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Buckling design of stiffened sheet-based inner core based on bifurcation analysis

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ABSTRACT

In the structural design of the sandwich plate, the inner core plays a key role to have its maximum performance. A shaped pyramidal truss core is proposed in order to increase the strength and productivity of the sandwich core. In this paper, the design guidelines of the shaped pyramidal truss core, which is enhanced by forming a cross-section of an arc shape at the strut of the inner core, is described. The inner core is composed of a stiffened section and a transient section with a varying cross-section. The critical load for bifurcation in compressive instability is calculated using an analytical and FEM simulation. The analytical equation for the critical load of the shaped column is derived using the energy method. The various buckling modes (global, distortional, local) occur due to these effects. Therefore, complications induced by such effects must be taken into account in the design. Parametric studies for the stiffened core are conducted. The effect of geometric parameters is investigated for optimal design of the inner core and their influence have been discussed.

1. Introduction

The development of sandwich material over the last few decades has contributed much to the effective design of structures in buildings and transportation vehicles to save material and energy. A sandwich structure is fabricated by attaching two thin but stiff skins to a lightweight core. The core material has normally low strength, but its relatively large overall thickness provides the sandwich structure with high bending stiffness with overall low density. As environmental problems and resource depletion issues become important, sandwich panels as lightweight materials has come into the limelight. Accordingly, there are increasing applications for sandwich structures in a wide range of areas including aerospace, marine, and automotive fields. This has led to numerous studies on the improvement of existing materials as well as the development of new skins, adhesives and core materials of the structure. The mechanical properties of the skin and core have been extensively studied in designing high performance sandwich structures. Among sandwich designs, studies of the inner core are actively underway. The important factors in the design of the inner core are the shear stress between the outer plate and the inner core and the deformation mode due to practical compression.

In design of sandwich panels, various topological types of inner core geometry such as a pyramidal truss core, corrugated-core, honeycomb, etc. have been investigated. [1]. The most studied core material is the honeycomb, which offers high stiffness and strength-to-weight ratio, especially in the out-of-plane direction. Honeycomb structures are closed cells with very limited pore connectivity within the core region. Panels with curved shapes can also be difficult to make because of the high bending resistance of conventional honeycomb core structures [2]. In contrast, a lattice structure with open cells as an inner core is quite flexible, facilitating the fabrication of curved shapes that can then be brazed or laser welded to solid face sheets to form sandwich structures. Typical examples of several lattice topologies configured as the cores of sandwich structures are pyramidal and tetrahedral cores. The lattice topology, core relative density, and mechanical properties of the basic material combine to determine the mechanism of truss deformation and accordingly the loading mode and direction depending on mechanical properties of these structures. Recent experimental and theoretical studies have shown that open cell lattices with solid truss members can achieve strengths that are comparable to that of a honeycomb. In addition, to overcome the weakness of the lattice structure, low productivity in manufacturing, various manufacturing methods of sandwich panels have been presented.

The sequential bending process is one of the most common and simpler manufacturing methods. Using the process, panels can be fabricated from ductile alloys by perforating a metal sheet to form a periodic pattern, followed by a folding process [3]. By using a fabrication process of combined extrusion and electro-discharge machining (EDM), it is possible to prevent the incidence of defects

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during the manufacture of sandwich panels [4]. Ray [5,6] proposed a structure arranged in a bi-directional core and cross-corrugated core. It was determined by Ray [7] that the cross-corrugated core was more efficient in transverse shear stiffness than the conventional corrugated core. This may be due to the presence of a series of corrugated strip plates both in the x and y directions. Because of the high aspect ratio of the strip cross-section, however, the minimum moment of inertia of the strip is smaller than that of a square cross-section with the same area. As a result, the structure is weak in the failure mode of buckling near the center of the truss under compression.

It has been recently reported that certain sandwich structures employ hollow trusses for enhanced specific structural strength. The hollow trusses in these structures had higher moments of inertia than a solid truss with the same area; the hollow truss was found to increase the inelastic buckling strength. The use of hollow truss structures also provided a means for changing the cellular structures relative density without changing the cell size or the slenderness ratio of the truss. Queheillalt [8,9] manufactured cellular metal lattices using hollow tubes. These tubes led to high strength and lightweight structures. In addition, many studies using hollow type cores have been performed. For example, Xiong [10] designed and manufactured a light weight sandwich plate with hollow Al–Si alloy tubes; Andrews [11] used a hollow strut to increase the mechanical properties of open-cell foams. Design of a hollow tube was achieved by stabilization of the radius of gyration of the truss [12]. Increasing the value of the moment of inertia at the hollow tube is a well-known means for increasing the tube radius while decreasing the wall thickness. The mechanical response of a tubular column loaded in axial compression becomes quite complex as the wall thickness is reduced; axially loaded tubular columns fail through various competing failure modes. If a column is sufficiently long and thin, it fails by the global buckling mode. Generally, the buckling load increases with increasing moment of inertia until another failure mode is induced.

Lee and Yang [13] introduced a new pyramidal truss core that increases the buckling resistance; they proposed an effective manufacturing process from steel strips. This core is more effective in meeting industrial needs. The cross-section of the core has an arc shape that is formed while bending the strip. The shaped core is aligned along the longitudinal and transverse directions and is joined using the conventional bonding methods such as brazing or adhesive bonding to fabricate the inner core. The proposed method has various advantages such as allowing mass production, reducing material loss, increasing bonding area, etc. The shaped pyramidal truss core shows excellent structural characteristics compared to conventional pyramidal cores with the same area. The inner core has various design parameters due to variable cross-section. In this work, a pyramidal truss sandwich plate with locally stiffened core, which is formed as an arc-shaped cross-section, is introduced and the effects of its design are presented. Simple analytic relationships based on the mechanics of material are provided for the compression test, as a method to evaluate the performance of the inner core. For the design parameters, like the cross-sectional shape and the overall shape of strut, a numerical simulation is carried out to analyze the buckling behavior and influence of the design variables.

2. Design of stiffened core

Fig. 1 shows the inner core of the shaped pyramidal truss. When various loads are applied to the lightweight structure, the strut, as an internal structure of sandwich materials, supports mainly the axial load. In order words, the external generated force is transmitted by the strut to the outer plate. Axial load along the strut is provided primarily at the sandwich core. Inelastic buckling then determines the strength of the trusses, the cellular material's out-of-plane compression and in-plane shear strength. Therefore, the inner core generally fails by buckling well before the compressive yield strength is reached. The value of the critical load to cause buckling depends on the slenderness ratio and the shape of the cross-section of the strut. In order to analyze the buckling behavior at the inner core, the model in consideration is simplified as shown in Fig. 1(b). The shape of the cross-section in the strut is assumed to be an arc. The end part of the strut has to be rectangular because the strut connects the flat part, which is the bonding region with skin sheet, as shown in Fig. 1(a). Considering the productivity and formability of steel strips, the formed shape does not use a closed type core, such as a hollow circle, but uses an open type core, such as a semicircle or an arc, for which the central angle is less than 180°.

Among the existing research on structures with shaped sections, Weaver and Ashby [14] introduced a dimensionless shape factor to characterize the stable load-supporting efficiency of a sectional shape for a given mode of loading; they define a column shape factor (r/t) as the ratio of the stiffness of the shaped column to that of a solid circular column; maximum load-supporting relations for axially compressed tubular columns expressed in terms of shape factor were also developed. Amani [15] studied buckling and postbuckling behaviors of curved plates under in-plane shear. Featherston [16] presented the effects of various imperfection shapes and amplitude on the buckling and postbuckling behavior of a curved panel under combined shear and compression.

The design parameters of the unit strut are aspect ratio and the shape of the cross-section used to reinforce the core. The shape of the stiffened strut is divided into two parts, the stiffened region and the transient region. The behaviors of the column change according to the length of the stiffened region. Finally, the design parameters are the aspect ratio ($\alpha = L/w$), arc angle ratio ($\beta = \theta/\pi$), and stiffened length ratio ($s = a/L$). In Fig. 2, the strut models with different stiffened ratios are shown.

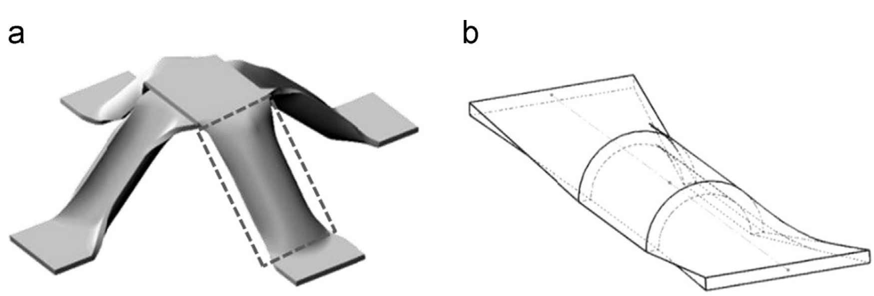

Fig. 1. Shaped pyramidal truss core: (a) unit core and (b) simplified model of strut.