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Flexural behaviour of corrugated panels of self-reinforced polypropylene hybridised with carbon fibre: An experimental and modelling study

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ABSTRACT

The present work investigates the influence of the laminate layup on the flexural properties and failure mechanisms of corrugated panels made of self-reinforced polypropylene (SRPP) hybridised with carbon fibre. The influence of the layup on the stiffness and strength of the corrugated hybrid composite panels was much less important than the carbon fibre content. The experimental program was complemented by finite element analysis. The model revealed the importance of SRPP's non-linear behaviour and difference in tensile and compressive behaviour in controlling the flexural properties of corrugated panels. The compressive behaviour of SRPP was characterised to provide reliable input data for the model.

1. Introduction

Self-reinforced composites (SRCs) outperform conventional polymers as they are reinforced with oriented polymeric chains, giving way to higher stiffness and strength while still offering higher failure strain [1]. Among SRCs, self-reinforced polypropylene (SRPP) has attracted the most attention thanks to its combination of high service temperature and toughness, wider processing window and low price compared to other SRCs [2,3]. The use of SRPP in applications involving flexural loads is not straightforward as its compressive strength is significantly lower than the tensile strength as revealed in previous research on unidirectional [4] and woven [5] SRPP. This explained why specimens tested in flexure always failed on the compressive side while tensile and flexural moduli were found to be the same [6].

SRPP's stiffness and strength are still relatively low in comparison with fibre reinforced plastics like carbon or glass fibre composites, having limited its use in structural applications [2,7]. By hybridising SRPP with carbon fibres, a new composite can be designed with improved overall performance, including flexural properties. Hybridisation has been used as a strategy to increase the flexural properties of composites. For example, the flexural strength of carbon fibre composites was shown to increase by replacing the carbon fibres on the compressive side by glass or silicon carbide fibres [8,9]. The flexural properties of hybrid composites do not only change with the constituent properties but also with the laminate layup [10,11]. If the stiffer layers are further away from the neutral plane of the laminate, their contribution to the stiffness and strength is higher.

When using corrugated panels, the distance between the layers and the neutral plane is larger than the thickness of the panel (see Fig. 1). Corrugation therefore increases the flexural stiffness of the panel made of any material. These corrugated structures are very stiff in the longitudinal direction, but they remain relatively compliant in the transverse direction [12] (see Fig. 1). Properly designing the materials used in a corrugated panel is fundamental for their effective use.

The classical laminate theory (CLT) is a useful tool for the design of composite corrugated panels. Analytical equations have been derived following the CLT approach to convert a corrugated structure into an orthotropic plate [12,13]. Another approach was taken in [14] where the panel was divided into flanges and webs (see Fig. 1). The authors derived an apparent modulus of a corrugated panel which takes into account the material properties and the cross-sectional shape. For non-linear materials such as SRPP, the applicability of the CLT is limited. It can still be used for tensile loading conditions [15] but not for flexural as the stress varies along the length of the panel. Contrary to CLT, finite element (FE) methods can be used to capture highly non-linear materials flexural behaviour such as that of SRPP.

The current study aims to provide guidelines for the design of corrugated panels made of hybrid SRPP laminates loaded in flexure. Manufacturing SRPP in an inherently stiffer corrugated geometry provides opportunities for broadening SRPP's potential use in higher load carrying applications. The layup of the hybrid corrugated panel is varied to assess its influence on the flexural properties and failure

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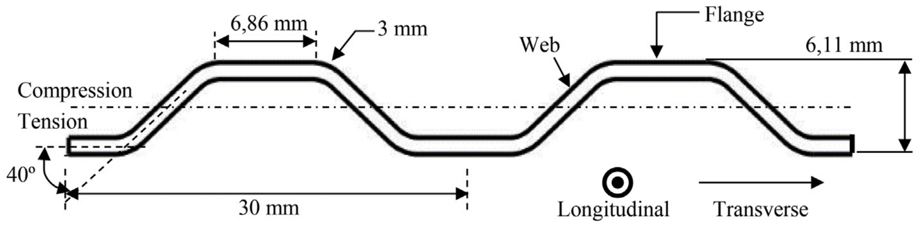

Fig. 1. Geometry and dimensions of the corrugated panel. The corrugated panel's cross section is trapezoidal with round edges.

mechanisms. An FE model is developed to help the interpretation of the experimental results. The model predicts the mechanical behaviour of the corrugated panels. The compressive properties of SRPP are less investigated in the literature and are measured in the current study to support the modelling work.

2. Materials and methods

2.1. Materials

Propex Fabrics GmbH (Germany) provided polypropylene (PP) tapes with a width of 2.4 mm and woven into a twill 2-2 pattern. Prior to hot compaction, the tapes have a tensile strength, modulus and failure strain of 500 MPa, 10 GPa and 9% respectively [16]. After compaction, the woven layers have a thickness of 150 μm. Propex Fabrics GmbH also provided PP films with a thickness of 20 μm and consisting of the same polymer grade as the tapes. Unidirectional carbon fibre reinforced polypropylene (UD CFRPP) prepregs were sourced from Jonam Composites (United Kingdom). The prepregs contain T700 carbon fibres but the exact grade of polypropylene is not known. Prior to hot compaction, the prepregs have a thickness of 160 μm and a carbon fibre volume fraction of 32 ± 1%.

2.2. Hot compaction

The corrugated panels were manufactured using a Pinette Press Zenith 2. Layers of woven SRPP and UD CFRPP prepregs were stacked between two halves of a polished aluminium mould with the shape of the corrugated panel (see Fig. 1). No PP films were used in the production of the corrugated panels. The hot compaction was performed at 188 °C and 39 bar for 5 min [17]. The cooling rate was 5 °C/min on average. The processing temperature has a minor influence on the tensile modulus and strength between temperatures of 184–191 °C as demonstrated in [17]. The press was not pre-heated prior to the manufacturing as that would imply heating the thick mould as well.

During the hot compaction process, the PP in the CFRPP prepreg had the tendency to flow out of the mould. The result was that the thickness of the carbon fibre layers was reduced from 160 to 100 μm, which was confirmed later with the use of optical microscopy. The SRPP layers maintained the nominal thickness of 150 μm. The panel's thickness was not homogenous. By performing thickness measurements, it was observed that the real panels had a higher thickness in the webs oriented in one direction than on the other webs, as shown in Fig. 2. The influence of the non-uniform thickness is further discussed in section 3.3.1.

To produce specimens for compression testing, 25 layers of woven PP-tapes were stacked between flat aluminium plates. One polypropylene film of 20 μm was placed between each two layers of SRPP to assure good adhesion between layers. A Fontijne Grotnes LabPro 400 press was used for the hot compaction of these specimens using the same parameters as for the corrugated panels described above. The plates were then cooled down to 40 °C in 5 min. For these panels, the press was first pre-heated up to the compaction temperature to ensure a homogenous temperature distribution.

2.3. Specimen description

2.3.1. Corrugated panels

The basic geometry of the corrugated panel is trapezoidal with round edges (see Fig. 1). The length and width of the panel were 310 and 120 mm, respectively. The mould was designed for a nominal thickness of 1,11 mm, making the use of 7 layers in total appropriate. The stacking sequences were restricted to the ones where SRPP was the outmost layer for surface quality reasons. Imposing the additional constraint of using only symmetrical layups leaves 8 layups possible. The layups studied and their CF volume fraction (V_f) are presented in Table 1. To determine the CF V_f of each lay-up, equation (1) was used,

$$V_f = \frac{n^C \cdot t^C \cdot V_f^C}{n^C \cdot t^C + n^S \cdot t^S} \quad (1)$$

where n^C is the number of UD CFRPP layers, n^S is the number of SRPP layers, t^C is the initial thickness of the UD CFRPP prepregs, t^S is the thickness of the SRPP layers and ${V_f}^C$ is the carbon fibre volume fraction within a single layer of UD CFRPP. The letters “S” and “C” in the layup annotation in Table 1 stand for SRPP and UD CFRPP, respectively. The “*so*” outside the parenthesis means that the lay-up is symmetrical and contains an odd number of layers. In this case, the fourth letter represents the middle layer. The thickness values were measured in the mid-span line on the extremities of the panel along the width. These values are approximate as it was also verified that the thickness is not homogenous along the panel (see Fig. 2).

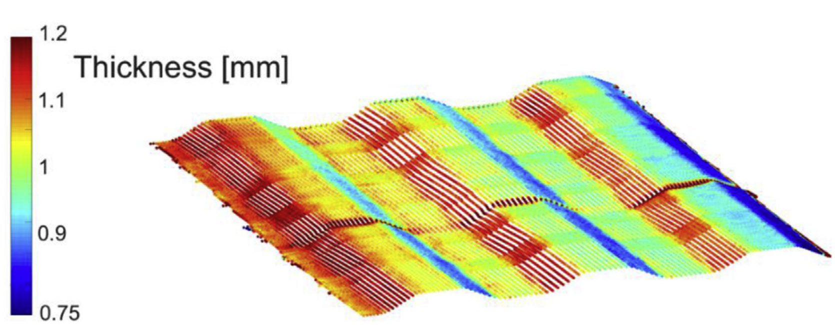

Fig. 2. 3D coordinate measurements on a part of a tested hybrid corrugated panel. The thickness is higher in the webs oriented to one of the sides than on the others. The panel is generally thicker on the left side of the image.