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Corrugated all-composite sandwich structures. Part 2: Failure mechanisms and experimental programme

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Abstract

A novel corrugated composite core, referred to as a hierarchical corrugation, has been developed and tested experimentally. Hierarchical corrugations exhibit a range of different failure modes depending on the geometrical properties and the material properties of the structures. In order to understand the different failure modes the analytical strength model, developed in part 1 of this paper, was used to make collapse mechanism maps for the different corrugation configurations. If designed correctly, the hierarchical structures can have more than 7 times higher weight specific strength compared to its monolithic counter part. The difference in strength arises mainly from the increase in buckling resistance of the sandwich core members compared to the monolithic version. The highest difference in strength is seen for core configurations with low overall density. As the density of the core increases, the monolithic core members get stockier and more resistant to buckling and thus the benefits of the hierarchical structure reduces.

Keywords: Smart structures, hierarchical structures, composite corrugation, failure mechanism maps

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1. Introduction

Corrugated sandwich cores have proven excellent shock resistant properties [1, 2], mainly due to their high longitudinal stretching and shear strength. The transverse strength of the corrugations is, however, dominated by buckling of the core members preventing full utilisation of the material. Steel corrugations, especially, have too thin core members at lower core densities ($<150\text{kgm}^{-3}$) resulting in a very weak structure. Côté et al [3] performed an experimental and theoretical study on the behaviour of steel corrugations with densities in the range 260kgm^{-3} to 720kgm^{-3} . These corrugations typically fail by elastic buckling for the low densities and plastic buckling at the higher densities. Further, Rubino et al [4] experimentally investigated the blast properties of corrugated cores and Y-cores with a nominal core density of 200kgm^{-3} which verified the beneficial blast resistance performance of corrugated cores.

To date, no good alternatives of corrugated cores with lower densities have been suggested. Fibre composite materials generally have significantly lower density than metal materials which enable the possibility of making low density corrugated cores with sufficient transverse strength. For the case of ultra lightweight cores, a novel corrugation concept has been developed to prevent the core members from buckling. In this concept each core member is made in a sandwich configuration creating a hierarchical sandwich structure.

In part 1 of this paper an analytical model was developed for corrugated cores. Two different sandwich beam geometries were studied: with monolithic composite corrugations and hierarchical sandwich corrugation cores, see Fig.1. The model assumes that the core members have fixed boundary conditions with stiff face sheets and therefore accounts for both stretching and bending of the corrugation members. The

derived differential equation for a single core member and its solution resembles that of classical Berry functions for which the combined action of bending and in-plane loads are accounted for, however with the extension of the inclusion of transverse shear deformations. The solution provides a complete displacement field enabling the calculation of transverse force and bending moment distributions and thereby stresses in the member. The model was validated with geometrically non-linear FE-analyses and the correlation was found to be very good.

The aim of the present paper is to manufacture all-composite corrugated sandwich beams, both monolithic and hierarchical architectures, test them in simple compression and shear and compare the results with the developed analytical model. The model is further used to create failure mechanism maps allowing for the design of efficient configurations. The experimental obtained failure modes are then compared with these maps in order to validate the model also for failure modes.

2. Manufacturing routes and experimental protocol

The corrugated cores were manufactured using a machined aluminium mould. Prepreg laminates were stacked to obtain the desired thickness and the laminate was cured for 1 hour in 120°C under vacuum pressure, see figure 1. The hierarchical corrugation core was manufactured in the same way as the monolithic corrugation with the addition of PMI foam (Rohacell) in the core members, see figure 1b. Several different core configurations were investigated but all with the same core member length l_1 and core member foam thickness t_{cweb} (in the case of a hierarchical structure). At least two specimens of each corrugation configuration were tested and all results are presented as mean values of the conducted experiments.

Figure 1: Manufacturing route of (a) monolithic corrugation and (b) hierarchical corrugation structures

2.1 Properties of parent material

The corrugations were made of unidirectional carbon fibre SE-84LV prepreg system supplied by Gurit. All corrugations were made using unidirectional laminates with the fibre direction along the corrugation. Measured material properties for a unidirectional lamina are presented in table 1.

E_1 [GPa]	140
E_2 [GPa]	7.45
G_{12} [GPa]	3.85
$\hat{\sigma}_{1t}$ [MPa]	1950
$\hat{\sigma}_{1c}$ [MPa]	858
$\hat{\sigma}_{2t}$ [MPa]	26.6

Table 1: Material properties of unidirectional SE-84LV carbon fibre prepreg. E is the Young's modulus, G the shear modulus and $\hat{\sigma}$ the ultimate strength. The notations 1 and 2 refer to the direction of the load where 1 is along the fibres and 2 is transverse the fibres. The notations t and c refers to tensile or compressive loading.

2.2 Test method

Single-block shear tests were conducted according to ASTM C273-00. Two unit cells of the corrugation were bonded to rigid steel blocks and tensile loading was applied at the ends of the rigid plates, see figure 2(a). Deflections were measured using extensometers and digital calipers. Compression tests were conducted on a unit cell of the corrugation mounted between two stiff steel plates, see figure 2(b). All experiments were conducted in a screw-driven 100kN test machine at a quasi-static strain rate.

Figure 2: (a) Testing of the core shear properties and (b) testing of the out-of-plane properties of the core.

3. Summary of experimental results

Experimental results for the out-of-plane compression test of a monolithic corrugation are presented in figure 3. The load versus displacement response for the analytical model is included as dashed lines. The analytical strength predictions are marked with crosses. The analytical model predicts failure for the 45-degree corrugation at a load of approximate 1000 N depending on the amplitude of the initial imperfection. This is in agreement with the experimental observations. The predicted failure load is, however, approximately 20 percent lower than the theoretical critical buckling load of a clamped strut. Initial imperfections induces larger bending moments on the core member which leads to material failure at loads significantly lower than the theoretical bifurcation load. The reduction in stiffness caused by the imperfections is captured by the analytical model as well.

The core members tend to fail through a combined splitting and compressive material failure. The splitting failure mode is, however, predominant; this since all the

corrugations are made from unidirectional laminates. The same failure mechanisms are observed for all monolithic corrugation configurations examined within this study.

Figure 3: Load-deflection response of (a) 70-degree monolithic corrugation and (b) 45-degree monolithic corrugation. Dashed lines show analytical predictions for two different initial imperfection amplitudes.

The out-of-plane compressive force-deflection response of four different hierarchical structures is shown in figure 4. The failure mode and the strength of these structures are highly dependent on the material and geometrical configuration of the core members. In the experiments, shown in figure 4, all configurations have the same foam thickness in the core members. The 70-degree corrugation (figure 4a) has an intermediate density foam while the 45-degree corrugation (figure 4b) has high density foam. Both of the 45-degree configurations fail through core member face fracture while the 70-degree configurations fail through local buckling ($t_f = 0.2$ mm) and shear buckling ($t_f = 0.4$ mm). The analytical strength predictions generally show good agreement with experimental results. However, configurations with face fracture failure mode tend to be considerably

weaker than predicted by the analytical model. This might be due to small imperfections of the core member face sheets which will decrease the micro buckling strength.

Figure 4: Load deflection response of (a) 70-degree hierarchical corrugation with 110kgm⁻³ foam density, 5 mm foam thickness for two different face thicknesses. (b) 45-degree hierarchical corrugation with 200kgm⁻³ foam density, 5 mm foam thickness for two different face thicknesses.

The shear response of two monolithic corrugations is presented in figure 5. The failure load predictions are in good agreement with the experiments. As for the out-of-plane compression experiments the core members undergo elastic instability followed by compressive failure and/or splitting of the material. The shear response of the hierarchical structures was predominantly governed by the strength of the interface between the core and the face sheets. A typical failure mode of a shear loaded hierarchical structures is shown in figure 6. The tensile loaded core member fails due to

the high peel stresses at the boundaries. These types of failure modes can be prevented by stitching the core to the facing.

Figure 5: Load-deflection response of (a) 70-degree monolithic corrugation and (b) 45-degree monolithic corrugation. Dashed lines show analytical predictions for two different initial imperfection amplitudes.

Figure 6: Peel-off failure of a tensile loaded core member. This failure mode can be prevented by stitching the core to the face sheets.

4. Collapse mechanism maps for the hierarchical structures

Collapse mechanism maps were used in order to understand the failure modes and the weight specific performance of the hierarchical structures. These maps are essential in the design process of structures that exhibits several different types of failure modes.

Figure 7: Collapse mechanism maps for out-of-plane compression loaded (a) 70-degree hierarchical corrugation and (b) 45-degree hierarchical corrugation with 0.2 mm face sheets thicknesses. The maps have contours of weight normalised strength (MPa/g) and are presented as a function of core member foam densities and thicknesses.

The maps were made by altering the core member foam density and the foam thickness. Comparisons are made using the weight specific strength of the different structures. The weight specific strength for a 70-degree corrugation and a 45-degree corrugation is shown in figure 7a and figure 7b respectively. Both configurations have the same core member face thickness of 0.2 mm. Four different failure modes are observed for the two configurations; general buckling, shear buckling, local buckling and face fracture. The contours of weight specific strength show that the configurations with approximately 2.5 mm foam thickness and a foam density larger than 180 kgm^{-3} have the highest strength performance.

Experiments were conducted for structures with 5 mm foam thickness and at three different foam densities; a low density foam, an intermediate density foam and a high density foam. These are marked with crosses on the collapse mechanism maps. The analytical failure mode predictions agree well with the experimental observations.

Figure 8 shows collapse mechanism maps for a 70-degree corrugation and a 45-degree corrugation with 0.4 mm core member face sheet thickness. The region of general and shear buckling failure is considerably larger compared to the configuration with 0.2 mm face sheets. Analytical predictions agree well with the experimental observations. However, as discussed in previous section the strength of configurations with face fracture failure modes is considerably lower than predicted.

Figure 8: Collapse mechanism maps for out-of-plane compression loaded (a) 70-degree hierarchical corrugation and (b) 45-degree hierarchical corrugation with 0.4 mm face sheets thicknesses. The maps have contours of weight normalised strength (MPa/g) and are presented as a function of core member foam densities and thicknesses.

5. Comparison of core designs

The load-deflection response of three different corrugation concepts, monolithic corrugation, foam filled corrugation and hierarchical corrugation is shown in figure 9. The foam-filled concept was not included in Part 1 of this paper and thus not modelled. It was however tested herein for the sake of comparison being an obvious way of preventing premature buckling of the monolithic core. The manufacturing of the foam-filled topology simply involved pre-cutting foam blocks and adhesively bonding them into a monolithic structure.

The load in figure 9 is normalised with the weight of the core. Recall that the dominating failure mode of the monolithic structures is elastic instability. By including structural foam as an elastic support the buckling resistance of the core members can be increased and consequently the strength of the core is improved. Figure 9 shows that by foam filling a corrugation with low density foam the weight specific strength is increased by a factor of three. The same increase in performance is obtained by including low density foam as the core in a sandwich core member. The weight specific stiffness of the foam filled core is, however, considerably lower than the weight specific stiffness of the hierarchical structure. The reason for this is that the polymer foam gives a very small contribution in increased stiffness but does add considerable weight.

Figure 9: Weight normalised load-deflection response of three different corrugation core concepts; monolithic corrugation, foam filled corrugation and hierarchical corrugation.

Further, if one uses an intermediate density foam as the core in a sandwich core member the weight specific strength is increased by a factor of 7. Worth elucidating is the fact that these configurations are not optimised and thus even higher specific gains in strength can be achieved.

Figure 10: Comparison of different corrugated core design subjected to an out-of-plane compression load. All corrugations have 45-degree angle and the hierarchical structures have 5 mm foam thickness. Solid lines are analytical predictions and the free points represent experimental observations.

A summary of the out-of-plane strength of different 45-degree corrugations is presented in figure 10. The solid lines represent analytical predictions for monolithic and hierarchical structures. The free points are mean values of experimental observations. At low core densities the hierarchical structures outperform the monolithic ones but the difference becomes smaller as the total core density increases. Monolithic steel structures have very slender core members at low core densities resulting in very low strength compared to the composite structures.

Using the hierarchical sandwich configuration one can use materials with lower strength but with other beneficial properties such as biocompatibility or fire resistance. Although the materials themselves have lower strength they can be designed in a

hierarchical configuration in order to perform equally well as a traditional sandwich structure with high performance materials.

Table 2 shows a summary of different sandwich core properties at two nominal densities, 50kgm⁻³ and 80kgm⁻³. Both the monolithic and the hierarchical carbon fibre corrugation have superior strength properties compared to aerospace grade foams and honeycombs, especially at the higher core density. In the given example, the hierarchical structures are not optimised for any load condition and have significantly lower shear performance compared to its out-of-plane performance.

Core type	ρ_c (kgm ⁻³)	$\hat{\sigma}_{zz}$ (MPa)	E_{zz} (GPa)	$\hat{\tau}_{xz}$ (MPa)	G_{xz} (GPa)
Rohacell WF51 [R]	52	0.8	0.075	0.8	0.024
Nomex honeycomb [R]	48	2	-	1.41	0.046
Aluminium honeycomb [R]	49	2.32	0.66	1.71	0.31
70° UD Carbon Corrugation	50	3.5	2.6	1.30	0.35
70° hierarchical Corrugation	50	20.3	1.58	2.83	0.22
Rohacell WF71 [R]	75	1.7	0.11	1.3	0.042
Nomex honeycomb [R]	80	4.83	-	2.24	0.074
Aluminium honeycomb [R]	83	5.40	1.57	3.42	0.57
70° UD Carbon Corrugation	80	14.3	4.2	5.23	0.56
70° hierarchical Corrugation	80	30	2.3	4.3	0.33

Table 2: Typical performance properties of aerospace grade PMI-foam, aerospace grade honeycombs and carbon fibre corrugations. Values are given for two nominal densities.

6. Concluding remarks

A novel corrugated composite core with superior strength properties has been developed, modelled and tested experimentally. The sandwich concept has been used at two orders creating a hierarchical structure where each core member in the corrugated core is a sandwich structure. The hierarchical structures exhibit a range of different failure modes when the material properties and the geometrical properties of the structure are altered. In order to validate the analytical model, developed in part 1 of this series, failure mechanism maps were created and experiments were conducted for the different failure modes. Good agreement was found between the analytical predictions and the experimental observations. Compared to a monolithic corrugation, the hierarchical structures can have at least seven times higher weight specific strength.

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