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High Strain Rate Compressive Behaviour of Self Reinforced-Poly(ethylene Terephthalate) Composite Corrugated Cores

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1 Introduction:
Weight reduction is a proven and efficient way to reduce fuel consumption of road and airborne vehicles. To achieve this, the use of lightweight alloys and composite materials has increased significantly during the last decade. The major challenge is, however, to reduce the weight of structures while reducing costs and improving the recyclability of structural material.

An established way to reduce structural weight is by replacing the current material by a material with higher specific strength and/or stiffness properties. A recent example of this is the rapidly growing usage of ultra-high strength steel in cars. For high-end applications, glass and carbon fiber reinforced composite materials have also been used as they possess high weight specific stiffness and strength properties. Another approach to reduce structural weight is by using the materials more efficiently. An example of a geometrically efficient structure is the sandwich structure where two thin plates are separated by low density core material resulting in increased moment of inertia and hence structural bending stiffness and strength.

During the past decade, many studies have focused on further improving the specific properties of sandwich structures by developing different core topologies, e.g. corrugations, honeycombs, pyramidal and lattice truss cores [1-6].

More recently, ultra-lightweight core topologies have been presented where the core members are made of a lightweight composite material and/or a second order sandwich structure (hierarchical structure). [7-9].

In addition to good weight specific quasi-static properties, structures used in vehicles need to have good impact performance (e.g. to achieve required crash safety in cars). The compression impact properties of corrugated composite sandwich cores out of glass fiber composite materials have been investigated by Russel et al. [10]. They showed that the maximum dynamic compression strength of the corrugated core was a factor of 5 times higher than its quasi-static compressive strength. This increase in dynamic strength was mainly attributed to the strain rate sensitivity of the composite matrix which stabilized the fibers from failing by micro buckling.

Kazemahvazi et al. [5] investigated the high strain rate compression properties of corrugated carbon cores with different slenderness ratios. They found that the dynamic strength of the core can be up to 8 times higher than the quasi-static peak strength. The more slender the core members were, the higher dynamic strengthening effect was observed. It was concluded that the mechanism that causes the strengthening was inertial stabilization of the individual struts making them more resistant to buckling.

Although showing good quasi-static and impact performance, traditional composite materials have two main drawbacks, complex and expensive manufacturing and poor recyclability. A typical composite sandwich structure can be composed of more than 4 different materials, making material separation and recycling a costly and complicated endeavor. Recently, a new generation of composite materials has been introduced where the fibers and the matrix are made from the same recyclable thermoplastic base material. Being made of the same base material, this new family of composites, generally referred to as self-reinforced polymers (SrP), has shown great recyclability [11].

The fibers used in SrP’s have higher molecular orientation which results in improved stiffness and
strength compared to the unreinforced matrix materials. The matrix material is often amorphous and/or a polymer with lower melting temperature. The SrP composite fibers are much more ductile than the matrix, which is an unusual property for a composite material, but results in the ability to absorb a high level of energy when (plastically) deformed [12,14]. Some examples of commercially available SrPs include poly (ethylene terephthalate) (PET) [12] and polypropylene (PP) [13] SrPs. Schneider et al. [12] investigated the quasi-static in-plane compression properties of SrPET composites and showed that although they have lower stiffness than traditional composites; SrP’s have a high ductility. In structures where the material is used in a geometrical efficient way, SrP’s can be used to create structures with good specific mechanical performance. In this paper, a recyclable corrugated sandwich structure made out of 100% SrPET is presented. A novel manufacturing process together with quasi-static and dynamic out-of-plane compression test results of the corrugated SrPET sandwich are presented.

2 Material and Manufacturing

The material used in this study is a commingled balanced SrPET twill 2/2 woven fabric with an areal weight of 0.750 kgm$^{-2}$ manufactured by Comfil® ApS [15]. The yarns of the fabric consist of a base matrix material PET, and a high tenacity PET which is termed fibre material. The melting temperature of the matrix is around 160-180 °C and the fibres melt at around 260 °C which is significantly higher than the matrix.

The consolidation time of the material is governed by the consolidation temperature and consolidation pressure. With increasing consolidation time and temperature, the fibre – matrix bonding is enhanced but on the other hand the fibre properties are degraded. A proper bonded laminate with only slightly degrading of reinforcement can be manufactured at 220 °C for 20 min under a pressure of 1 bar [15]. Under these conditions, one layer of fabric results in a lamina with a thickness of about 0.5 mm and a material density of 1380 kgm$^{-3}$. The all-SrPET corrugated sandwich structures were manufactured in a machined aluminium tool of the size of 400 x 400 mm in a single sequence process as depicted in Fig.1a.

To ensure successful demoulding of the sandwich structures possible all parts of the mould were coated with a layer of Tygovac RF260 Fluoropolymer FEP release film. Thereafter, the fabric for the first face sheets was placed in the mould. The fabric of the core was wound around the metal profiles so that a single layer of fabric is part of the core strut and the face sheet. This was done to ensure a proper bonding of the face sheet to the sandwich core (see Fig.1b). Finally, the fabric for the second face sheet was placed in the mould. The mould was put under 1 bar pressure in a hot press and heated at 10 °C/min to 220 °C. The temperature was held for 20 min and subsequently cooled at 10 °C/min to room temperature. The pressure was released and the sandwich was demoulded. With this manufacturing process is it possible to produce complete sandwich structures with a size of 400 mm x 400 mm in a single sequence.

The final sandwich structure had a core thickness $t$ = 20 mm, a corrugation angle $\omega$ = 45° and a hat length of $l$=10 mm which results in a unit cell length $L_N$ of 60 mm (see Fig. 2). Each unit cell was cut into a square base area of 60 mm x 60 mm. Three different strut slenderness ratios were investigated where the core density is presented in Table. 1. For reference purpose, a sandwich structure with a corrugation angle of 90° was manufactured to investigate the compression properties of the parent material. The trapezoid metal profiles from the 45° core were replaced with quadratic 25 mm x 25 mm aluminium profiles which resulted in a core with similar strut lengths as in the 45° core. In order to investigate the compression properties without any buckling the strut thickness of the 90° was 11 mm. The same manufacturing process as for the 45° core was used.

3 Test Methods

Static transverse compression tests were performed on a unit-cell in a screw-driven uniaxial loading machine (Instron4045). The load was recorded with either a 100 kN or a 30 kN load cell depending on the expected failure load of the unit cell. All static compression experiments were performed with a constant cross-head displacement of 1 mm/min at room temperature of 23±3 °C. The axial compression displacement of the 45° core unit cell was measured using a linear variable displacement
transducer (LVDT) extensometer that was mounted on the rigid steel compression plates (see Fig. 2b).

The compression strain of the 90° specimens was measured by using a digital image correlation technique [16] where a virtual extensometer was used to calculate the overall engineering compressive strain [12]. A minimum of 3 specimens per material configuration were tested.

Dynamic compression tests have been performed on an instrumented Imatek IM 10-20 drop weight impact test machine. The compression test method to determine dynamic compression properties was based on the equivalent static method where a specimen is compressed between two flat plates. Diagnostics included a Phantom v210 high speed camera and force, energy, displacement and velocity information of the impact event. 3146 fps were captured during every single test. The force was measured with a 60 kN piezoelectric force transducer between striker and mass carriage, as shown in Fig. 3.

In order to ensure as constant impact velocity as possible, the mass of the striker was varied by adding weight into the mass carriage. All slender specimens and specimens with an impact velocity above 2 m/s were performed with an impact mass of 16.4 kg. All other samples were tested with an impact mass of 31.4 kg.

4 Summary of Experimental Results and Discussion

4.1 Quasi-static testing of unit cells

Quasi-static compression experiments were performed on the 90° core to investigate the compression properties of the parent material. The compressive stress was calculated using the measured compressive load on the 90° core divided by the cross section area of the two core members.

Fig. 4 shows the compressive stress-strain responses of the parent SrPET material with a type stress-strain response up to the yield point, (peak stress, at about 85 MPa) and minimal softening. At the yield stress, the struts start to deform into a barrel-shape which is a typical yield deformation mode for SrPET composites [12]. The E-modulus of the parent material is 4.5±0.1 GPa.

In order to investigate the failure modes of the 45° corrugated cores, beam theory is used to estimate the quasi-static buckling strength of each unit cell. The buckling strength of a corrugated unit cell is,

$$\sigma_{th} = \frac{P_{cr} \sin(\omega) I}{L}$$  \hspace{1cm} (1)

where $\omega$ is the inclination angle of the core member, $L$ is the length of the unit cell and $P_{cr}$ is the critical buckling load for a single core member,

$$P_{cr} = \frac{Eln^2 \pi^2}{K^2L^2}$$  \hspace{1cm} (2)

where $E$ is the elastic modulus, $I$ the area moment of inertia, $n$ is the buckling mode and $K$ and $L$ are factors for the boundary conditions (expected to be 0.5 for a clamped-clamped beam). Using above equations, the compressive buckling strength of the slender core is 0.43 MPa, the intermediate core 3.5 MPa and the stubby core 11.8 MPa.

The quasi static stress - strain response of the corrugated cores is presented in Fig. 5. The peak stress of the slender and intermediate core is approximately the same as the above calculated theoretical mode 1 buckling stress. The stubby core however only reaches half its theoretical buckling load indicating a different failure mode than core member buckling. The stubby and intermediate cores show a clear stress peak whereas the slender core has no well-defined peak/bifurcation point. The difference in stress-strain response between the slender and stubby structures may be related to the strong influence of imperfection for cores with slender core members.

In a slender strut, the relative imperfection is typically larger and results in lower and less defined buckling peak strength [5].

4.2 Dynamic Testing of Unit Cells

The impact performance of each unit cell has been tested by applying a dynamic load to the face sheet. The results are shown relative to the quasi-static data using a dynamic strengthening factor, defined as the dynamic peak stress normalized by the quasi-static peak stress for a core of the same geometry. This strengthening as a function of the compression velocity is presented in Fig. 6. The core with slender struts shows the highest strengthening effect followed by the intermediate and the stubby core. At velocities above 2.5 m/s the peak stress for all core configurations starts to level off. It can be further observed that the slender cores show a high variation in the dynamic peak strengths. As discussed
previously, slender cores have larger relative imperfections which cause a larger variance in strength.

As the unit cell is loaded in compression, the core struts are loaded in a combination of axial compression and bending. The core member wall stress $\sigma_M$ can be approximated to the axial compression stress by,

$$\sigma_M = \frac{\sigma_A \sin(\omega)}{2A_M}$$  \hspace{1cm} (3)

where $\sigma$ is the unit-cell core peak stress, $\omega$ is the inclination angle of the core member, $A$ and $A_M$ are the cross-section areas of the entire core and the core member respectively.

The core member stresses for all cores are plotted as function of the compression velocity in Fig. 7. In addition to the dynamic core member strength, the quasi-static (QS) core member strength of each core is also presented in the graph. The quasi-static core member strengths are lower than the corresponding dynamic core member strengths for all experiments indicating a strengthening effect as the loading rate increases.

In order to compare the core member stress at peak load with the parent material SrPET, a dashed line representing the quasi-static yield stress is plotted in Fig. 7. The core member stress at core peak load for the slender cores is below the quasi-static yield stress of the parent material SrPET. This suggests that the slender core members do not fail by compression yielding of the material but through a different failure mode.

The intermediate and stubby cores show a different behavior compared to the slender cores when subjected to dynamic loading. For a velocity lower than approximately 1.5 m/s the core member stress is lower than the quasi-static yield stress of SrPET. On contrary, at velocities higher than 1.5 m/s, the core member stress is higher than the quasi-static yield stress of the material.

The stubby core member reaches a stress level which is higher than the quasi-static yield stress of parent material. At a compression velocity higher than approximately 3 m/s, the core member stress is 1.5 times higher than the quasi-static yield stress of the parent material. This behavior illustrates that the compression yield stress of SrPET is rate dependent and increases with increasing loading rate.

Photographs of a unit cell with slender core members loaded at a velocity of 0.8 m/s and corresponding compression stress-time / stress-strain diagram is displayed in Fig. 8. When the specimen is loaded no deformation of the struts (core members) can be observed up to 80% of the compression peak stress (point 1). At the peak stress (point 2), buckling of struts can be observed with a mode 2 buckling shape. With increasing deformation, the strut to the left suddenly switches buckling shape to a mode 1. This mode change can be seen in the stress-time diagram as a drop in compression stress (point 3). However, the corrugation does not collapse entire and the compression stress increases once again until the strut to the right changes its shape (point 4). Finally, both core struts move into a mode 1 buckling shape and the compression stress falls rapidly. The theoretical quasi-static buckling stress for a mode 2 buckling is higher than that measured during the dynamic testing (see Fig. 8) because the influence of imperfections is not considered in theoretical model. Further it can be seen, when the left strut changes the buckling mode to mode 1 and the right strut is still in mode 2, the compression stress of the core is still higher than the theoretical quasi-static buckling stress for mode 1 buckling.

Photographs of a unit cell with a slender core member loaded at a velocity of 3.8 m/s and the corresponding compression stress-time / stress-strain diagram is displayed in Fig. 9. The first deformation is observed in the left strut as a buckling mode 2 shape at 85% of the core compression peak stress. With increased deformation, both struts buckle in mode 2 (point 3). Subsequently, the struts change the buckling mode from mode 2 to mode 1. The core member strut to the left buckles outwards and the strut to the right buckle inwards causing a compression stress drop. The compression stress increases again until the strut to the right suddenly changes the buckling shape. First the strut bends inwards and at point 6 the strut bends outwards similar to a snap-through. Post this “snap-through effect” the compression stress rapidly falls to zero.

The theoretical quasi-static buckling stress for the slender sandwich core is presented in Fig. 9 where the upper dashed line represents mode 2 buckling and the lower mode 1 buckling respectively. The mode 1 and 2 buckling in the experiment occurs at higher stress than the corresponding theoretical quasi-static buckling stress.
The compression stress – time response of the intermediate core is displayed in Fig. 10. No deformation of the struts could be observed until the struts were loaded with peak load (point 1) where first the right strut buckles in a mode 1 shape (point 2) followed by buckling of the strut to the left. Both struts buckle in mode 1 and in contrast to the slender core, no mode 2 buckling could be observed. Although the structure buckles into a mode 1 shape, inertia stabilization effects can be seen as the dynamic compression peak stress is well above the predicted quasi-static mode 1 bifurcation stress.

The compression stress-time / stress-strain response of an intermediate core loaded at a velocity of 3.8ms⁻¹ is presented in Fig. 11. No deformation of the core struts is observed until the compression load reaches peak load where the strut to the right buckles in a mode 1 shape (point 2). A plastic hinge formation is observed in the middle of the strut.

With increased deformation, the compression stress increases again until the strut on the left shows a snap-through effect (point 4-5). The left strut bends inwards and then snaps-through to an outwards buckling shape. The theoretical quasi-static buckling stress, displayed as a dashed line in Fig. 11, is well below the compression peak stress of the structure. This strengthening effect is believed to be mainly caused by inertial stabilization of the core member.

The compression stress-time / stress-strain response of a unit cell with stubby core members is presented in Fig. 12. The stress-strain diagram shows a linear response up to 6 MPa where the slope of the curve changes and the stiffness decreases (point 1). At a unit cell stress of 6 MPa (point 1), the wall stress in the core members reach the static yield point of the material, 85 MPa, causing the reduction of stiffness. With increasing deformation, the core strut to the left deforms a plastic hinge on the upper end of the strut (point 4) causing a drop in compression stress.

The calculated core member stress for a stubby core member at 1.5 m/s compression velocity was above the quasi-static yield stress of the parent material (see Fig. 7). Therefore only a small local stress concentration is needed to cause the material to start to deform plastically and the strut fails in plastic hinge formation.

The theoretical quasi-static buckling stress for mode 1 buckling is higher than the compression core peak stress because the struts fail in a different failure mechanism, plastic hinge formation, at a lower core compression stress level.

The compression stress – time / stress-strain response of the stubby core at a compression velocity of 5 m/s is displayed in Fig. 13. At a unit cell compression stress of 6 MPa, the wall stress in core member reaches the yield point of the material causing a slope change of the stress –strain response (point 2). With increasing deformation, both struts failed at a peak stress which causes a compression stress drop. The strut to the left fails in the middle where the right strut fails at the upper end. Both struts show a plastic material deformation.

**Final remarks regarding SrPET as a structural material**

The motivation of this study was to determine if SrPET composites can be used for structural parts if the material is used geometrically efficiently. A unique single stage manufacturing process for corrugated SrPET sandwich structures has been presented. During this process, no second or third material is added which results in significant recycling benefits compared to a traditional sandwich structure where adhesives are often used. The presented corrugated structures are believed to be the first all-composite sandwiches where fibers from the core members are integrated with the fibres in the face sheets. This novel manufacturing method enhances the interface strength and makes the sandwich structure more resistant to impact loading.

Figure 14 shows a high speed photography sequence where a sandwich beam with slender core members is subjected to 3-point bending impact loading. The striker, weighing 10.4 kg, hits the mid span of the beam at 4.2 m/s. Although severe deformations can be observed, the core-face interface is intact. Thanks to the high ductility of this material no catastrophic material failure is observed and the post-test specimen looks largely un-damaged. It is concluded that SRPET materials be used to create efficient structures.

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Composite Materials (CACM) at the University of Auckland, New Zealand.

**Fig. 1.** a) Aluminum mold for manufacturing the corrugated sandwich structures, b) Schematic fiber placing in the mould where fabric is displayed by a dashed lines

**Fig. 2.** a) Photograph of the manufactured corrugated sandwich structure, b) Schematic static compression test setup with extensometer

**Fig. 3.** Drop-Tower for dynamic compression testing

**Fig. 4.** Quasi-static stress-strain response of the parent material
Fig. 5. Quasi-static stress-strain response of the slender, intermediate and stubby corrugated sandwich core with a corresponding photograph taken during compression testing.

Fig. 6. Dynamic strengthening shown by normalizing the dynamic compression peak stress with quasi-static compression strength displayed as function of the compression velocity.

Fig. 7. Compression core member stress at core peak load as function of the compression velocity, quasi-static core member stresses are presented at velocity 0 m/s.

Fig. 8. Compression stress – time response of a slender core during a dynamic compression test with compression velocity of 0.8 m/s and corresponding captured images.
Fig. 9. Compression stress – time response of a slender core during a compression test with a compression velocity of 3.8 m/s, and corresponding captured images.

Fig. 10. Compression stress – time response of an intermediate core during a compression test with a compression velocity of 1 m/s and corresponding captured images.
HIGH STRAIN RATE COMPRESSIVE BEHAVIOUR OF SELF-REINFORCED POLY(ETHYLENE TEREPHTALATE) COMPOSITE CORRUGATED CORES

**Fig. 11.** Compression stress – time response of an intermediate core during a compression test with a compression velocity of 3.8 m/s and corresponding captured images

**Fig. 12.** Compression stress – time response of a stubby core during a compression test with a compression velocity of 1.5 m/s and corresponding captured images
Fig. 13. Compression stress – time response of a stubby core during a compression test with a compression velocity of 5 m/s and corresponding captured images.

Fig. 14. 3-point bending experiments with an impact energy of 100 J and a velocity of 4.2 ms⁻¹.

Tab. 1. Geometry of the corrugated unit cell and core density

<table>
<thead>
<tr>
<th>Core Type</th>
<th>t_c/l</th>
<th>t_c (mm)</th>
<th>l (mm)</th>
<th>ω (°)</th>
<th>ρ (kg/m³)</th>
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</thead>
<tbody>
<tr>
<td>Slender</td>
<td>0.035</td>
<td>1</td>
<td>28.28</td>
<td>45</td>
<td>65</td>
</tr>
<tr>
<td>Intermediate</td>
<td>0.074</td>
<td>2.1</td>
<td>28.28</td>
<td>45</td>
<td>136</td>
</tr>
<tr>
<td>Stubby</td>
<td>0.113</td>
<td>3.2</td>
<td>28.28</td>
<td>45</td>
<td>202</td>
</tr>
<tr>
<td>90deg</td>
<td>0.440</td>
<td>11</td>
<td>25</td>
<td>90</td>
<td>422</td>
</tr>
</tbody>
</table>

References: