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Core–skin interfacial toughness of stitched sandwich structure

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ABSTRACT

Improvement of the interfacial toughness of composite sandwich by stitching process is studied in this paper. Double cantilever beam tests are performed to quantify the influence of the presence of the through-the-thickness reinforcement on the skin–core interfacial toughness. The compliance method is used to determine the energy release rate but with a specific formula where an exponential fitting is preferred instead of the power classical fitting. The failure mechanisms for energy absorption are observed and experimental crack travel through the stitches gives an explanation of the particular evolution of the loading curve. An analytical approach is also proposed to predict the overall behavior of the interface. The classical theory of crack propagation is adapted in order to consider the lack of symmetry of the test as the crack does not propagate in the middle of the specimen and to consider additional plate device strengthen the brittle skin of the sandwich. The result of the model is satisfying for the unstitched structure and the range of the predicted critical energy release rate is in accordance with the experimental result. Regarding stitched sandwich, the limits of the model is highlight due to the theory that does not take into account the transverse reinforcement.

1. Introduction

Sandwich structures made up of two skins and a lightweight core are an original generation of laminate materials bringing various advantages such as mechanical, soundproofing and thermal performances. The conventional cores are honeycombs [1,2] and foams [3,4]. These sandwich panels have superior mechanical properties to their solid plate counterpart. Recently, lattice truss cores have begun to be explored as candidate core materials because of their superior specific stiffness to mass ratio. In order to improve the load carrying capacity of sandwiches, especially in the transverse shear behavior (by increasing the equivalent transverse shear stiffness), without decreasing the lightness, the low density core layer is strengthened by appropriate reinforcements. One of the simplest ways to proceed – already done in the case of monolithic composites – is to add orthogonal reinforcements embedded in the upper and lower skins such as z-pin (carbon or titanium or steel) or fiber rods (carbon or glass) [5–8]. Indeed, the "through-the-thickness" stitching improves the overall stiffness of the sandwich structure as well as the low velocity impact damage tolerance [5,9–11]. In the same time, considering laminate composite, one of the main improvements involved by this reinforcement is the benefit under skin–core delamination [12–16]. In the case of stitched structures, the implementation of the 3D reinforcement involves damages on the composite layers [17–19]. Despite the loss of performance observed in the literature, the gain in terms of cohesion between the layers is such that the technical solution is attractive.

The objective of this work is thus to establish an experimental procedure adapted to the specificity of the stitched sandwiches, then to evaluate the contribution of the stitches in the initiation and the propagation of a crack in the skin/core interface. This paper will be divided into two essential parts: First, the measurement of the experimental parameter G_{IC} after explaining the physical phenomena observed during the delaminating and, finally the analytical determination of the expression of the compliance. Then experimental and theoretical results will be compared.

2. Experimental approach

2.1. Specimen

A sandwich structure consists of lightweight core material bonded to two thin face sheets of stronger and stiffer material.

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The stitched sandwich is produced from a traditional sandwich panel by introducing rows of stitches whose role is to reinforce the link between the two face sheets and eventually increases the mechanical properties in the third direction (Fig. 1).

In this paper, the material is composed of two skins made from 2 plies of woven plain glass (440 g/m^2), a 35 kg/m^3 polyurethane foam core and the stitches composed of two 2400 Tex glass yarns.

Due to the stitching process, the spacing between the rows is 24 mm and cannot be changed. The stitching process has been explained in previous work [5] and is a 2 steps stitches implantation (Fig. 2). The addition of these stitches is done on the initial dry sandwich (foam core and the plies of the skins). The first one gives the rising slope and leaves a longitudinal wick on the external part of the recto skin and a ringlet on the back skin. The second one is complementary to the first one and gives the downward slope and leaves also a longitudinal yarn on the external part of the back skin and a ringlet on the recto skin. At the end of the process, a symmetrical preform is obtained presenting a stitch in cross at the center of the core. An unstitched sandwich is used as a reference.

All the dry preforms (stitched and unstitched) are impregnated with a Reichhold Polylite PD-6184 polyester resin using a VARTM process. The total thickness of the panels is 22 mm:20 mm core thickness and each skin has a thickness of 1 mm. The fiber volume ratio of the skins and the stitches is determined by incineration method (standard ISO 1172) after removing mechanically the foam. For the skin, the fiber volume fraction is 25% and for the stitches, the fiber volume fraction is 15%.

2.2. Mechanical testing

2.2.1. Experimental setup

Experiment measurements are performed using a 100 kN INSTRON 1195 universal testing machine. The mechanical loading consists on a monotonically increasing crack opening displacement at a rate of 2 mm/min to the pre-cracked end of the DCB specimen. A data acquisition is used to collect simultaneously time, displacement between the two fixtures and loading. Testing device is based on the ASTM D5528 standard as presented in Fig. 3. Steel plates bonded on the sandwich are used to ensure a good stiffness of the skins during testing. After testing, the crack propagates through the material along the skin/core interface and the failure of stitches is presented in Fig. 4. The point of anchoring of stitches on the skin seems to be the weakest point of the structure and even if some crack deflection into the core occurs during the test, the stitches never break in their center. For the unstitched sandwich, as the foam core is weaker than the interface, crack deflection occurs to use the path that requires the least energy.

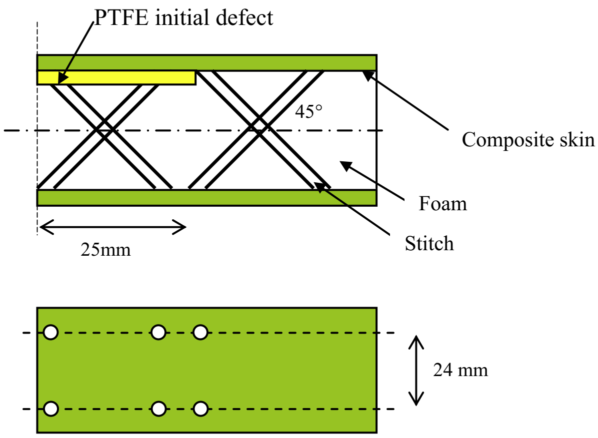

Fig. 1. Initial crack (PTFE) into the stitched sandwich.

2.2.2. Determination of the G_{IC}

In order to determine the value of the parameter G_{IC}, Griffith [20,21] proposed an approach based on the determination of the compliance C and gives the relation:

$$G_{IC} = \left(\frac{1}{2B}\right)\left(P^2 \times \frac{dC}{da}\right) = \frac{P}{2B}\frac{d\delta}{da} \tag{1}$$

where B is the width of the specimen, P is the maximum loading before the first failure, a is the initial crack length and d is the displacement of the fixture.

The compliance C then is defined as the linear evolution of the loading P according to the displacement δ of the fixture device determined form the classical recorded curve presented in Fig. 5 for a test configuration with an initial crack length. The evolution of the loading according to the displacement is usually linear until the first load fall [20,21] but the curve can here be decomposed within two parts; thus two compliances can be defined:

> The $C1$ compliance corresponds to the phase 1–2 and concerns the propagation of the crack in the foam before the stitch in the foam/core interface.
> The $C2$ compliance corresponds to the phase 1–3 and concerns the whole crack propagation until the ultimate loading P_{cr}.

In the rest of this paper, the two compliances will be used in parallel to discuss the opportunity to use the first one or the second one. Fig. 6 gathers experimental curves for each crack length from 35 mm to 70 mm.

In the same time, from Eq. (1), the compliance can be considered as a function of the crack length and in previous works [22–25] this function is generally written as $C = m \cdot a^n$ where m and n are constant parameters.

In Figs. 7 and 8 experimental values of C are fitted with such functions and it can be seen that for both compliance, an exponential function seems to be a little bit closer to experimental data than traditional power law especially for the high pre-crack length. This remark has been already done in few papers [25,26] where results are treated without using a power function.

2.3. Determination of the delaminating energy

2.3.1. Crack initiation on the unstitched sandwich

For the unstitched sandwich, a classical evolution of the load according to the displacement is observed (Fig. 9) and thus only $C1$ compliance is used. Then the energy needed to the crack initiation G can be represented in Fig. 10 as a function of the initial length. The two evolutions of the energy are presented in this graph: the G determined from the power expression of the compliance (G power) and the one from the exponential compliance (G exponential). Mechanically, the energy used for crack initiation is the same for any size of the initial crack and the Fig. 10 shows that the representation resulting from exponential compliance gives an almost constant value of this energy equal to 0.28 kJ/m^2. This remark can be done for the rest of the test of this study leading to the conclusion that the compliance evolution must be fitted with an exponential function. Even if both fitting methods are presented in the rest of this paper, the discussion about mechanical behavior will be done only from the exponential fitting method.

2.3.2. Stitch failure

Concerning the stitched sandwich, Fig. 11 gathers the evolution of the energy. Using the $C1$ compliance, the value of the energy is