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Investigation for the bending modes of a semi-circular pyramidal kagome sandwich structure and the bending load calculation

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ABSTRACT

Lattice-based sandwich structures are being widely investigated to meet increasing demands for lightweight components. In the recent research works, lattice-based open cell structures have exhibited higher specific strength compared to closed cell structures, such as a honeycomb structure. Generally, a kagome structure is more effective than other lattice structures for compression and bending. In this work, cross-sections of the strut of pyramidal kagome (PK) structure are developed to strengthen the sandwich structure. A PK structure based on a semi-circular cross-section (SCC) was applied to the bending load calculation. The bending deformation modes of the SCC-based PK sandwich structure were investigated. The bending load was calculated when the PK sandwich structure was bent as stable shear mode and the equation could express the non-linear elastic characteristics during the bending process by applying the effective shear modulus of inner PK cores. The calculated bending load–deflection curve was compared with the bending load–deflection curve obtained by FEM. The tendency of the calculated bending load–deflection curve was similar to the FEM result.

1. Introduction

Sandwich structures that are composed of face sheets and a designed inner core are very effective in terms of specific strength [1,2]. Truss based structures, which are referred to as open cell structures, have some advantages over closed cell structures, and for this reason open cell structures are considered to be desirable alternatives to closed cell structures [3–5]. An open cell structure subject to in-plane shear load has more strength than a honeycomb structure, and the open cell structure can easily include additional functional properties by filling with a heat insulation material [6]. The other advantage of the open cell structure is its high specific strength compared to the closed cell structure [7]. The fabrication methods and mechanical characteristics of open cell truss cores have been investigated for an octahedral truss [8], pyramidal truss [9,10], and tetrahedral truss [11,12], kagome structure [13–15], and so on. The above studies on truss structures demonstrated that the kagome structure has superb mechanical properties. Generally, the kagome structure has been fabricated by a weaving method [16], laser melting method [17], or investment casting method [18]. However, the fabrication time is typically long because of the complicated process, and production cost is also expensive.

Most of the truss structures in these studies were based on struts with rectangular cross-section [19,20] or round wire struts [21]. Recently, sandwich structures based on metal tubes such as the tube-woven kagome structure [22] and hollow truss pyramidal lattice [23] have been introduced. There was also an attempt to make a hollow composite truss structure using CFRP [24]. Even though there have been a few studies on the cross-sectional effect of truss core structures, research works on fabrication processes employing hollow struts with triangular or square cross-sections [25] is subject to further investigation.

In addition, the stress analysis of the composite sandwich structure which has complicated cross-sections became more difficult because of its huge number of elements for the complicated cross-sectional area. There were attempts for analysis of composite sandwich structure by the homogenization method [26], calculating the elastic load and the critical fracture load of sandwich structure [27]. However, there was no attempt to calculate the bending load of truss sandwich structure including the non-linear deformation of inner cores.

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In this paper, the method for bending load calculation for the composite sandwich structure has been developed. The bending deformation modes were categorized into three types such as stable shear, local compression, and face wrinkling according to gap distance between two neighboring inner cores and a ratio of bending stiffness of the face sheet to the shear stiffness of inner cores. The bending load was calculated only in the case that the specimen was bent as the stable shear mode. The shear deformation of inner cores was approximated and the shear modulus of inner cores was calculated according to its shear deformation. The shear modulus value was obtained from the pure shear load–displacement curve of the unit core structure. The bending load of the composite sandwich structure was calculated by using the shear moduli of cores. The bending load calculation was conducted with a pyramidal kagome (PK) structure which had the semi-circular cross-section.

2. PK core structure design and materials

The manufacturing process of the polymer PK structure was developed in the previous research [28]. The PK structure was fabricated by the injection molding and adhesive bonding process. The flat mesh was fabricated by the injection molding process as shown in Fig. 1(a). The pyramidal structures that are shown in Fig. 1(b) were formed from the flat mesh. Two pyramidal structures were welded face-to-face by ultra-sonic wave welding device as shown in Fig. 1(c). The inner PK structure was made of polypropylene and the PK structure was bonded adhesively with the GFRP face sheets as shown in Fig. 1(d).

2.1. Cross-sectional design for core strut

The cross-section of the PK structure was a flat rectangular shape in the previous research [28]. The rectangular strut was weak in terms of sustaining the bending load and the structure is vulnerable to buckling. The PK structure could be strengthened by changing the cross-sectional shape of the PK structure because the critical buckling load is proportional to Young's modulus and the geometrical moment of inertia of the strut. Even though the cross-section areas are same, the moment of inertia can be greatly increased depending on the cross-sectional shape. A tubular and a semi-circular cross-sections were considered as improved alternatives to the conventional PK structure based on flat rectangular cross-sections. The designed cross-sections of the strut are shown in Fig. 2. The cross-sectional areas were same as 0.6 mm^2 while the moment of inertia of the tubular cross-section was 4.4 times greater than that of rectangular shape. The mechanical strength including the bending stiffness and strength could be improved by changing the cross-sectional shape from a flat rectangular shape to a tubular or semi-circular shape.

The investigation of bending deformation modes was made with the SCC-based PK sandwich structure because the fabrication process of SCC-based PK structure was easier than the tubular shape. Moreover, the difference of geometrical moment of inertia between the semi-circular cross-section and round tubular cross-section was small. The SCC-based PK structure was designed as shown in Fig. 3. The strut angle, θ, was 45° which was the optimum angle from the previous research [28]. The height of the core, c, was 3.6 mm. The thickness of the core, t_c, was 0.4 mm. The width of the core, w, and unit length of the core, l, were 1.36 mm and 4.18 mm, respectively.

2.2. Analysis modeling for the bending deformation mode

Generally, the failure of the sandwich structure occurs as face yielding, face wrinkling, core yielding, core buckling, and face indentation [27]. However, composite sandwich structures composed of strong face sheets do not easily fail by face yielding and face indentation. Therefore, the failure modes of face wrinkling, core buckling, and local compression were investigated for the composite sandwich structure. The three failure modes of sandwich were expressed by the bending deformation mode in this work. An adhesive failure between the core and face sheets was not considered because the adhesive failure did not occur in the similar bending condition [28].

The bending deformation of a sandwich structure can be affected by design parameters such as a gap distance and a flexural rigidity of the face sheet. The gap distance means the distance between the PK structures. From the reason, the major parameter for the deformation mode was the ratio of bending stiffness of the face sheet to shear stiffness of the inner cores and the gap distance between the inner cores. The analysis for the bending deformation mode was conducted with five different stiffness ratios as shown in Table 1. The gap distance was varied from 0 mm to 7.5 mm with 0.15 mm of increments.

The bending analysis was conducted by the commercial finite element analysis software (ABAQUS, Dassault systems, France). The bending specimen was designed as a 1/2 scale model and a symmetric boundary condition was applied. The bending specimen model is shown in Fig. 4. The thickness of the face sheet, t_f, was 0.6 mm and the core structure was designed as the SCC-based PK structure. The length of the face sheet, L_f, was 120 mm. The width, b, of the sandwich structure was 4.2 mm. The diameters of the rolls were 4 mm and the span length between bottom rolls, L, was 75 mm. The bending deflection was set to be 7.0 mm.

The material properties were examined by material tests and applied to the analysis. Young's modulus of polypropylene, Poisson's ratio, and yield strength of polypropylene were 1222 MPa, 0.35, 15 MPa, respectively. The true plastic stress vs. true plastic strain curve was calculated and applied to the analysis. Young's modulus of the GFRP and Poisson's ratio material was

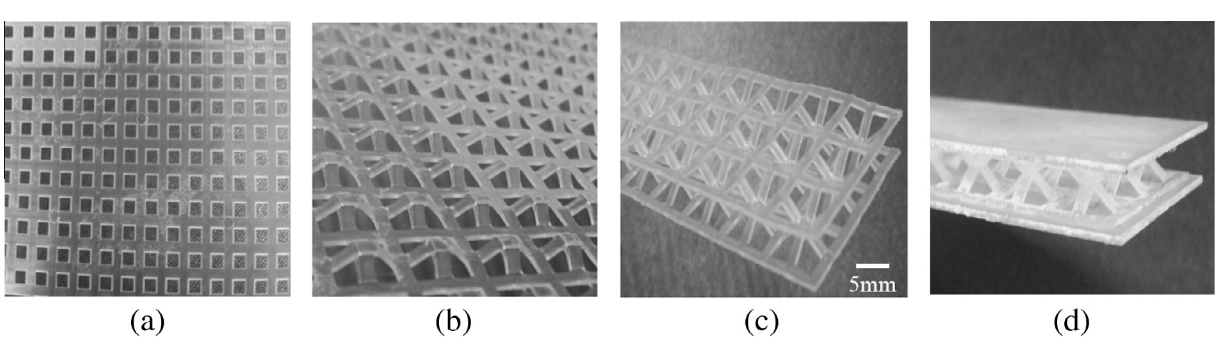

Fig. 1. Fabrication of the pyramidal kagome structure: (a) flat mesh; (b) pyramidal core; (c) pyramidal kagome structure; (d) pyramidal kagome sandwich structure.