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Load-carrying behaviour of web-core sandwich plates in compression

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ABSTRACT

This paper investigates theoretically the compressive load-carrying behaviour of geometrically imperfect web-core sandwich plates. Slender plates, which first buckle globally, are considered. The study is carried out using two approaches, both solved with the finite element method. The first is the equivalent single-layer theory approach. First-order shear deformation theory is used. The second approach is a three-dimensional shell model of a sandwich plate. Plates are loaded in the web plate direction. Simply supported and clamped boundary conditions are considered with a different level of in-plane restraint on the unloaded edge. The results show that the behaviour of the sandwich plate is qualitatively equal to the isotropic plate of the same bending stiffness for deflections lower than the plate thickness. As the deflections increase, the lower in-plane stiffness of the sandwich plate results in lower post-buckling stiffness. Local buckling of face plates in the post-buckling range of the sandwich plate further reduces the structural stiffness.

1. Introduction

Steel sandwich plates are light-weight structures which can save space and improve safety; see Naar et al. [1], Ehlers et al. [2]. Their stiffness-to-weight and strength-to-weight ratio are higher than those of stiffened plate when bending is concerned. This study concentrates on sandwich plates which consist of two face plates separated by web plates. Sandwich plates are typically slender when used e.g. in a ship or a bridge deck. Such application exposes the structure to compressive in-plane loads and thus its stability becomes a design issue.

Buckling and post-buckling of web-core sandwich structures have only been considered in a few studies. Kolsters and Zenkert [3], Kolsters and Zenkert [4], and Kolsters [5] studied the local buckling and post-buckling behaviour of face plates. Kozak [6] studied the ultimate strength of sandwich columns. Jelovica et al. [7] studied the global bifurcation buckling strength of sandwich plates. Thus, these investigations leave a gap for understanding the geometrically non-linear load-carrying behaviour of web-core sandwich plates. Web-core sandwich plates are periodic and in that respect can be considered as being similar to corrugated-core sandwich plates. The ultimate strength of corrugated board plates was studied by Hahn et al. [8] and Nordstrand [9]. Nordstrand [10] developed an analytical expression for the load-carrying behaviour of imperfect corrugated board plates and verified it with an average experimental load-deflection curve. The plates exhibited first global and then local buckling, as in the study by Hahn et al [8]. However, the investigations did not discuss the effect of boundary conditions and local buckling of the faces plates and the core.

Byklum et al. [11] and Byklum and Amdahl [12] have developed a two stage approach for the buckling and post-buckling assessment of stiffened plates. Local buckling is calculated first and the non-linear ABD-matrix is derived for global analysis. However, the investigations do not consider the influence of out-of-plane shear deformations. As shown by Romanoff et al. [13], Nordstrand [14] and Jelovica et al. [7], the shear deformations have large effect on the response of the sandwich plates with discrete, unidirectional core. In Rhodes [15] the influence of in-plane edge restraint has been discussed for isotropic plates. From there it is concluded that the in-plane restraint has large effect on the post-buckling behaviour of the plates.

The aim of this study is to investigate the load-carrying behaviour of geometrically imperfect web-core sandwich plates under in-plane compression. The influence of imperfection amplitude and possible local buckling on load-deflection and load-end shortening curves is studied. The investigation is limited to linear-elastic material behaviour and slender plates, which buckle first globally and then locally. The interest in primarily global buckling is justified by the typically large span of girders in ships or bridges. The investigation is carried out with two theoretical approaches that have different kinematic assumptions, both of which are solved with the finite element method (FEM). The first is the large deflection equivalent single-layer (ESL) theory approach, described for example in Reddy [16]. There, first-order shear deformation theory is used. The second approach is a 3-D shell model of the

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List of symbols

a	Length of the plate in x-direction (m)
A_{ij}	Extensional (in-plane) stiffness coefficients, i, $j=1,2,3$. (N/m)
b	Width of the plate in y-direction (m)
b_e	Effective width of the plate
B_{ij}	Extensional-bending stiffness coefficients, i, $j=1,2,3$. (N)
d	Distance between the neutral axes of the face plates, $d=h_c+(t_t+t_b)/2$ (m)
d_b	Distance between neutral axis of the bottom face plate and the mid-plane of the sandwich plate (m)
d_c	Distance between the point in the web plate and the mid-plane of the sandwich plate (m)
d_t	Distance between neutral axis of the top face plate and the mid-plane of the sandwich plate (m)
D_{ij}	Bending stiffness coefficients, $i,j=1,2,3$. (Nm)
D_t	Bending stiffness of top face plate (Nm)
D_w	Bending stiffness of web plate (Nm)
D_{Qx}	Transverse shear stiffness in x-direction (Nm)
D_{Qy}	Transverse shear stiffness in y-direction (Nm)
E	Young's modulus (Pa)
G	Shear modulus (Pa)
h	Height of the sandwich plate, $h=t_t+h_c+t_b$; thickness of the isotropic plate (mm)
h_c	Height of the sandwich plate core (mm)
k_θ	Rotation stiffness of laser weld (kN)
m	Number of buckling half-waves in x-direction
n	Number of buckling half-waves in y-direction
N_0	Buckling load per unit width (N)
N_{cr}	Plate buckling load (N)
s	Spacing of the web plates (mm)
t_b	Thickness of bottom face plate (mm)
t_f	Thickness of face plates (mm)
t_t	Thickness of top face plate (mm)
t_w	Thickness of web plate (mm)
u	Displacement component in x-direction, edge shortening (m)
w	Deflection of the plate (m)
ν	Poisson's ratio
σ_x	Membrane stress in x-direction (MPa)
$\sigma_{x,\ max}$	Maximum membrane stress in x-direction in the middle of plate length (MPa)
τ_i	Shear stress in the structural member of the cross-section (MPa)

sandwich plate topology. Models are compared for plate buckling with analytical solution. Plates are loaded in their main load-carrying direction, i.e. parallel to the web plates. Simply supported and clamped boundary conditions are considered with a different level of in-plane restraint on the unloaded edge. A cross-section of relevant industrial applications is considered. Sandwich plate behaviour is compared with that of an isotropic plate, since the isotropic plate post-buckling theory is well established; see e.g. Jones [17], Timoshenko and Gere [18].

2. Analysis methods

Geometric non-linear analysis is carried out by increasing the compression in small steps on the initially imperfect structure. The first eigenmode is used as the shape of the initial imperfection, which was in all studied cases a global mode with a single half-wave in both longitudinal and transverse directions. The measurements in EU Sandwich project [19] suggest that this is the only imperfection for the plates of the size and the cross-section as studied here. The analyses are carried out using the Abaqus software, version 6.9. A modified Riks procedure is used in the second step; see Abaqus [20]. Shell elements with four nodes (S4) are used.

2.1. 2-D model

The orthotropic sandwich plate is described through a single layer in its geometric mid-plane, where the loads and boundary conditions are also described. The equivalent stiffness properties for extension, coupling, bending and shear are described through *ABD*- and D_Q-matrices, respectively; see Appendix A. The mesh consists of 100 elements in the length and 100 elements in the width direction. The correspondence in bifurcation buckling load to analytical solution [16,21] is excellent; see Appendix B.

This study considers two types of flexural boundary conditions: (SS)—all edges simply supported and (CC)—all edges clamped. Loaded edges are kept straight in-plane. Unloaded edges are considered with three different in-plane boundary conditions: (free)—edges free to move; (straight)—edges kept straight, and (fixed)—edges not moving in-plane. Thus, six boundary condition cases are studied. Typical deflection patterns for a plate of unit aspect ratio a/b are shown in Fig. 1.

2.2. 3-D model

Face and web plates are modelled with shell elements to form an actual topology of the sandwich plate. Concentrated nodal forces act on the nodes in the geometric mid-plane. Six elements per web plate height are used. The face plates have six elements between the webs. Mesh density is considered sufficient since the difference in bifurcation buckling load to analytical solution [16,21] is less than 2%; see Appendix B.

For the simply supported edges and unloaded edges free to move in-plane (SS-free), the deflection restraint is set only on the nodes at the geometric mid-plane. This allows the rotation of the plate around the mid-plane edge. Furthermore, the vertical nodes along the edge are displaced equally in the edge direction to prevent the rotation of the in-plane axis orthogonal to the edge. For example, all the nodes at a certain web plate have the same displacement in the y-direction, v; see Fig. 2. Additionally, the nodes at the geometric mid-plane at $x=0$ are required to have the same displacement in x-direction, u. The same is required at $x=a$.

3. Load-carrying behaviour

3.1. Description of the plates

Three plate cross-section geometries are considered: (a) a standard web-core sandwich plate for marine and civil applications; (b) as in Case a, but with thinner face plates, and (c) an isotropic plate. The standard web-core sandwich plate has face plate and web plate thicknesses of 2.5 mm and 4 mm, respectively. The core height is 40 mm and the web plate spacing is 120 mm. A plate with 1.5-mm-thick face plates is considered as Case b. The thickness of the isotropic plate is 30.7 mm, chosen in such a way that the plate has equal bending stiffness in the loading direction, i.e. D_{11}, as Case a. The properties of the plates that are studied are given in Table 1. It can be