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Analysis of twist stiffness of single and double-wall corrugated boards

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ABSTRACT

The twist stiffness of single and double-wall corrugated board is analyzed using first order shear deformation (FOSD) theory. Results are compared to finite element analysis (FEA) and dynamic test data for a large range of torsion loaded rectangular board specimens. The FOSD approach and FEA employ a homogenized core. In addition, a structural finite element model was developed where the web core is represented by shell elements. According to FOSD analysis, the twist stiffness is linearly dependent on the transverse shear moduli of the web core along both principal directions of the core. Good agreement between the torsional stiffness predictions by analytical and numerical approaches and test results is found for the range of single and double-wall boards examined. The FOSD solution is significantly less computationally demanding than FEA, and appears viable for prediction of the twist stiffness of corrugated board.

1. Introduction

Corrugated board is a sandwich structure consisting of web core glued to flat sheets (liners), all made from paper. Corrugated board is manufactured with different number of layers depending on the packaging application. Two common commercially available boards are the single and double-wall corrugated boards. Single-wall (SW) corrugated board is a regular sandwich, consisting on three layers, viz, two flat linerboards bonded to a sine wave shaped web core. Double-wall (DW) corrugated board consists of two layers of corrugated web bonded to three flat liner sheets, one in the center separating the two corrugated layers, and two at the outer surfaces. The liners and corrugated webs consist on paper layers made from cellulose fibers approximately 1–3 mm long, aligned in the plane of the layers in such a manner that the material is considered orthotropic. During the manufacturing process the paper web is stretched along the direction of manufacture (machine direction) which results in further stiffening. The principal material directions of each layer are denoted by MD (machine-direction), CD (cross-direction) and ZD (thickness-direction). The CD of the liners and web core layers is oriented parallel to the corrugations.

The concept of determining the twist stiffness of a sandwich strip specimen under torsion was first introduced by McKinlay [1]. He constructed a twist tester, patented in 1990 [2], where a strip of corrugated board is clamped at both ends and under torsional oscillations by the aid of a counter weight. The twist stiffness of the board is calculated from the natural frequency according to the harmonic equation of the torsional pendulum. An important feature of this test is that the twist stiffness is very sensitive to factors such as damage of the core, face/core adhesion and shape of the web core [1–3]. A common source of damage inflicted on the web core during the corrugation and board assembly processes is delamination. Such damage is detrimental to the out-of-plane stiffness and strength of the corrugate panel. The twist response of corrugated board panels may also be determined using a quasi-static test method, called the sandwich plate twist test, see Mure [4], Pommier and Poustis [5] and Carlsson et al. [6]. Recently, Hernández-Pérez et al. [7] developed a Fourier series solution for the sandwich plate twist specimen using first order shear deformation (FOSD) theory.

In this study, the FOSD solution is used to determine the twist stiffness of corrugated boards with single and double web cores. In addition, finite element analysis (FEA) and experiments are conducted to validate the predictions. Parametric analysis of the twist stiffness of corrugated board as a function of the core out-of-plane shear moduli is presented.

2. Twist test

This work focuses on the twist stiffness of single and double-wall boards. This test was first proposed as a shear test of thin plates by Nádai in 1968 [8]. For this specimen, torque is achieved

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by two end couples produced by application of two concentrated forces ($P/2$) at diagonally opposite corners of the panel with the other two corners pin supported, see Fig. 1. For sandwich panels, a very important deformation mode is transverse shear deformation of the core. To analyze the twist stiffness of a sandwich panel, a solution based on first order shear deformation (FOSD) theory has recently been derived [7]. This solution utilizes plate stiffnesses defined in layered plate theory [9], which are calculated from the effective elastic properties of each layer in the sandwich panel as explained in Appendix A. On the other hand, definition of plate stiffnesses are given in Appendix B. FEA of the twist test specimen is conducted using two types of models, one with a structural model of the web core, and the other with a homogenized core.

Fig. 1 shows single and double-wall boards panels under twist loading. The specimens are 25 mm wide and 105 mm long.

Chalmers [10] considered a twist loaded specimen as shown in Fig. 2, and defined the torsional stiffness (twist stiffness) D_{QM} as,

$$D_{QM} = \frac{Ta}{\theta b} \tag{1}$$

where T is the torque applied by the concentrated forces ($P/2$) and θ is the angle of twist at each end of the specimen, see Fig. 2. a and b are the length and width of the loaded area of the specimen defined by the rectangle formed by the four loading and support pins. In order to maintain a linear elastic response, the angle θ must be small ($\tan\theta \approx \theta$) and it can be approximated by,

$$\theta = \delta / b \tag{2}$$

According to Figs. 1 and 2 the magnitude of the torque applied at the ends of the corrugated boards is given by,

$$T = Pb/2 \tag{3}$$

By substituting Eqs. (2) and (3) into (1), the twist stiffness D_{QM} becomes,

$$D_{QM} = \frac{P\ a\ b}{2\delta} \tag{4}$$

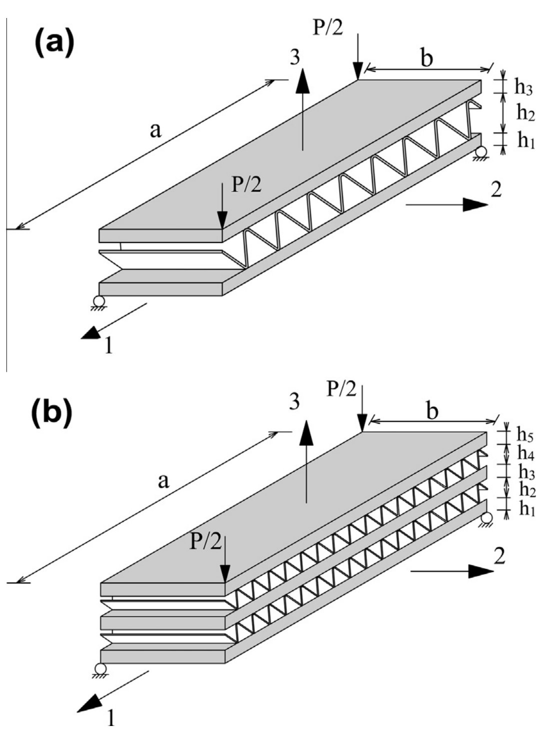

Fig. 1. Plate twist test for board specimens. (a) Single-wall and (b) double-wall.

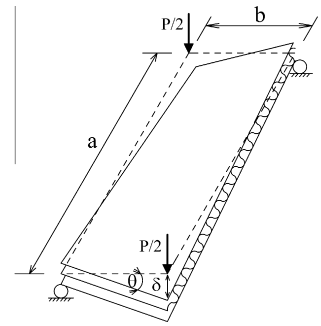

Fig. 2. Deformed shape of a single-wall board loaded in torsion.

Notice that the units of the twist stiffness D_{QM} are in Nm. Eq. (4) is used to determine the twist stiffness of single and double-wall boards by the FOSD and FEA approaches.

3. Materials and specimens

A total of 14 boards were considered, 7 single-wall and 7 double-wall boards. Tables 1 and 2 provide the specific combination of liners and web cores considered in the analysis of the single and double-wall boards, Fig. 1. In these tables L refers to liner, W to web and the number next to W and L specifies the liners and cores as specified in Tables 3 and 4.

All constituent layers of the boards are considered orthotropic with in-plane elastic stiffnesses (E_1, E_2 and G_{12}) listed in Tables 3 and 4. Since the out-of-plane stiffnesses of the constituent paper sheets have negligible influence on the twist stiffness of the board, they were assumed to be the same for all papers considered here, i.e., E_3 = 37 MPa, G_{23} = 75 MPa and G_{13} = 133 MPa [11–14]. Furthermore, an in-plane Poisson's ratio (ν_{12}) of 0.43 was assumed for all papers [15]. Although ν_{12} may vary somewhat, the results from the analysis are very little influenced by such variations.

3.1. Structural finite element model of panels

A structural FEA model of the twist specimen was implemented in ANSYS [16]. The web core layers were assumed to be sinusoidal with wavelengths of 7.7 and 6.41 mm. The lay-ups and core heights are specified in Tables 1 and 2. The specimen length (a) was 105 mm and the width (b) was 25 mm, see Fig. 1. Each layer was modeled by 8-node quadrilateral isoparametric shell elements (SHELL93) [16,17]. In total, 23,040 elements were employed for the single-wall specimens, and 26,400 elements for the double-wall specimens. The elements are flat, making necessary to use small elements to represent the wave-shaped cores, see Fig. 3. The face sheets and core are connected by common nodes at the fluting crests. Elastic properties of the face and web sheets are listed in Tables 3 and 4.

Table 1
Lay-ups and ply thicknesses of single-wall (SW) boards. L = liner, W = web.

Board	Ply number/material/thickness (mm)			Core height (mm)
	Top face	Web	Bottom face	
SW1	L1 (0.243)	W1 (0.240)	L1 (0.243)	3.6
SW2	L2 (0.228)	W2 (0.220)	L2 (0.228)	3.6
SW3	L3 (0.215)	W2 (0.220)	L3 (0.215)	3.6
SW4	L4 (0.185)	W5 (0.181)	L4 (0.185)	3.6
SW5	L2 (0.228)	W4 (0.220)	L3 (0.215)	2.54
SW6	L4 (0.185)	W3 (0.181)	L4 (0.185)	2.54
SW7	L5 (0.170)	W3 (0.181)	L5 (0.170)	2.54