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Eigenfrequency analyses of laser-welded web–core sandwich panels

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ABSTRACT

A web–core steel sandwich panel is a lightweight structure where thin plates are welded together by laser-welding technique. The plates form a T-joint which has in the center a weld thinner than the plates themselves. Thus the rotational stiffness of the joint is not infinite. The paper investigates the influence of T-joint rotational stiffness on the lowest natural vibration frequency of the panel. The methods used in the study have different kinematic assumptions. Equivalent single-layer (ESL) theory is used to obtain the frequency of the global vibration. The local vibrations are predicted using an isolated part of the panel, the I-beam model. In addition, three-dimensional model of a sandwich panel is analyzed. Finite element method (FEM) and analytical solution are used to obtain the frequencies. First-order shear deformation theory (FSDT) is used. The joint is considered through its rotational stiffness whose quantitative values are presented in the literature. Four different cross-sections with industrial relevancy are considered. The rotational stiffness of the T-joint affects the transverse shear stiffness of the panels. The results show up to 22% reduction of the fundamental frequency when compared with the case of the rigid joint for the global vibration mode. The effect on local vibrations is up to 11% in the case of asymmetric rotation in the T-joint and is otherwise insignificant. The study furthermore outlined the limitations of the ESL approach for assessment of natural frequencies in web–core sandwich panels depending on the vibration mode shape. The results show that the rotational stiffness of the T-joint has to be considered in the conceptual design of these structures.

1. Introduction

Increasing demands for energy efficiency promote the use of lightweight structures. All-metal sandwich panels are an option to fulfill these requirements. The panels are produced in various core topologies using different manufacturing methods. Web–core sandwich panels have large potential due to their optimal positioning of material, durability in fire, blast and dynamics loads. These structures consist of two face plates supported by a periodic core made from webs; see Fig. 1(a). Developments in the laser-welding technology in recent decades [1–3] have made possible the use of thin plates in the panels. Face plates are laser-welded to webs; however, the thickness of the weld is less than the thickness of the web plate due to production requirements; see Fig. 1(b) and [1]. Due to the difference in scale between the resulting weld and the panel, the tendency in design would be to neglect the existence of the weld and assume the right angle between the plates not to change when the panel is deformed. Nonetheless, Ref. [4] showed that the rotational stiffness of the laser-welded T-joint is finite, as opposed to the case where the full-thickness weld or some other production method would result in the joint stiffness that would be considered infinite. It was already shown that the finite rotational stiffness has to be considered for accurate prediction of deflections and stresses in web–core sandwich beams [5] and that it has substantial influence on the buckling load of the panel [6].

Another important design aspect of the panels is vibration. In the conceptual design stage, where different structural configurations need to be assessed for adequacy, fast analysis methods are needed. Typically, the concept design relies on eigenfrequency calculations. Web–core sandwich panels are periodic only in one direction which makes them highly orthotropic especially in terms of shear stiffness. Natural and forced vibration models for orthotropic plates have been developed for example in Refs. [7–11]. There it is assumed that the transverse shear stiffness is infinite and bending deformations dominate the plate response. However, as presented [12–14] in web–core sandwich panels the transverse shear stiffness has finite value and this affects the vibration response considerably. However, it was assumed that the stiffness of the T-joint is infinitely rigid. The panels were assessed according to the first-order shear deformation theory (FSDT). In addition, these models are based on the assumption that the sandwich plate vibrates globally and there are not local modes between or within the face and web plates. Since the assumption of the rigidity of the

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Nomenclature

a, b	Panel dimension in the x-(length) and y-directions (width), respectively
d	Distance between neutral axes of the face plates
h_c	Height of the sandwich plate core
f	Frequency of plate vibration
k_θ	Rotational stiffness of the T-joint
m, n	Number of vibration mode in the x- and y-directions, respectively
s	Spacing of the web plates
t_f	Thickness of the face plate
t_w	Thickness of the web plate
u, v, w	Displacement in the x-, y- and z-directions, respectively
w	Deflection of the mid-plane of the panel
D_{ij}	Bending stiffness of the sandwich plate, $i,j=1,2,3$.
D_f	Bending stiffness of the face plate
D_{Qx}, D_{Qy}	Transverse shear stiffness in the x- and y-directions, respectively
D_w	Bending stiffness of the web plate
E	Young's modulus
G	Shear modulus
I_0, I_1, I_2,	Mass moment of inertias of orthotropic plate
ν	Poisson's ratio
ρ	Density of the material for the face plate and the web plate (steel)
θ_x, θ_y	Rotation around the y- and x-axes, respectively

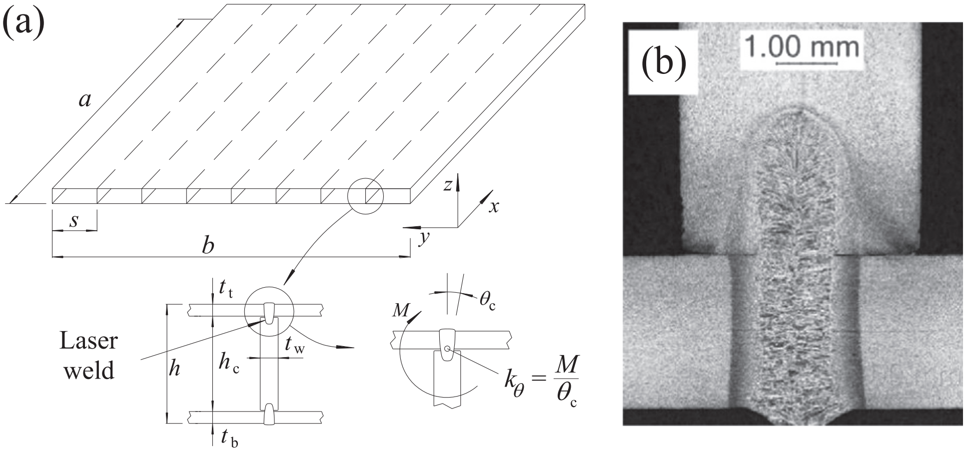

Fig. 1. (a) A laser-welded web–core sandwich panel; (b) T-joint with laser weld.

face to web plate connection is violated in laser-welded web–core sandwich plates, the conclusions drawn for plates with infinite rigidity become questionable.

The purpose of this study is to investigate the influence of T-joint rotational stiffness on the lowest natural vibration frequency of web–core sandwich panels. Global, local and combined vibrations modes are investigated. Analytical and numerical analyses are used to solve the vibration problem. They are based on equivalent single-layer (ESL) theory and FSDT. Numerical analyses are carried out using Finite Element Method (FEM). Analytical solution is used for simply supported boundaries and two-dimensional (2-D) FEM model for the both simply supported and clamped boundaries. The local vibrations are predicted using an isolated part of the panel, the I-beam model. The results are validated with three-dimensional (3-D) FEM models based on shell and spring elements for typical sandwich panel geometries.

2. Analysis methods

2.1. ESL theory approach

2.1.1. Kinematics

The x-direction of the sandwich plate is taken parallel to the web plate orientation while z-direction is normal to the plane of the sandwich. The deformation of the sandwich plate is assumed to consist of two parts, namely the global and local deflection. Thus, the displacements are given as

$$\begin{aligned} u_i &= u_0(x, y) - z\theta_x(x, y) - z_i\theta_x^i(x, y), \\ v_i &= v_0(x, y) - z\theta_y(x, y) - z_i\theta_y^i(x, y), \\ w_i &= w_g(x, y) + w_l^i(x, y), \end{aligned} \tag{1}$$

where subscript 0 denotes displacements at geometrical mid-plane of the sandwich panel while the sub- and superscript i is used to denote the structural element in question, i.e. face or web plates. The distance z is the distance from the mid-plane of the sandwich, while z_i from the mid-plane of the face plate. Furthermore, the standard definition of small strains is assumed and the material is assumed to follow Hooke's law. The superscript i is used to denote the fact that top and bottom face plate has generally different local shape. Further it is assumed that the local deflection due to vibrating face plate and shear force Q_y have the shape

$$\begin{aligned} w_l^i(x, y_l) &= w_l^i(x, y_l) + w_{Qy}^i(y_l), \\ w_{l,b}^i(x, y_l) &= \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} w_{0,mn}\sin\left(\frac{m\pi x}{L}\right)\sin\left(\frac{n\pi y}{s}\right), \\ w_{Qy}^i(y_l) &= \frac{Q_{Q,y}sdy_l}{12D_i}\left[k_1^i\frac{y_l}{d}\left(3 - 2\frac{y_l}{s}\right) + 12\frac{D_i}{dk_\theta^i} + 2k_2^i\frac{D_i}{D_w}\right],\ i = t, b, \end{aligned} \tag{2}$$

which means that the deflection due to local bending between the webs has sinusoidal form, being odd-function over the supports at $x=0$ and $x=a$ and $y_l=0$ and $y_l=s$. The shear-induced local warping deflection varies in y-direction inside the unit cell and in x-direction has the same shape as the mid-plane of the sandwich, i.e. w_i.