Affordable Thermoplastic Matrix CFC / Metallic Framework Structures Manufacture

Project Report

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1. Introduction

Stressed skin carbon fibre composite structures are highly weight efficient for simple structures such as wings and shells. For more complex structures which are frameworks; either bare or panel covered, carbon fibre structures have very high manufacturing cost, and have complex joints which compromise weight saving. Examples are aircraft fuselage sections, automotive upper bodies and engine frames.

A structural concept to exploit the extreme stiffness of carbon fibre where aligned with the principal load, but also to provide simple and low cost attachment, is to combine thermoplastic matrix CFC tubing with metallic joints for structural attachment.

A current limitation to this concept is that for highly loaded structures, the CFC to metallic interface design is complex and their reliance upon adhesive bonding has quality assurance and safety difficulties.

The aerospace and automotive design communities have been excited for decades by the potential offered by the fast processing and the damage tolerance of thermoplastic matrix CFCs. However, conventional stressed skin manufacturing has proven extremely problematic due to the complexity of high temperature forming and mould tooling cost. Tubular sections of constant geometry are however relatively easy manufacture by tow winding or prepreg tape rolling and possibly by pultrusion or braiding/ RTM.

This project investigates the design and manufacturing technology for CFRP sections and metal jointed framework structures.

2. Project Objectives

Establish the feasibility and potential affordability of the conceptual process in terms of; frame section and joining piece manufacture and frame and joint attachment technique.

Propose framework designs based on the proposed approach for two structural applications.

3. Methodology

The following activities were undertaken:

A. Framework design and section manufacturing study

B. Section and joint attachment study

C. Joining process investigation

D. Manufacture and testing of structural elements

E. Framework structures demonstrator concepts

4. Framework design and section manufacturing study

4.1 The Challenge

The requirement of this activity is to define structural concepts, which most effectively utilise the design benefits of carbon fibre composite (CFC) whilst accommodating the manufacturing constraints for automated manufacturing. This is a significant challenge since all current CFC structures, which are weight efficient, are only suitable for very low rate manufacturing.

A structural and manufacturing study was carried out for a car structure using a structural analysis tool, Altair Optistruct and processing considerations. This optimisation takes into account the manufacturing factors and limitations of a light weight multi-material design, based on three main scenarios: geodesic and bionic shapes; tubular composite structures with metallic nodes; and over-moulded metallic skeletons. Structural lay outs and manufacturing technologies are considered to solve the challenges for each experimentally developed scheme. This enables the development of industrial feasible schemes.

4.2 Use of structural optimisation to guide the design of medium volume automotive body components

A recent trend in the marketing of additive manufacturing is to highlight its ability to create seemingly impossible organic style shapes and structurally optimised parts (Figure 1: Three of the four above images come from the EDAG, who are feeding the trend of optimised 3D printing with substantial use of the software package Optistruct™, from Altair.) Creating such shapes in a traditional layer by layer 3D printing approach presents mechanical weaknesses due to layer interfaces, particularly when placed perpendicularly to the load in the branches of the frame (which are naturally loaded in tension when triangulation is applied [1]). In addition, the additive manufacturing technology is currently far from capable of meeting medium volume production rates compared to sheet moulding type current techniques. It is an extremely slow process [2].

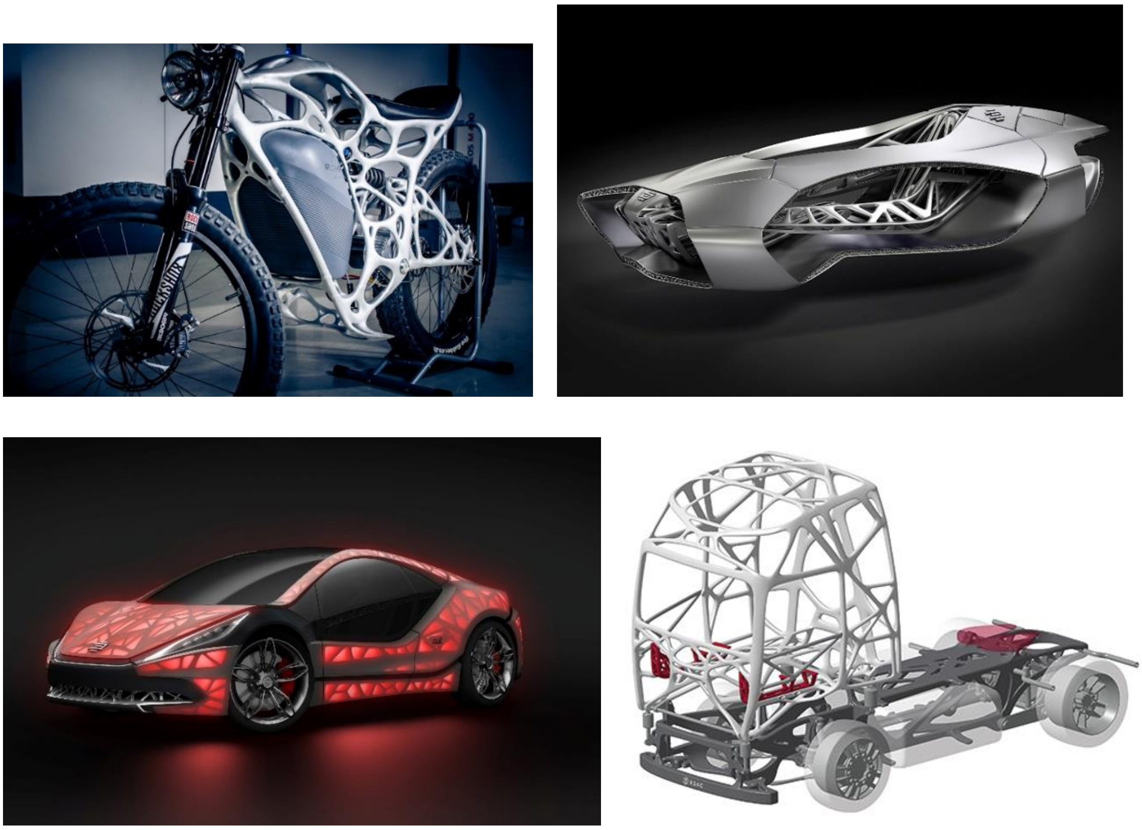


Figure 1: Three of the four above images come from the EDAG, who are feeding the trend of optimised 3D printing with substantial use of the software package Optistruct™, from Altair.

The study has applied function driven structural optimisation [4], suitable for a medium volume manufacturing rate, adapted to hybrid metallic / composites, multi-material, light weight structures.

4.3 Framework Concepts Studied

Within this project, three main structural concepts have been determined:

a. Geodesic and bionic shapes
b. Tubular composite structures with metallic nodes
c. Over moulded composite skeletons

a. Geodesic and bionics shapes

Figure 2: The Cirkomp isogrid bike, a mix of bionic and geodesic shapes

Similar to the above described 3D printed extreme solution, isogrids [5], anisogrids [1], and bionic shapes provide, in theory, the most radical weight saving solutions. Structures are particularly lightweight if the composite fibres can be aligned with the natural tension-compression state of every branch of the structure. Thermoplastic matrix structures potentially allow the use of an articulated pultrusion head (Figure 3, left) that will deposit tapes or tows along the frame branches. Since the material can be conformable during cooling at the exit of the die, the technique could allow the provision of continuous material around all parts, the straight and the curved areas of a structure. Thermoset matrix pultrusion needs consolidation when curing inside the die, which limits it to straight profiles. A vehicle manufacturing facility can be imagined where the car components are placed in their locations and the structure is subsequently built around it by one or several robots (Figure 3.)

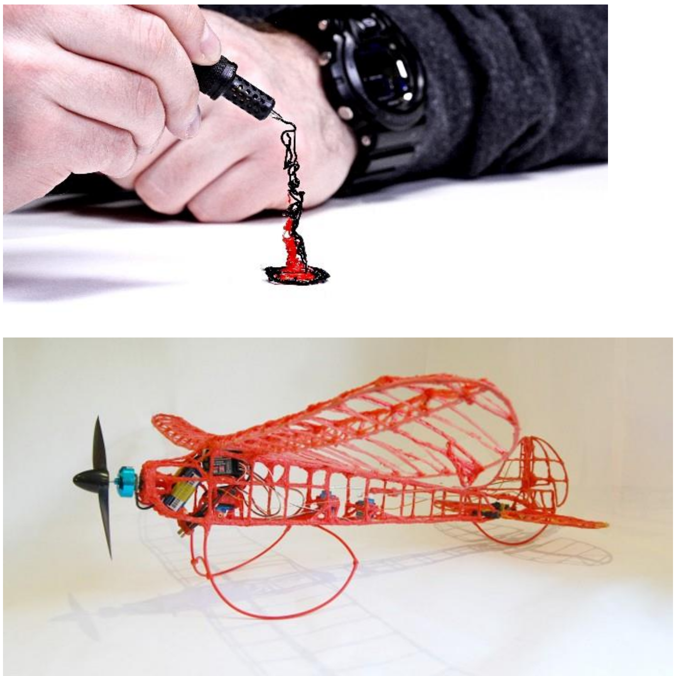


Figure 3: Thermoplastic pultrusion head and an in-situ pultruded load bearing structure

The method would provide the advantage of being able to create the most optimised shape together with the most aligned material, which could lead to maximum weight reduction over metal. However, the cycle time issue remains a challenge. In addition, any structure which requires fewer sections and places bending or twisting loads on the sections will require the short solid sections to be replaced with larger tubular sections and manufacturing a tube by this deposition technique using a lay-up with non-axial fibres may be impossible owing to access for the deposition head. Other problems arising may be crash energy absorption, dismount ability for maintenance and repair, laminate quality, and process robustness. In addition, there is a crystallinity issue when welding/consolidating one thermoplastic tape on top of another. The variable level of crystallinity of the polymer may result in susceptibility to fluids and warpage. There is a trade-off between the performance of a highly crystalline material, providing toughness at low temperature and chemical resistance and the process capability of an amorphous one [6–11].

b. Tubular composite structures with metallic nodes

Figure 4: Cikoni's lightweight shelves for The Vision Van of Mercedes-Benz Vans [12]

Compared to the geodesic / bionic shape concept, a tubular composite structure jointed by metallic nodes appears more realistic for high rate manufacturing. However, weight saving capability is likely to be reduced by some level for structures where the joint loads are in plane. However, metal nodes are likely to be weight effective compared to CFC where bending and twisting will introduce complex loading, especially through thickness (peel) loads.

There are many opportunities provided by this solution in terms of manufacturing. Technology. The tubes can benefit from a continuous production process. This would either be braiding or pultrusion or both, both of these already provide high levels of fibre angle tailoring [13,14]. In addition, taking advantage of the physics of thermoplastics can allow novel metal-to-composites joining techniques by virtue of the materials reform ability [15–17]. Interlocking can become the main mechanism of joining (see Figure 5), rather than traditional adhesion (with the difficulty of managing quality for high rate manufacturing, and rather than traditional mechanical fastening (which is not well suited to highly stressed composite components due to fibre disturbance).

Figure 5: TU Dresden's blow-moulding interlocked assembly

Metallic nodes are an effective and practical option, when considering the need for complex stress state bearing, as well as ductile failure and the complex load paths of joining components; in particular, through thickness loading.

c. Over-moulded skeletons

The tubular section / metallic node approach’s main challenge is a robust and lightweight joint design. This is due to the unavoidable proximity of the composite to metal interface with the critical complex loading zone of the nodes. To overcome this problem, an alternative approach using and over-moulded skeleton would transfer loading away from this interface for the most critical load cases. Similar to Gordon Murray’s Design iStream™ solution, a simple shape metallic skeleton would form the whole main load bearing structure, without discontinuity and ensure ductile failure during crash. An in-situ over-moulded composite would provide the complete body shape and handle the secondary loads.

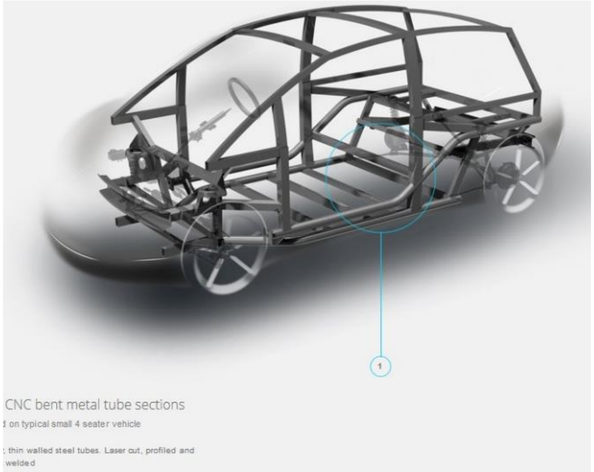


Figure 6: Gordon Murray Design iFrame

The structure is predominantly glass fibre composite, but the continuous presence of the metal throughout the structure provides additional stiffness and easily predictable crash behaviour. The main challenge, in addition to guarantee sufficient weight saving despite the substantial presence of metal, is to develop automated in-situ over moulding processes.

In terms of joining, the opportunity of interlocking is also present here, through use of the flow of short fibres during compression moulding (Figure 7 below).

Figure 7: Audi and Secar over-moulding concepts

4.4 Summary

Initial framework layouts were generated using comprehensive simulation models. They are function driven, taking into account as many design constraints as possible (crash, passenger space, visibility, safety equipment…) Those constraints are applied to a design space that is not inspired from existing metal structure. The shapes were generated from the function of the object and the novel manufacturing solutions to be developed, rather than from existing metallic forms. A composite solution should not be an adaptation of a metal solution. The structure layouts and associated joints have been re-schemed and developed.

The initial study indicates that the most weight efficient concept for structural stiffness is the geodesic / bionic approach. However, this will incur the greatest manufacturing challenge, requiring both a novel material deposition technique and result in very complex structures, having many small section elements.

The metal frame with short fibre over-moulding approach offers the lowest cost solution, but with the highest mass.

The CFC section / metallic node option is the most practical approach for both light weighting and fast, automatable manufacturing, the challenge being to develop a robust joining solution.

Design studies were carried out, to investigate solutions for the limitations of each of the three routes of development (**Error! Reference source not found.**.)

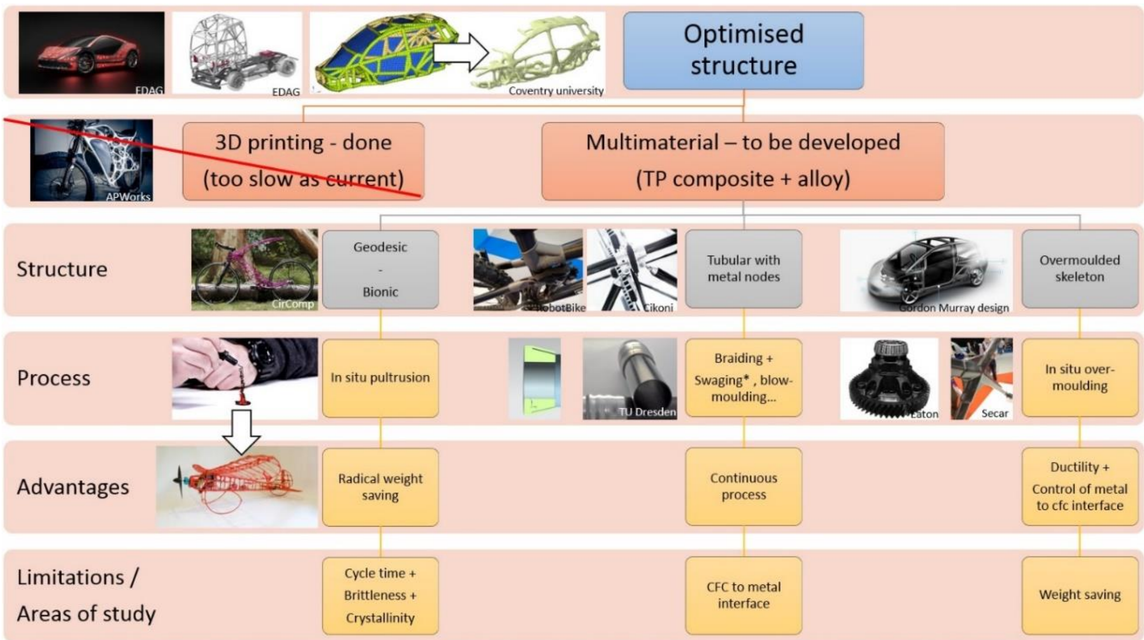


Figure 8. Overview of the structural approach comparison

4.5 Application of the Thermoplastic Framework Concepts to a Complete Automotive Body

Introduction

The aim is to re-design automotive structures, in order to sustain the industry technological transition from metals to carbon fibres. The design strategy to adopt was function driven, in order to avoid black metal design. Therefore, a comprehensive definition of an automotive structure functions in terms of vehicle dynamics, crash resistance, and passenger comfort was first drawn up. Then, a structural optimisation process using FEA package HyperWorks was used to provide a futuristic re-visiting of an automotive structure. The concepts need to meet high expectations in weight saving, costs of manufacture, and cycle time.

The recent development of optimisation software packages such as Altair HyperWorks, LS-Dyna, and Abaqus has enabled few structural revisiting for automotive structures and similar transports:

- EDAG has developed multiple concepts for structurally optimised vehicle structures. Mainly relying on the development of additive manufacturing to achieve the bionic shapes obtained, most of their concepts are unrealistic, in terms of close future high volume production application. However, a truck concept could be translated into a feasible structure, when applying some metal manufacturing constraint to its wacky design [1]
- Cavazzuti et. al. made a topology optimisation study in 2011 for Ferrari, trying to extract what the structure of the F430 could look like if it were to be radically light weighted [2]. The strategy of optimisation developed consists in applying a comprehensive set of dynamic performance constraints to a design zone, in order to obtain a function driven optimised design. However, similarly to EDAG, the manufacturing aspect is underdeveloped, and the design models obtains are unfeasible in an industrial scenario.
- Coventry University has given clues for optimal designs to be translated into metallic beam design [3].

The vice president of Altair mentioned in November 2016 the need to push the structural optimisation algorithms forward and integrate industrially realistic manufacturing aspects in order to bring light weighting to reality [4]. Our proposal is to apply function driven structural optimisation [2,3], in a high-volume manufacturing environment, adapted to alloy-composites multi-material light weight structures.

Methodology

Similarly to the study of Cavazzuti et. al., the first part of the study concerns the definition of a design zone. In other terms, defining in 3D which are the physical boundaries within which the structure can be deployed. Once the design space is defined, a list of relevant boundary conditions needs to be defined. It needs to include the most influent parameters for the structure design. Indeed, the longer the list, the greater the computational time, exponentially.

The physical and geometrical boundary are input in an FEA model, with a topology optimisation solver. The shape obtained is at this point the most lightweight shape to serve the structural constraints defined in the model. Assuming those constraints are both the most relevant and are weighted according to the needs of the application, material and manufacturing considerations need to be taken in consideration, in order to satisfy the needs of high volume production.

a. CAD definition

Using Catia V5, the case study of the Audi R8 was considered. The chassis of the R8 is shown in Figure 9. below, in parallel to one of its variants, the Lamborghini Huracan:

Figure 9: Audi R8 and Lamborghini Huracan. Both structures are made of aluminium and carbon fibre composites. The platform is the same, but the upper part differs due to exterior aspect.

Two models are generated, as shown on Figure 11. below. The first one takes exterior styling and aerodynamics into account. The second one is more simplistic, which is planned to have a positive effect on computational time, and not to restrict the scope of design to existing technology. The aesthetic will follow the technology, and not the inverse! Since not only the manufacturing technique is considered as radically different from the existing R8, but also the propulsion including one electric engine in each wheel and a battery floor, the second CAD model is taken into account for the rest of the study.

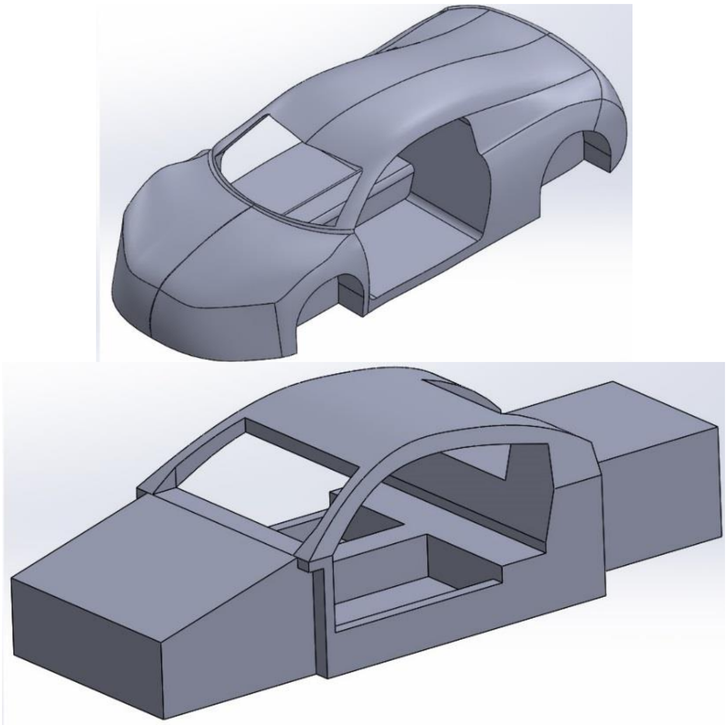


Figure 10: CAD design zones for the case study of a revisited Audi R8. On the left, the design is conservative and follows the current envelop of the R8. On the right, a simplified design zone that allows faster computational time, and greater design freedom.

b. Boundary conditions

Crash is the main design constraint in automotive, due to its severity for homologation. Passenger safety for front crash, side crash, and roof crash represent most of the cases for EuroNCAP and USNCAP regulations [5]. In addition, in the case of high-end cars such as the R8, a structural indicator of performance is taken into account: the torsional stiffness.

i.Front crash calculation

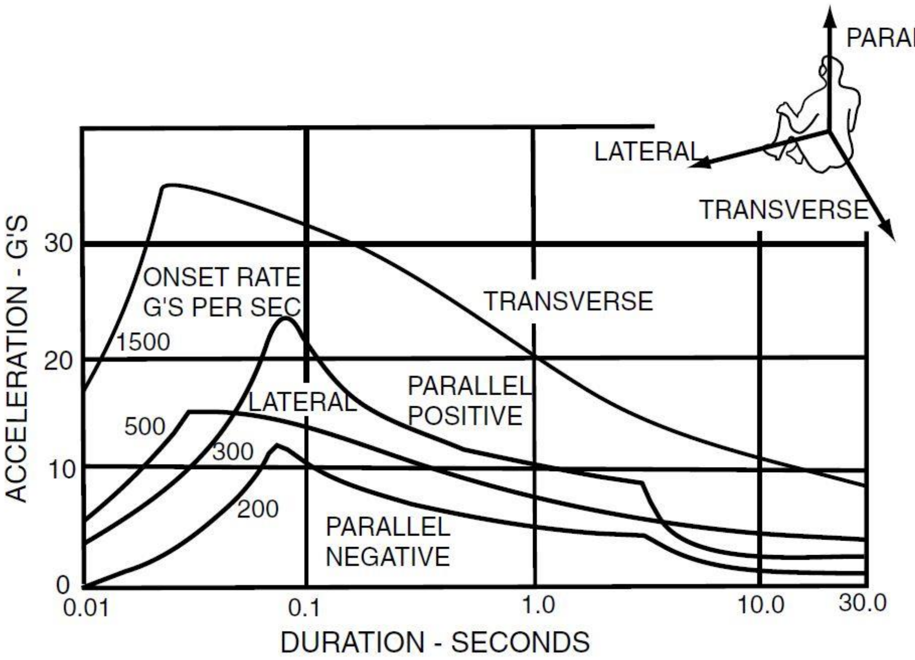


Figure 11: Limits of human tolerance to linear acceleration [6]

The G-force that a human body can withstand in a transverse direction is determined from Figure 11. above. In the front crash, the car is moving with the speed of 17.7 m/s and the weight of it is 1600kg. From basic acceleration equation (1), calculating the minimum rate that a human body can decelerate. By approximating the G-force and seeing the time it needs to stop at, the G-force is selected.

$$\vec{a} = \frac{\Delta\vec{v}}{\Delta t} \rightarrow \Delta t = \frac{\Delta\vec{v}}{\vec{a}} = \frac{\frac{17.7\left[\frac{m}{s}\right]}{2}}{25[G] \cdot 9.81\left[\frac{m}{s^2}\right]} = 0.036s \quad \textbf{(1)}$$

By having the time needed to stop the speed and the weight of the car, the impact force can be calculated, considering the momentum principle. So for this, equation (4) is used.

$$\vec{F} = \frac{\Delta\vec{p}}{\Delta t} = \frac{m \cdot \vec{v}}{t} = \frac{1600[kg] \cdot 17.7\left[\frac{m}{s}\right]}{0.036[s]} = 786666[N] \quad \textbf{(2)}$$

ii.Side crash calculation

The process is the same as in the front crash only the values are different. The speed and the weight of the barrier crashing into the side of the car are 13.8m/s and 1500kg. The G-force that can be exerted in lateral direction is determined to be 13G from the Figure 11.

$$\vec{a} = \frac{\Delta\vec{v}}{\Delta t} \rightarrow \Delta t = \frac{\Delta\vec{v}}{\vec{a}} = \frac{\frac{13.8\left[\frac{m}{s}\right]}{2}}{13[G]\cdot 9.81\left[\frac{m}{s^2}\right]} = 0.054s \quad \textbf{(3)}$$

From this the impact force is calculated

$$\vec{F} = \frac{\Delta\vec{p}}{\Delta t} = \frac{m\cdot\vec{v}}{t} = \frac{1500[kg]\cdot 13.8\left[\frac{m}{s}\right]}{0.054[s]} = 383333[N] \quad \textbf{(4)}$$

iii.Roof crash calculation

A roof crash is calculated differently as previous ones. Here the calculated force acting on the roof is.

$$\vec{F} = W\cdot g\cdot STWR = 1600[kg]\cdot 9.81\left[\frac{m}{s^2}\right]\cdot 4 = 62\ 784\ [N] \quad \textbf{(5)}$$

Where W stands for weight of the car, and STWR stands for strength to weight ratio.

iv.Torsional stiffness calculation

This parameter is determined based on the torsional stiffness of Audi R8. The value for it is found on the web page [7] and is equal to 40kNm/degree.

c. FEA model definition

The four above boundary condition input are applied to the FEA model, as shown on Figure 12.

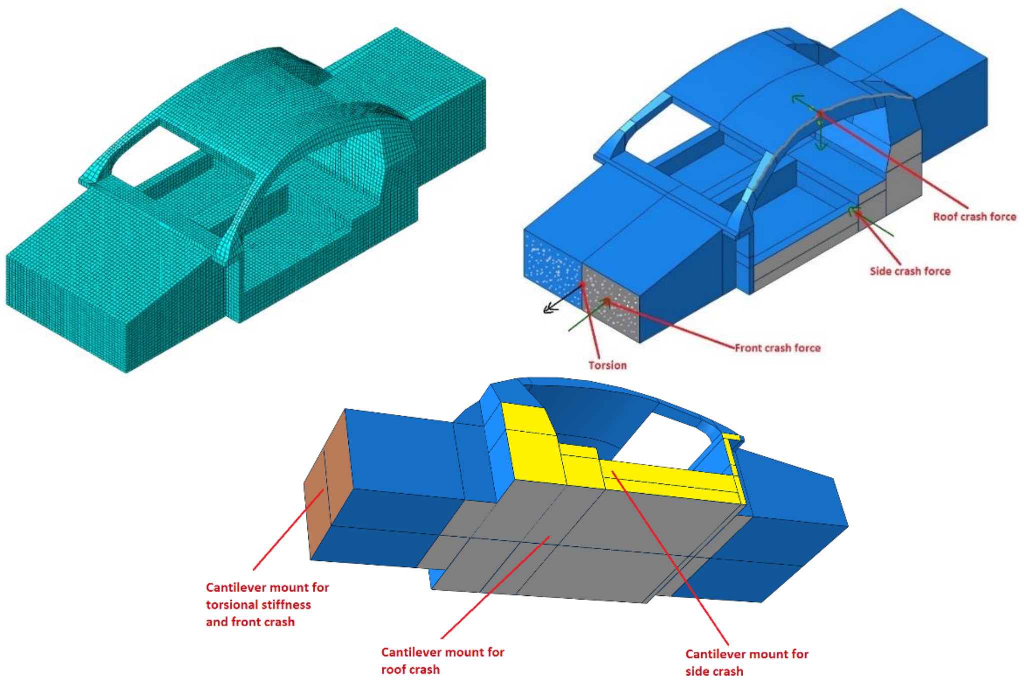


Figure 12: Top left: the number of elements of the model is around 90,000, determine by convergence study. The geometry of the model is divided in areas where the boundary conditions are applied.

The solver for FEA and topology optimisation is Abaqus.

The results of the topology optimisation will allow setting scenarios of manufacturing, including metal-cfc multi-material solutions. Those scenarios will have to present various degrees of compromise, in comparison to the theoretical optimisation obtained numerically. Therefore, they will have to be compared on the following criteria:

- Weight at equivalent mechanical performance
- Cycle time
- Total production costs

Results and discussion

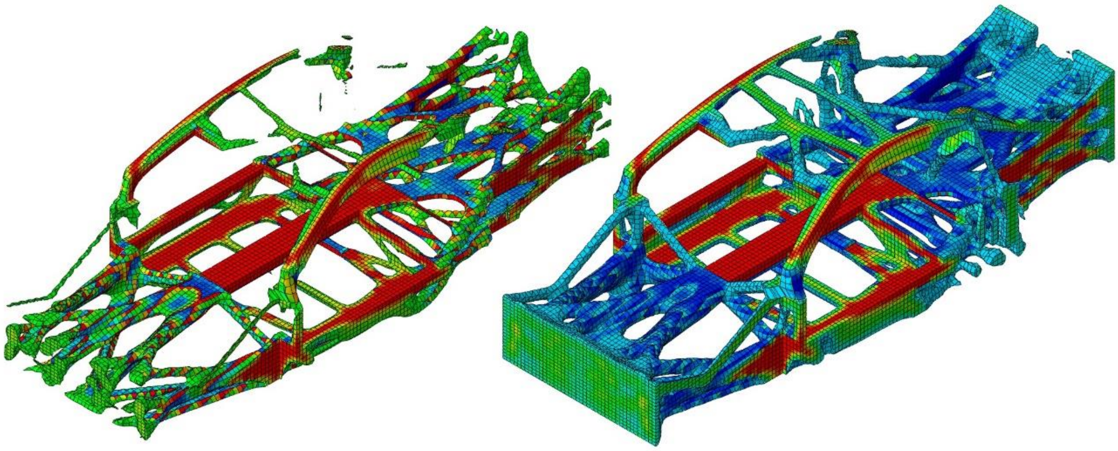


Figure 13: topology optimisation result, for as minimum element density set respectively to a value of 0.5 and to a value of 0.25

The four previously defined boundary conditions have created within their design zone the shape shown on above Figure 13. The electric solution considered for the propulsion of the vehicle increases the design possibilities for the front and rear axles. It is interesting to see that the floor tunnel, without its function of making space for the torque shaft, still has a structural interest. Despite interesting bionic shape development at the front and the rear of the cockpit, it is chosen to focus on the cockpit itself, as being the richest universal case, to discuss manufacturing (Figure 14).

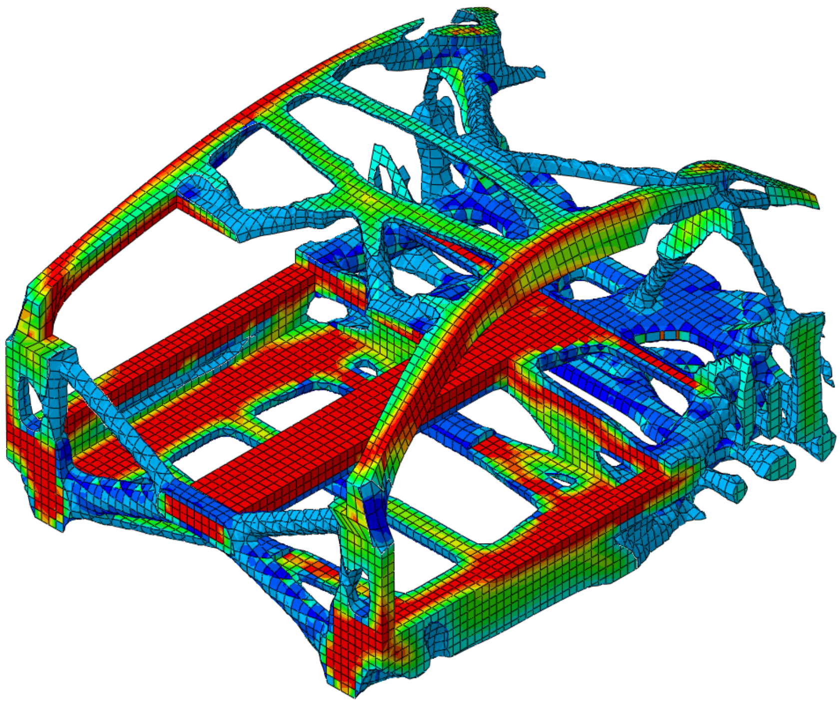


Figure 14: topologically optimised life cell

Two multi-material manufacturing scenarios have been considered, with the aim to be close enough to the optimised model of Figure 14. to guarantee significant light-weighting in comparison to metal design, while still including a high volume production feasibility. The first scenario takes mainly existing manufacturing technologies into account, or technologies imaginable to be applied in a very close future concerning the thermoplastic matrices. The second scenario implies more significant step change in metal-to-composites joining technology.

Manufacturing scenario 1

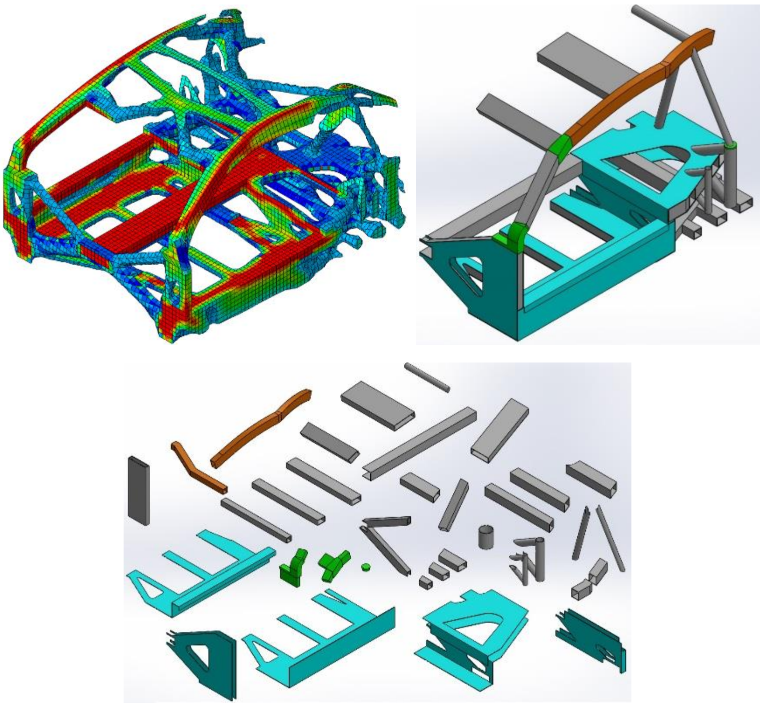


Figure 15: from optimised cockpit, to concept 1 (half view), to corresponding exploded view. Four different manufacturing processes are highlighted, in four different colours

The first concept described on the above Figure 15. relies for most of its parts on traditional pultrusion (highlighted in grey).

The panel shaped parts (in blue) are thermoplastic matrices flat organosheets produced in a continuous process, cut in complementary patterns and folded. This is close to current folded metal sheets techniques, and gives a great opportunity for exploiting the re-formability of thermoplastic matrices. It has a potential of only few seconds cycle time per part, as they can be formed simultaneously, from the continuous production of flat organosheet. In addition, in has a potential for reduced investment costs, as it can use existing metal sheet folding systems. Finally, in comparison to metals, the total energy cost is likely to be lower.

Short fibres connecting nodes appear in green. Their isotropic properties can withstand complex loads. The use of thermoplastic matrices can allow welding as a joining mechanism with the other parts. The essential criteria for those nodes being the isotropy, they can also be considered as metal mouldings. The dimensioning of the nodes on Figure 15. corresponds to aluminium. A short fibre solution would require bigger sections.

Finally, the brown parts are curved pultrusions. If this has been an area of research for thermoset matrices [8], curved pultrusion shows much greater potential with thermoplastics, thanks to its re-formability, higher speed of consolidation, and ability to be coupled with a continuous process such as braiding [9].

Manufacturing scenario 2

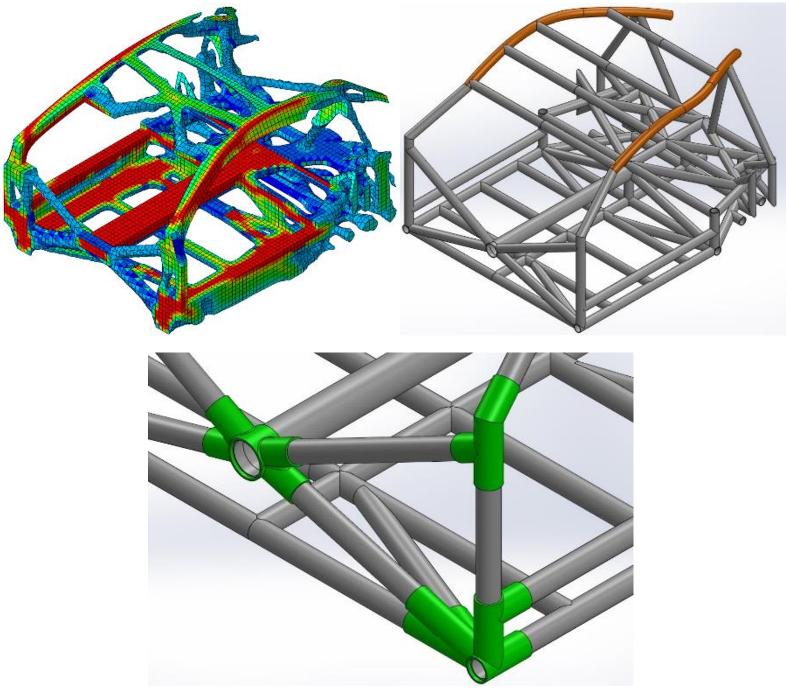


Figure 16: from optimised cockpit, to concept 2, to corresponding zoom on nodes. Three different manufacturing processes are highlighted, in three different colours

In comparison to the first concept, the straight pultrusions also appears in grey; and the curved pultrusions in brown correspond to the same parts. This concept has the particularity of presenting metallic connector to a large number of straight pultrusions. This large proportion can suggest a radical reduction of production costs and cycle times. However, this concept relies on effective novel joining methods between metal and composites. The swaging of the pultruded tubes can be considered in order to create a mechanical interlocking [10]. Alternatively, wrapping is an option that will be further developed.

Conclusions and further work

Although the two scenarios developed above present concepts for multi-material optimised lightweight structure for high volume production, there is a need for further developing the range of scenarios, as well as their metallic and prepreg baselines. In addition, following the comparison defined in section c, an FEA model needs to be generated for each scenarios in order to be able to compare them in terms of performance, lightweight potential, as well as costs and cycle times.

This study has highlighted the potential of thermoplastic matrices for high volume production, and particularly concerning CFC-to-CFC as well as metal-to-CFC joining. Several options and hypothesis for solutions will be developed experimentally:

- Wrapping
- Swaging
- Forming
- Over-moulding

References

[1] EDAG. Light, easy and flexible future for heavy commercial vehicles 2014. http://www.edag.de/en/edag/press-media/press-information/press-releases/news-single/getarticle/News/detail/light-easy-and-flexible-future-for-heavy-commercial-vehicles.html (accessed October 23, 2017).

[2] Cavazzuti M, Costi D, Baldini A, Moruzzi P. Automotive Chassis Topology Optimization : a Comparison Between Spider and Coup ´ e Designs 2011;III.

[3] Bastien C, Prem A, Bastien C, Dickison M. Multidisciplinary Design Optimisation Strategies for Lightweight Vehicle Structures Multidisciplinary Design Optimisation Strategies for Lightweight Vehicle Structures. 10th Eur. LS-DYNA Conf. 2015, Wurzburg, Germany: 2015.

[4] Autocar Pro News Desk. "No matter what material is being used, we have the optimisation technology to facilitate lightweighting for automakers." Nov 14 2016.

[5] Lukaszewicz DHJA. Automotive Composite Structures for Crashworthiness. In: Elmarakbi A, editor. Adv. Compos. Mater. Automot. Appl. Struct. Integr. Crashworthiness. 1st ed., John Wiley and Sons, Ltd.; 2014, p. 99–127.

[6] Brulle R V. Engineering the Space Age: A Rocket Scientist Remembers. Air Univer. Maxwell Airforce Base, Alabama: 2009.

[7] Carr. Car Body Torsional Rigidity – A Comprehensive List (Updated 12/27/2016). You Wheel n.d.

[8] Britnell DJ, Tucker N, Smith GF, Wong SSF. Bent pultrusion — a method for the manufacture of pultrudate with controlled variation in curvature 2003;138:311–5. doi:10.1016/S0924-0136(03)00091-8.

[9] Maron B, Garthaus C, Hornig A, Lenz F, H??bner M, Gude M. Forming of carbon fiber reinforced thermoplastic composite tubes - Experimental and numerical approaches. CIRP J Manuf Sci Technol 2016;170028. doi:10.1016/j.cirpj.2016.09.004.

[10] Barfuss D, Gr??tzner R, Garthaus C, Gude M, M??ller R, Langrebe D. Intrinsic manufacture of hollow thermoplastic composite/metal structures. AIP Conf Proc 2016;1769. doi:10.1063/1.4963580.

5. Thermoplastic Sections and Metallic Node Concepts – Section and Joint Attachment Study

Following the initial framework layouts, design concepts for frame sections and joints were proposed. The common idea to the forming candidates described is to take advantage of the physics of thermoplastic matrices and their ability to be re-shaped during an assembly process.

5.1 The Challenge

Current connections between CFC sections use either adhesive bonding, bolting or ply lamination to transfer loading through the joint. Bonding is vulnerable to failure through either surface preparation or adhesive application variability and hence requires very costly NDE or proof testing. Bolting requires massive thickness build-ups and heavy metallic overlap flanges. Laminating plies is highly laborious to provide the necessary fibre alignment.

For fast assembly, a new type of joining technique is required. These should utilise the formability of thermoplastic matrix CFC to provide an interlocking type of connection to overcome the three described disadvantages of the current techniques.

In spite of many drawbacks, thermoplastic matrices are often presented as the future of composites in the high volume production industry, thanks to its potential for fast processing. However, the recent advances in thermosetting snap-cure matrices, allowing isothermal processes shorter than a minute [1], tend to question the idea that thermoplastics are the only way.

The reversibility of thermoplastics can actually offer much more than just a slightly accelerated cycle time. Joining and assembly can be completely redefined thanks to their physical properties, leading to abilities that were not achievable so far with thermosetting matrices:

- Re-shaping
- Interlocking
- Welding
- Over-moulding
- Thermoforming
- Wrapping
- Swaging

- Flowing
- Etc…

Taking advantage of thermoplastics physics is going to be one of the main themes of study. In complement, taking advantage of the possibilities offered by short fibres is going to be essential in the perspective of high volume production scenarios which will require complex geometry designs and flexible manufacturing techniques. Keeping an eye on a symbolic objective of 50% weight saving to be achieved versus current alloy solutions, the proportion of short fibres will have to remain limited, due to low mechanical properties.

Within the same trade-off between the modularity of design and manufacturing on one side, and radical light-weighting on the other side, the aim will be to find a multi-material approach. It will have to include alloys for their multi-directional load bearing capability, their ability to fail in a controlled manner, and their low-cost processing.

This scope will be applied to each of the three previously defined routes for optimised lightweight high volume production structures (Figure 8.)

- Geodesic and bionic structures
- Tubular composite structures with metallic nodes
- Over-moulded skeletons

5.2 Geodesic / Bionic structures

How does a thermoplastic composite heal to itself? This question will be central in the consideration of an in situ deposition of impregnated fibre tows. The application of temperature and pressure in correlation with the part geometry during the process presents a high complexity. It is particularly true when aiming to satisfy aerospace requirements in mechanical properties and quality control [2–8].

An in situ 3D tow placement presents the potential of achieving relatively complex geometries with a continuous tow, therefore guaranteeing the highest possible mechanical properties. This is an opportunity for improved metal-to-composite interface, thanks to avoiding the fibre disruption that almost all the current joining methods induce, as well as improving the stiffness match between dissimilar materials. The picture below illustrates the form it could take. An interlocking is created through a groove path for fibres in the metal. The tow is wrapped around the metal part, taking advantage of the high cooling shrinkage of thermoplastics to constrain the joint.

Figure 17: seen at JEC Paris 2017, Fraunhofer's optimised frameworks are in reality made using OOA prepreg processes. However, they set an accurate design model for future 3D tow placement structures and joining.

The integrity of the interlock created will not only be experimentally investigated in terms of load transfer capability, but also fatigue behaviour, and failure brittleness. Those two points are inherent to highly directional properties of the tow, and thermoplastic matrices creep and relaxation.

In addition to working on redefining the metal-to-cfc interface geometry, the in situ 3D tow placement may lead to redefinition of the access to car components. Compared to the traditional process of assembling finished parts together, an in-line process of structure consolidation around the components of a car will open the possibility to assign a greater part of the volume of the car to structural purposes. The access to those components for repair and maintenance will have to be integrated in the structural design. One of the possibilities to answer this challenge would be to replace the single bonnet by a system of several drawers to access compartments (see analogy with phone concept in Figure 18.)

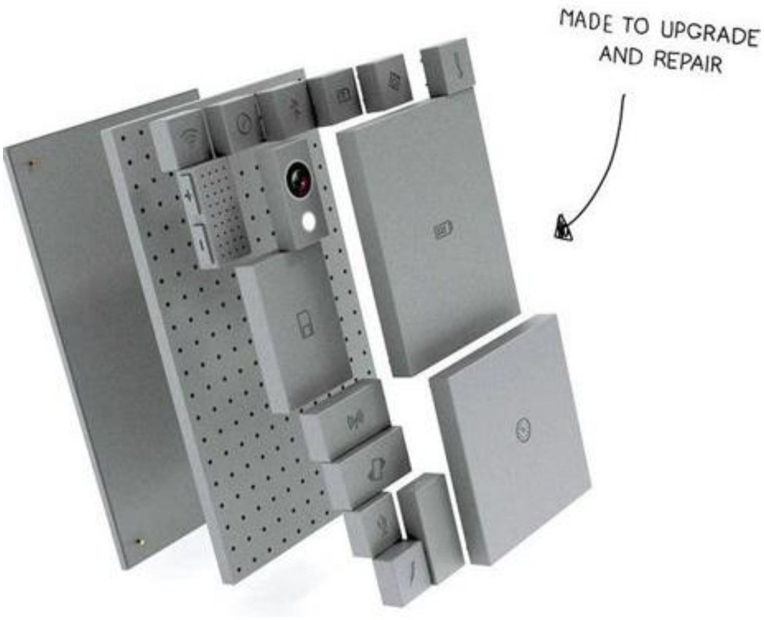


Figure 18: Phonebloks mobile phone concept by Dave Hakkens [13]**. The access to components have been redefined, here to serve another purpose than structural. Source: Dezeen.com**

5.3 Tubular composites structure with metallic nodes

The sections of framework have mainly highly directional stresses, which offers high structural potential for composites. The load becomes multi-directional in the area of the nodes, which is why isotropic materials such as alloys can be preferred. The choice of alloys in areas of stress concentration and complex loading is also justified by a better knowledge of their failure mechanisms.

Figure 19. illustrates those design choices [9]. The Robot Bike™ is considered as one of the most desirable mountain bike frames by people who are used to spend 4400£ in a 3kg assembly of 6 tubes and 6 nodes. Part of the 4400£ is the price of exclusivity, but production cost and time are nevertheless high, due to the use of long cure aerospace grade epoxies, hand lay-up, titanium 3D printing. In addition, the designers had no other choice but to use double lap shear as a joining technique, rather than destroying the fibres using traditional mechanical fastening. Double lap shear presents high mechanical performance when perfectly processed, but cannot avoid major drawbacks:

- Long cycle time, due to thermoset curing.
- Difficult quality control, both dimensionally and in terms of adhesion, cure distribution.
- Brittle behaviour. Made to work exclusively in shear, an adhesive joint will tend to break catastrophically. Tougher resins can be used, but with a knockdown in stiffness. The surface of adhesion tends to be over-dimensioned to overcome any uncertainty. The over-dimensioning is accentuated by the fact that the stress distribution is parabolic along the interface, making the two ends of it taking most of the load.

In order to solve the dependency to adhesion alone and its multiple issues, it is suggested to use the re-shaping ability of thermoplastics to increase the number of joining mechanisms. Dresden illustrates it by a multi-scale approach (Figure 20.) The micro- and meso-scale joining mechanisms are the ones of

Figure 19: Robot Bike™, thermosetting composite tubes and titanium nodes. The frame alone costs 4400£. The cycle time is 48h. Source: RobotBike.co

adhesive. The macro scale mechanisms is a mechanical interlock created by the controlled deformation of the fibres thanks to thermoplastic resin melting. It is made by blow moulding [10], using internal pressure to mould the composite into the aluminium insert.

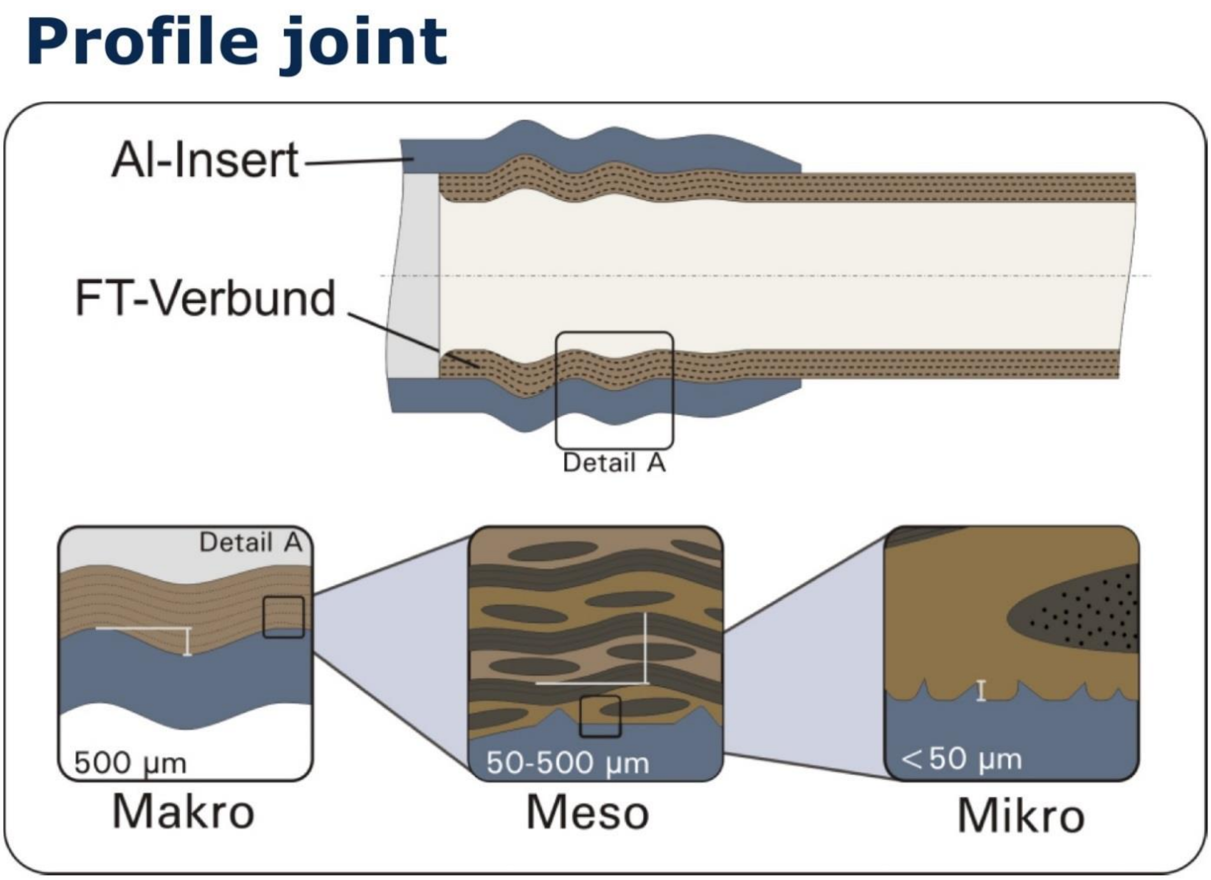


Figure 20: TU Dresden's multi scale approach of joining. The macro scale being the essential benefit to traditional adhesion joints. Source: TU Dresden internal report

This example is a relevant starting point for further thinking around shaping methods to allow macro scale interlocking in addition to micro scale bonding, without inducing fibre disturbance via mechanical fastening. An experimental study of swaging has been being carried out, using carbon tubes and two-part aluminium fittings relying on a threaded junction to clamp the deformed end of the tube. This way it avoids fibre disturbance and provides a tension-compression-shear load bearing capacity, where all scales of joining are participating (Figure).

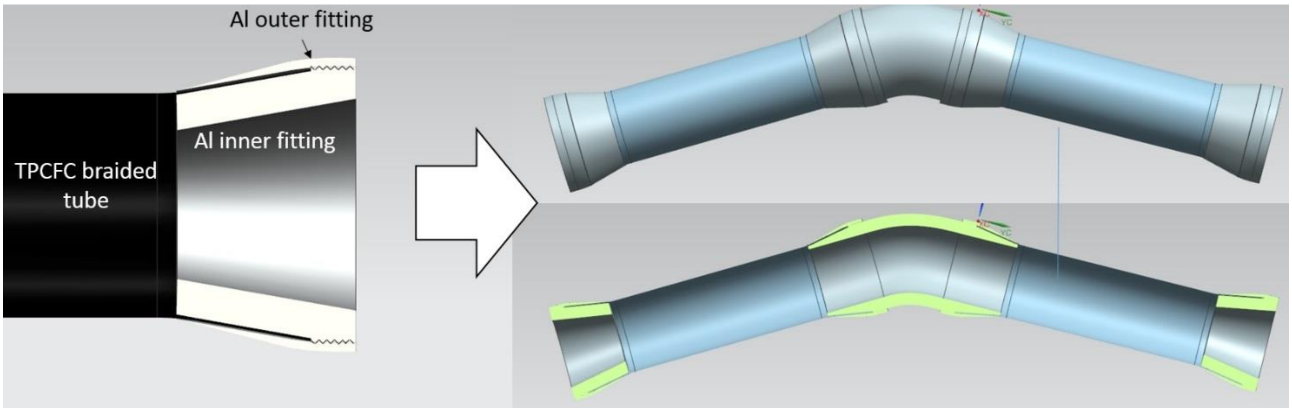
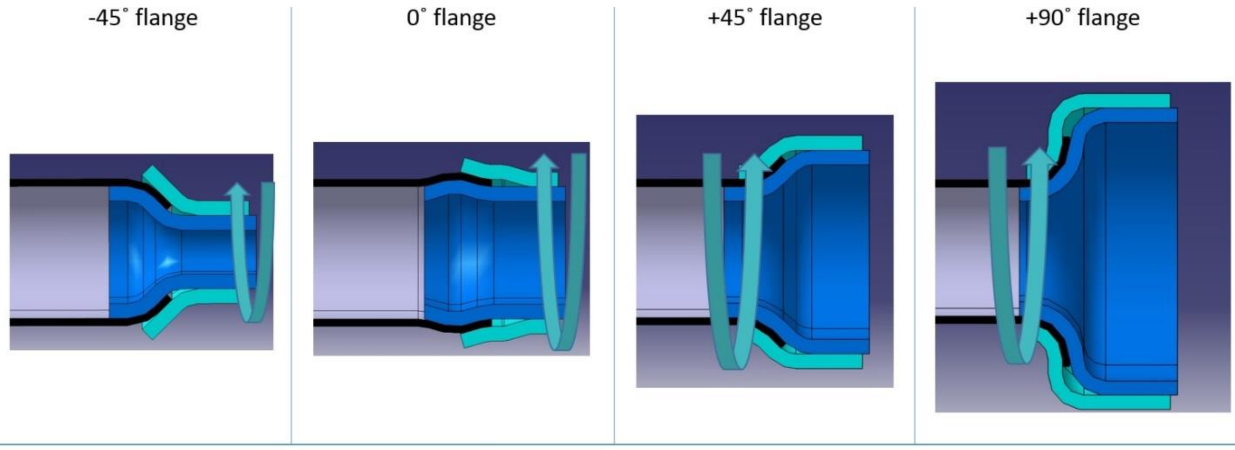


Figure 21: TP carbon tube swaging. Threaded metal-to-metal connection

The lay-up, angle of swaging, and fitting geometry have an influence on the performance of the joint, and are being assessed by simulation and experimentally. Increasing the angle of swaging affects the alignment of the fibres and increases the space taken by the joint, as well as its weight (Figure 22). An increasing proportion of 0˚ fibres in a triaxial braid will reduce the maximum angle of swaging. Figure 22. also shows that a stress concentration on the edge of the fitting will have to be attenuated. The understanding of this first step will allow considering further development in interlocked tube to metal joints.



The hot end of the **TP matrix braided tube** is formed onto the **threaded mandrel**, then the **threaded hat** is screwed to the **mandrel**, resulting in clamping the **tube**
The four flange angle configurations will be compared to traditional joining in tension, compression, and torsion

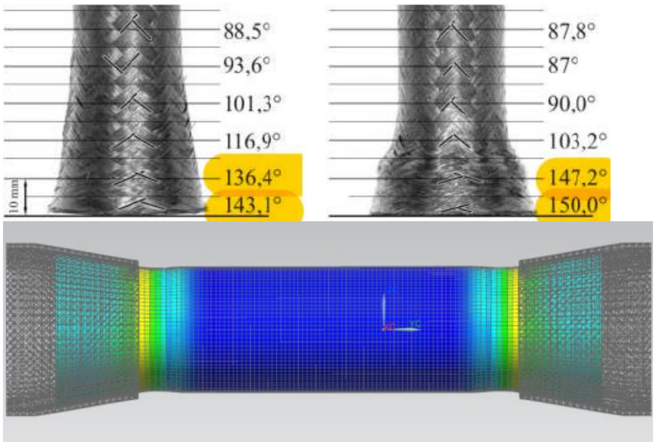


Figure 22: Top: flange angle and influence on space and weight. Bottom left: influence of swaging on fibre orientation [11]**. Bottom right: stress concentration at the tip of the fittings.**

5.4 Over moulded skeletons

Similarly, to the metal nodes described above, the integration of short fibres in a framework will provide the necessary isotropy for complex load bearing. Audi and Secar have therefore started developing over-moulding at nodes (Figure 23), but the principle of over-moulding could be taken further. The process of forming and joining parts could happen in one-step, in situ (Figure 23). This will participate both in the reduction of manufacturing steps, as well as the reduction of number of parts, which is essential in the perspective of a transition from metal to multi-material design.

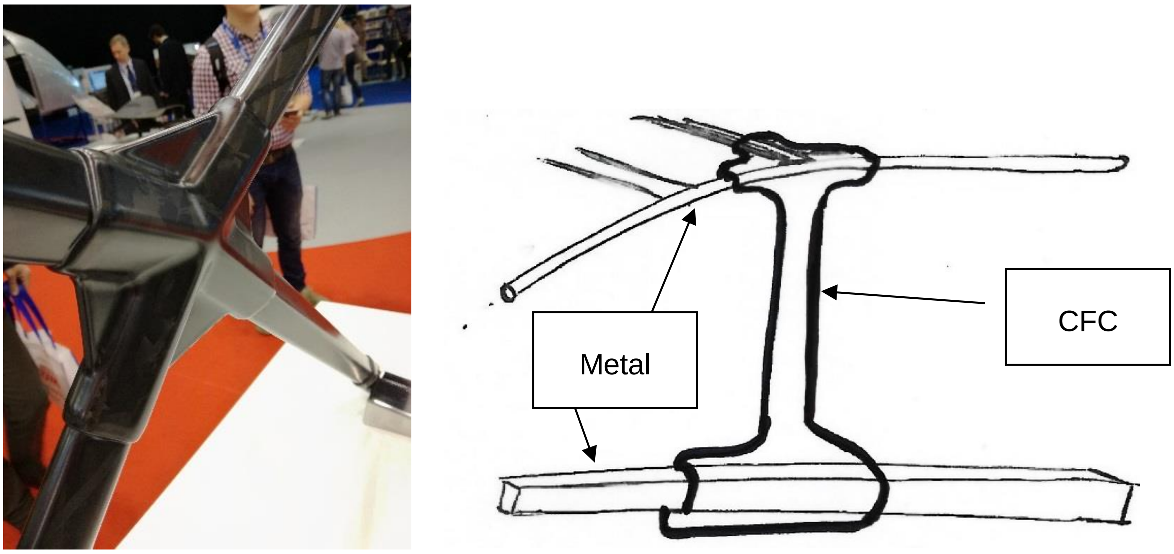


Figure 23: Left: Secar for Audi R8, four pultruded tubes are assembled by over moulded SMC node. Right: B-pillar + composite-to-metal joint as a single part

Another opportunity for over moulding is the necessity to mix properties of composites and metals within the same region of the structure. TU Dresden have integrated a metallic tube, over braided with thermoplastic CFC, as a lightweight shock absorbing element at the front of its multi-material electric InEco™ car concept (picture below). The metal provides the controlled deformation during front crash and the carbon braid provides extra stiffness with a low weight impact.

Figure 24: TU Dresden InEco™ lightweight car concept

Extrapolated to a whole BIW, this concept will use the ductility of the metal while providing bulk stiffness via short fibres, without depending on metal-to-CFC joint being close to complex loading zones. The two concepts below, presented as a section view of the profile of a typical car profile, predict the importance of tooling development. In situ over moulding requires applying high pressure and temperature in a reduced space. There will be a trade-off between the reduction of size of the presses, the achievable pressures associated, and the number of interfaces created by successive mouldings.

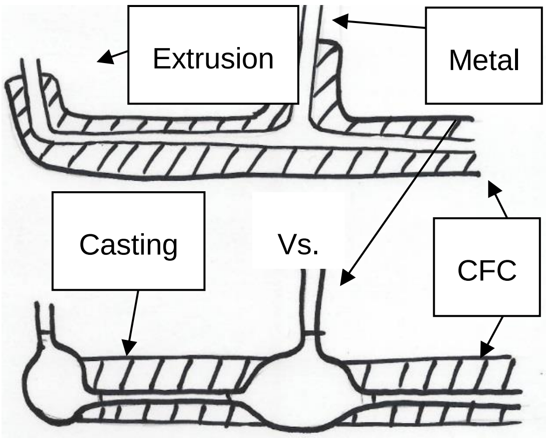


Figure 25: Short fibre CFC to bring bulk stiffness to a thin metal skeleton

The idea of a light metallic skeleton in between which composites are sitting corresponds to the iStream technology developed by Gordon Murray Design. RTM panels are bonded to a metallic skeleton. The above described in situ over-moulding process is an optimistic way of imagining how to replace all the

RTM panels by moulding compounds. In addition, a scenario without continuous fibre would erase most of the light-weighting potential.

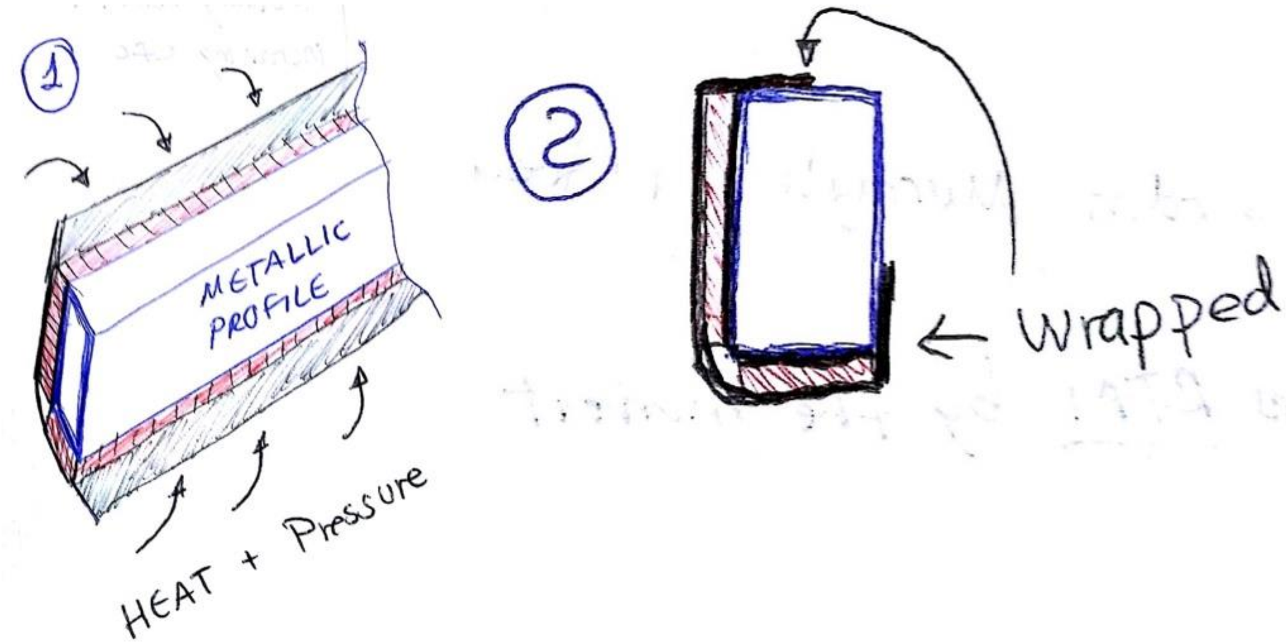


Figure 26: wrapping of CFC panel around a tube

However, continuous fibres panels including thermoplastic matrices will allow re-shaping the fibres to wrap the metallic tubes (Figure 26). Similarly to the above described swaging (section 5.3), the mechanical interlock completes the bonding, allowing giving an increased structural contribution to composites.


Figure 8: Left: Kelly Williams's over moulded differential housing, for Eaton®. Right: Rotite® technology.

Lastly, it is worth mentioning multi-material components, created via thermoset over moulding, and opening a range of new design possibilities. The picture above (Figure 8) shows a truck differential housing where the metallic skeleton has been used as a mould itself. The SMC applied to it is lodged during moulding in cavities drilled in the metal, creating cohesion via interlocking [12]. Following the same principle, using the Rotite geometry - on the right of Figure 8 above - as a mould for SMC will create a dismountable interlocked metal-to-composite joint.

5.5 Applying Metallic Approaches to Framework Joining using Thermoplastic Composites

Figure 28. Flattened metallic tube, bolted joint (personal photograph courtesy of L. Cook)

Figure 29.Flattened metallic tube, angled, bolted joint (personal photograph courtesy of L. Cook)

An excellent example of a simple, but highly effective framework construction technique is that whereby metallic tubes are cut to length and flattened at their ends to permit assembly and joining together with other similarly shaped sections (Figure 28).

By appropriately shaping the end of the metallic section, it is also possible to accommodate angular variations between each section (Figure 29.).

In many instances, such joints are affixed by means of a mechanical fastener or screw passing through a hole in each section – although welding and bonding could be equally effective for this purpose.

This method of fabricating frameworks is sufficiently simple, lightweight and low-cost to permit use in applications such as children's play equipment and outdoor structures, whereby the framework is often shipped as a kit ready for assembly on-site.

Fibre reinforced, thermoplastic polymer composite materials present a corrosion resistant, potentially recyclable and low-weight alternative to metallic materials in framework manufacturing.

Unlike thermoset polymer counterparts, hollow sections manufactured in thermoplastic polymers can be re-shaped or formed after their production. Advances in pultrusion and braiding technology mean that such sections or profiles can be manufactured quickly and cost effectively using thermoplastic polymer materials.

Given the re-formability of thermoplastic polymers, it should be possible to form tube or section ends into similar shapes as those seen in Figure 28 and Figure 29., and join them using either mechanical fastening or welding techniques. The ability to fabricate and construct thermoplastic composite frameworks in a manner similar to those commonly used in metallic frameworks would present a revolutionary and attractive approach to adoption of lightweight, recyclable and corrosion resistant composite materials. This would be most useful for applications where tooling costs, production times and joint complexity would typically prohibit the production of individually "moulded" framework elements using thermoset polymer composites.

Pending suitable forming and joining technologies, this presents the exciting possibility that frameworks could be manufactured using thermoplastic composite materials and "metal" fabrication techniques. In essence, one would be able to quickly and cost-effectively manufacture thermoplastic composite materials as constant sections in appropriate sizes and shapes, cut them to desired lengths, shape or manipulate the ends into "joinable" shapes, then assemble into a structure and fix, fasten or join the sections into a final structure.

5.6 Joint Forming Techniques

Three main joint forming techniques proposed for thermoplastic section joining are:

1. **Swaged metallic/ thermoplastic CFC joints**
2. **Crimped metallic/ thermoplastic CFC joints**
3. **Hot-pressed sheet metallic/ thermoplastic CFC joints**

All processes capitalise on the thermo-formability of thermoplastic matrices in CFC material, and are suited to assembly/ joining of hollow framework sections.

In all concepts, the joining process occurs after initial manufacturing of the CFC section material, but provides mechanical interlock between the joint components.

The described approaches would not be possible in thermoset CFC materials without significant integration of the metallic component embedment into the CFC manufacturing process – thus prohibiting the possibility of simple, fast, low-cost manufacturing of CFC framework sections in constant, cost/ time effective lengths/ geometries.

1. Swaged metallic/ thermoplastic CFC joints - Clinching

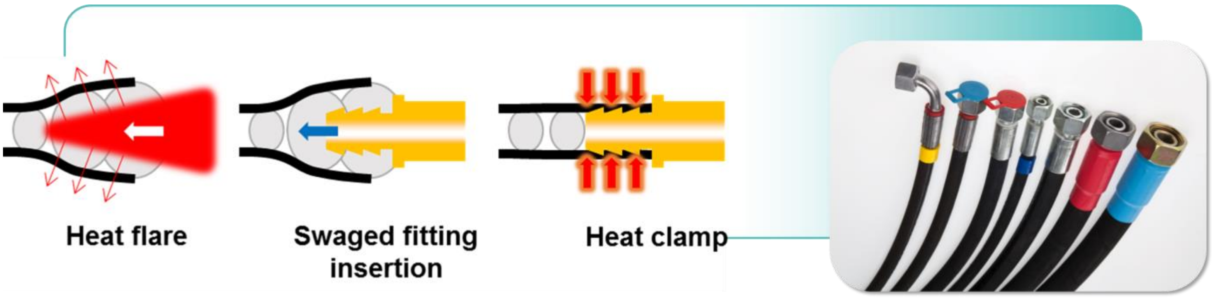


Figure 30. Clinched joint concept

The swaged fitting concept draws on an earlier study conducted at Cranfield in partnership with Sigma/ Avingtrans[1], looking at carbon reinforced PEEK/ stainless joints in aircraft jet engine fuel lines. The principal concept being:

- Manufacture PEEK/ carbon pipe sections by braiding to cost efficient lengths (e.g. 2 ~ 3 metres)
- Cut, heat form & consolidate pipe sections according to the required
- Prepare end-fittings by thermoforming the tube ends onto swaged metallic fittings

The heat flaring process for braided thermoplastic/ carbon tubes has proven feasibility through work conducted at the Institute of Lightweight Engineering and Polymer Technology, Technische Universität Dresden[2] - see Figure 31.

[1] "*Attachments techniques for metallic fittings to braided thermoplastic matrix CFC fuel pipes*", Cueto Carrion, Melodie, Mills, Andrew, Cranfield University, MSc Thesis, September 2015.

[2] Cranfield/ ILK information exchange visit, 24th May 2017, Dresden, Germany

In a similar manner to swaged high-pressure fluid hoses, joint designs utilising compression "collars" could also apply a further mechanical interlock onto the joint region. This could prevent CFC section to joint dis-attachment by eliminating out of plane loading causing peel type failure. However, the use of collars must demonstrate a clear mechanical advantage in order to offset the associated increase in weight and manufacturing complexity.

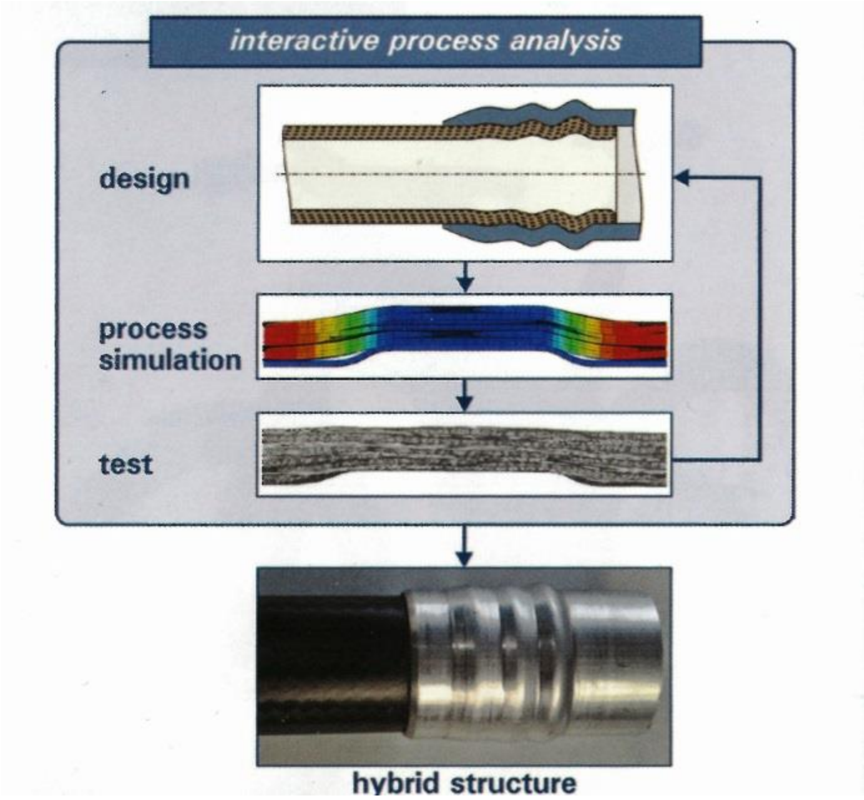


Figure 31. - swaged metallic/ thermoformed CFC joint, courtsey of ILK TU

Whilst the swaged interlock feature is likely to offer sufficient mechanical strength for framework applications in static loading, further assurance of joint integrity and durability may be achievable through ensuring adhesion of the thermoplastic matrices to the metallic component by use of surface preparation technologies[3].

[3] "*Joining of Composites and Dissimilar Plastics in Volume Manufacture"*, Warmbier, Terrence, Oxford Advanced Surfaces, MultiComp Conference, 15th June 2017, Nottingham, UK

2. Crimped metallic/ thermoplastic CFC joints

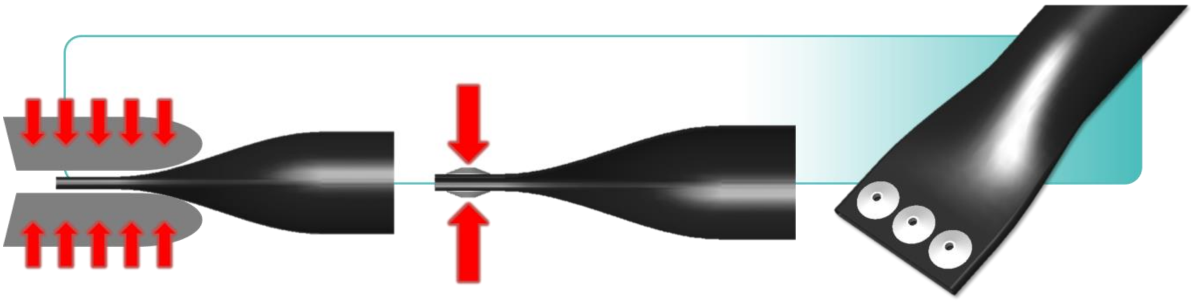


Figure 32. The Tube crimping concept

The end-crimping concept draws on joining techniques commonly employed in metallic section forming, especially in children's play equipment (Figure 33..) and end-attachment techniques in architectural frameworks . It is the simplest and probably fastest technique for connecting tubes to end fittings.

Figure 33. - flat-ended metal tubes for children's play equipment (courtesy of www.homedepot.com)

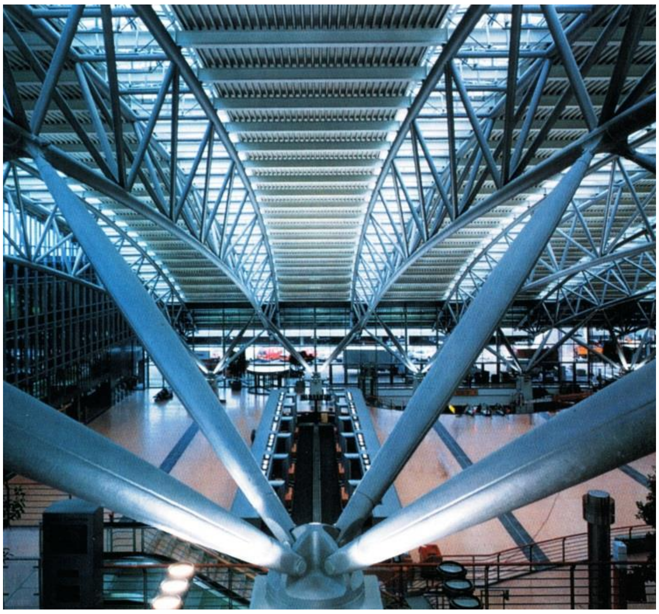


Figure 34. - metallic framework joints at Hamburg Airport (courtesy of Materia #33, December 2000, Architettura in acciaio, Federico Motta (ed.), Milan)

The approach typically involves flattening of the section end and preparing it with through-holes in order to facilitate bolting, fastening, bonding or welding onto another section or a joint node. In the context of fibre-reinforced polymer, through-holes and associated bearing loads are undesirable; therefore, the crimped end section concept proposes incorporation of a metallic fitting to support such loads where bolting/ fastening occurs. As a thermoform able material, welding techniques could also join the flattened section ends to other structural elements.

The team at ILK TU Dresden have demonstrated the thermoformed, end-flattened section concept using braided thermoplastic/ carbon fibre tubes of approximately 25 mm diameter – although their designs currently feature simple drilled holes to facilitate fastening/ bolting to other components[4].

- The thermo-forming, end flattening process is feasible for cylindrical tube sections, and demonstrated by ILK TU Dresden
- The CIMComp Structural Joints programme has demonstrated the benefit of, and manufacturing techniques for, metallic fittings in bearing load configurations
- Bolting, fastening, and polymer welding are all well understood technologies

Crimped Section End – Manufacturing Approach

Continuous Manufacturing of Sections

Even with thermoset matrices, braiding or pultrusion are perhaps the fastest and most cost-efficient means of producing large volumes of CFC sections. Advancements in braiding with thermoplastic carbon fibre tapes (such as those demonstrated by ILK Dresden or comingled polymer/ carbon fibre yarns, and the ability to in-situ polymerise thermoplastic matrices during pultrusion ensure that these processes are equally relevant to production of thermoplastic CFC sections. Production rates of hundreds of metres per day are tangible using these processes – i.e. composite tubes or sections in a given shape or size can be produced in similar volumes to metallic ones, making them cost-effective for use in industrial or high-volume applications.

Section End Forming

It is possible to simply "squash" or press the ends of metallic tubes or sections in order to prepare them into flat shapes for joining or assembly alongside other components. As previously described, tube sections with such end-shapes lend themselves particularly well to quick and low-cost framework assembly.

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[4] Cranfield/ ILK information exchange visit, 24th May 2017, Dresden, Germany

As an example, it is also possible to produce tubes with flattened end sections using fibre reinforced polymer materials – however, the choice of matrix polymer heavily influences the cost and complexity of doing so.

For thermoset materials, each tube and either one or both flattened end-sections must be formed by shaping and curing the fibre and polymer materials using suitable tooling and processing equipment. To alter the “flattened” geometry or the tube length would require new tooling for each variation.

For thermoplastic materials, it is possible to simply manufacture constant lengths of “finished” fibre reinforced polymer tube section, cut it to the desired length, and then shape the end sections into the desired geometry. This was demonstrated at Cranfield Composites Centre using a pre-manufactured section of braided thermoplastic CFC tube, application of heat, and rudimentary tooling (see Figure 35.)

Figure 35. Braided thermoplastic CFC tube with subsequent end-flattened geometry

Whilst the item in Figure 35 demonstrates a simple tube “flattening”, it is theoretically possible to further manipulate the flattened section into angled geometries such as that seen in Figure 29.. Furthermore, it is conceivable that the flattened section could be formed into a right angle to permit joining onto surfaces perpendicular to the main section, or even wrapped around an adjoining structure to create a secure joint without the need to mechanically fasten or bond the materials together.

5.7 Attachment / Fastening Techniques

The ROBOT bike shown in Figure 19.is an example of typical framework construction using thermoset CFC sections with metallic “over” nodes. It has flexible geometries, uses constant section tubes that are cut to appropriate lengths, but each node is bespoke manufactured using metallic ALM – in automotive or other “volume” applications, having many individual framework node geometries increases part count and tooling quantity which add to manufacturing complexity and cost. In addition, any framework design changes require the re-designs of multiple parts.

Non-node joints reduces part count and allows easy reconfiguration/ redesign without need for significant parts redesign – just change section length and maybe adjust end-shape slightly.

Joining options for TP CFC include:

Mechanical fastening - Embedded nodes - Welding of elements, CFC to CFC or CFC to metal -

Press-formed interlocks

1. Hot-stamped sheet metal/ thermoplastic CFC “dimple interlock joint” concepts

In certain framework applications, such as automotive chassis, carbon fibre composite (CFC) sections will need to combine with metal sections in order to satisfy the “right material, right place” approach. The hot-stamped sheet concept arises from a desire to provide a joining technique between metallic sheet and thermoplastic CFC materials without making a hole in the CFC material or relying on an adhesive between the two.

Instead of requiring a fastener to pass through holes in the sheet metal, the new concepts use thermoforming of the CFC material to provide an interlocking fastening, complemented by adhesion of the polymer to the metallic surface. Variations of the concept can include co-processed polymer interface layers or over-caps to provide increased polymer flow (and therefore greater interlock) in the joint area. Visually monitoring the amount/ geometry of exuded material in the hole/ dimple could provide a simple means of joint validation, providing it is possible to establish a relationship with subsequent joint strength and integrity.

In order to determine suitability for progression to full-scale development project, this feasibility study investigated manufacturing, and subsequent mechanical performance of pressed-plate metallic/ CFC joint concepts. Early indications from this work are positive, with polymer flow into the dimpled shape of the metallic sheet occurring. Adhesion between the two materials is currently limited, as the specimens simply used the zinc-coated steel material after an acetone wash, although surface preparation techniques are undoubtedly beneficial in this respect, and relatively easy to incorporate into future specimens.

As these concepts could be relatively novel, it is advisable to also consider whether any there is any protectable IP within them, and avoid disclosing the concept details/ study findings until the IP outlook is fully understood.

The feasibility study into hot-stamped, dimple shaped metallic/ CFC joint concepts, as described herein, provided the following outcomes:

- New applied knowledge and learning on thermoplastic CFC material behaviour during hot stamping with dimple-hole metallic plates, and the mechanical strength capabilities of such joints.
- Knowledge and understanding of the processes and associated parameters required for successful manufacture of dimple joint concepts.
- Recommendations and guidelines for new processing equipment for dimple joint manufacturing, based on understanding of the limitations of currently available laboratory equipment.

Joint usage scenario/ application example

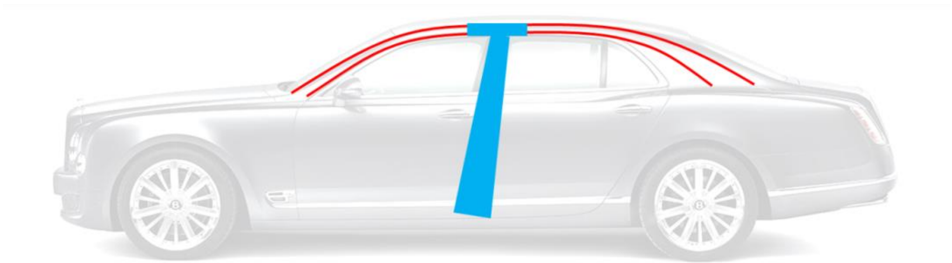


Figure 36. Automotive B-Pillar/ roof joint schematic (original image courtesy of Bentley Motors Ltd.)

Figure 36. illustrates a typical application for a sheet metal/ CFC section joint – the T-shaped B-pillar/ roof joint, whereby the pillar is of sheet metal construction, and the roof beam is of CFC construction. At least one current multi-material design of upper B-pillar joint utilises a combination of adhesive and mechanical fastening (see Figure 37..) However, through fastening into CFC materials is undesirable as the hole itself can cause localised weaknesses in fibre reinforced polymer structures and adhesive bonding (when used alone) suffers from a lack of confidence amongst designers, engineers and regulators. Other examples of framework joints in automobiles, such as that shown in Figure. 37 demonstrate the reliance on through-bolting techniques in automotive structural applications. Such

techniques can be time consuming to implement, rely on accurate hole alignment between the joint components, add weight and increase overall part count.

Figure 37. Metal over-plate joints onto CFRP structures in BMW G11/ G12 (7 series), JEC World 2017

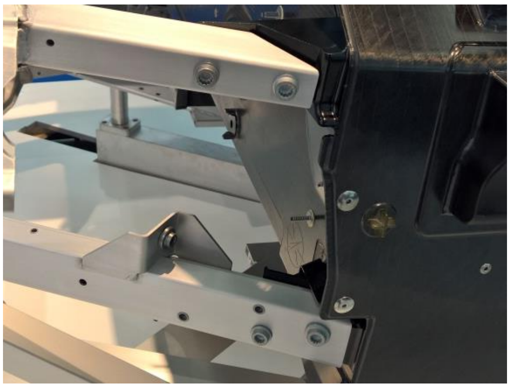


Figure 38. Through-bolted multi-material joints in an Audi R8 rear chassis framework, JEC World 2017

The hot-press, dimple/ hole plate concept, as described by Figure 39 and 40. presents an instant fixture, thermoplastic compatible solution for this application – it is fastener-less but mechanically interlocked, with no through-holes in the CFC material. The concept offers additional benefits of reduced part count and single operation joint manufacturing – thus a step-change in automotive manufacturing productivity. The key questions are whether the concept is feasible from a manufacturing aspect, and whether associated mechanical strengths and durability are compatible with application expectations.

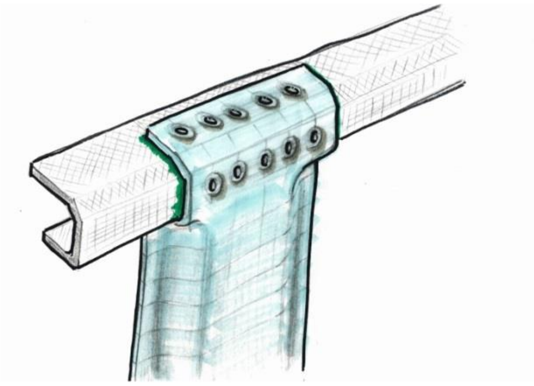


Figure 39. Schematic sketch of dimple-joint concept applied to upper B-Pillar metallic/ CFC structure

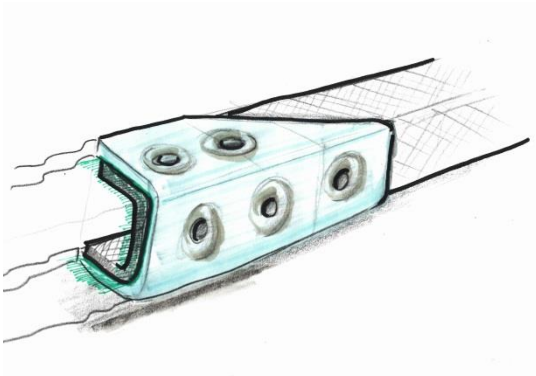
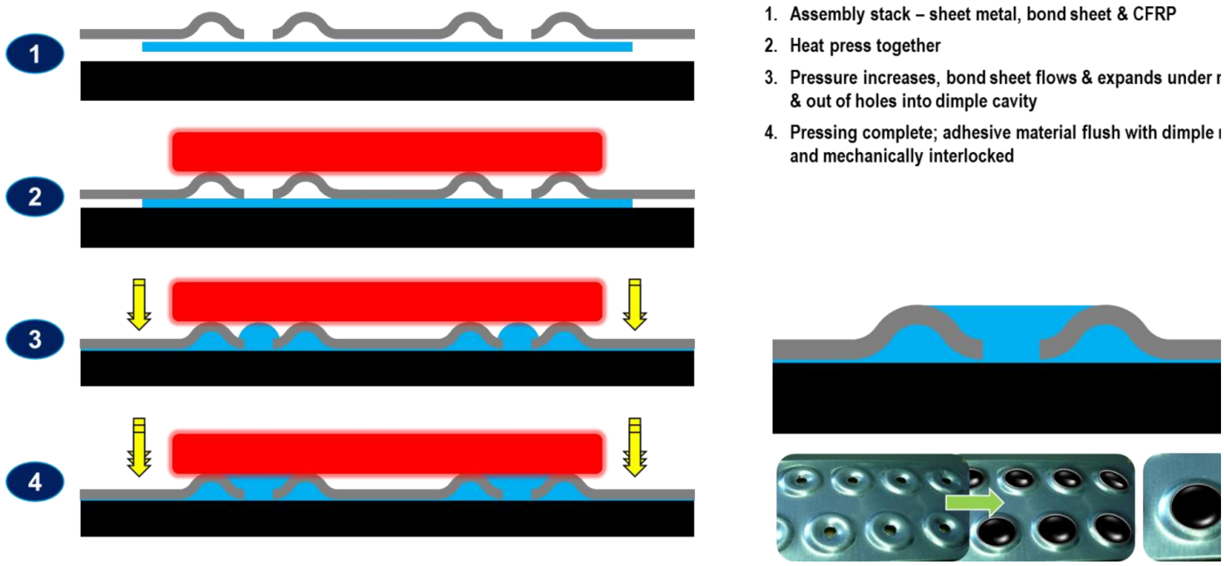


Figure 40 Schematic sketch of dimple-joint concept applied to C-Shape CFC framework element to metallic end-node structure

Metallic/ CFC dimple-joint manufacturing concepts

Five potential dimple-joint manufacturing concepts were schemed, as described in this section, along with foreseeable challenges and a comment on the innovation level offered by the concept.

Concept 1 - Heat press sheet metal onto thermoset CFC with bond sheet



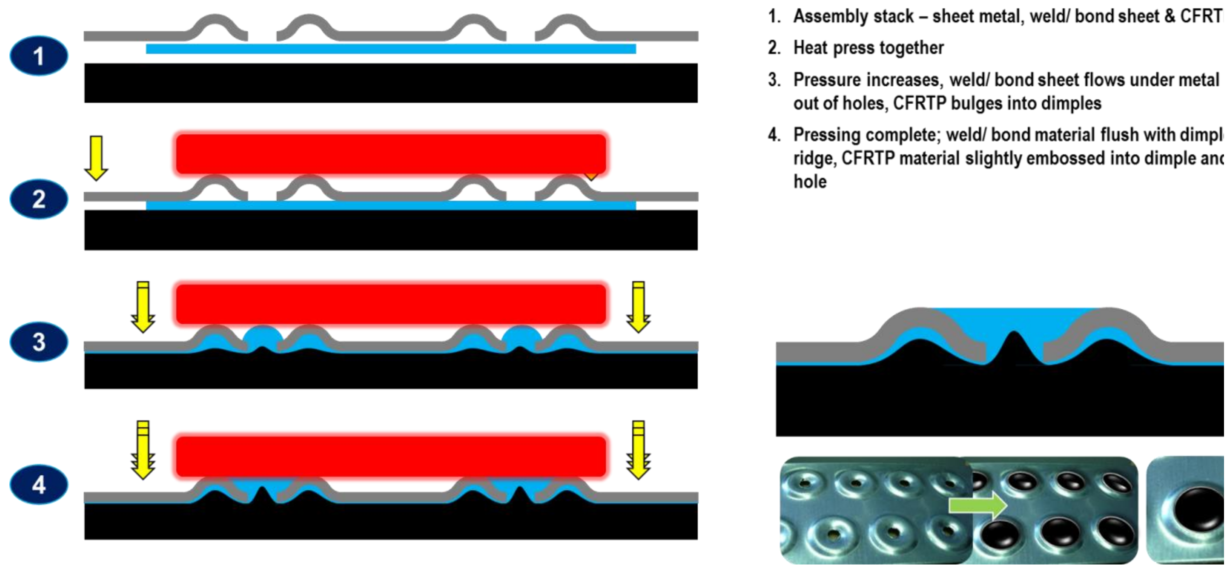
Key challenges:

- Sufficient expansion of adhesive into dimple cavity
- Adhesion to both metallic sheet and thermoset polymer matrix

Innovation level:

- Low, existing technologies will meet these challenges with minimal development required
-

Concept 2 - Heat press sheet metal onto CFRTP with weld/ bond sheet



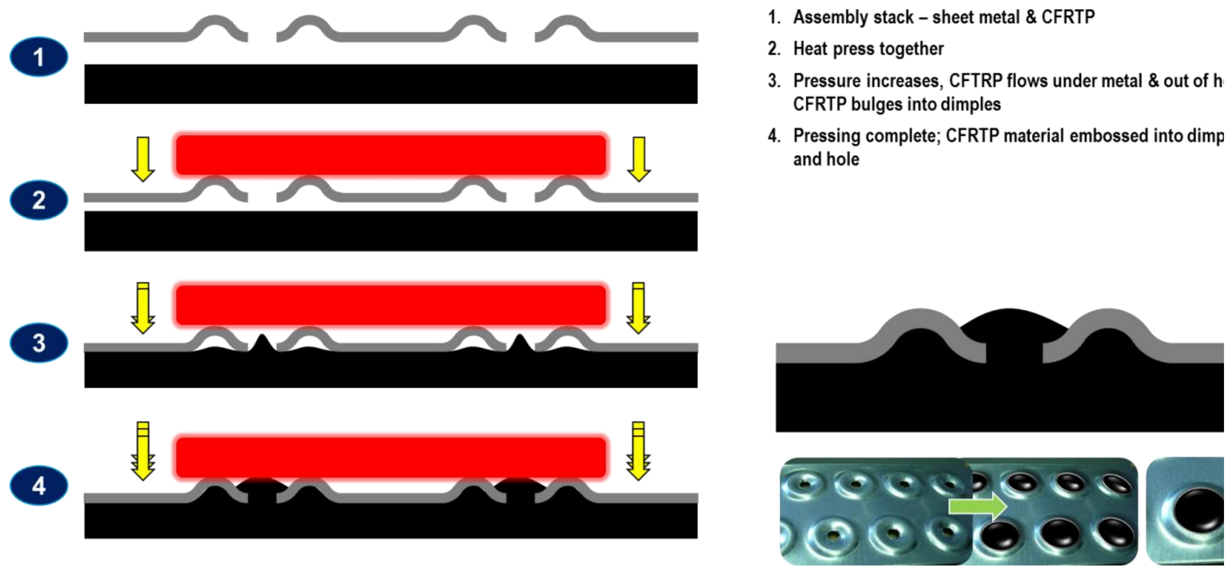
Key challenges:

- Sufficient flow of CFC material into dimple cavity
- For adhesive, compatibility with co-processing together with thermoplastic matrix
- For weld-sheet, ability to fuse with CFC material and adhere to metallic surfaces

Innovation level:

- Very high, requires process development and, potentially, new bond/ weld sheet materials development

Concept 3 - Heat press sheet metal onto CFRTP without weld/ bond sheet



Key challenges:

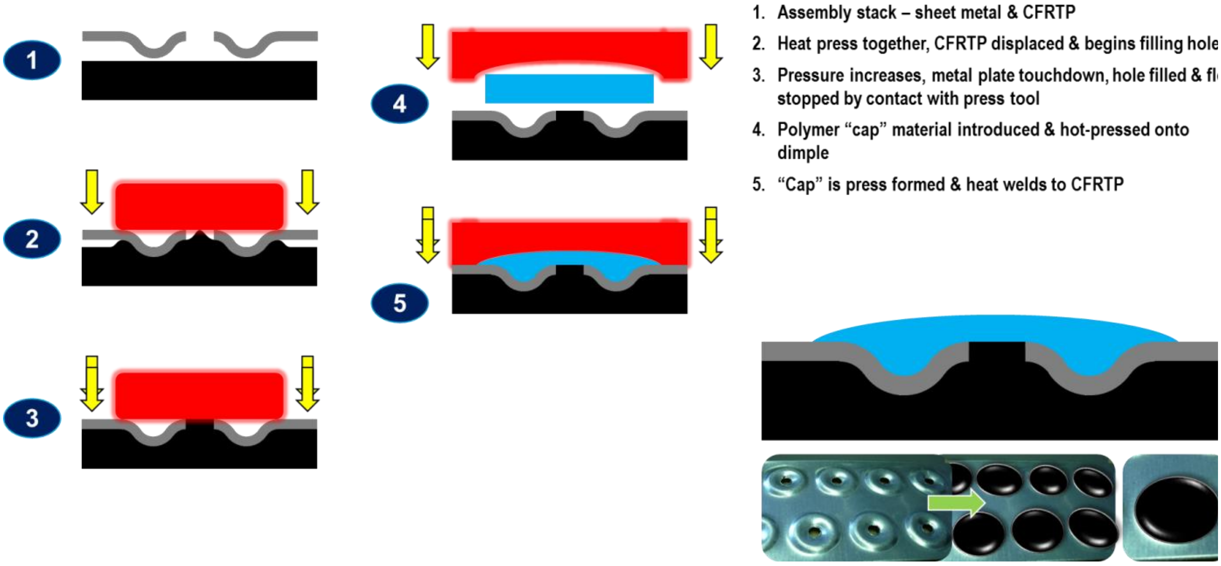
- Sufficient flow of CFC material into dimple cavity

- Adhesion of CFC material to metallic surfaces

Innovation level:

- High, requires process development, adhesion promotion solutions exist but must demonstrate compatibility with joint manufacturing process

Concept 4 - Heat press sheet metal into CFRTP & over-mould



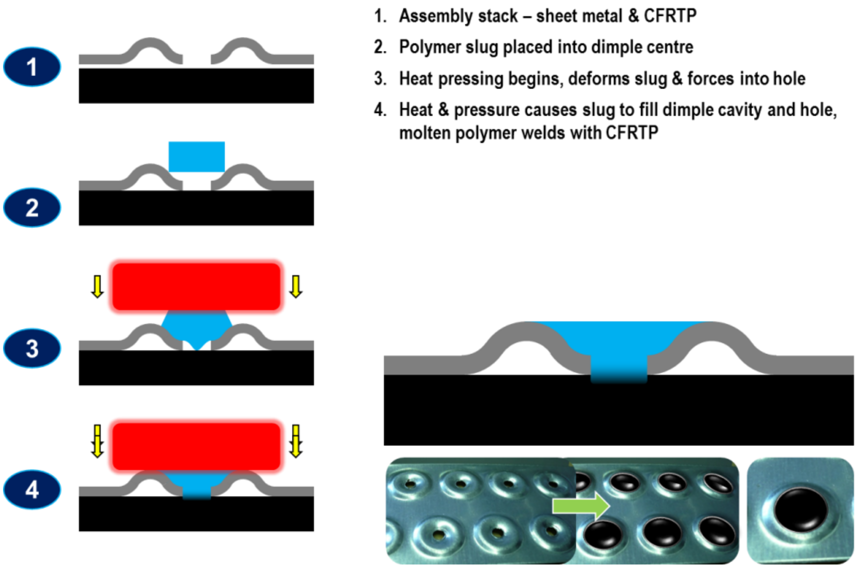
Key challenges:

- Achieving weld between polymer "cap" and thermoplastic substrate material
- Adhesion of CFC material to metallic surfaces
- Sufficient weld & cap strength to resist flat-wise and peel forces across joint

Innovation level:

- High, requires process development for joint and ancillary materials (polymer caps), adhesion promotion solutions exist but must demonstrate compatibility with joint manufacturing process

Concept 5 - Sheet metal to CFRTP stud weld/ rivet with LFP slug



Key challenges:

- Achieving weld between long-fibre polymer (LFP) "cap" and thermoplastic substrate material
- Sufficient weld & cap strength to resist shear, flatwise and peel loading forces across joint

Innovation level:

- High, requires process development for joint and ancillary materials (polymer caps)

These five techniques have been investigated and the results are presented in section 6.

5.7 Summary

Thermoplastic matrix carbon fibre composites offer a new range of design possibilities, thanks to the use of its re-shaping properties abilities in manufacturing and for improved joining mechanical behaviour. Short fibres also present promising structural abilities using the over-moulding technique.

Following the three main defined routes for the manufacture of an optimised multi-material structure (figure 8.), the areas of study are the following:

- Geodesic and bionic structures:
  - Tow wrapping around metal
    - Geometry
    - Adhesion

- Tubular composite structure with metallic nodes
    - Thermoplastic matrix CFC tube re-shaping
        - Swaging
            - Outcomes in tension, compression, shear, fibre distortion
            - Influence of geometry and angle of swaging
        - Other forms of multi-scale joining

5.8 References

[1] Bras A, Walch E, Mills A. Design and Processing of Carbon Fibre Epoxy Resin Moulding Compound Hybridised with Selectively Placed Uni-Directional Reinforcement for Low-cost Automotive Structural Parts A. Bras , A. R. Mills , E. Walch. In: SAMPE Europe Conference 2016, editor., Liege: 2016, p. 1–8.

[2] Lyu M, Choi TG. Research Trends in Polymer Materials for Use in Lightweight Vehicles 2015;16:213–20. doi:10.1007/s12541-015-0029-x.

[3] Batista NL, Olivier P, Rezende MC, Botelho EC, Talim R. Correlation between degree of crystallinity , morphology and mechanical properties of PPS / carbon fiber laminates 2016;19:195–201.

[4] Morgan P. Polymer matrices for carbon fiber composites. In: Francis T and, editor. Carbon fibers their Compos., 2005, p. 501–49.

[5] Shinohara M, Isshiki S, Fukushima Y, Katayama T. Moulding of carbon fiber reinforced polycarbonate (CF / PC) using UD tape n.d.;124:249–57. doi:10.2495/HPSM120221.

[6] Comer AJ, Ray D, Obande WO, Jones D, Lyons J, Rosca I, et al. Composites : Part A Mechanical characterisation of carbon fibre – PEEK manufactured by laser-assisted automated-tape-placement and autoclave. Compos PART A 2015;69:10–20. doi:10.1016/j.compositesa.2014.10.003.

[7] Grouve WJB, Warnet LL, Rietman B, Visser HA, Akkerman R. Composites : Part A Optimization of the tape placement process parameters for carbon – PPS composites. Compos Part A 2013;50:44–53. doi:10.1016/j.compositesa.2013.03.003.

[8] Bastien C, Prem A, Bastien C, Dickison M. Multidisciplinary Design Optimisation Strategies for Lightweight Vehicle Structures Multidisciplinary Design Optimisation Strategies for Lightweight Vehicle Structures. 10th Eur. LS-DYNA Conf. 2015, Wurzburg, Germany: 2015.

[9] Robot Bike Co. Robot Bike | Technology 2017. https://robotbike.co/technology/?v=79cba1185463 (accessed July 7, 2017).

[10] Barfuss D, Gr??tzner R, Garthaus C, Gude M, M??ller R, Langrebe D. Intrinsic manufacture of hollow thermoplastic composite/metal structures. AIP Conf Proc 2016;1769. doi:10.1063/1.4963580.

[11] Maron B, Garthaus C, Hornig A, Lenz F, H??bner M, Gude M. Forming of carbon fiber reinforced thermoplastic composite tubes - Experimental and numerical approaches. CIRP J Manuf Sci Technol 2016;170028. doi:10.1016/j.cirpj.2016.09.004.

[12] Fritz P, Williams K, Mapkar J. Metal-to-Composite Joining for Drivetrain Applications. In: Cloud G, Patterson E, Backmann D, editors. Join. Technol. Compos. Dissimilar Mater., Southfield: Springer International Publishing; 2016, p. 107–13.

[13] Etherington R. Phonebloks mobile phone concept by Dave Hakkens 2013. https://www.dezeen.com/2013/10/19/phonebloks-mobile-phone-concept-by-dave-hakkens/ (accessed July 6, 2017).

6. Joining Process Investigation, Manufacture and Testing of Structural Elements

Metal joint to composites section joining is investigated as one of the potential solutions for frameworks design concepts previously defined. Structural CFC tubes are swaged to create an interlock as a parallel joining mechanism to adhesive bonding with aluminium frame nodes.

6.1 Composite Tube Swaging onto Metallic Joints

In a similar way to the concept of wrapping (see Chapter 1), the objective of this study is to take advantage of the physics of thermoplastic matrices, not only for cycle time, but also and most importantly for joining. In fact, the thermoplastic matrix of a Carbon Fibre Composite (CFC) material allows the reshaping of an already consolidated laminate. Similarly, to metal forging, a structural CFC part can be rapidly re-shaped locally to create a joining mechanical interlock without disturbing the continuity of the fibres. This increases the strength and predictability of the joint in comparison to traditional mechanical fastening that disturbs or breaks fibres. Interlocking also provides an additional joining mechanism to traditional adhesive joining, which also increases predictability and reduces brittleness.

For the current study, a tubular car frame made of CFC tubes and metal nodes was taken as a case study (see **Error! Reference source not found.** below). The critical point of joining between metal node and CFC tube was investigated. It is assessed that the joint studied has to withstand 50kN in tension and compression. A torsion component should be further investigated.

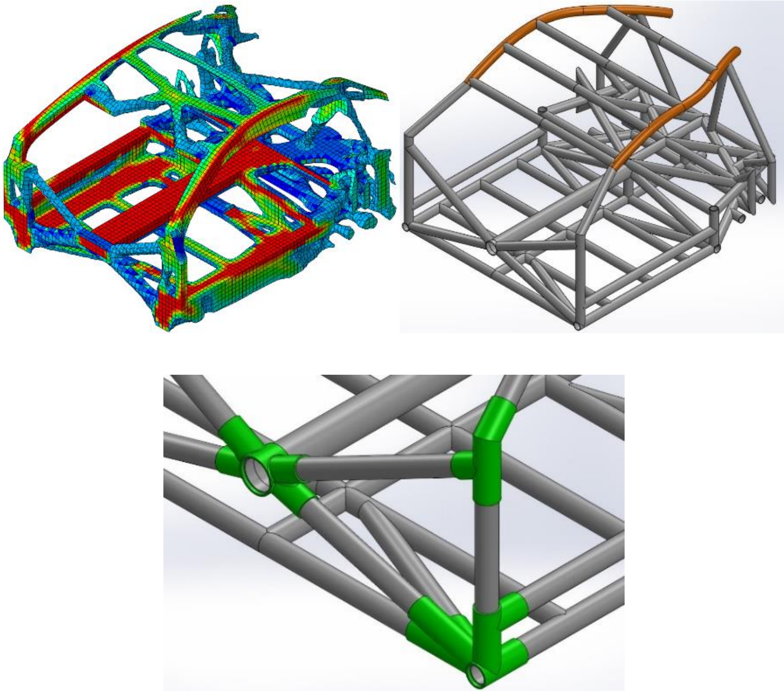


Figure 40: From optimised cockpit, to concept 2, to corresponding zoom on nodes. Three different manufacturing processes are highlighted, in three different colours.

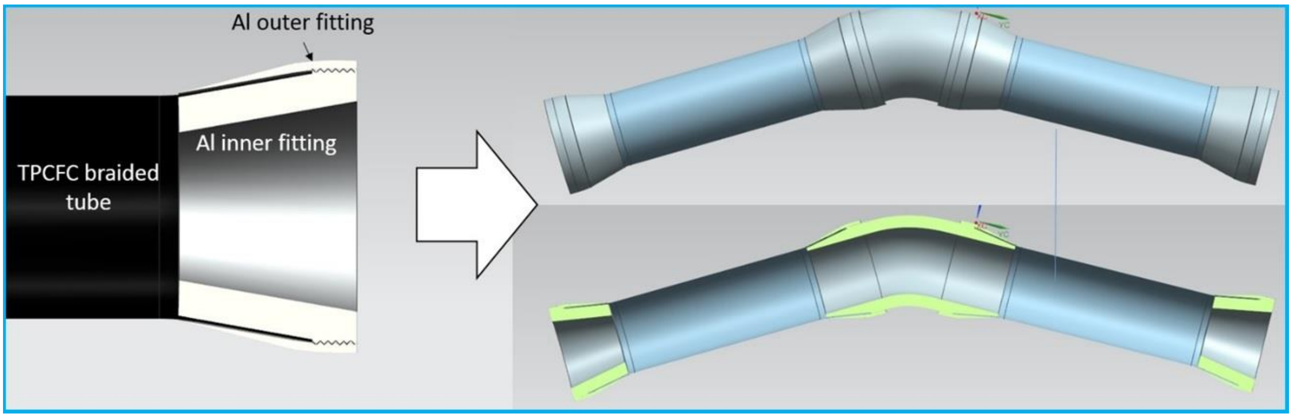


Figure 41: Concept for metal to CFC interlocking joint.

Following the investigations of Dresden TU concerning swaging of PA6 braided and blow-moulded CFC tubes [1,2], the following concept is suggested (**Error! Reference source not found.**.) Using similar swaging angles, the addition of a two-part metallic fitting allows symmetrical response in tension and compression: the outer fitting is effective in tension while the inner fitting creates an interlock in compression. The inner and outer fitting are connected by a thread, which allows metal-to-metal assembly. This has the advantage to be stronger and more predictable, but also to require much looser geometrical tolerances than bonding assembly.

The current study consists in manufacturing a representative element of this assembly concept, and to assess the benefit of CFC tube swaging for tensile behaviour between two aluminium nodes.

Methodology

The objective is to investigate experimentally the following tensile load case:

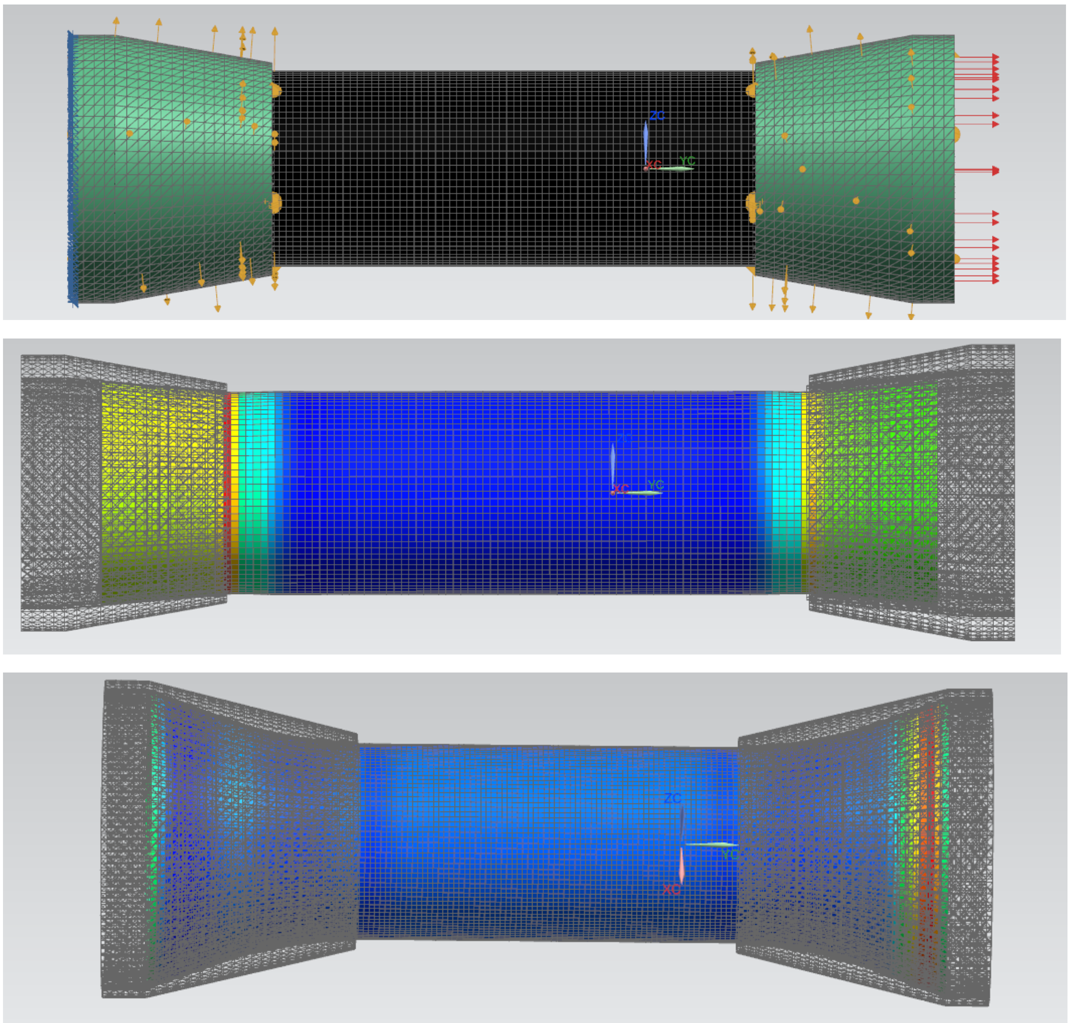


Figure 42: Top: tensile FEA model. Middle: tensile FEA result. The scale is relative, highlighting stress concentration at the edge of the fitting. Bottom: Compression result on a greater swaging angle. Relative scale

A biaxial braided tube presenting 50% vol. PA6 matrix, 50 mm diameter and 2 mm thickness has been provided by Dresden TU (see **Error! Reference source not found.**) in order to withstand the objective of 50kN. For equipment availability reasons, tubes have been manufactured from HS dry fibres and infused L&L L-F610 reform able epoxy, presenting lower melting temperature than PA6 (around 140˚C, compared to 200 ˚C)

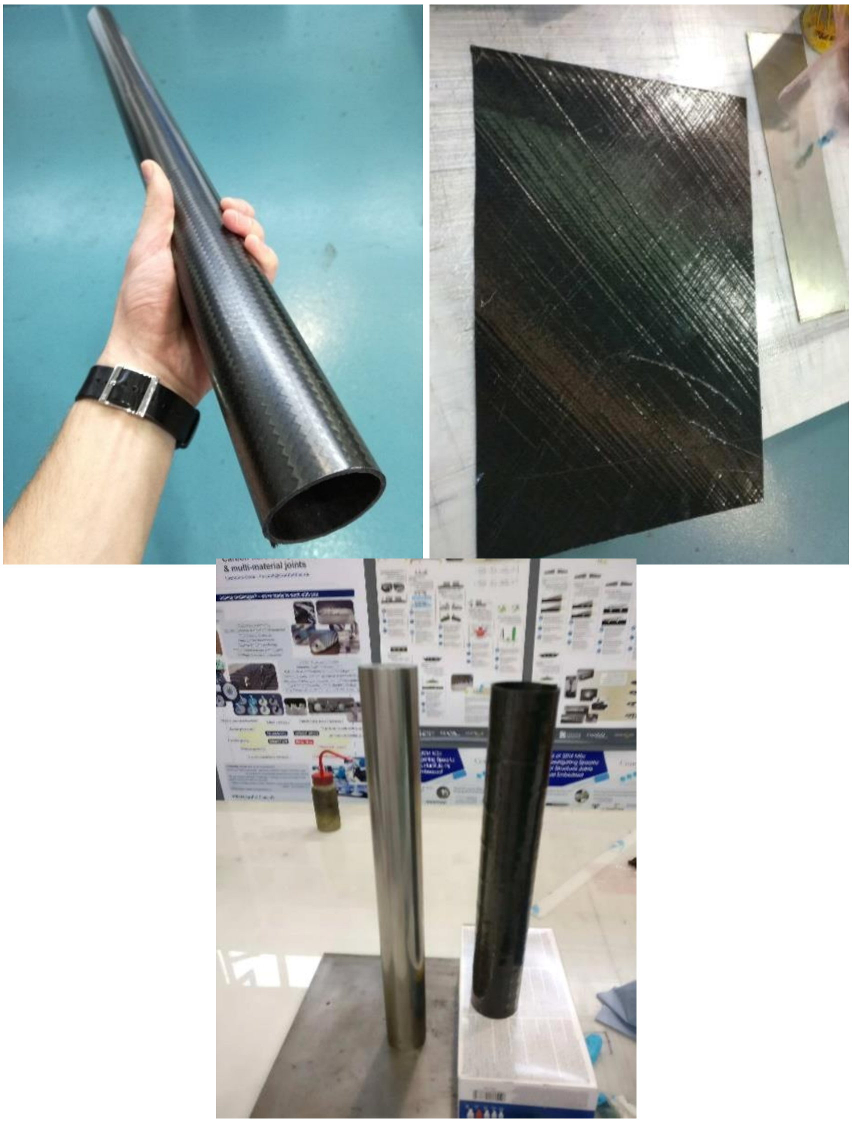


Figure 43: Left: Dresden TU biaxial braided PA6 CFC tube. Middle: HS carbon fibres infused with L&L L-F610 reform able epoxy. Right: mandrel and tube formed from infused HS. The laminate is biaxial too, and the volume fraction is 50%

For pressure and temperature application that are necessary for swaging, a tooling apparatus has been designed and manufactured (**Error! Reference source not found.**.) The temperature is applied by electric resistance to the bottom cylinder. The pressure is applied to the tube from a piston at the top of the assembly.

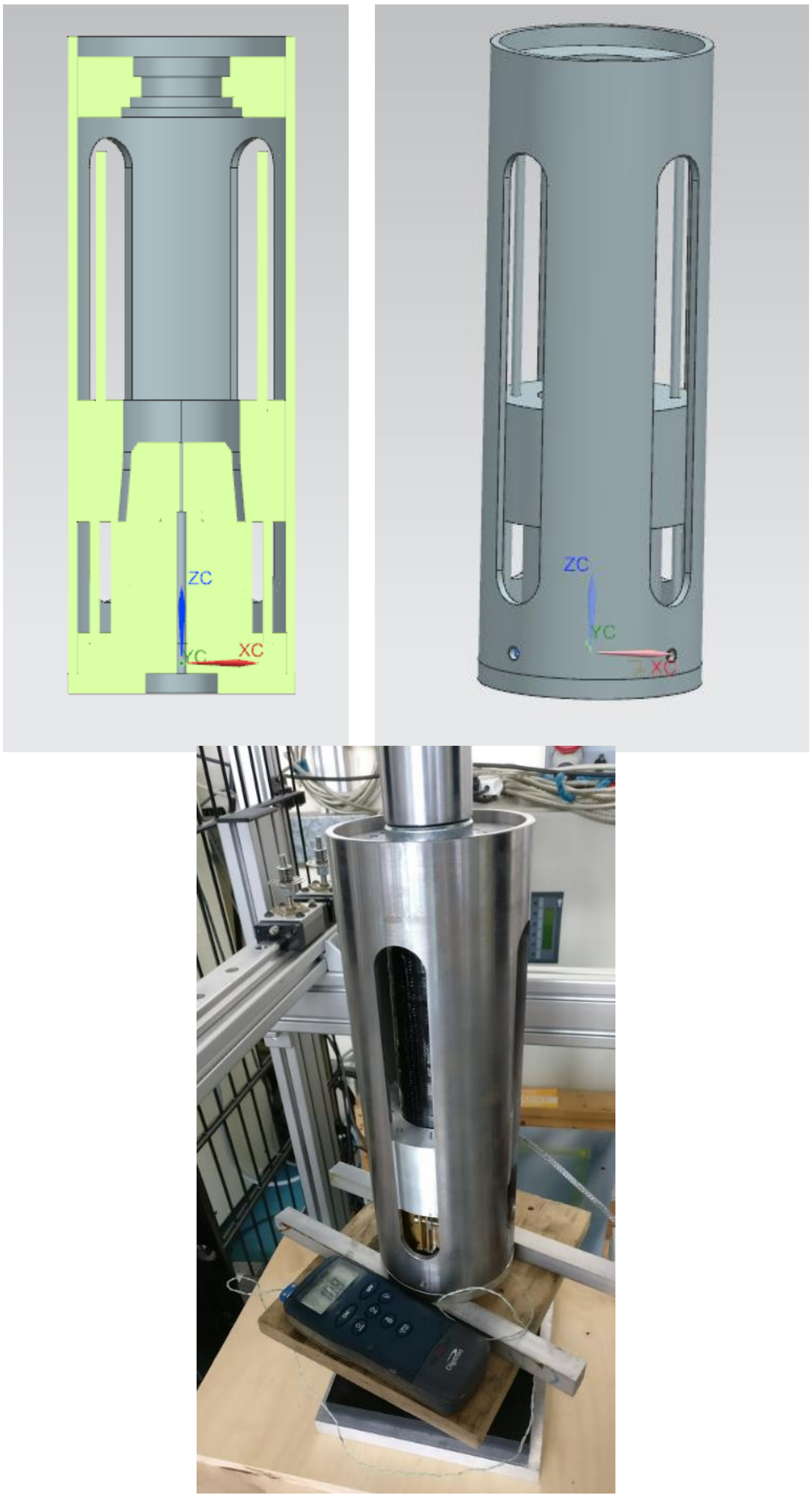


Figure 44: Tooling assembly section view, side view, and manufactured part.

The manufactured assembled coupon presents five parts: the carbon fibre composite tube, two outer aluminium fittings, and two inner aluminium fittings. The inner fittings present a geometry adaptable to the Instron 5500R tensile apparatus (see **Error! Reference source not found.**).

Figure 45: Final assembled coupon, and tensile test apparatus

Results and discussion

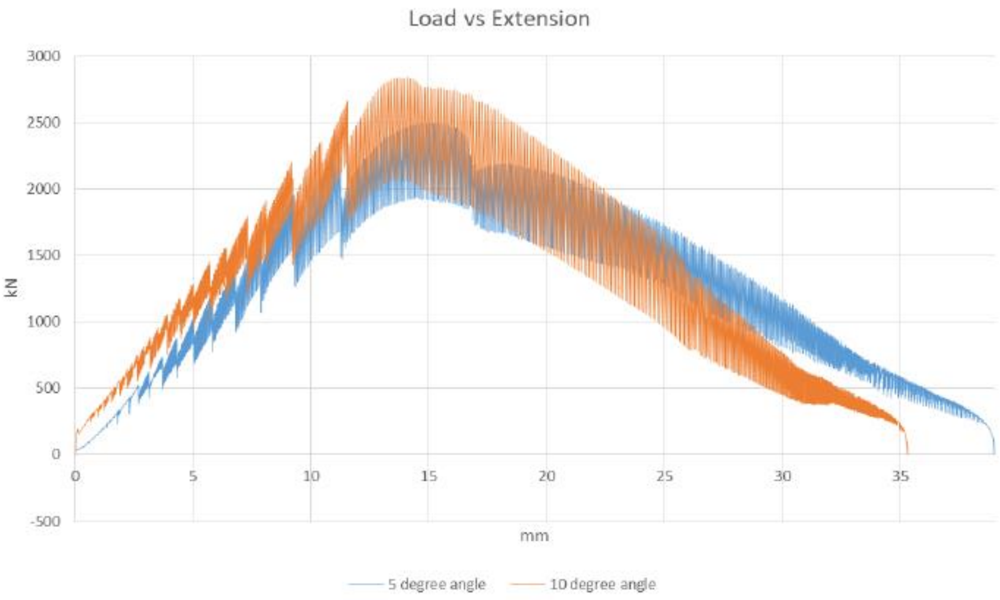


Figure 46: tensile test results comparison between 5 degrees swaging angle coupon and 10 degrees swaging angle coupon

The stiffness and strength of the coupon is the same independently from the swaging angle. The strength is around 2 kN, which corresponds to 4% of the 50kN objective. The mode of failure observed for all the coupons has been the elastic deformation of the tubes, which slid out of their aluminium fittings.

The tube was too compliant under the swaging angles considered. Few areas of improvement can be extracted:

- Increasing swaging angle. This however increases manufacturing difficulty. The following point should therefore be treated in priority.
- Using a state of the art PA6 matrix with a braided tube. The potential presence of defects in the laminate used is likely to have induced performance knockdown.
- Add adhesion as a parallel joining mechanism, and compare joints presenting both interlock and adhesion to joints presenting only one of the two. The interlock should have a positive effect on the bond line behaviour, as the geometry of the system favours compression rather than peeling in the adhesive.
- Most importantly, the biaxial layup of the fibres is too compliant tangentially. The diameter of the tube has been locally crushed by the sliding fitting. The layup has allowed the diameter to reduced, elastically. An increase of 90˚ fibres should be considered to increase tangential stiffness. However, it will induce a complexification of the process. If the braided fibres are closer to 90˚, the swaging process will require more force and the system will become more susceptible

to buckle. Alternatively, a second stage can be added to the swaging process, where a 90˚ fibre patch is added.

- The biaxial layup is also too compliant axially. A switch to triaxial layup including 0˚ fibre should be considered.

Conclusions and further work

Tube swaging for joining CFC to metal nodes presents theoretical advantages in terms of design and manufacturing. However, the experiment has not yet proven the strength potential of such architecture. This is likely to be principally due to parameters of design that were not accurately tuned. Further work will consist in improving joint strength based on observations made:

- Modification of the layup
  - Inclusion of 0˚ fibres for axial stiffness
  - Inclusion of 90˚ fibres, either in the braid or as an added patch, for tangential stiffness
- Improvement of the impregnation stage, using PA6, braiding, and blow moulding
- Include adhesion as one more parameter of the system, as adhesion is likely to benefit from the interlocking, in comparison to a lap-shear architecture were the peeling force is unneglectable.
- Increasing the range of swaging angles considered.

The design of the metallic inner and outer joint components will also need to be investigated to establish whether this joint concept is sufficiently lightweight compared to bonded or mechanically fastened joints.

References

[1] Wang Z, Riemer M, Koch SF, Barfuss D, Grützner R, Augenthaler F, et al. Intrinsic Hybrid Composites for Lightweight Structures: Tooling Technologies. Adv Mater Res 2016;1140:247–54. doi:10.4028/www.scientific.net/AMR.1140.247.

[2] Barfuss D, Gratzner R, Garthaus C, Gude M, Muller R, Langrebe D. Intrinsic manufacture of hollow thermoplastic composite/metal structures. AIP Conf Proc 2016;1769. doi:10.1063/1.4963580.

6.2 Thermoplastic CFC Laminate Joint Wrapping

Thermoplastic matrices have had a recent interest for industrial high volume applications, due to their potential for high speed processing. This advantage has been slightly reduced by recent advances in thermoset matrices processing time. Another aspect of thermoplastics physics is investigated here: how to use the re-shapability of thermoplastic composites laminates for joining?

Tradition mechanical fastening presents multiple drawbacks when applied to composites. In particular, it disrupts the fibres of the composites in the joining area, either breaking or misaligning them. It provokes an uncontrolled drop of mechanical performance. This leads to using greater safety factors, and therefore increases both weight and material cost.

Similarly, to mechanical fastening, traditional lap shear bonding presents relative uncertainty in its mechanical properties. It forces the manufacturing steps to be highly controlled, particularly in terms of surface preparation.

To overcome design and manufacturing issues linked to traditional joining techniques, as well as reducing the number of parts and the number of manufacturing steps, wrapping is suggested for a continuous fibre structural part around a metallic of composite framework (**Error! Reference source not found.**).

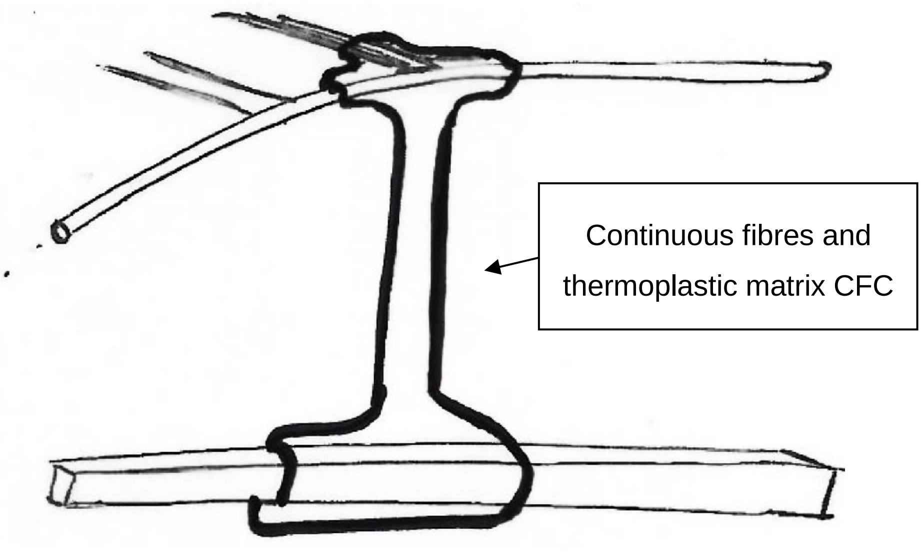


Figure 47: concept sketch of a CFC B-pillar attached to a framework via the deformation of its ends

This concept has the advantage of coupling two joining mechanisms: interlocking and bonding. The continuous fibres are not disrupted and participate in the interlocking. The bonding can be ensured via adhesive application or, in the case of a thermoplastic framework, via welding of the part matrix with the framework matrix. The bonding surface is curved, which allows it to be loaded mainly in shear and compression. This is an advantage compared to lap shear joints where peeling is present (**Error! Reference source not found.**).

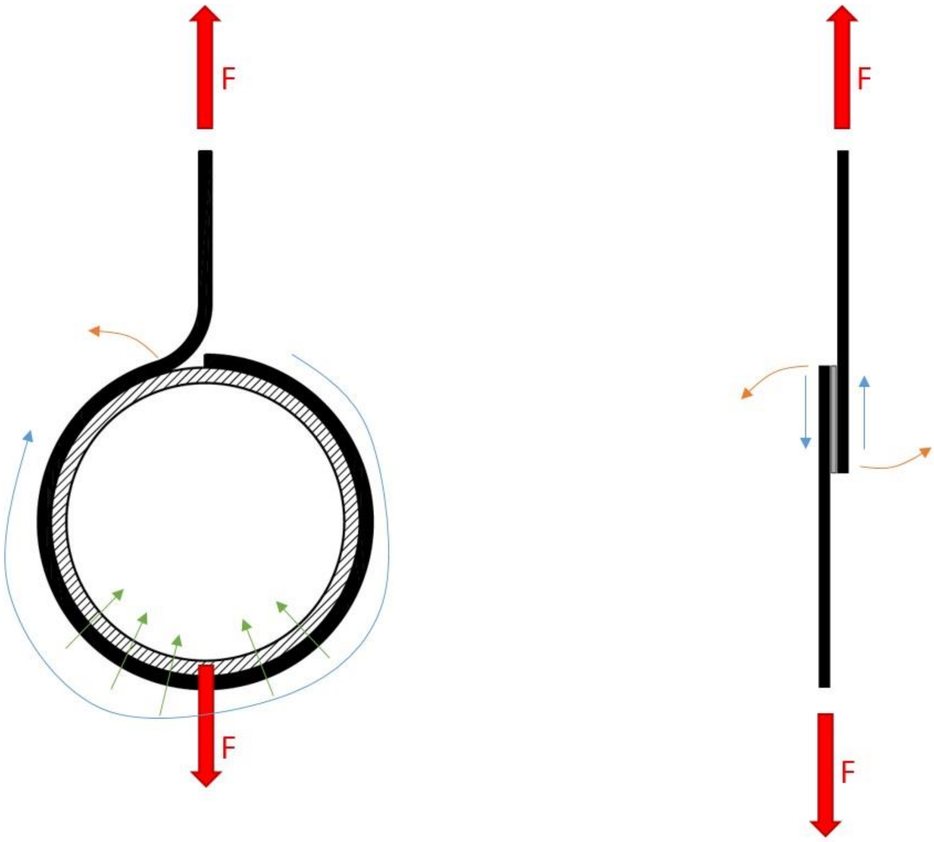
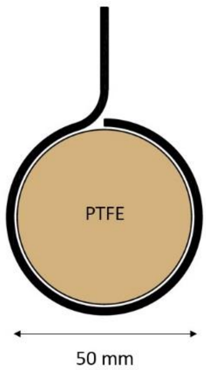
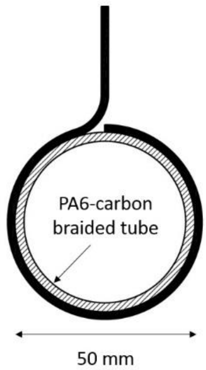


Figure 48: on left, a laminate wrapped around a tubular structure presents predominantly shear (in blue) and compression (in green), in comparison to lap shear, on the right, which presents a larger proportion of peeling (in orange)

Methodology

The present study investigates experimentally six wrapping combinations, where the variable parameters are geometry, laminate, and bonding (**Error! Reference source not found.**). The load case is the one illustrated in **Error! Reference source not found.** above. UD and +/-45˚ laminates are investigated for each configuration, as they represent the two ends of the compromise between strength and ease of shaping. The diameter of shaping varies from 25 mm to 50 mm. There is no bonding from combination 1 to 4, whereas combinations 5 and 6 present similar matrix materials between substrate and laminate. The ±45˚ laminates present PA6 matrix (Porcher industries 2009 P56), and UD laminates present PA12 matrix (Evonik Vestape CF45). The braided tubes were provided by Dresden TU, present ±45˚ fibre orientation, and a thickness of 2mm. All laminates and tubes present HS fibres, with volume fractions ranging from 45% to 50%.

Table 1: plan of experiments

Sample configuration			
± 45˚ laminate	1st combination	3rd combination	5th combination
UD laminate	2nd combination	4th combination	6th combination

Process

Organosheets

± 45˚ laminates and UD laminates are consolidated in the form of organosheets. Their dimensions are 250x25x1.8mm. They are consolidated at 260˚C, 10bar, in a closed mould in a platen press. Figure 49. shows UD organosheets, and ± 45˚ organosheets after cooling down to room temperature before release from their moulds.

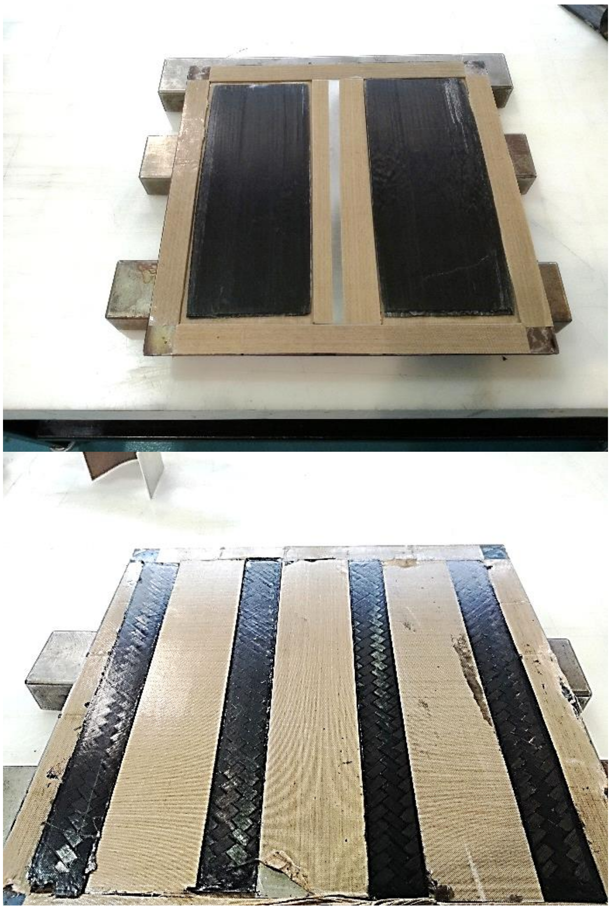


Figure 49: Organosheets. On the left: UD laminates, before being cut in 25mm wide strips. On the right: ±45˚ laminates, 25mm wide.

Wrapping of configurations 1 to 4

The organosheets are heated to 250˚C on the bottom platen. Being above melting temperature allows re-shaping them manually, as shown on **Error! Reference source not found.**.

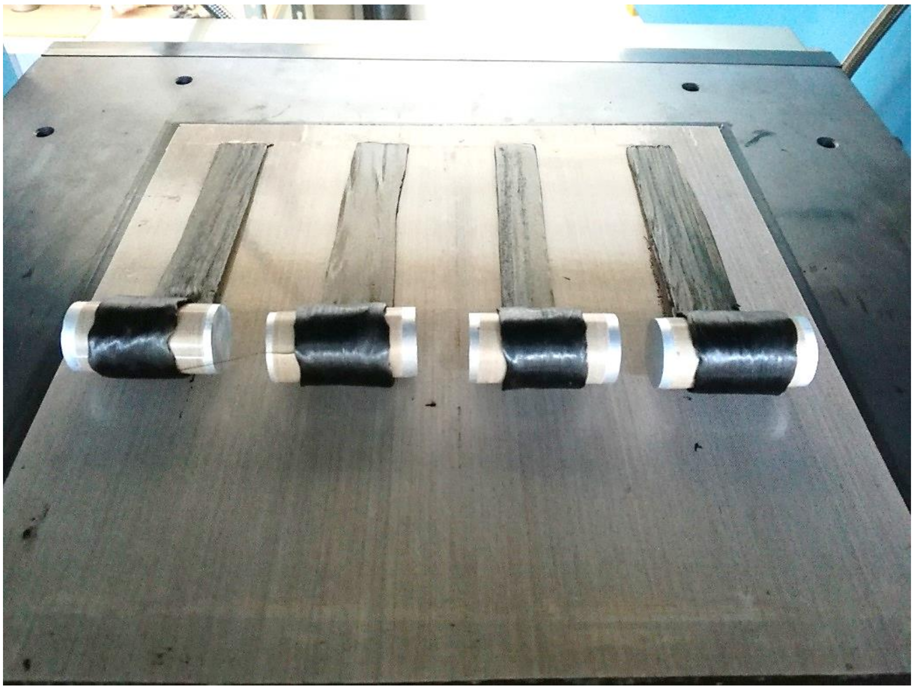


Figure 50: UD laminates wrapped around 25mm diameters

Wrapping forces the inner plies of the laminates to contract. The organosheets being already consolidated, it creates shear between plies. The ±45˚ laminates adapt to this shear, whereas a visual defect appears on the inner side of UD wrapped samples. This defect is characteristic of shear, as it consists on all samples of a chevron pattern at 45˚ along the laminate, as shown on **Error! Reference source not found.**1.

Figure 91: On the left: wrapped UD sample where the inner diameter exhibits a chevron pattern of wrinkles. On the right: ±45˚ samples do not present the same defect.

i.Wrapping of configurations 5 and 6

Similarly, to the configurations 1 to 4, the laminates are wrapped around the braided tubes. Despite processing above melting temperature, adhesion between the matrices of the laminates and the tubes does not happen. This is due to the insufficient consolidation pressure of the manual processing. A consolidation step is then added to the process: tube and laminate are put together between inner and outer moulds, consisting of respectively a metal spiral spring and an aluminium rigid curved plate (see **Error! Reference source not found.**).

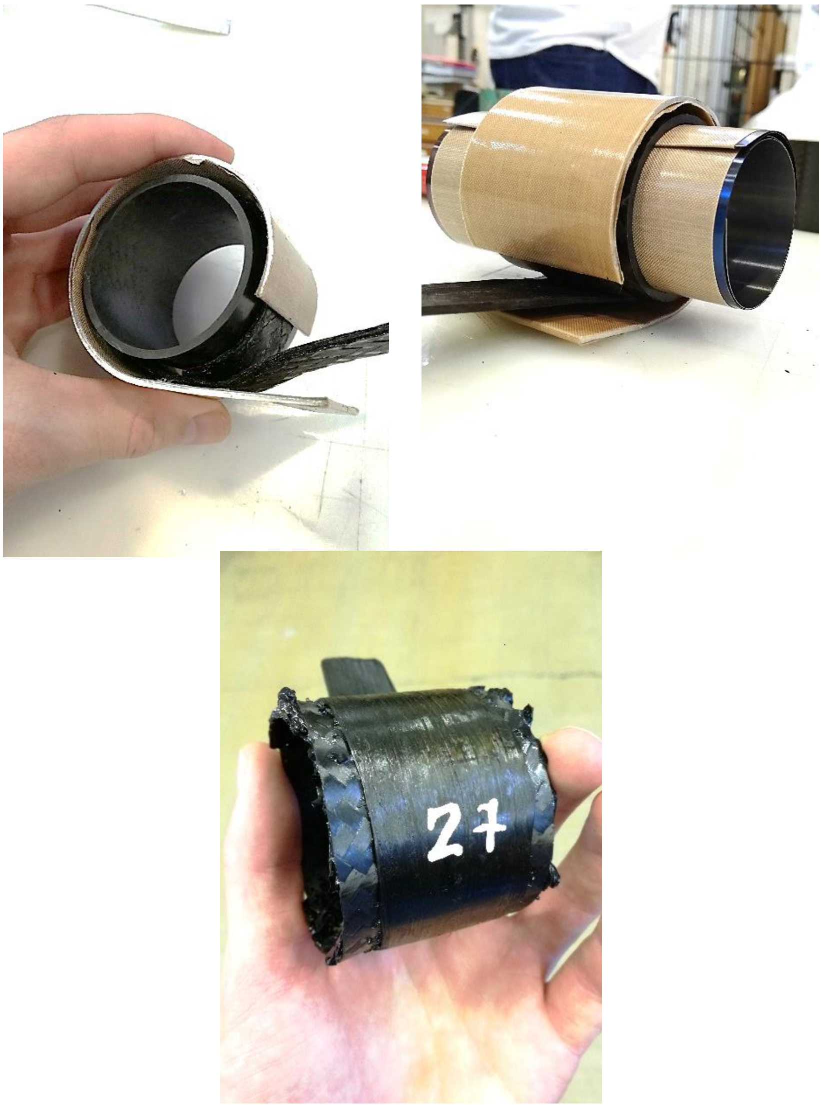


Figure 52: Left: positioning of the tube and wrapped laminate in the outer mould. Middle: the inner spiral spring mould in added. Right: finished sample, after consolidation at 250˚C and release. The pressure in the mould was sufficient to create an excess flash of resin on the sides of the tubes.

Mechanical testing

The samples are tested according to the load case described on **Error! Reference source not found.**. previously. The experimental apparatus is shown on **Error! Reference source not found.** To be representative of the application load case, the rotation of the substrate tube is blocked using a pin going through it. This is not necessary for configurations 1 to 4 due to the absence of friction between substrate and laminate.

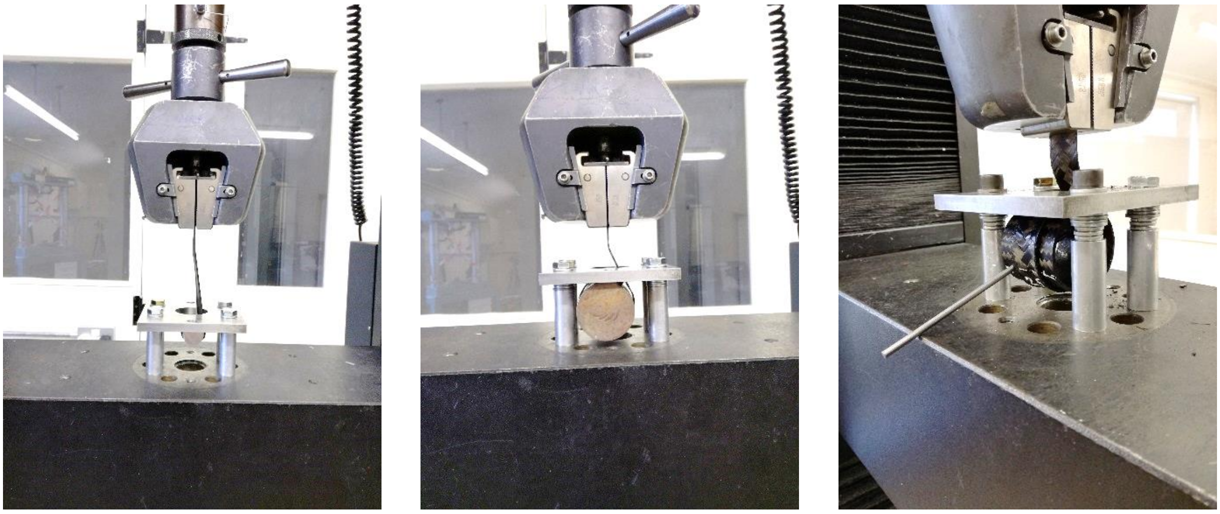


Figure 53: From left to right: testing apparatus for configurations 1 and 2; 3 and 4; 5 and 6

Results

Error! Reference source not found. shows the strength values obtained for the 30 samples that have been manufactured.

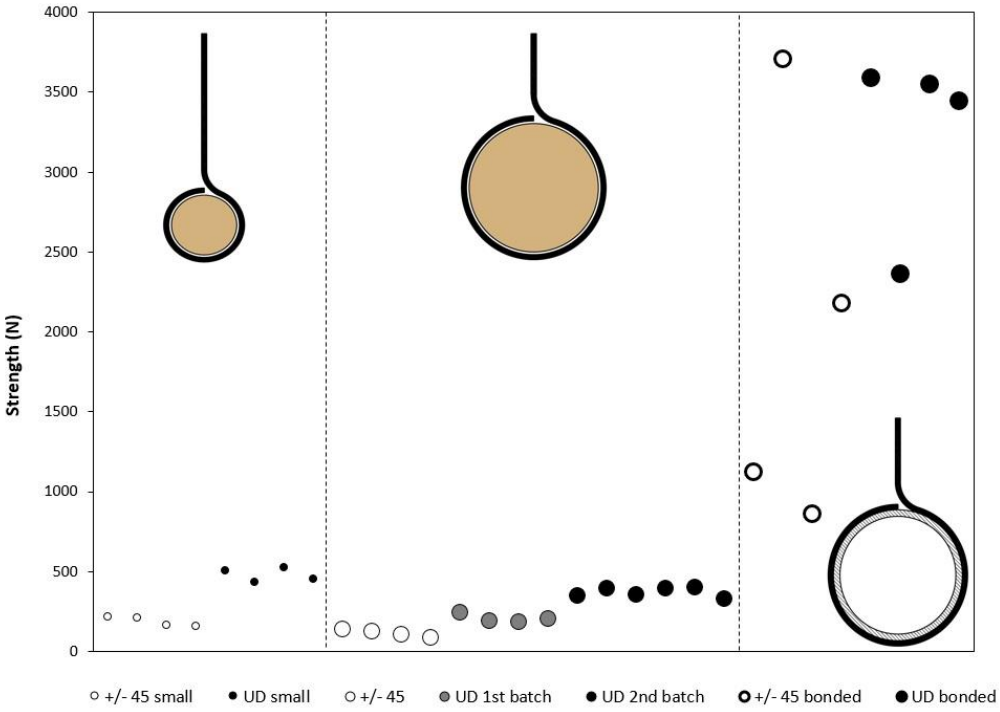


Figure 54: Strength results for all the wrapped samples manufactured. The three zones concern respectively configurations 1 and 2; 3 and 4; 5 and 6.

Regardless of diameter change, samples from configurations 1 to 4 present strengths lower than 600N. They present a factor 3 increase in strength from ±45˚ to UD laminates. The "UD first batch" presented a higher void content than expected during manufacturing. This is why a second batch had been manufactured and compared to it. The failure of configurations 1 to 4 is ductile, and a large proportion of the deformation remains in the elastic zone. The samples are unwrapped during the test, behaving mostly like a spiral spring. They then recover a part of the deformation they were subject to, as shown on **Error! Reference source not found.**.

The samples of configurations 5 and 6 have strength ranging from 900N to 3700N, which is an increase of a factor 7 compared to the highest strengths of configurations 1 to 4. The 4 highest strength of those bonded samples exhibit a failure in the laminate (see **Error! Reference source not found.**) rather than at the interface between laminate and substrate, which is the case of the 4 others.

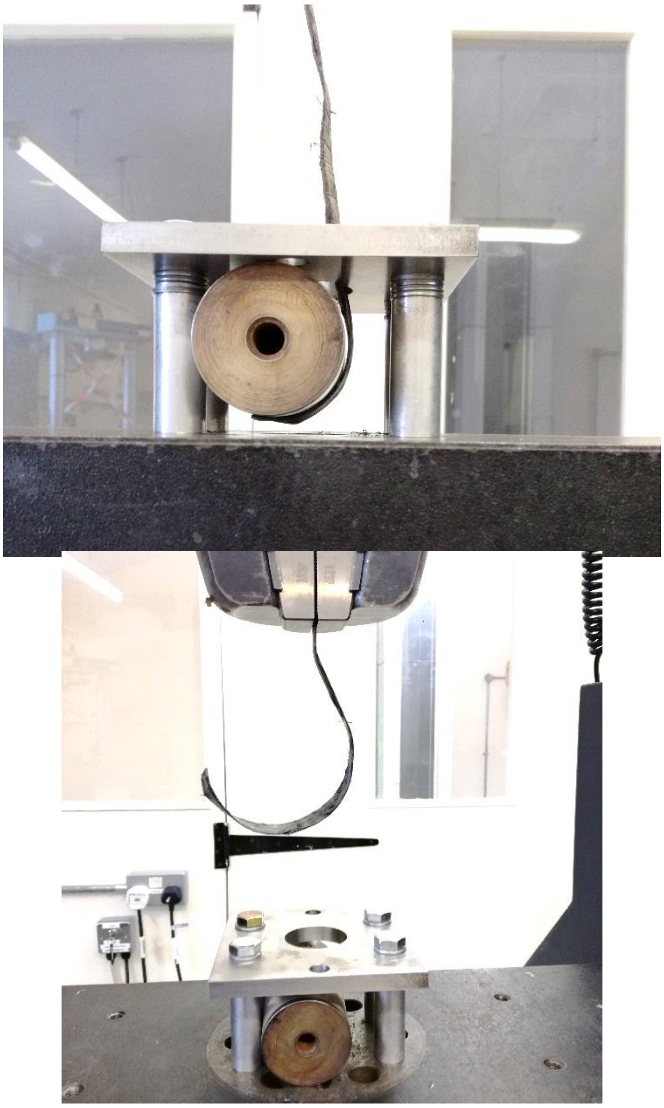


Figure 55: on the left: the laminate is unwrapped during testing of configurations 1 to 4. On the right: it recovers a part of its original shape at the end of the test.

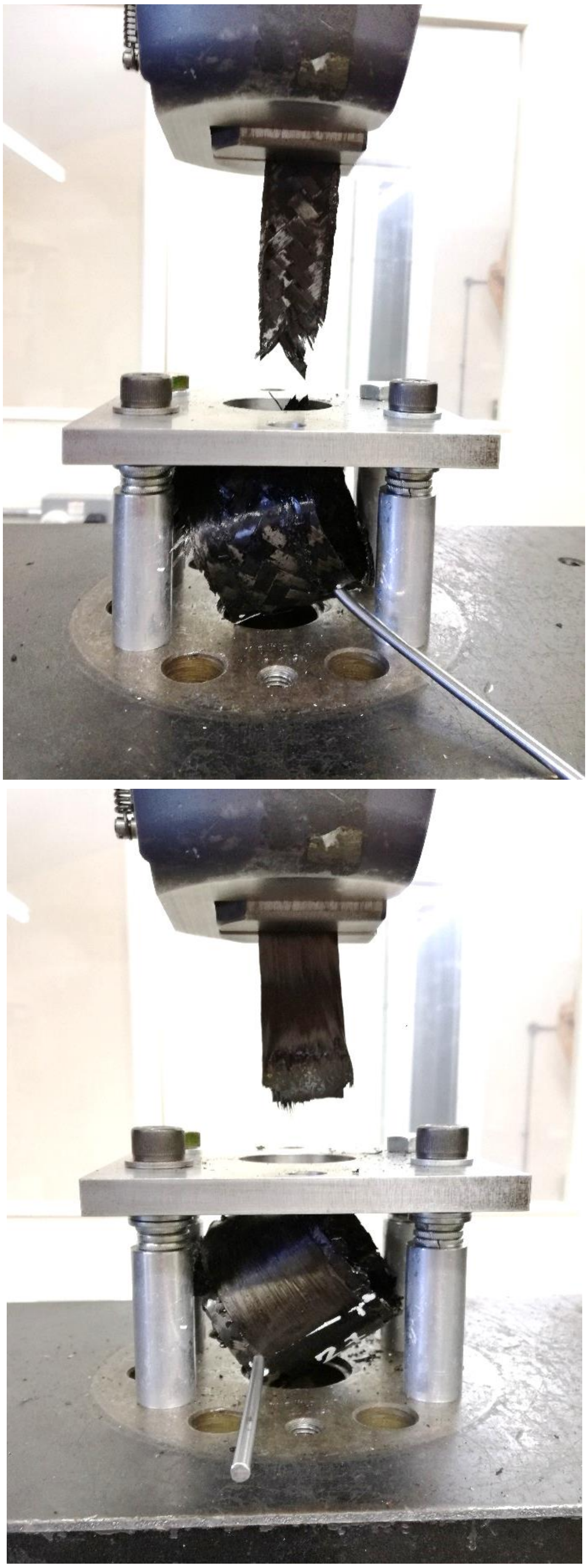


Figure 56: the laminate, respectively ±45 and UD, has failed before the bonding interface

Discussion

The geometrical factor for strength has relatively low influence on strength compared to bonding. However, only half of the bonded samples (configurations 5 and 6) presented sufficient bonding strength to have a failure appearing in the laminate. This can be due to the relatively low manual consolidation conditions explained in section **Error! Reference source not found.** above, in comparison to a controlled automatized process. It can also be partly explained by matrices materials that are slightly dissimilar, as introduced in section **Error! Reference source not found.**.

Yet, the strength obtained for the four other samples is around 3500N. The failure appears out of the bond line, which implies that the strength of this one is greater than 3500N. In order to achieve this strength force, a single lap joint using a high strength epoxy adhesive (τ_u=12.5 MPa [1]) will require on the same 25 mm wide laminate a bond length of around 55 mm, assuming a single lap bonding efficiency η=0.2 [2]. It will also require a defect-free surface preparation, and will be subject to catastrophic failure propagation. **Error! Reference source not found.**. puts those two joints in parallel. The wrapped configuration is a heavier solution, yet requiring fewer parts, less manufacturing steps, and is less sensitive to surface preparation.

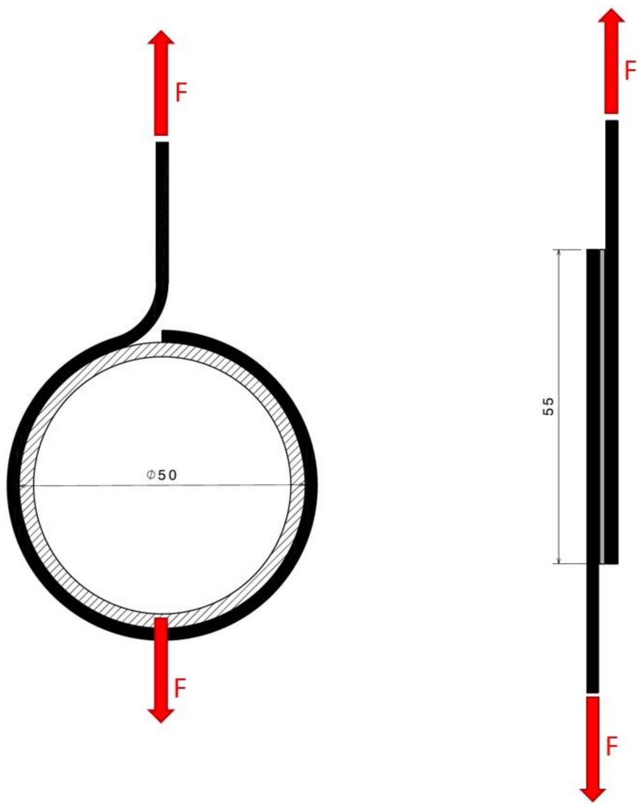


Figure 57: Configurations 5 and 6 (left) provide equal or greater strength than scaled single lap joint (right).

Moreover, improved configurations can be derived from the wrapped solution. Three suggestions are illustrated in **Error! Reference source not found.**. Each illustrated solution presents increased bonding area within the same design volume. A sandwich structure would have the benefit to reduce peeling stresses by aligning le laminate with reaction loads. Further experimental investigation should also include finer tuning of laminate architecture. Cycle time and quality aspects will also be introduced, in the study of the wrapping process automation where pressure and heat application will be robotised.

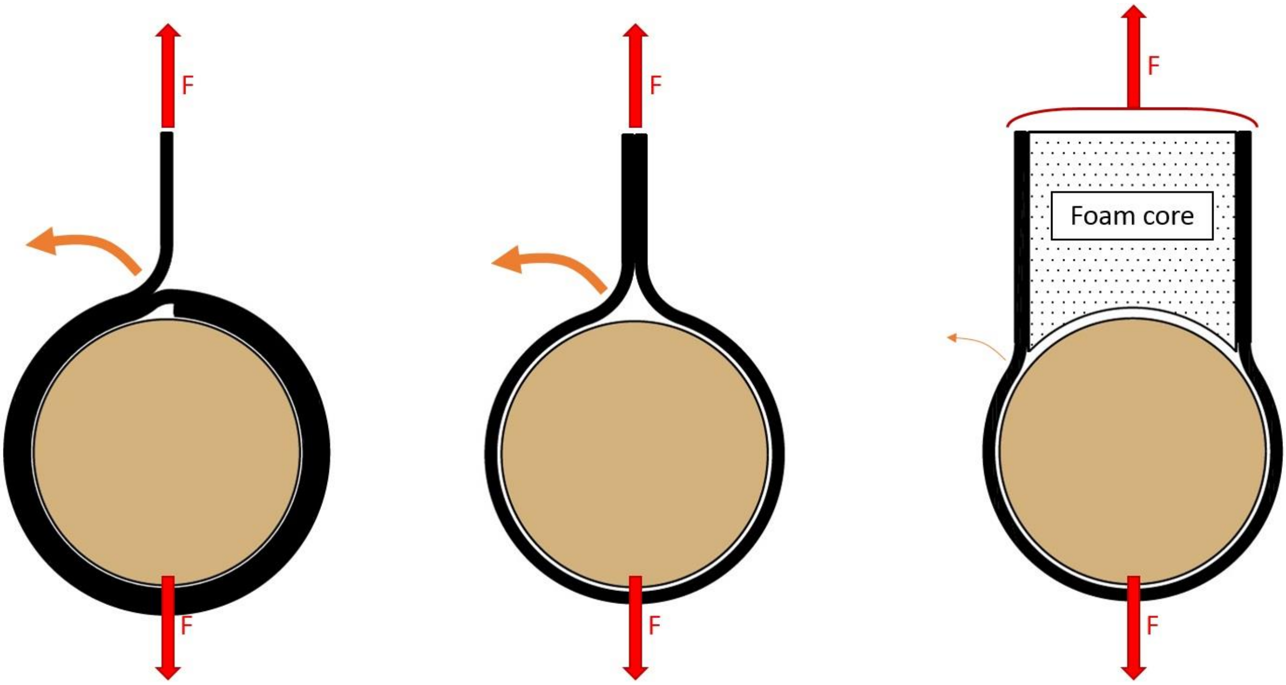


Figure 10: three configurations for wrapped joints to be further investigated. It can be expected from the third configuration to exhibit lower peeling stresses (in orange)

Conclusions

- Aside of their known potential for short cycle times, thermoplastic matrix composites have the ability to be re-shaped, which can be used to create high strength joints.
- In comparison to mechanical joining, the wrapped joints preserve alignment and continuity of the fibres.
- In comparison to adhesive bonding, those joints are relatively tolerant to manufacturing variability.
- The number of parts and manufacturing steps can be reduced in comparison to traditional joining methods.
- The radius of wrapping has relatively low influence on the joint strength, compared to the laminate layup, and mostly to the length of the bond line.
- Wrapping allows increasing the bond line length without major increase in design space. This is planned to be further investigated experimentally, as well as the inclusion of foam cores for load paths tailoring.

Process optimisation and shortening of cycle time should be investigated, through the automation of pressure and temperature application during wrapping.

References

[1] Caruta BM. Polymeric Materials: New Research. New York: Nova; 2005.

[2] Hart-Smith LJ. Adhesive bonded single lap joints. Hampton: 1973.

6.3 Manufacturing Investigation of metallic/ CFC dimple-joints

Based on the previously described five concepts, the aim for initial feasibility studies was to demonstrate the manufacturing process and gain a basic understanding of the mechanical strength offered by selected concepts. Thereafter, further work should investigate deeper into the details of mechanical strength and durability performance and explore possible techniques for validating the joint manufacturing and assuring subsequent performance levels.

Feasibility study objectives – hot-press metal/ CFC interlock joints

1. **Develop manufacturing process & build competency in joint manufacturing:**
   - Pressing process development - production trials using different thermoplastic materials and fibre architectures
   - Description of joint behaviour during processing, recommendations for improvements
   - Development of optimal joint pressing parameters
   - Incorporation of surface treatment techniques
2. **Understand mechanical performance, demonstrate capability:**
   - Comparison of pressed metal plate/ thermoplastic interlock joints against adhesively bonded joints.
   - Identify any areas requiring specific further investigation
3. **Identify needs/ challenges for industrial adoption to assist detailed scoping for full-scale project:**
   - Present guidelines/ recommendations for press-plate process
   - Identify dedicated equipment requirements/ modification for future work
   - Propose production & joint validation scenarios, plans for how full-scale project would evaluate

Description of the dimple joint concept;

The dimple joint concept is a proposed method for direct, interlocking joining of metallic materials with thermoplastic matrix fibre reinforced polymer composite materials.

The basic joint concept comprises the following key features:

- A metallic component constructed from sheet metal.
- A series of dimple shaped features within the metal component design, each featuring a small through hole.
- A fibre reinforced polymer composite material, typically containing carbon reinforcing fibres and a thermoplastic matrix.

The general manufacturing process for the dimple joint concept is as follows:

- Place the metallic and carbon fibre composite (CFC) components together in their intended joint location/ assembly.
- Working from the metallic side of the joint, apply localised heat and pressure to the overlapping surfaces of the metal/ CFC joint area. (A counteracting force/ joint support may be required from the CFC side of the joint).

- After providing sufficient heat, pressure and time to ensure CFC material flow within the joint, reduce the joint temperature to below the polymer melting range and remove the apparatus.
- The metallic/ CFC joint is thus created.

Experimental Investigation

The feasibility study into dimple-joint concepts investigated the following:

- **Direct dimple joining of metallic and CFC materials, using pressing and co-curing/ forming of the metallic plate with the CFC material:**

  Material A: Hexcel 8552 thermoset epoxy/ unidirectional carbon fibre pre-preg

  To provide basic understanding of fibre flows and materials behaviour during joint pressing

  Material B: L&L L-F610 re-formable epoxy/ bi-axial carbon fibre material

  Representing the significant majority of press process development work and mechanical test specimen manufacturing

  Material C: Polyamide 6.6/ woven carbon fibre thermoplastic pre-preg
  Material D: ABS/ woven carbon fibre thermoplastic organosheet
  Material E: PPS/ woven carbon fibre thermoplastic organosheet

  To provide understanding of the effect of fibre architecture and different polymer selection on the joint manufacturing process

  Material F: PAEK/ carbon fibre thermoplastic tape

  To demonstrate the process compatibility/ suitability with high-temperature melting point thermoplastic matrices

- **Dimple joining of metallic and CFC materials with an extra polymer over-cap**

  Material B: L&L L-F610 re-formable epoxy/ bi-axial carbon fibre material

This translates into the following test matrix/ plan:

Mat:	Specimen type:	Production trials	Inspections	Mechanical tests
A	8552 epoxy	Dimple, upwards protrusion	Visual	None
B	L-F610 thermoform	Simple hole Dimple, upwards protrusion	Visual	Tensile, overlap type specimen

		Dimple, downwards protrusion Dimple, downwards protrusion + over cap Dimple upwards and extra polymer interface	Sections Metallographic sections	
C	PA6.6 thermoplastic	Dimple, upwards protrusion	Visual	None
D	ABS thermoplastic	Dimple, upwards protrusion	Visual Metallographic sections	
E	PPS thermoplastic	Dimple, upwards protrusion	Visual Sections Metallographic sections	
F	PAEK thermoplastic	Dimple, upwards protrusion	Visual	

Dimple joining - pressing process

In the absence of bespoke pressing equipment, a press arrangement was constructed using a metallic interface block (19 mm x 150 mm surface) and a George Moore 40T heated hydraulic press (platen size approx. 400 x 400 mm). This arrangement utilised heating on the upper press platen only, with heat transferring through the metallic press block into the specimen (see Figure 59)

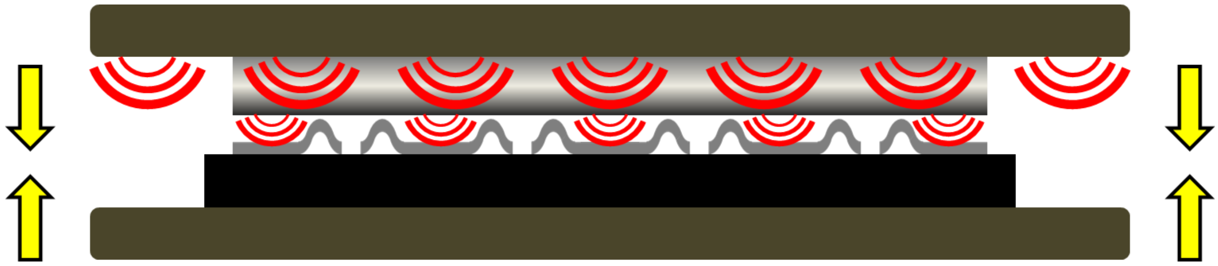


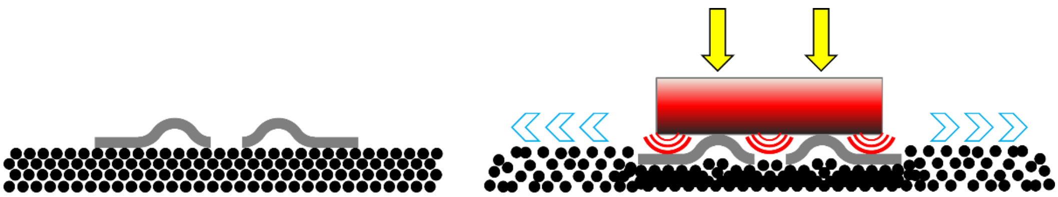
Figure 59. Dimple joint pressing arrangement (not to scale)

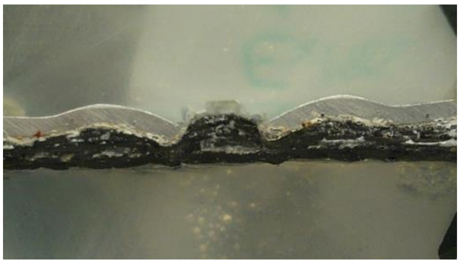
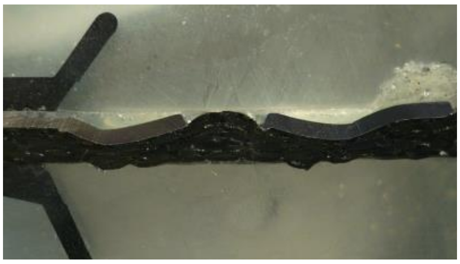
Trial joints were manufactured by pressing the heated metallic block into the 25 mm x 150 mm metallic dimple plate, in order to impress it into the carbon fibre polymer material. Typical press force was 50 kN, which translates to a minimum of 17 MPa compression on the metallic block. Accounting for the dimple geometry as a non-contact surface, the 50 kN load translates to approximately 32 MPa compression on the flat surfaces of the metallic dimple plate with dimples in the "upwards" position.

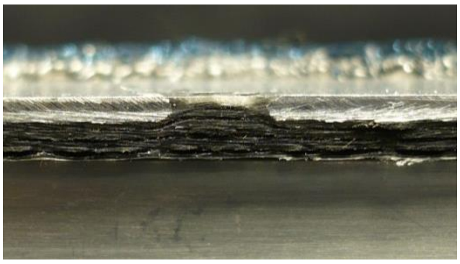
Mechanical test specimen manufacturing

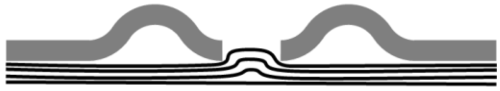
Test specimens were prepared by pressing each end of a metallic dimple plate into the carbon fibre reinforced polymer sheet.

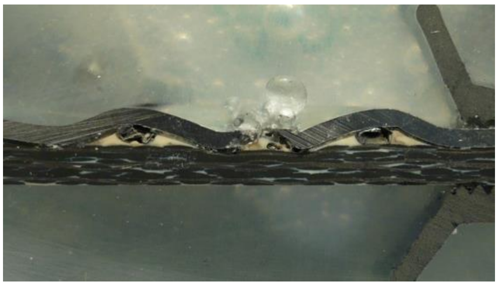
Dimple joining – joint examinations

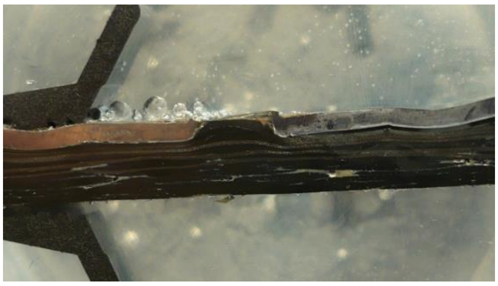
Type: A	Material: 8552 epoxy	 Pre-preg material spread outwards, perpendicular to the fibre orientations, some evidence of fibres flowing into dimple holes. Supports conclusion that localised fibre mobility and flow into dimples is possible with viscous matrix material, but indicates that limiting heating to upper surface and joint areas only is key to avoiding global material flow.

Type: **B**	Material: L-F610 thermoform	 **Position 1 – dimple "up"** Visible material flow into dimple hole and cavity – estimate 50% filled Both the hole edges and dimple cavity offer mechanical interlock between metal and composite materials Localised compression and potential stress intensification at edges of metal in central hole region	 **Position 2 – dimple "down"** Visible material flow into and filling of dimple hole – estimate 40 to 50% filled Both the hole edges and dimple impression offer mechanical interlock between metal and composite materials Differences in consolidation level across joint
		 **Position 1 + extra polymer layer** Material flow into dimple hole cavity appears more pronounced than without extra sheet of polymer material between metallic & composite materials – estimate 100% filled and extra material protruding Suggests that extra polymer material supports greater mobility of polymer and fibre materials during pressing	 **Position 2 + polymer over-cap** No apparent significant difference to material flow in comparison to non-capped counterparts – estimate 40 to 50% filled Extra polymer cap material appears to be fused with composite matrix material, and cap has completely filled dimple shape and hole/ cavity

		Highly inset nature of metallic edges into composite raises concerns of significant stress intensification sites	
			**Open hole in flat metallic sheet** Some degree of material flow into hole, estimate 20 to 30% filled Mecanical interlock limited to metallic edge against pillowed composite layers

Type: C	Material: PA6.6 thermoplastic	  Metallic plate pressed in “dimple up” position, some evidence of material flow into dimple hole – inconsistent across the plate, some holes exhibiting material movement (as per line diagram), others only slight pillowing of material into hole.

Type: D	Material: ABS thermoplastic	 Metallic plate pressed in “dimple up” position, no evidence of fibre movement into dimple holes, some evidence of polymer flow (light coloured material) into dimple cavity and hole, significant porosity in exuded material.

Type: E	Material: PPS thermoplastic	   

		Position 1 Metallic plate pressed in “dimple up” position, near complete filling of hole with fibre and polymer material, significant polymer exudation into dimple cavity on upper side of joint, evidence of significant flattening/ deformation of metallic plate during pressing.	**Position 2** Metallic plate pressed in “dimple down” position, limited evidence of fibre flow into hole, some polymer flow into hole but no exudation of polymer into dimple cavity on upper side of joint, evidence of metallic plate deformation/ flattening.

Type: **F**	Material: PAEK thermoplastic		Metallic plate pressed in “dimple up” position, similar material behaviour to type A epoxy pre-preg specimens, limited fibre movement into dimple hole, some exudation of polymer material as small globules into open areas, degradation of metallic anti-corrosion coating due to high process temperature.

Dimple joints - mechanical testing results

Dimple-joint mechanical test specimens were prepared by pressing metallic plates into CFRP plates, in a single-sided overlap or “strap” configuration (see Figure 60.). With the specimens retained at both end in manual wedge action grips, each underwent tensile loading until failure. Table 2 reports the peak loads for each specimen, and Figure . presents these results to permit simple comparison of the average peak loads for each specimen along with an indication of the maximum and minimum load exhibited for each type. Figure 62, Figure 11 & Figure 64 present the load/ cross-head displacement curves for each of the tested specimens.

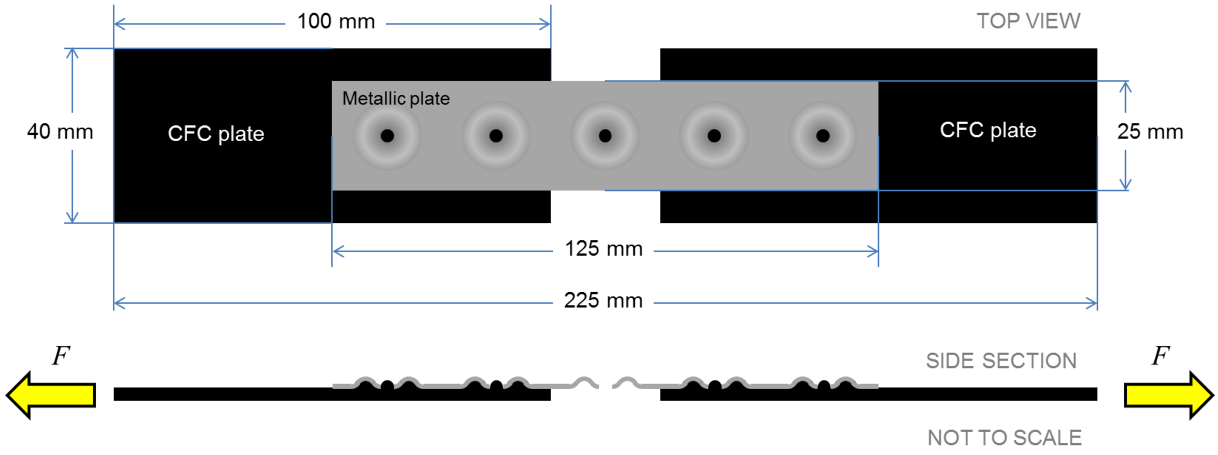


Figure 60. Mechanical test specimen configuration

Specimen type / Peak loads (kN)	Dimple "up" "Position 1"	Dimple "down" "Position 2"	Dimple "down" "Position 2" + polymer cap
Specimen 1	0.34	1.26	1.05
Specimen 2	1.96	0.74	0.62
Specimen 3	0.88	1.37	0.33
Mean peak load (kN)	1.06	1.12	0.67
Standard deviation	0.82	0.34	0.36
Test conditions	Instron 4467 test frame with calibrated 30 kN load cell 1 mm/ minute loading rate 21 °C ambient room temperature		

Table 2 - mechanical testing results for dimple joints

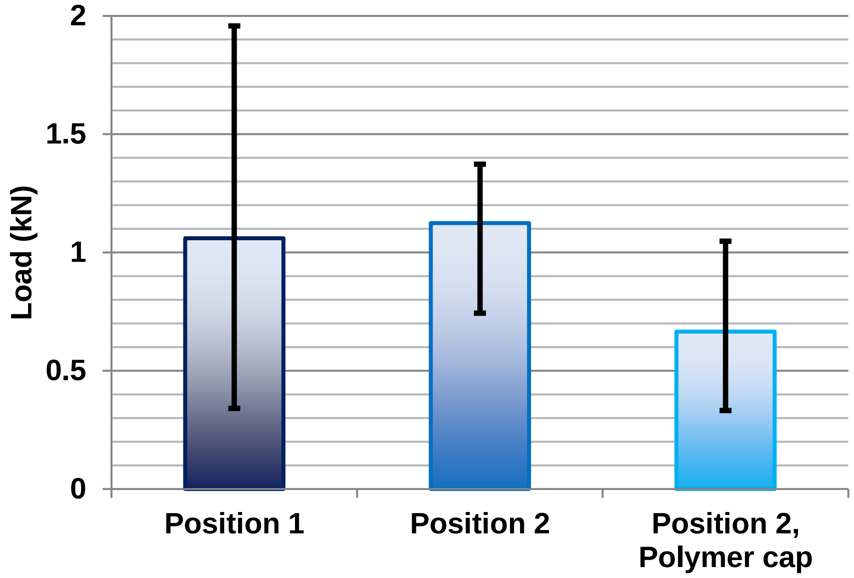


Figure 61 Mechanical testing results for metallic/ CFC dimple joint specimens

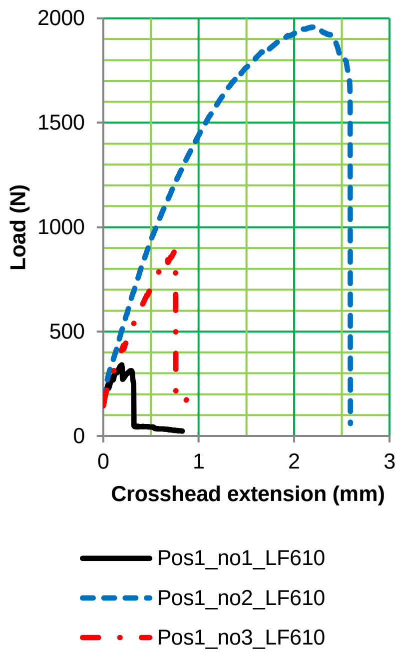


Figure 62 - load/ displacement curve for "position 1" specimens

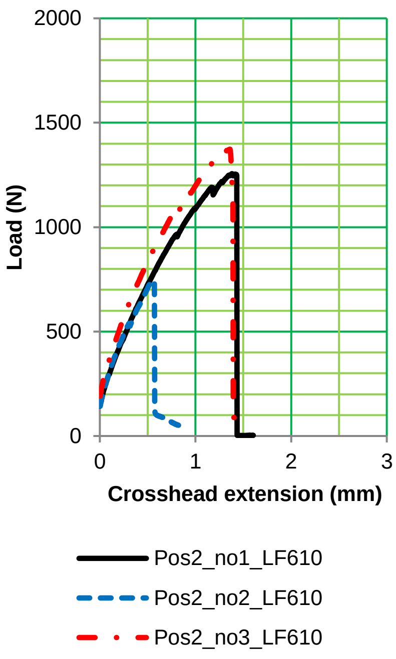


Figure 11 - load/ displacement curve for "position 2" specimens

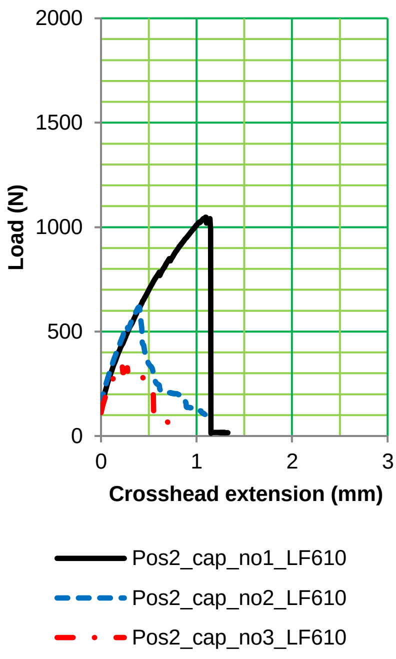


Figure 64 - load/ displacement curve for "position 1 + cap" specimens

Summary of mechanical testing results

Each joint configuration demonstrated ability to support some degree of tensile loading, with peak loads typically in the 0.5 to 1.0 kN range, with some exceptions below, and one “position 1 or dimple-up” specimen failing at a measured peak load of over 1.5 kN . Variation in peak loads was significant for each specimen type, although the “position 2 or dimple down” specimens exhibiting the smallest overall variation in measured peak load (Std Dev. 0.34). In absence of any other influential factors, the most logical explanation for the high level of variation in peak loads is variations in pressure or temperature profiles during individual specimen manufacturing, which may have caused differences in the level of polymer of fibre interlocking and adhesion between the polymer and metallic interface.

Conclusions from mechanical testing

For each specimen type, the typical failure mode was de-lamination or failure of the CFC material within the open “dimple” hole. For dimple-up and dimple-down specimens, there is evidence of fibres and polymer detached from the surrounding laminate (Figure 65, Figure 66). For the polymer cap type specimens, there is evidence to suggest that the polymer cap tore away from the main laminate material, with limited fibre damage (Figure 67). This explains the apparently lower loading capability of the “cap” type specimens compared to their uncapped counterparts.

Figure 65 - "dimple-down" specimen exhibiting failure of CFC material where interlocked into through-hole

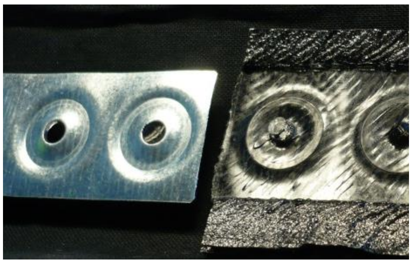


Figure 66 - "dimple-up" specimen failure surfaces (metallic component, left, inverted from test orientation to reveal joined faces)

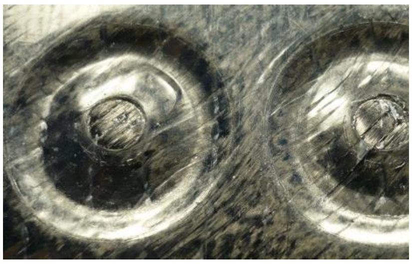


Figure 67 - "capped" dimple after failure, exhibiting removal of polymer material from fibres in centre-most circular regions corresponding to through-hole in metallic plate

In all specimens, the visual evidence suggests that loading was predominantly transferred between the CFC material and metallic plate through the interlocked CFC or polymer material protruding into/ filling each dimple hole. In all cases, failed specimens exhibit little evidence of cohesive or substrate failure at the metallic/ CFC interfaces, which suggests only limited adhesion of the polymer to the metallic surfaces (Figure 66). In view of this apparently limited adhesion between the CFC and the metallic component, it is logical to suggest that slipping of the metallic faces over the CFC material caused a flatwise separation force between the metallic and CFC components, thus contributing to failure of the CFC within the interlocked laminate region inside the dimple hole.

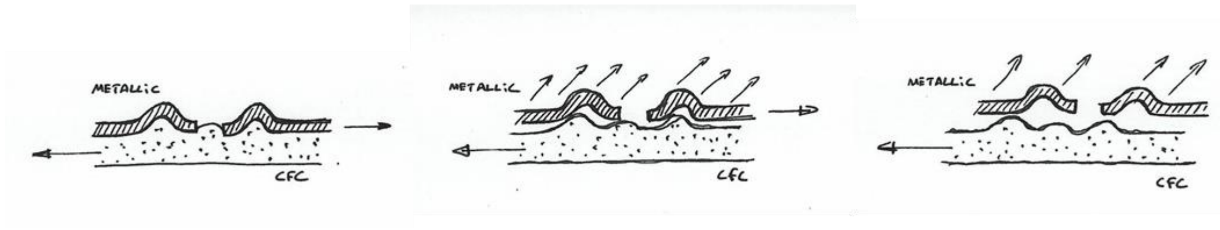


Figure 68 - sketch of metallic plate/ CFC slipping and separation as joint loading increases

The implications of these findings are thus:

- The mechanical loads, averaging between 0.5 and 1 kN were supported predominantly by the interlocking of CFC or polymer material within each of the four through holes (Ø 4 mm) in the metallic plate.
- It therefore follows that increasing the number of holes should increase the loading capability of these joint concepts, although this will most likely result in an increase in joint size in order to accommodate a greater number of dimple-hole features.
- This study used only one geometry of dimple, and one size of through hole in the metallic plates – significant further work is required in order to understand the effect of dimple shapes and through hole sizes on CFC material flow, and their subsequent effects on interlock and joint loading capability. Likewise, the relationship between dimple and through-hole geometry and CFC material architecture requires far greater exploration and understanding.
- The addition of a polymer cap is apparently detrimental to the performance of the press-formed, interlock concept, whereas encouraging greater amount of laminate fibre/ polymer flow into the hole should yield greater benefit. Future research should undoubtedly focus on optimising the manufacturing parameters and geometries of the metallic features in order to maximise material flow and interlocking.
- The single-lap specimen configuration does not restrict slipping of the metallic plate over the CFC material, and joint designs such as a C-section overlap should be more resistant to this behaviour due to the clamping nature of the metallic component around the CFC within.
- The ability of these specimens to support meaningful loading, despite apparent lack of adhesion between metallic and CFC materials, suggests that the interlocking dimple-hole feature, and associated press-manufacturing technique, could be a viable joining technique for metallic and thermoplastic CFC materials, that ensures mechanical interlock and thus eliminating requirement for extra mechanical fastening.

Future investigation required

- Appropriate pressing equipment suited to joint specimen manufacturing
- Understanding of how dimple & through-hole geometry affects material flow
- Optimisation of geometry and processing parameters to maximise interlock

- Incorporation of adhesion promoting technologies to improve metallic/ polymer adhesion
- Greater understanding of mechanical behaviour of improved, optimise joints and modelling/ understanding of crash-behaviour for automotive applications
- Demonstration on a range of joint geometries including flat-plate joints, right-angle joints and C-section joints

References

[1] Vasiliev V V, Barynin VA, Razin AF. Anisogrid composite lattice structures – Development and aerospace applications q. Compos Struct 2012;94:1117–27. doi:10.1016/j.compstruct.2011.10.023.

[2] Oak Ridge National Laboratory - 3D Printed Shelby Cobra n.d. http://web.ornl.gov/sci/manufacturing/shelby/ (accessed June 16, 2017).

[3] Autocar Pro News Desk. “No matter what material is being used, we have the optimisation technology to facilitate lightweighting for automakers.” Nov 14 2016.

[4] Bastien C, Prem A, Bastien C, Dickison M. Multidisciplinary Design Optimisation Strategies for Lightweight Vehicle Structures Multidisciplinary Design Optimisation Strategies for Lightweight Vehicle Structures. 10th Eur. LS-DYNA Conf. 2015, Wurzburg, Germany: 2015.

[5] Design for manufacturing of fuselage panels with curved grid stiffening 2014.

[6] Batista NL, Olivier P, Rezende MC, Botelho EC, Talim R. Correlation between degree of crystallinity , morphology and mechanical properties of PPS / carbon fiber laminates 2016;19:195–201.

[7] Comer AJ, Ray D, Obande WO, Jones D, Lyons J, Rosca I, et al. Composites : Part A Mechanical characterisation of carbon fibre – PEEK manufactured by laser-assisted automated-tape-placement and autoclave. Compos PART A 2015;69:10–20. doi:10.1016/j.compositesa.2014.10.003.

[8] Grouve WJB, Warnet LL, Rietman B, Visser HA, Akkerman R. Composites : Part A Optimization of the tape placement process parameters for carbon – PPS composites. Compos Part A 2013;50:44–53. doi:10.1016/j.compositesa.2013.03.003.

[9] Lyu M, Choi TG. Research Trends in Polymer Materials for Use in Lightweight Vehicles 2015;16:213–20. doi:10.1007/s12541-015-0029-x.

[10] Morgan P. Polymer matrices for carbon fiber composites. In: Francis T and, editor. Carbon fibers their Compos., 2005, p. 501–49.

[11] Shinohara M, Isshiki S, Fukushima Y, Katayama T. Moulding of carbon fiber reinforced polycarbonate (CF / PC) using UD tape n.d.;124:249–57. doi:10.2495/HPSM120221.

[12] Cikoni. Lightness made in Stuttgart: Tech start-up combines bionic design with high tech materials for future logistics. January 9th 2017. http://cikoni.com/en/lightness-made-in-stuttgart-tech-start-up-combines-bionic-design-with-high-tech-materials-for-future-logistics (accessed June 16, 2017).

[13] Secar. PullBraiding 2017. http://www.secar.at/index.php/de/technologien/werkzeug-design-und-bau (accessed June 16, 2017).

[14] CQFD composites. Curved pultrusion 2017. http://cqfd-composites.com/curved-pultrusion/ (accessed June 16, 2017).

[15] Wang Z, Riemer M, Koch SF, Barfuss D, Grützner R, Augenthaler F, et al. Intrinsic Hybrid Composites for Lightweight Structures: Tooling Technologies. Adv Mater Res 2016;1140:247–54. doi:10.4028/www.scientific.net/AMR.1140.247.

[16] Barfuss D, Gr??tzner R, Garthaus C, Gude M, M??ller R, Langrebe D. Intrinsic manufacture of hollow thermoplastic composite/metal structures. AIP Conf Proc 2016;1769. doi:10.1063/1.4963580.

[17] Maron B, Garthaus C, Hornig A, Lenz F, H??bner M, Gude M. Forming of carbon fiber reinforced thermoplastic composite tubes - Experimental and numerical approaches. CIRP J Manuf Sci Technol 2016;170028. doi:10.1016/j.cirpj.2016.09.004.

7. Conclusions

Many concept for thermoplastic matrix and metallic hybrid structures have been identified. Taking a sports car fully body structure geometry and carrying out a loading study, novel structures suitable for high rate manufacturing have been proposed. These utilise combinations of pultruded tubular sections and folded thermoplastic ‘organosheets’. The tubular parts are proposed to be joined using low cost metallic connectors. The concepts do not therefore require dedicated mould tooling for shaping the parts.

The following concepts are considered to offer the most potential for structural application and further investigation:

a. Metallic joint wrapping
b. Composite tube swaging
c. Metal joint interlocking with composite sections

a. The wrapping of section ends around other parts offers the potential to form framework structures able to resist the tearing forces during crash loading without the need for bolting or manufacturing large complex shape structures, which are so difficult to lay up by automation. This would greatly reduce both assembly time and cost. The wrapped joint investigation has shown that load transfer is achieved through straighter fibres and over a longer shear area than for conventional bolted or bonded overlap joining. Hence, less localised thickening or adding fasteners maybe eliminated for joints subjected to high tensile loading; such as for A, B or C pillars during vehicle crash.

a. and b. offer the potential benefits for manufacturing complexity and cost of being able to use standard sections or either curved plate or tube and to locally form connections to joint parts using the geometry of the joint part as form and jig tooling. Taking cut lengths of section and forming attachment during assembly will massively reduce both tooling cost and parts handling and tracking.

b. Tube swaging and interlocking metallic sleeves did not provide joints of significant tensile strength during this study. It is believed that this resulted from the non-availability of thermoplastic CFC tubing with axial tows and sections with triaxial fibres would show greatly increased joint strength. The design of the metallic inner and outer joint components will also need to be investigated to establish whether this joint concept is sufficiently lightweight compared to bonded or mechanically fastened joints. A simpler tube end crimping and mechanical fastening may provide a lighter and lower cost joint. The thermoplastic CFC tube end crimping was demonstrated to be a simple and fast process.

c. The dimple interlocking concept offers a means of provide strong shear connections between sections and metallic joints since load transfer is provided by interlocking rather than adhesion. The provision of strong joints, which can be inspected by camera, is a major benefit to high rate manufacturing.

8. Recommended next research stages

This feasibility project has investigated many aspects of TP CFC and metallic framework design and manufacture. The techniques below all show the potential for more detailed investigation:

a. Metallic joint wrapping
b. Composite tube swaging
c. Metal joint interlocking with composite sections

Each of these techniques will require equipment for local heat and pressure application, which is capable of being adaptable eventually fast moving robotic assembly equipment. This will require both equipment and skills from a collaborative research group, such as a manufacturing catapult; for example the AMRC, MTC or NCC.

Alongside development of the joining techniques, continuous forming techniques for either tubular section or shaped plate as a feedstock for the framework sections. Continuing collaboration with the Technical University of Dresden is advised to investigate continuous forming and tailorable fibre angle sections.

For each of the three processes, further and much more detailed investigation of realistic joints using various permutations of inner and outer thermoplastic composite sections and metal joining pieces which are best suited to the structural loading requirements. This will entail the manufacture of a wide range of experimental joints.

Once effective forming techniques have been developed, the durability of the joints will need to be investigated. Whether interlocking, or local bonding / welding or complete adhesion/ welding in the joining areas is required. Adhesive application or welding techniques may need to be utilised.

The strength and weight of the joints produced using all three techniques will need to be compared with local fastener application. This is an additional step, but may provide the required load transfer for either reduced manufacturing cost or weight.

In addition to further framework design and manufacturing investigation, the effect of the forming processes on both the laminate compaction and fibre disruption will need to be studied. The effect of local heating may cause an unacceptable level of disruption to the thermoplastic composite pre-manufactured laminates.

Finally for the selected and developed techniques, simulation tools for the forming processes and the process parameters required to provide reliable forming will need be developed.