Formability of roll-formed carbon fibre reinforced metal hybrid components and its experimental validation

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Keywords: CFRP, Hybrid, Lightweight, Roll Forming, Formability

Abstract: Carbon Fibre Reinforced Metal Hybrid (CFRMH) materials that combine a sheet metal substrate with a reinforcing carbon fibre patch represent a promising solution to reduce weight while increasing the structural and crash performance of future automotive vehicles. CFRMHs cannot be formed with conventional stamping processes and at high volumes. This currently reduces their widespread application. Roll forming is increasingly used in the automobile industry for the forming of lightweight and high-strength metal structural components. The major deformation mode in roll forming is simple bending and this reduces interlaminar shear and compressive stresses that lead to fibre failure and delamination issues when stamping CFRMH sheet materials. This work analyses the potential of applying the conventional roll forming process for the manufacture of a simple top hat section shape from CFRMH sheet. For this, first, the material is produced in a hot press and then formed to shape in a laboratory roll forming facility at room temperature. Different layup sequences are tested, and component quality is analysed after roll forming by visual inspection. The results suggest that roll forming presents a promising manufacturing method for the production of automotive components from CFRMH sheets. The roll formed open shells are joined to produce crash box structure and tested in 3-point bending. The results show that depending on the fibre orientation a significant increase in weight specific strength is achieved.

1. Introduction
Carbon Fibre Reinforced Metal Hybrids (CFRMH) contains a metal sheet substrate that is laminated to a carbon fibre reinforcement patch. CFRMH was first developed and applied in the aerospace industry to provide high specific strength and stiffness, good fatigue resistance and wear capacity. Recently, with the
increasing focus on lightweight design lightweight CFRMHs have been introduced to the automobile industry[1].

Early studies on the manufacture of fibre metal hybrid laminate mainly focused on common autoclave curing processes and Vacuum-Assisted Resin Transfer Moulding (VARTM) and were aimed at the aerospace industry[2,3]. These methods require a long cycle time and high cost in the moulding process [4], which has become the main obstacle to promoting the application of CFRMH in the transportation industry. The existing direct forming technologies for fibre/metal laminates include incremental sheet forming, laser forming and die stamping. However, the formability of hybrid sheet materials is lower than that of conventional sheet metals. This is mainly due to the delamination at the metal/carbon fibre interface and the tearing or buckling of fibres when formed[5].

Roll forming is increasingly used for the manufacture of automotive structural and crash components from high-strength steel such as rocker panels and bumper beams. The major deformation in roll forming is pure bending and this allows the forming of sheet materials with high material strength and low ductility. The tool contact is reduced to point contact between the top and the bottom forming rolls which can reduce interlaminar shear stress when forming a hybrid composite structure [6]. Therefore, roll forming may present a promising alternative for the rapid forming of CFRMH components [7].

In this study, flat CFRMH plates containing a flat mild steel sheet substrate laminated to various carbon fibre lay-up directions are produced in a hot press and then roll-formed to a hat-shaped open-shell component. Part quality after roll forming is visually inspected, after that crash box type hollow structural components are produced by rivet joining two roll-formed open-shell components; this is then followed by three-point bending tests to investigate the structural performance and compare load-bearing ability between the metal and the hybrid crash box. Finally, the damage on the tested parts was visually examined.

2. Materials and method

2.1. Materials and CFRMH sheet preparation

A mild steel (MS) with a thickness of 0.8 mm was used as the substrate and standard tensile tests were conducted according to ASTM E8/E8M [8]. The engineering stress-strain curve of three samples oriented in the rolling direction is shown in Figure 1. A commercial thermoplastic PA6 based CFRP supplied by Celanese (Celstran® CFR-TP PA6 CF60-03) with a continuous unidirectional (UD) fibre tow and a thickness of 0.13mm[9], was used as the reinforcement patch. This was bonded to the steel substrate with a thermoplastic adhesive multilayer-film Nolax Cox 490-I (Nolax) from the Nolax AG [10]. The material properties provided by the supplier are given in Table 1.

![Figure 1 Engineering stress-strain curves for three samples of mild steel](image-url)
Table 1: Material properties for CFR-PA6 and Nolax adhesive [9, 10]

| Physical properties       | CFR-PA6 | Nolax Cox 490-1 |
|---------------------------|---------|-----------------|
| Melting temperature (°C)  | 220     | 152-188         |
| Glass transition temperature (°C) | 57      | -               |
| Forming temperature (°C)  | 271     | -               |
| Tensile strength (MPa)    | 1909    | -               |
| Tensile Modulus (GPa)     | 100     | -               |

The hot press process can be split into two steps. First, the Nolax film was trimmed to size and then fixed in the centre of the steel substrate. After this, the sheet was hot pressed at 200 °C and 1 bar for 2 mins. The 0.9 mm shims were used to prevent the foil from squeezing out and then the compound was taken out to cool down under a weight of 5kg. Subsequently, six layers of CFR-PA6 composite were stacked up the top surface of metal sheet facing the fixed Nolax film. The sheet was then hot pressed for a second time at 250°C, 1 bar and 50 seconds. This was followed by cooling to 50 °C with a weight of 5kg. In Figure 2a, the dimensions of the steel substrate, the adhesive and the of CFR-PA6 composite are shown.

CFRMH blanks with three different lay-up conditions were produced and those are shown in Table 2.

Table 2: Test setup

| Description                          | Fibre orientation |
|--------------------------------------|-------------------|
| [0°]₆ oriented in the rolling direction and the subscript means six layers of CFR-PA6 | [0°]₆             |
| [90°]₆                                 | [45°/-45°]₃       |

2.2. Roll forming of the U-channels

The trapezoidal cross-section shape shown in Figure 3 was manufactured with the roll forming mill shown in Figure 4 and a strip feeding speed of 30mm/s was used. The roll former was limited to three roll stations and one feed-in guide. The roll gap was set as the total thickness of the hybrid blank (1.58 mm) and the
station distance was 300 mm. The bend angle increment was 10°. To form the final bend angle of 50°, therefore, the material had to be first roll-formed to 30° followed by a retooling of stations and the re-feed of the preformed sheet into the roll former to manufacture the final 50° angle. The roll forming flower pattern is given in Figure 3. Forming defects such as fibre breakage and delamination were analysed by visual surface inspection.

![Figure 3 Profile geometry and the roll forming flower pattern](image)

2.3. Crashbox assembly and flexural test
To test the structural performance, a crash box was created with two roll-formed trapezoidal parts. For this, the flange area was bent to form a top hat structure using a folding die. Then, two open shells were assembled using aluminium blind rivets in the top hat flange region (Figure 5a). In the centre section where the major deformation occurred the rivets were positioned close to each other with a distance of 12.5 mm to ensure sufficient joint strength. The cross-section profile of the profile is shown in Figure 5a. After joining, three-point bending tests were performed based on DIN-EN-ISO 14125 [11] with the test setup shown in Figure 5b. The span length between two supporters is set as 105 mm. The tests were conducted at a rate of 5 mm/min and terminated at the maximum punch stroke of 19 mm.

After the test, the deformed crash box was opened up by removing the rivets and material damage analysed by visual surface inspection and compared to the as-roll formed condition.

![Figure 5: (a) Cross-section profile of riveted double-hat crash structure and (b) flexural test setup](image)
3. Results

3.1. Product quality of the roll formed parts
Images of the patch surface after roll forming are shown in Figure 6 for the 3 different fibre lay-up conditions. When the fibres are aligned with the profile radius direction, MS/CFRP \([0°]_6\), a successful hybrid patch is roll formed with no visible defects. For the MS/CFRP \([90°]_6\) specimens, fibre buckling perpendicular to the bend line was observed. The fibre patch is positioned on the inner side of the bend and this leads to compressive stresses perpendicular to the bend line and parallel to the fibre direction of the CFRP \([90°]_6\). The results suggest that the fibres do not compress sufficiently when formed at room temperature and instead buckle to accommodate the compressive deformation. There is also some fibre cracking \(45°\) to the bend line direction in the CFRP \([45°/−45°]_3\) specimen. No obvious delamination between the CFRP and the metal substrate was observed for all fibre directions.

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3.2. Bending load and specific strength
The weight of all samples was estimated using the individual material densities and volumes. For the Mild Steel (MS), the CFRP and the Nolax adhesive densities of 7.86 g/cm³ and 1.447 g/cm³ and 1.10 g/cm³ were assumed respectively. This in combination with the individual material volumes gives an overall weight of 0.453 kg for the single mild steel crash box and of 0.501 kg for the CFRMH crash box counterpart. Figure 7a presents the recorded load-displacement responses of the MS base condition and the three different CFRMH conditions. The peak values were taken as the maximum bending load and the specific strength was determined by dividing the maximum bending load by the sample weight. Figure 7a illustrates the

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Figure 6 Top view: Surface quality of cold roll formed CFRMH parts with various layup orientations
highest maximum bending load for the MS/CFRP [90°]_6 condition. This represents an increase of 44% compared to the sole MS base condition. Even though the MS/CFRP[0°]_6 showed the best roll forming result it only led to a load improvement of 24% compared to the sole metal base condition. When the weight factor is considered, specific strength comparison was given in Figure 7b. All hybrid samples have a higher specific strength in comparison to the sole metal sample. The MS/CFRP [90°]_6 still shows the highest specific strength improvement which is 35.6% compared to the sole metal condition.

Figure 7 Mechanical performace (a) Bending load-displacement response (b) Specific strength comparison

After the 3-point bending test, the crashboxes were removed from the tester and then separated into the top and bottom channels followed by visual inspection. Figure 8 shows that during three-point bending deformation a centre bend is formed into the web. This leads to stretch deformation perpendicular to the part length direction, i.e., parallel to the fibre direction of the MS/CFRP [0°]_6 and results in fibre breakage as can be seen in Figure 8a. In the MS/CFRP [90°]_6, the fibres are oriented perpendicular to the direction of stretch. This leads to matrix cracking and the spacing out of fibres (Figure 8b). Inter-ply delamination near the bending line is obvious for the MS/CFRP [45°/−45°]_3 sample in Figure 8c. Overall, the occurrence of fibre cracking suggests that interface lamination after roll forming is sufficient to enable the loading of fibres during the structural 3-point bend test loading.

Figure 8 Failure status after 3-point bending

4. Conclusion
A Carbon Fibre Reinforced Metal Hybrid (CFRMH) component consisting of a sheet metal substrate laminated to a carbon fibre patch was successfully produced by hot pressing and conventional roll forming at room temperature. Subsequent 3-point bending trials performed on crash boxes produced from the roll-formed hybrid shells indicate an increase in specific strength of up to 35% compared to the sole metal sheet solution depending on the fibre orientation in the carbon fibre patch.
In the future, the hot-pressing step may be replaced by a continuous in-line hybrid sheet production process. If this can be achieved the roll forming process may represent a cost-effective solution to produce lightweight CFRMH components for the transport industry. The following conclusion can be made:

- The roll forming process allows the forming of metal/carbon fibre hybrid at room temperature.
- The roll formed component quality depends on the fibre orientation in the carbon fibre reinforcement patch. If the fibres are oriented parallel to the roll formed bend line (MS/CFRP [90°]ₖ) and then the best part quality is achieved.
- The roll formed CFRMH components showed a higher specific strength compared to the sole steel counterpart. The level of the increase in specific strength depends on the fibre orientation.

5. Acknowledgements

The authors would like to thank ARC Training Centre in Lightweight Automotive Structure (project number IC160100032) and the Ford Motor Company for their financial support. The authors further acknowledge the support provided by Nikolai Müller from the Technische Universität Braunschweig in performing the experimental work of this study.

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