel wires of diameter $d = 0.7$ mm were formed into a helical form with pitch $2c = 13.3$ mm and helical radius $r_h = 0.424$ mm by using a specially designed wire twister. The helical wires were manually assembled into a wire-woven metal of 3D Kagome-like structure, namely WBK. The details of the assembly process are given in Lee et al. [2]. Then an aqueous mixture of copper brazing paste (Chem-Tech Korea, 17LR-283) was sprayed on the assembly, and then the assembly was dried and heated to be brazed at 1120 °C in de-oxidation atmosphere of H_2–N_2 mixture. The brazed WBK cores were trimmed and ground to flatten the upper and lower surfaces. Finally, each WBK core was brazed again with a pair of face sheets of thickness $t_f = 0.5$ mm and wedge-shaped plugs at the ends.

Two kinds of specimens were prepared, Type-I and Type-II. Fig. 2(a) and (b) depicts their configurations with dimensions. Type-I specimens were relatively short and thick. The length, width and thickness of their cores were $L_c = 200$ mm, $b = 82.4$ mm and $H_c = 32.7$ mm. Type-II specimens were relatively long and thin. The length, width and thickness of their cores were $L_c = 450$ mm, $b = 50$ mm and $H_c = 10.7$ mm. Both types of specimens had plugs with sharp wedges at the ends. To investigate the effect of the constraint of the WBK core near the plugs, the cores near the plugs of some specimens were filled with epoxy.

3.2. Experimental procedure

In order to measure the material properties of the wires, tensile tests were performed according to ASTM: A931-08 (2013) for the specimens that were heat-treated during the thermal cycle of the brazing process. The wires were tensioned, as wound around pins at both their ends. The 0.2% offset yield strength of the wires was measured to be 230 MPa, on average. The face sheets were cut into dog-bone type specimens using an electro-discharging machine. Tensile tests of the face sheets were performed according to ASTM: A370-12a. The width/thickness ratio in their gage sections was 30. Hence, the specimen was presumed to be under plane strain condition, and the measured yield strengths were considered as σ_f^o but not σ^o in Eq. (3). The 0.2% offset yield strength of the face sheets was measured to be $\sigma_f^o = 235$ MPa on average.

Each specimen was installed between a pair of V-shaped blocks so that the wedge ends of the plugs tightly contacted the valleys of the blocks. Then a compressive load was applied by displacement control at 0.002 mm/s. The load–displacement behavior was monitored by a digital data logger. The deformation of the specimen during a test was monitored by a digital camera. The displacement of each specimen was measured by an LVDT (Linear variable differential transformer) sensor built-in the test machine. However, the measured displacement included ground displacements due to

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