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Second order hierarchical sandwich structure made of self-reinforced polymers by means of a continuous folding process

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ABSTRACT

One typical way to obtain higher stiffness and strength to weight ratios within structural applications is to use sandwich structures containing lightweight cellular cores. In this study a novel second order hierarchical sandwich structure and its manufacturing principle are described. The whole hierarchical structure is made of a fully recyclable material – different forms of poly-ethylene terephthalate (PET): PET matrix, reinforced with PET fibres (Self reinforced - SrPET) and PET foam resulting in a recyclable structure. The manufacturing path is developed such that it can be implemented within a continuous production line. Out-of-plane compression test are carried out in order to determine the stiffness and strength properties of the proposed structure. An analytical model is developed for evaluating the out-of-plane stiffness and strength properties and used for investigating the influence of the geometric parameters on the structural performance of the proposed hierarchical sandwich structure.

1. Introduction

One way to reduce the vehicles' parts weight is to use materials that provide higher specific stiffness and strength to weight ratios. Therefore, material (re)selection represents an important weight optimization criterion and composite materials having improved mechanical properties are usually searched [1]. However, apart from material type, shape criterion is also important and it may represent an added advantage [2,3]. An example of a near optimal use of material is given by the sandwich concept [22]where the bending stiffness of the structure is increased by placing a lightweight and thicker core between two thin and stiff face sheets while the weight is negligibly increased. The continuing research on improving the overall mechanical performance of sandwich structures focuses also on developing novel core configurations, made of composite materials, in order to gain an improved mechanical behaviour of the core. Examples of such efforts include composite corrugated cores [21], square honeycomb cores [23], rhombic and kagome honeycombs [24], pyramidal lattice truss cores [13,19,25–28] or novel expanded cores [29,30]. Although many of these structures provide competitive weight specific strength and stiffness, their main drawback is related to manufacturing steps which are often complicated and difficult to be integrated within a continuous production line. The more recent development of additive manufacturing technologies allows generating complicated and efficient cellular shapes but on a limited scale yet [7,20].The hierarchical sandwich concept has been introduced as a solution to increase the in-plane shear and the out of plane compression performance [9–11,15,31]. The up to date developed hierarchical sandwich structures are obtained by assembling at least three separate components through a specific joining method, the contact area being placed within geometric planes that are parallel to the middle surface of the structure. This configuration leads to a disadvantageous way of transferring loads between components because the in-plane shear behaviour of the structure is influenced by the shear properties of the joint.

Moreover, the recycling capability represents another important issue which is currently difficult to deal with as typical hierarchical sandwich structures consist of several different materials.

This article presents a novel constructive solution for corrugated second order hierarchical sandwich structures made of self-reinforced thermoplastic composites and a thermoplastic structural foam core resulting in a recyclable structure. A manufacturing process for hierarchical sandwich structures suitable for continuous line production is presented. The proposed manufacturing process can be used for materials that can suffer plastic deformations at room temperature or under heat influence. The stiffness properties in out-of-plane compression of the proposed hierarchical sandwich structure are determined experimentally. A theoretical model is further on used in order to

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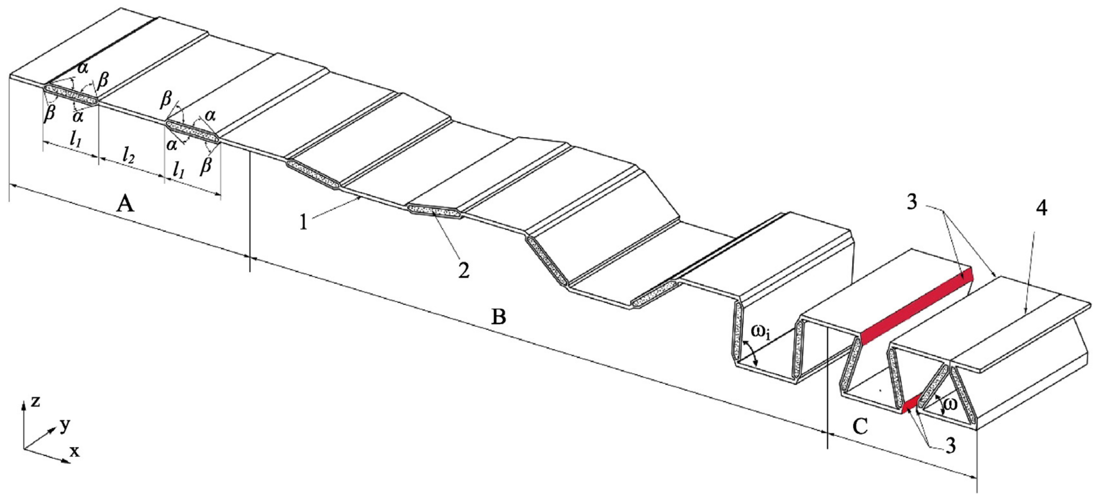

Fig. 1. Schematic illustration of the manufacturing principle for the second order hierarchical sandwich structure.

study the influence of the geometric configuration on the structural performance of the proposed structure.

2. Design and fabrication

2.1. Manufacturing principle

The second order hierarchical sandwich structure is obtained through a continuous flow of operations described further on, related to Fig. 1:

The process starts with the first phase (A) from a single sheet material which contains monolithic (1) and sandwich sections (2) arranged in an alternative way; the folding begins within the second phase (B) where the sandwich sections (2) are rotated along their edges with an angle equal to $90 + \omega$-α. The joining (4) of the sandwich sections is made within phase (C) through the contact areas (3) which are placed perpendicular to the neutral plane of the structure and which are obtained by the definition of the α and β angles in terms of the desired final angle ω and of the sandwich sections length l_2.

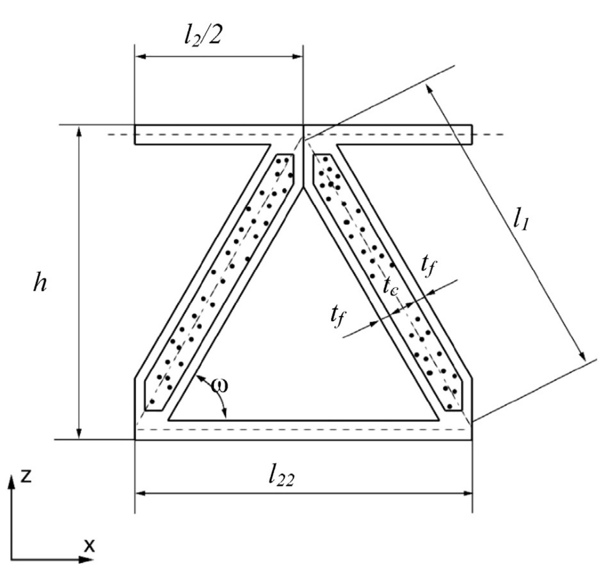

Fig. 2. Unit cell and its geometric parameters. The dotted area is representing the structural foam.

2.2. Constituent materials

The materials used in this study for the hierarchical corrugated folded structure are poly-ethylene terephthalate matrix reinforced with poly-ethylene terephthalate fibres (SrPET) and poly-ethylene terephthalate foam (PET).The SrPET composite material proves to be a good alternative with respect to lightweight design but also considering its lower life cycle environmental impact [17] an high impact energy absorption capacity [32].

The used SrPET composite consists of a low melting temperature matrix PET (termed LPET) and a high tenacity PET (termed HTPET) as fibre material. The LPET is chemically modified to melt at approximately 170 °C whereas the HTPET melts at 260 °C. During consolidation, the temperature should be as high enough to melt the LPET and wet the fibres but not too high so that the HTPET fibres degrade and lose their reinforcing properties. A previous study showed that laminates with good mechanical properties can be consolidated at 220 °C for 20 min under a pressure of 1.5 bar above ambient pressure [33].The SrPET material used in this study is a commingled balanced 2/2 twill fabric with an areal weight of 0.75 kg m^{-2} and 50% reinforcement fibres measured by weight (supplied by Comfil®APS [19]). Using the above mentioned process parameters, one layer of woven fabric results in a lamina with a thickness of 0.45 mm and a material density of 1380 k gm^{-3}.

The compression modulus and ultimate compression strength for the SrPET composite is 5.3 $\pm$ 0.2G Pa and 94.7 $\pm$ 0.7 MPa, respectively. A material yield point is observed at 35 MPa after which the stiffness of the material reduces and results in softening. For details on test procedures and specimens dimension readers are referred to previous work performed by Schneider et al. [12,33].

The foam used is an ArmaForm PET AC with a density of 100 kg m^{--3}.According to the manufacturer reference, the compression modulus is 105 MPa, the shear modulus is 25 MPa while the compression strength is 1.5 MPa and the shear strength is 0.9 MPa [4].

No additional materials are used for joining.

2.3. Manufacturing steps for the unfolded structure

A hot-press is used for consolidating the fabric and at the same time joining it with the foam, thus the unfolded plate containing the alternative monolithic and sandwich sections results. Firstly, the bottom aluminum profiles (see Fig. 3) are arranged parallel to each other at a specific offset in such way to allow the profiled PET foam and the layer(s) of fabric to fit in between. Secondly, the top aluminum profiles are aligned correspondingly, being guided by the edges of the profiled foam covered