IMPACT PROPERTIES OF CORRUGATED COMPOSITE SANDWICH CORES

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Abstract. The out-of-plane impact properties of corrugated carbon fibre composite cores have been investigated experimentally. Cores with slender core members show dynamic strengthening of approximately 12 times compared to quasi-static experiments whereas cores with stocky core members show a dynamic strengthening of approximately 2 times. Carbon fibre corrugated cores have superior compressive performance in the density range of 100 kgm$^{-3}$ to 300 kgm$^{-3}$.

1 INTRODUCTION

Sandwich structures, made of thin high performance face sheets separated by a thick low-density core, have superior bending stiffness and strength compared to a monolithic structure of equal weight. Traditionally, the low density cores of the sandwich structure are made of polymeric foams of various relative densities. Foam materials are however bending dominated structures, and the material is thus not fully utilized, which results in a lower weight specific performance compared to a stretching dominated structure [1]. During the past decade there has been an effort to develop novel core topologies that are periodic and stretching dominated for one or several different loading scenarios [2, 3]. The core topologies can be divided into two main categories, prismatic cores and lattice truss cores. Examples of prismatic cores are square honeycombs [4, 5], corrugated cores and diamond configuration cores [6-8]. Lattice truss cores typically consist of pyramidal, tetrahedral, kagomé or textile configurations [9-13]. Since these periodic core configurations are stretching dominated the predominant mode of failure is onset of elastic or plastic buckling, especially for core configurations with a low relative density. In order to increase the resistance to buckling without adding substantial weight, variants of tubular lattice truss cores [14-16] and hierarchical core concepts [7,17,18] have been developed and show significant increase in strength compared to its monolithic counterpart. Figure 1 summarises the experimental compressive strengths for a majority of sandwich core materials available in the literature today. In addition to good quasi-static performance, sandwich structures that are used in military vehicles or naval ships need to have good resistance to blast and ballistic loading conditions. Several studies have investigated the behaviour of prismatic and
lattice truss cores when subjected to ballistics [19, 20] and blast loading [21-27]. Most studies report an increase in blast performance for sandwich configurations compared to monolithic structures, with square honeycombs having the best out-of-plane performance, corrugated and diamond cores having high longitudinal stretching performance and lattice trusses having competitive performance at low core densities.

Dynamic loading scenarios of the aforementioned periodic cellular cores differ from the quasi-static loading case in three fundamental ways. First, the constituent material of the structure may show strain rate dependence. Second, since the cellular cores are buckling dominated, inertial effects can delay the onset of buckling and/or change the wave length of the buckling mode. Finally, propagation of elastic, plastic and bending waves can be transmitted through the core which can affect the macroscopic properties of the structure. Ferri et al [28] conducted a comprehensive study on the dynamic behaviour of stainless steel I-core configurations and found strong inertial influence resulting in a substantial decrease of the buckling wave length as the loading rate increased. Tilbrook [24] et al investigated the dynamic crushing of stainless-steel corrugated and Y-core configurations. Both core topologies showed strong inertial stabilisation as the loading rate increased which resulted in substantial increase of the collapse strength and a decrease of the buckling wave length. At impact velocities below 30 m/s, the stresses measured at the front and rear faces of the sandwich were approximately the same. This indicates a state of axial equilibrium as the core collapses. As the impact speed increased, wave propagation effects played a dominant role and the measured peak stresses at the front face exceeded that of the rear face. In fact, the peak stress of the rear face remained approximately constant (and equal to the low speed impact peak stress) while the peak stress of the front face continued to increase as the loading rate increased (up to a certain limit).

Although the dynamic response of metallic lattice truss and prismatic cores have been
thoroughly explored there has been little research done on the fibre composite counterpart. In this work the out-of-plane compressive dynamic behaviour of a prismatic composite core is explored with a thought future application as high performance and multifunctional cores in naval ship hulls. Experiments are performed at quasi-static loading rate, low speed impacts and high speed impacts. The low- and intermediate speed impacts would resemble a loading scenario of a ship collision and hull slamming loads while the high speed impacts simulate blast loading scenarios. Especially the effects of inertial stabilization are studied and its effect on the out-of-plane compressive strength of the core.

2 MATERIALS AND EXPERIMENTS PROGRAMME

The corrugated cores were made out of low temperature curing epoxy prepreg system reinforced with carbon fibres [29]. Both unidirectional and weave configuration was used. Each material configuration was tested in tensile and compression according to ASTM D3039 and ASTM D3410 respectively, and the strengths and modulus were measured accordingly. A summary of the material properties is found in table 1. The core members were bonded to the face sheets using Araldite 420A/B epoxy adhesive.

<table>
<thead>
<tr>
<th>Type</th>
<th>Ply thickness</th>
<th>Fibre architecture</th>
<th>$E_1$</th>
<th>$\sigma_{1c}$</th>
<th>$\sigma_{1t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TR50</td>
<td>~0.26 mm</td>
<td>UD</td>
<td>142 GPa</td>
<td>650 MPa</td>
<td>2030 MPa</td>
</tr>
<tr>
<td>RC203P</td>
<td>~0.18 mm</td>
<td>0/90 plain weave</td>
<td>75 GPa</td>
<td>500 MPa</td>
<td>1380 MPa</td>
</tr>
</tbody>
</table>

Table 1: Experimentally measured material properties of SE-84LV low temperature curing prepreg system. Index 1 refers to the properties in the fibre direction, $\sigma_{1c}$ the compressive strength and $\sigma_{1t}$ the tensile strength.

A flat sheet of monolithic composite laminate or a sandwich laminate was manufactured by stacking the desired amount of plies and curing the prepreg at 120ºC for 1h. The sheet was cropped into several smaller sheets of the size of a core member and then mounted into a gluing fixture, see figure 2a. Side supports were bonded to the bottom face sheet to give lateral support to the core members. In a plate or a beam structure this would not be necessary since the core is periodic and each core member would then be supported by its neighbouring core member. Subsequent to the bonding of the bottom face sheet, the top face sheet was bonded to the core using a fixture that ensures that the face sheets are parallel, see figure 2b.

A schematic view of the unit cell configuration is given in figure 3 and a summary of the core configurations that are analyzed within this work is summarised in table 2.
Table 2: A summary of the different manufactured core configurations.

<table>
<thead>
<tr>
<th></th>
<th>Mono1</th>
<th>Mono2</th>
<th>Mono3</th>
<th>Mono4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core density (kg/m³)</td>
<td>35</td>
<td>70</td>
<td>55</td>
<td>210</td>
</tr>
<tr>
<td>ω (°)</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>t (mm)</td>
<td>0.26</td>
<td>0.52</td>
<td>0.46</td>
<td>1.81</td>
</tr>
<tr>
<td>Material</td>
<td>TR50</td>
<td>TR50</td>
<td>RC203P</td>
<td>RC203P</td>
</tr>
<tr>
<td>l (mm)</td>
<td>35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s (mm)</td>
<td></td>
<td></td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3: Unit cell of a corrugated core. The left core member shows a monolithic version and the right core member shows a sandwich version.

For the monolithic configuration four different densities were tested, two with unidirectional core members and two with plain weave fibre architecture as core member.

Quasi-static axial compression of a single unit cell was performed in a standard screw-driven Instron machine with a 100 kN or a 30 kN load cell depending on the expected failure load of the unit cell. The axial compression displacement of the unit cell was measured using an extensometer that was mounted between the rigid steel plates that compress the unit cell.

The dynamic compression experiments were performed by firing rigid projectiles using a gas gun set-up and the load response was measured using a Kolsky bar [30]. Experiments were performed at projectile impact velocities, V_p, ranging from 5 m s⁻¹ to 50 m s⁻¹. The mass of the projectile, m_p, was chosen so that a constant velocity crush of the unit cell was obtained. High speed photography confirmed that the velocity of the striker remained approximately constant. Readers are referred to Radford et al [31] for further details including the calibration procedure.

3 SUMMARY OF EXPERIMENTAL FINDINGS

3.1 Quasi-static experiments

The compressive failure modes of the different core configurations are presented in figure 4.
Mono 1-3 are all slender structures and the failure is governed by elastic buckling of the core members. Mono 4 is sufficiently stocky to prevent elastic buckling and the failure is governed by the compressive material strength of the core member. The mode of failure for mono 4 is a combination of delamination and fibre micro buckling as is seen in figure 3d. In the proceeding sections mono 1-3 will be referred to as buckling dominated structures and mono 4 will be referred to as compression failure dominated structure.

Figure 4: Quasi static failure modes of (a) Mono 1, (b) Mono 2, (c) Mono 3 and (d) Mono 4.

3.2 Dynamic experiments

A summary of the normalised dynamic strength of the different core configurations, impacted at different velocities, is given in figure 5. The buckling dominated structures, mono 1-3, show significantly larger increase in strength as function of impact velocity compared to the compression failure configuration. Further, the increase in dynamic strength is the highest for the configurations with the lowest bending stiffness, mono 1 and mono 3. In the proceeding section these findings will be discussed and compared to the observations made using high speed photography.

3.2.1 Buckling dominated configurations

The buckling dominated structures show a significant increase in strength with increasing impact velocities. Typically there is a sharp increase in strength which is followed by a plateau of approximately constant strength as the impact velocity increases. The knee of the plateau is at approximately 10 m/s\(^{-1}\) for the low bending stiffness configurations, mono 1 and 3, and at 20 m/s\(^{-1}\) for the mono 2 configuration.

Figure 6 shows photographs of the mono 1 structure at two nominal displacements for different impact velocities. At low speed impacts, 5 m/s\(^{-1}\), the core members deform into a buckling mode shape similar to the first and second buckling mode of a clamped-clamped strut. This buckling mode shape is immediately followed by splitting failure of the core member. At 10 m/s\(^{-1}\) the buckling wave length of the core members continues to decrease and consequently the failure load increases. The decrease in wave length and increase in failure load is due to the inertia effects that arise when the core members are forced into a certain buckling mode at high speeds.
At impact velocities that are on the plateau, 27 ms\(^{-1}\) and 50 ms\(^{-1}\), the core members are fully stabilised due to inertia and the failure is set by the compressive strength of the material. This strength is about 12 times the quasi-static strength of the structure. The shift in failure mode is clearly elucidated in figure 6 where the initial failure, of both the 27 ms\(^{-1}\) and 50 ms\(^{-1}\), occurs while the core members are considerably straight.

To ensure that there were no three dimensional buckle modes of the core members, perspective view photographs were taken. Figure 7 shows a series of perspective view photographs of the mono 1 structure impacted at 27 ms\(^{-1}\). Immediately after impact the core members deform in a very short wave length mode and areas of splitting failure can be observed. The deformation mode of the core member is the same over the width of the unit cell and it can be seen that a band of bending failure forms close to the bottom boundary.
The failure behaviour of the mono 3 structure is shown in figure 8. The mono 3 structure behaves similar to the mono 1 structure with a few exceptions. The decrease in the buckle wave length is observed for the mono 3 structure as well but the proceeding failure mechanism is however not splitting but fibre failure which can be observed in figure 8. This is since the weave architecture of the laminate prevents it from splitting and hence fibre failure occurs once the curvature of the core member becomes sufficiently large. At 10 m/s\(^{-1}\) the buckling wave length of the structure is very small and as the impact velocity increases the structure is fully stabilised and compressive material failure is observed.

Figure 8: High speed photography of impacts at various speeds on the mono 3 structure.

The perspective view of the mono 3 configuration is shown in figure 9 and the photographs confirm the 2D deformation state of the core members.

Figure 9: Perspective view of the development of failure of the mono 3 configuration impacted at 27 m/s\(^{-1}\).
3.2.2 Compression failure dominated structures

The compression failure dominated configuration show considerably smaller increase in strength as the impact velocity increases. Since the structure fails in compression failure at quasi-static loading rate, only small effects of inertia stabilisation are present in the dynamic loading scenario. Hence the observed dynamic strengthening is mainly due to the material strain rate sensitivity. At an impact speed of 50 m$\text{s}^{-1}$, the strain rate over a core member is approximately 1000 s$^{-1}$ and the dynamic strength is approximately twice as high as the quasi-static strength which is in agreement with studies on the compressive material properties of carbon fibre composites [32, 33]. Figure 10 shows high speed photographs for three different impact speeds. At low speed, delamination and fibre failure occurs over the entire core member and as the speed increases the failure gets more localised and occurs closer to the front face (impacted face) of the specimen.

![Nominal strain](image.png)

Figure 10: High speed photography of impacts at various speeds on the mono 4 structure.

4 CONCLUDING REMARKS

The dynamic response of four different corrugated composite cores has been investigated experimentally by impacting unit cells of the core with projectiles at impact velocities ranging from 10 m$\text{s}^{-1}$ to 50 m$\text{s}^{-1}$. The main observations are summarised as follows.

- Low relative density cores show significant dynamic strengthening (up to 12 times the quasi-static strength). The strengthening is primarily due to inertial stabilisation of the core members.
- High relative density cores are compression failure dominated at quasi-static loading and hence they show small inertial stabilisation when loaded dynamically. The dynamic strengthening, which is in the order of 2 at strain rates of 1000 s$^{-1}$, is thus primarily due to material strain rate strengthening.
- Monolithic corrugated carbon fibre composite cores, together with carbon fibre composite square honeycomb cores, show highest compressive strength at core densities between 100 kg$\text{m}^{-3}$ to 250 kg$\text{m}^{-3}$.
ACKNOWLEDGMENTS

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REFERENCES

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