European Journal of Mechanics A/Solids 55 (2016) 57–66

Contents lists available at ScienceDirect

European Journal of Mechanics A/Solids

journal homepage: www.elsevier.com/locate/ejmsol

Large deflection behavior of circular sandwich plates with metal foam-core

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ARTICLE INFO

Article history:
Received 3 March 2015
Accepted 14 August 2015
Available online 18 September 2015

Keywords:
Circular sandwich plates
Load-carrying capacity
Large deflection

ABSTRACT

In this paper the 'equal area method' is used to investigate the load carrying capacity of circular sandwich plates (two metallic face-sheets adhered to a metallic foam-core) subjected to transverse quasi-static point central loading, and the plates are simply supported or fully clamped at the edges. During the process of the large deflection, the plate is regarded as a three dimensional body, which deforms into a shallow cone. To validate the analytical solution, a finite element simulation is performed. A parametric study is then carried out to examine the effects of the boundary conditions, core strength and face/core thickness ratio on the structural response. Results show that the analytical model gives a good description on the quasi-static behavior of circular sandwich plates as presented in finite element simulation. It is shown that the existence of an annular plastic hinge at the external boundary weakens the effects of radial stress in the case of fully clamped boundary. After the initial collapse, the face yield is the dominant failure mechanism especially at the stage of large deflection and the initial collapse of the sandwich structure is highly dependent on the face-sheets strength.

1. Introduction

Sandwich structures are widely used in many critical areas of engineering, such as ship, aircraft, automotive and aerospace industries. Generally, a sandwich plate always consists of two thin face-sheets adhered to a thick metallic foam core which is a typical lightweight structure. The face-sheets carry nearly all of longitudinal loads and bending moments while the core resists shear loads mainly. This idea of sandwich was presented in 1820s (Zenkert, 1995a), then, for the past recent years, a great number of new cellular core materials appeared, like metallic foams (Lu and Yu, 2003; Ashby et al., 2000; Gibson and Ashby, 1997), honeycombs (Lu and Yu, 2003; Ashby et al., 2000; Gibson and Ashby, 1997), lattice materials (Gibson and Ashby, 1997) etc. Energy absorbing and higher strength-to-weight ratio of sandwich structure than conventional monolithic constructions make it used in variety applications (Lu and Yu, 2003; Ashby et al., 2000; Gibson and Ashby, 1997; Wadley, 2006; Abrate, 1998; Goldsmith and Sackman, 1992; Meo et al., 2005; Allen, 1969). As energy absorbers and structural members, the mainly mechanical properties of sandwich structures include the load-carrying capacity (Tagarielli and Fleck, 2005; Tagarielli et al., 2004), deformation/failure mechanism (Ashby et al., 2000; Allen, 1969; Chen et al., 2000) and plastic energy dissipation (Tagarielli and Fleck, 2005; Tagarielli et al., 2004; Steeves and Fleck, 2004). To date, most works about the mechanical behaviors of sandwich structures under quasi-static loading are concentrated upon sandwich beams, by 3-point or 4-point bending experimental tests (Ashby et al., 2000; Allen, 1969; Tagarielli and Fleck, 2005; Tagarielli et al., 2004; Steeves and Fleck, 2004; Chen et al., 2000). Several main collapse modes (i.e., face yield, face micro-buckling, face wrinkling, and core shear and indentation) (Crupi and Montanini, 2007; Yu et al., 2008) have been identified theoretically and experimentally. Tagarielli and Fleck (2005) investigated the plastic collapse behavior of slender sandwich beams under either simply supported or fully clamped in an experimental and theoretical study, who also divided the process of the structure response into three phases, i.e. (1) elastic bending, (2) transition phase and (3) membrane phase. The punch force for deforming of the sandwich beams is higher than the solid beams of equal mass in a specific range of deflections, which was numerically studied by Xue and Hutchinson (2004).

It can be seen that the most works about sandwich structures are limited to beams from the previous discussions. However, the

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http://dx.doi.org/10.1016/j.euromechsol.2015.08.009
0997-7538/

sandwich plates are more commonly used in the realistic applications. Therefore, a overall understanding of the sandwich plates is required. In this paper, the deformation mode of sandwich plates is developed based on monolithic structures, which have been studied extensively. Onat and Haythornthwaite have found that a simply supported circular plate begins to deform into a shallow cone under a central 'point' load and obtained the plastic limit loads of shallow conical shells by an upper bound theory of plasticity (Onat and Haythornthwaite, 1956). And a load-deflection curve for large deflections of a circular flat plate has been deduced. Haythornthwaite also have studied large deflections of a steel beam with fully clamped by using up-bound theory (Haythornthwaite, 1957). These investigations indicated that the increasing loading was in proportion to the square of the transverse deflection above the predicting of simple plastic theory. Subsequently, Onat (1960) and Lance and Onat (1963) used an 'exact' limit analysis on shallow conical shells to study the large deflections of simply supported circular plates under central point loading and clamped under pressure loading. Then, according to upper-bound calculations, a general theory of large deflections of rigid-plastic plates has been developed by Sawczuk (1964). For the appropriate boundary conditions, its' results give good agreement with those of (Onat, 1960) and (Lance and Onat, 1963). Calladine considered a new mode of the plate's deformation named 'Equal area method' (Calladine,). In that mode a random radial cross-section rotates about an instantaneous centre I as a rigid body.

The major aim of this paper is to extend the theories of Calladine to sandwich plates, as the approach has been well established for monolithic circular plates. Analytical model for both simply supported and fully clamped sandwich plates is proposed and the corresponding verification also carried out through numerical simulation. Finally, the effects of several key parameters, e.g. boundary conditions, core and face thickness and yield strength etc., on the load-deflection response of circular sandwich plates are identified.

2. Analytical modeling

In this section, both face sheets and core of simple supported and fully clamped circular sandwich plates are assumed as rigid perfectly plastic materials which obey Tresca yield criterion and the associated flow rule. Based on the analytical model, load carrying capacities of sandwich plates can be assessed.

Consider a circular sandwich plates has a radius R, comprising two identical face-sheets with thickness h_f, which are perfectly adhered to a metallic foam core with thickness H_c as shown in Fig. 1. A central load P is applied on the sandwich plate, which is treated as a point load that this is an idealization of a load spread over a region sufficiently large for failure not to occur locally (Calladine,). For the simply supported and fully clamped cases, when the plates are loaded, there will be the reaction force at the boundary, so in order to assure the 'equal areas' condition corresponding to overall equilibrium of half of the plate in the direction perpendicular to the diametral cut, the radial reaction force is neglected.

Symbols E_f, σ_f, ν_f, ρ_f and E_c, σ_c, ν_c, ρ_c are defined as Young's modulus, yield strength, Poisson's ratio, and density of the face sheets and core, respectively.

2.1. Plastic collapse

Three main plastic collapse modes: face yield, core shear and indentation have been identified for the sandwich beams (Tagarielli and Fleck, 2005), and the initial limit load of each mechanism has been obtained by using the upper bound theory of plasticity. It is reasonable to assume that circular sandwich plates have similar plastic collapse modes and failure initiation mechanisms to sandwich beams due to the axisymmetric geometry. In this study, only face yield mode is modeled, but given the geometry studied it is probably the dominant mode at most realistic geometries. However, although the other standard failure mechanisms, core shear and indentation, are not likely active, some comments on punch-through would be useful for this is well-known to limit the performance of sandwich panels with this face-sheets. Furthermore we assume that either a simply supported or fully clamped circular sandwich plate begins to deform into a shallow cone under a central 'point' load. During this deformation process a random radial cross-section of sandwich plates rotates about an instantaneous centre I as a rigid body. The location of I can be determined later.

2.1.1. Analysis of a simply supported circular sandwich plate

For a simple supported circular sandwich plate the pivot point I is shown in Fig. 2.

Suppose the cross-section rotates through a rigid incremental angle α, the change of the radius of circular ring, such as F, is $y\alpha$, where y is the distance of F below or above the plane defined by I (Calladine,). Then the circumferential strain increment can be obtained as

$$\varepsilon_\theta = y\alpha/x \tag{1}$$

where x is the perpendicular distance of F from the axis of the plate. Obviously, the plastic work dissipated in the elementary circular ring is given by

$$\sigma_y \varepsilon_\theta dV = 2\pi\sigma_y \alpha y dA \tag{2}$$

where σ_y is the yield stress of the material (face sheet or core) in tension (or compression). It could be seen that the perpendicular distance x is an irrelevant parameter. Integrating over the radial cross-section and equating to the work done by the load P in its corresponding descent,

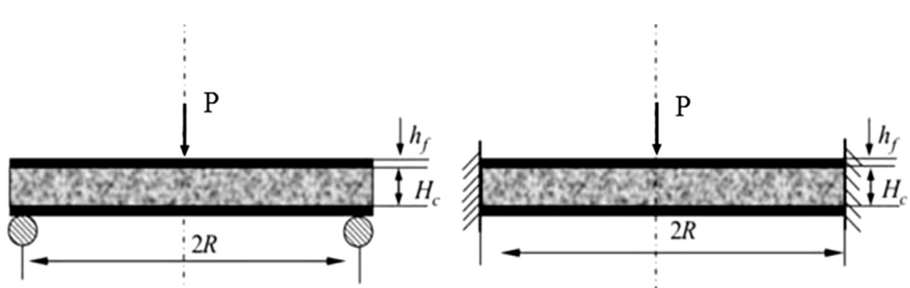

Fig. 1. Sketches of simply supported and clamped circular sandwich panels under a central load in the transverse direction.