Stamping of high performance thermoplastic composite intrusion beams

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Abstract. In this study, an experimental investigation was performed to evaluate the potential of thermoplastic composites to be used for the fabrication of an automotive intrusion beam using the composite stamping process. To assess the potential of this technology, mechanical properties of several high performance thermoplastic composite materials were first evaluated on coupons. Due to their higher load and displacement at failure, the most promising materials for the fabrication of a composite intrusion beam were found to be glass fibre/polypropylene (GF/PP) and carbon fibre/polyamide 66 (CF/PA66) laminates. Then, stamped intrusion beams were manufactured from these composites using three different stacking sequences. The beams were later tested under three-point flexural loading. For all components, failure occurred at the attachment points. However, higher properties were obtained for ±45 laminates for which shear-out failure could be avoided. From the load-displacement curves obtained, it can nevertheless be concluded that stamping of thermoplastic composites is promising for the fabrication of intrusion beams, but that further development will be required to avoid failure at the attachment points.

1. Introduction
In recent years, there has been increasing interest in the use of high performance polymer composites in the automotive industry to achieve weight reduction. As evidence of this growing interest, several strategic alliances have been developed between OEM’s and carbon fibre suppliers [1]. The main driver for the integration of composites in the automotive industry is the Corporate Fuel Average Efficiency (CAFÉ) regulation that requires fuel consumption of 54.5 mpg (4.3 L/100 km) to be reached by 2025. According to one study [2], the use of lightweight materials such as composites can result in significant fuel consumption reduction along with enormous environmental benefits: trimming the weight of a vehicle by 1 kg results in a 17-20 kg reduction in the amount of CO₂ emitted during the lifetime of that vehicle. A study from Oak Ridge National Laboratory also showed that replacing today’s steel body-in-white (BIW) with an integrated carbon fibre composite structure could result in a 60 percent mass reduction, boosting fuel efficiency by as much as 30 percent [3]. This offers significant potential not only for meeting new fuel-economy standards with conventional engines, but also to offset added weight from electric battery packs, fuel-cell storage cylinders and other equipment essential to alternative-powertrain vehicles. However, most manufacturing process adapted to high performance composites do not meet the cycle time targeted by the automotive industry for the high volume production.
One of the most promising processes to cost-efficiently manufacture high performance composite components for the automotive industry is the composite stamping process, a process similar to the widely used metal stamping process. One of the key advantages of this technology is the potential to manufacture light weight automotive parts in very short cycle times from continuous fibre thermoplastic composites. In addition, the composite stamping process also offer the potential of being implemented using existing infrastructure, since forming presses are commonly used in the automotive industry. Although this process has been used in the aerospace for several years [4], little work has been done to date on automotive applications.

In this study, an experimental investigation on stamping of an automotive composite intrusion beam is conducted. This component was selected because of the interesting challenges associated with the balance of stiffness, strength and deformation that must be achieved to meet the performance requirements of such a part [5]. In order to evaluate the potential of high performance thermoplastic composites to be used for the fabrication of such structural parts, the mechanical behaviour of several high performance composite materials is first investigated by performing flexural tests on coupons. From these small scale tests, the most-promising composite configurations are identified. Then, stamping trials are conducted to manufacture intrusion beams. Finally, flexural tests are conducted on full-scale stamped components to study their mechanical behaviour.

2. Experimental Procedures

2.1. Materials

Four continuous fibre thermoplastic composite materials were investigated in this study. These materials consist of glass fibre/polypropylene (GF/PP), glass fibre/polyamide 6 (GF/PA6), carbon fibre/polyamide 6 (CF/PA6) and carbon fibre/polyamide 66 (CF/PA66) composites. The materials considered in this study were all in the form of pre-impregnated thermoplastic unidirectional tapes. Table 1 shows the fibre content, density, thickness and the melting temperature of these composites, as determined by differential scanning calorimetry (DSC).

| Materials    | Fibre content (wt.%) | Density (g/cm³) | Tape thickness (mm) | Melting temperature (°C) |
|--------------|----------------------|-----------------|---------------------|--------------------------|
| GF/PP        | 70                   | 1.67            | 0.25                | 162                      |
| GF/PA6       | 60                   | 1.69            | 0.26                | 220                      |
| CF/PA6       | 60                   | 1.45            | 0.16                | 220                      |
| CF/PA66      | 60                   | 1.44            | 0.17                | 260                      |

2.2. Material characterization

Flexural tests were initially performed on rectangular coupons to identify promising materials and stacking sequences for the fabrication of stamped intrusion beams. To manufacture test specimens, composite tapes were first manually laid-down into a mould according to the desired stacking sequences. The stacks were then compression moulded to produce rectangular panels. During the compression moulding cycle, laminates were heated 40°C above their melting temperatures, held at high temperature for 5 minutes and then cooled to room temperature at a rate of approximately 10 °C/min. A constant pressure of 0.7 MPa (100 psi) was applied during the entire moulding cycle. Coupons of 38 mm in width and 250 mm in length were then machined using water jet equipment. An 8 mm diameter hole was machined at each end to fix the specimens into the flexural test jig (Figure 1). Load-displacement curves were then obtained from three-point flexural tests performed at a rate of 20 mm/min using a span of 200 mm. Three stacking sequences were considered for each material, i.e. 0/90, ±45 and quasi-isotropic (QI). A detailed description of the lay-up used is provided in Table 2.
Figure 1. Three-point flexural test on coupons.

Table 2. Stacking sequences investigated for flexural tests on coupons.

| Materials | Stacking sequence | Thickness (mm) |
|-----------|-------------------|----------------|
| GF/PP     | [0/90]_{4S}       | 3.9            |
|           | [+45/-45]_{4S}    | 3.9            |
|           | [+45/-45/0/90/+45/-45/0]_{S} | 3.9 |
|           | [0/90]_{3S}       | 3.1            |
| GF/PA6    | [+45/-45]_{3S}    | 3.3            |
|           | [0/90/+45/-45/0/90]_{S} | 3.3 |
|           | [0/90]_{3S}       | 2.8            |
| CF/PA6    | [+45/-45]_{3S}    | 2.9            |
|           | [0/90/+45/-45/0/90]_{S} | 2.8 |
|           | [0/90]_{3S}       | 3.2            |
| CF/PA66   | [+45/-45]_{3S}    | 3.1            |
|           | [0/90/+45/-45/0/90]_{S} | 3.4 |

2.3. Composite stamping process

Prior to performing stamping trials, composite sheets were first manufactured. Similarly to what was described earlier, composite tapes were laid-down manually to the desired stacking sequences prior to being compression moulded. Blanks of the proper dimensions were then cut from the produced sheets using water jet cutting.

During the composite stamping process, continuous fibre thermoplastic composite blanks were first heated above the melting temperature of the thermoplastic matrix in an external infrared (IR) oven and then rapidly transferred to a press where they were stamped (Figure 2a). Due to rapid cooling of the material during transfer from the oven to the press, pre-heat temperatures were selected to be 50 to 60°C higher than the melting temperatures shown in Table 1. To prevent excessive cooling of the material prior to stamping, a press closing speed of 500 mm/s was used. The 1000 Ton forming platform used to perform the composite stamping trials is shown in Figure 2b.
2.4. Characterization of stamped intrusion beams

The mechanical behaviour of the stamped intrusion beams was investigated by performing three-point bending tests. To conduct these tests, a test jig was manufactured (Figure 3) and installed into an Instron universal testing apparatus. Experiments were conducted at a cross-head speed of 380 mm/min. From the tests, the load-displacement curves were obtained. Cross-section of tested intrusion beam is also illustrated in Figure 3.

3. Results and discussion

3.1. Selection of promising materials

3.1.1. Glass fiber composites. Results of tests performed on glass fibre composite materials, using the experimental configuration in Figure 1, are described in this section (Figure 4 and Figure 5). As shown in Figure 4, significantly different mechanical behaviours were measured for the GF/PP composites depending on their stacking sequence. For ±45 lay-up, almost linear behaviour is observed up to
failure. Much larger displacement at failure is also obtained for this configuration. However, lower stiffness is measured due to absence of fibres along the length of the specimens. For this material configuration also, failure occurred at the attachment point (Figure 6) with multiple delaminations being observed at mid-span. No significant change in fibre orientation could however be measured on the top and bottom surfaces of the tested specimens. This suggests that large deformation was achieved through accumulation of damage in internal plies. As also shown in Figure 4, much smaller displacements at failure were obtained for the 0/90 and quasi-isotropic stacking sequences with only slightly higher displacement at failure being measured for the quasi-isotropic configuration. The higher displacement at failure measured for the quasi-isotropic laminate (relative to the 0/90 lay-up) is likely attributed to the presence of ±45 plies in the lay-up. A similar failure mode was obtained for the (0/90) and quasi-isotropic (QI) configurations. In both cases, failure at mid-span was observed (Figure 7).

Results of flexural tests performed on the GF/PA6 composites are shown in Figure 5. As shown in this figure, smaller displacements at failure are obtained for GF/PA6 composites as compared to those measured for GF/PP composites (Figure 4), even though the PA6 matrix can reach deformation at break in excess of 100% [6]. Further study will be required to explain this behaviour. From these results, it is apparent that the more brittle behaviour of the GF/PA6 composites makes them less suitable for the fabrication of intrusion beams. With regards to the failure mode, failure at the attachment point was observed for the (0/90) laminate. For the ±45 and quasi-isotropic configurations, failure at mid-span was observed, similarly to what is shown in Figure 7.

![Figure 4. Load vs. displacement curves for GF/PP composites.](image1)

![Figure 5. Load vs. displacement curves for GF/PA6 composites.](image2)

![Figure 6. Failure of GF/PP composite with ±45 lay-up.](image3)

![Figure 7. Failure of GF/PP composite with 0/90 lay-up.](image4)
3.1.2. Carbon fiber composites. Similarly to what was observed for the glass fiber composites (Section 3.1.1), significantly different mechanical behaviors were measured for the carbon fiber composites depending on the polymer matrix and stacking sequences (Figure 8 and Figure 9). For the CF/PA66 composites, larger deformation was obtained for composites having a ±45 lay-up (Figure 8). For this configuration, failure occurred in the span of the specimens by separation of the plies at multiple interfaces (Figure 10). Similarly to what was found for GF/PP composite, multiple delaminations were also seen at mid-span. In contrast, localized “brittle” failures at mid-span were obtained for the 0/90 and quasi-isotropic (QI) configurations (Figure 11).

Results of flexural tests performed on CF/PA6 composites are shown in Figure 9. As shown in this Figure, similar mechanical behaviours were obtained for 0/90 and quasi-isotropic configurations. As could be anticipated, much higher deformation was again obtained for the ±45 stacking sequence. However, for that particular stacking sequence, the displacement at failure obtained for CF/PA6 composite was seen to be significantly lower than the one measured for the CF/PA66 composite. It thus appears that CF/PA6 is less suitable for the fabrication of composite intrusion beams since large deformation is required for side impact protection [5]. For all CF/PA6 laminates, localized failure at mid-span was observed similarly to what is shown in Figure 11. In contrast, failure occurred by separation of plies at multiple interfaces for the CF/PA66 composite with the ±45 stacking sequence, as mentioned previously. This difference in failure mode probably explains the significantly different displacement at failure obtained for CF/PA66 and CF/PA6 composites.
3.2. Stamping of intrusion beam

3.2.1. Stamping trials. Stamping of composite intrusion beams was performed in this work using GF/PP and CF/PA66 composites, since these materials displayed the highest loads and displacements at failure during the identification of the most-promising materials (Section 3.1). Stamping trials were performed for three stacking sequences, i.e. ±15, ±30 and ±45. These stacking sequences were selected because most-promising results were obtained in the previous section for laminates solely composed of off-angle plies (±45 stacking sequence).

One of the biggest challenges associated with the composite stamping process is related to the deformation of the laminate since, unlike metallic sheets, a continuous fibre reinforced composite can be considered as essentially inextensible. For composites, the dominant deformation mechanisms are thus interlaminar shear and intralaminar shear. The former involves fabric plies slipping on top of each other while in the latter the fibres of successive plies rotate against each other. In this study, stamping trials were generally successful with the materials being able to deform to accommodate the geometry of the beam. However, as shown in Figure 12, fibre bridging could be observed on the surface of the stamped intrusion beams. This can be attributed to the high stiffness and low elongation of the reinforcing fibres which cannot conform to the small radius when in tension. Further work will be required to determine if such defects can be eliminated during the stamping process.

![Fibre bridging on stamped thermoplastic composite intrusion beam.](image)

3.2.2. Mechanical behaviour of stamped composite intrusion beams. Results of tests performed on stamped intrusion beams are shown in Figure 13 and Figure 14 for GF/PP and CF/PA66 laminates, respectively. As shown in these figures, similar trends are obtained for both materials with maximum loads and maximum displacements increasing with increasing fibre angle. Change of failure mode is also observed with increasing fibre angle. For ±15 and ±30 laminates, shear tear-out failure at the attachment point is observed (Figure 15), which probably explains the lower performance achieved for these configurations. For ±45 laminates, failure also occurred at the attachment point, but across the mounting point (Figure 16). Nevertheless, the displacement and loads at failure obtained in this study for the ±45 laminates suggest that thermoplastic composites are promising materials for the development of structural automotive applications, such as intrusion beams, where the combination of high load and high deformation are required. However, additional work will be performed in the future to prevent premature failure of the stamped intrusion beam at the attachment point.
4. Conclusions
An experimental investigation was performed to evaluate the potential of thermoplastic composites to be used for the fabrication of composite intrusion beam using the composite stamping process. To assess the potential of high performance thermoplastic composite materials, mechanical properties were first evaluated. From these tests, GF/PP and CF/PA66 laminates were identified as most-promising materials due to their higher load and displacement at failure. Stamped composite components were then manufactured from GF/PP and CF/PA66 laminates and tested under three-point flexural loading. Results showed that high loads and displacement at failure could be achieved, but that further work is necessary to avoid premature failure at the attachment point. From the results obtained in this study, it can be concluded that stamping of thermoplastic composites is a promising technology for the fabrication of structural automotive components such as intrusion beams.

5. References
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