# THIN PLY SHEET MOLDING COMPOUND ENABLES THIN LAMINATES WITH PROPERTIES AS OF CONTINUOUS FIBERS

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## ABSTRACT

In a research collaboration with Chalmers University of Technology, KTH Royal Institute of Technology (SWE) and Imperial College (UK), Oxeon AB has developed ultrathin carbon fiber sheet molding compound (SMC) products for high performance, thin laminate and ease of manufacture composite applications. Said SMC products are based on ultrathin (0.02 mm or 0.0008 in) Spread Tow Tapes that are cut by length and randomly distributed in order to obtain a preform with an in-plane isotropy in either dry or pre-impregnated form displaying the previously never seen minimum cured plate thickness of about 0.5 mm. Recent work has demonstrated that these SMC materials can reach high stiffness and strength making them good alternatives to metal alloys or even continuous fiber composites. In the conduced work, SMC composites were manufactured using ultra-thin tapes of high modulus and ultrahigh modulus fibers having a large length-to-thickness ratio. The paper will describe how these SMC products lead to high stiffness and to significant increase in strength compared to commercially available SMC materials.

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## 1. INTRODUCTION

Tow Based Sheet Molding Compounds (TB-SMCs) are an up and coming class of high-performance composite materials that consist of long chopped carbon fibre tows (20-50 mm length) randomly distributed in a polymeric matrix. TB-SMCs are actually also called Tow Based Discontinuous Composites (TBDCs) [1-5]. The random and discontinuous nature of the material makes it more manufacturable than conventional continuous-fibre composites; in addition, high fibre volume fractions (up to 60 %) are achievable with this type of microstructure, which leads to high mechanical properties [1, 6-11]. Some examples of current commercial applications of TB-SMCs include window frames of the 787 Dreamliner [12] and helicopter tailboom frames [13]. Compression moulded TB-SMC specimens have shown stiffness values comparable to those of quasi-isotropic continuous-fibre laminates [7, 8], hence making them a good alternative to continuous fibre composites for stiffness-driven designs. Moreover, due to the material

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architecture, with stiff inclusions embedded in a soft matrix, high damage tolerance has been achieved [2, 14]. However, the discontinuous architecture of TB-SMCs leads to stress concentrations near the tow-ends which generate damage at the interface between tows, potentially leading to failure due to tow debonding and pull-out. For this reason, the strength values of commercially available TB-SMCs are significantly (between 30-60 %) lower than those of quasi-isotropic continuous-fibre laminates [7]. It has been shown that the thickness of the tows has a significant effect on the mechanical properties of TB-SMCs [1, 3, 9]. Wan et al. [9] found that manufacturing TB-SMCs with thin tows (of approximately 50 μm) resulted in higher ultimate strength values (500 MPa), closer to those of continuous fibre composites. Li et al. [1] manufactured TB-SMC specimens using two different tow thicknesses (but similar specimen thickness) and found that the specimens with thicker tows lead to lower mechanical properties, both in terms of modulus and strength. This effect of increasing TB-SMCs strength for decreasing tow thicknesses has been successfully modelled by Li and Pimenta [4].

So far, only TB-SMCs material systems with relatively high tow thicknesses (50-200 μm) and standard-or intermediate-modulus fibres (below 300 GPa) have been tested and reported in the literature. This leaves room in the design space of the material's microstructure to investigate whether it is possible to achieve higher mechanical properties with these types of architectures. In this work, TB-SMCs manufactured with ultra-thin (20 μm) and high modulus carbon fibres tows (425-750 GPa) are explored, with the objective to maximise the material's mechanical properties, especially its ultimate strength. Section 2 details the manufacturing and testing procedures of TB-SMC plates with different microstructural configurations selected. Moreover, experimental studies are performed to independently assess how the materials' mechanical properties are affected by the thickness and stiffness of the carbon-fibre tows. The experimental results are analysed and discussed in Sections 3 and 4, and the main conclusions are drawn in Section 5.

## 2. MATERIALS AND EXPERIMENTAL METHODS

It has been suggested [4, 5] that tensile failure of TB-SMCs occurs through tow fracture (governed by the tensile strength of the fibres) and tow pull-out (governed by the fibre stiffness, tow thickness, and mode-II fracture toughness of the interface between tows). For typical tow dimensions, tow pull-out is the dominant failure mode, meaning that TB-SMCs tend to fail at much lower strains than those required to break the fibres. Therefore, it should be possible to increase the resistance of TB-SMCs to tow pull-out by using thinner tows with stiffer fibres and with a tougher fibre-matrix interface; achieving this goal could suppress failure of TB-SMCs via tow pull-out, allow for the properties of the fibres in the composite to be fully exploited, and ultimately increase the tensile strength of TB-SMC materials.

### 2.1 Materials and manufacturing procedure

In order to demonstrate the potential improvements in the mechanical properties of TB-SMCs as identified numerically by Li and Pimenta [5], TB-SMC plates were manufactured using tows of high-modulus carbon-fibres spread into ultra-thin tapes and epoxy films, as described next. The spread tapes were produced by TeXtreme® spread tow technology (a state-of-the-art procedure for spreading tows into thin flat tapes with desired thickness and width) at Oxeon AB, using HS40 (High Modulus - HM) PAN-based and K13916 (Ultra High Modulus - UHM) pitch-based carbon-fibres. The nominal mechanical properties of the fibres (modulus $E^f$, strength $X^f$ and strain to

failure $\epsilon_{fail}^{f}$) are presented in Table 1. The spread tapes had a width of 20 mm, and an areal weight of 21 gsm (corresponding to a thickness of approximately 20 μm) or 105 gsm (corresponding to a thickness of approximately 100 μm) for the HS40 fibres and of 105 gsm for the K13916 fibres; the spread tapes were cut in 50 mm long pieces, hereby referred to solely as tapes. The epoxy resin used was supplied by Oxeon AB in the form of thin resin films, with an areal weight of 30 gsm. The tapes were manually placed at random locations and orientation on resin films, forming one equivalent lamina (EL), as schematically represented in Figure 1a. After the tape placement, heated de-bulks were performed on each EL; this consists in placing each EL in a vacuum bag on a heated RIFT table (at 70 °C) for 10 min, in order to ensure a better resin infusion. The final TB-SMC plate was obtained by stacking several ELs (in order to produce plates with the number of tapes specified in Table 2), as shown in Figure 1a. During this stacking process, the reference direction of each EL was incrementally rotated by 90º in the stack, in order to further improve the randomness of tape orientations and the in-plane isotropy of the material. This stacking process was followed by a final heated de-bulk of the plate (ensuring a more uniform distribution of the resin along the through-the-thickness direction) before final curing; the plates were cured in an autoclave at 6 bars and 120 ºC for 1 hour, after an initial 30 min stage of at 75 ºC.

Table 1: Mechanical properties of the different fibre types used in the experiments

| Fibre type | $E^f$ (GPa) | $X^f$ (MPa) | $\epsilon_{\text{fail}}^{\text{f}}$ (%) | Ref. |
|---|---|---|---|---|
| HS40 (HM) | 425 | 4640 | 1.01 | [15] |
| K13916 (UHM) | 760 | 3000 | 0.40 | [15] |

Five different plate configurations (described in Table 2 under IDs coded as <fibre type> - <nominal tow thickness> - <number of tows in plate> - <testing direction>) were manufactured and tested in order to independently assess different effects:

Table 2: Configurations of the different manufactured TB-SMC plates

| Plate ID | Fibre type | Nominal $t^t$(μm) | Nominal $N_{tows}$ | Measured thickness (mm) | Measured $V_f$ (%) | Testing direction* (º) |
|---|---|---|---|---|---|---|
| HM-20-800-0 | HS40 | 20 | 800 | 0.187 ± 0.021 | 47 ± 3.7 | 0 |
| HM-20-800-90 | HS40 | 20 | 800 | 0.194 ± 0.029 | 46 ± 3.5 | 90 |
| HM-20-1600 | HS40 | 20 | 1600 | 0.480 ± 0.040 | 46 ± 1.7 | 0 |
| HM-100-800 | HS40 | 100 | 800 | 0.902 ± 0.064 | 54 ± 3.2 | 0 |
| UHM-100-800 | K13916 | 100 | 800 | 0.715 ± 0.075 | 55 ± 5.0 | 0 |

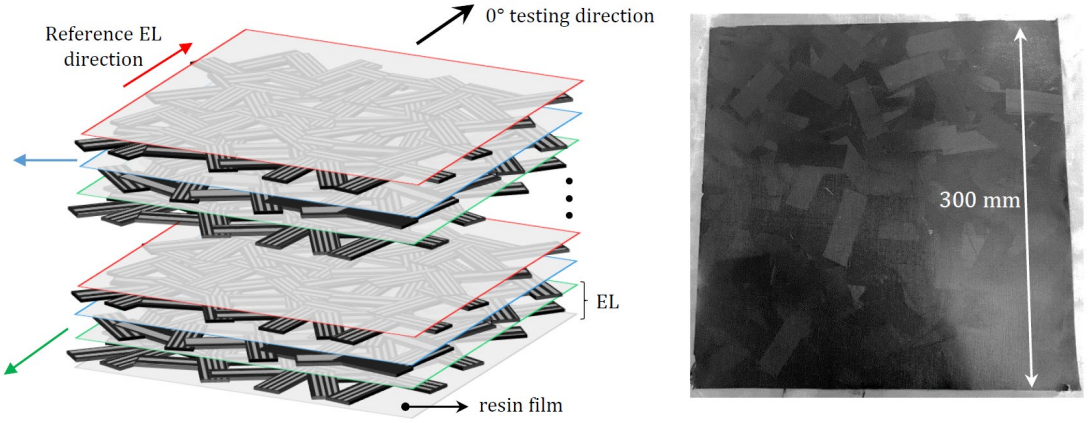
*Testing direction of the specimens relative to the reference working direction.

- In-plane isotropy (HM-20-800-0 and HM-20-800-90): both plates were manufactured with the same specifications, although the specimens of each plate were tested at different orientations (0º and 90º) to the testing direction.

- Effect of the areal tape coverage (HM-20-800 and HM-20-1600): both plates were manufactured with the same fibre type and tape thickness, but with different total number of tows in the plate ($N_{tows}$ = 800 and $N_{tows}$ = 1600, respectively).

- Effect of the tape thickness (HM-20-800 and HM-100-800): both plates were manufactured with the same fibre type and number of tows, but with different tape thicknesses (20 and 100 µm).

- Effect of the fibre stiffness (HM-100-800 and UHM-100-800): both plates were manufactured with the same tape thickness and number of tows, but with different fibre types (HM and UHM).




(a) Schematic representation of TB-SMC plate.

(b) Final manufactured TB-SMC plate

Figure 1: Manufacturing procedure of the TB-SMC plates.

## 2.2 Testing and analysis

Each plate was cut into 5 rectangular specimens, 250 x 50 mm in length and width respectively, which were then subjected to a standard uni-axial tensile test, with a gauge length of 150 mm (following the ASTM-D3039 standard [16], and with a head displacement of 1 mm/min). The strain in the specimens was measured with an optical strain gauge [17]; the total strain was taken as the average strain measured by three virtual extensometers, each with a strain gauge length of 75 mm, evenly spaced along the specimen's width. Furthermore, the modulus of each specimen was taken as the (best fit) slope of the measured stress-strain curve between 0.05 % and 0.2 % strain. Optical micrographs were used to analyse the resulting microstructure of each plate configuration at three distinct cross-sections; the volume fraction of each cross-section was obtained from processing these three micrographs ([0.15 x 0.40] mm) using simple threshold algorithms. Images of the fracture surface of each specimen were taken, in order to identify the predominant failure mechanism in each plate configuration.

# 3. RESULTS

## 3.1 Tensile test results

All modulus and strength results presented in this section have been linearly scaled to a $V_f$ = 57 % (which is a typical value for commercially available TB-SMCs [18]), in order to allow for a direct comparison between different material systems. Figure 2a shows the measured stiffness of the specimens from each plate configuration. The modulus values of the plates made with the HM is relatively constant across the different plate configurations. The plate with the UHM fibres yielded the highest average stiffness value, as expected, although, with a large standard deviation.

Figure 2b presents both the average strength value measured for each plate configuration as well as the standard deviation:

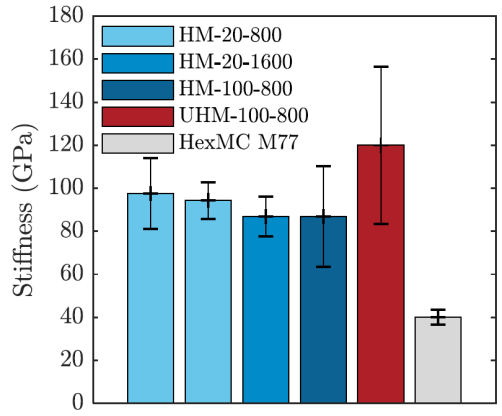
- The highest tensile strength value of 600 MPa was achieved with the thin HS40 tapes, and in particular for the plate configuration with 16 ELs.

- The strength difference between the HM-20-1600 plate and the HM-20-800 is quite significant, with a p-value = 0.06, (since it only differs in the total number of tows).

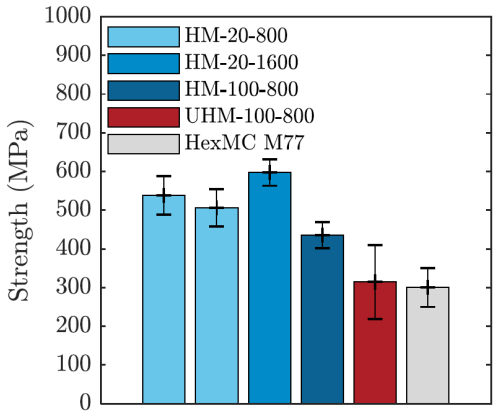
- The HM-100-800 plate, with the thicker tape configuration, presents a significantly lower average strength value when compared to the thinner tape configurations (HM-20-800), with a p-value = 0.05.

- The UHM-100-800 plate was the one that presented the lowest average strength. This was also the configuration with the most significant variability in the measured results, likely due to the fact that only 3 (out of 5) of the specimens produced valid failures (and only those 3 are included in Figures 2b- 2d).

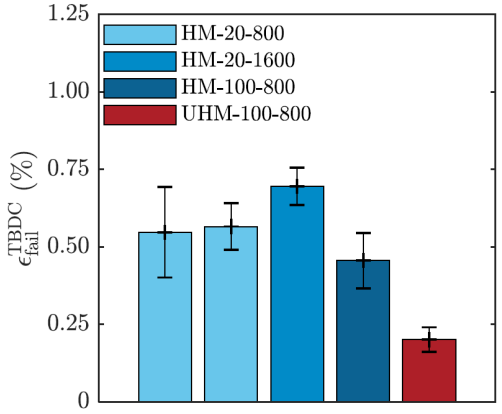
Figure 2c shows the failure strain of the TB-SMCs ($\epsilon_{fail}^{TB-SMC}$) tested; once again the HM-20-1600 configuration was the one that presented the highest $\epsilon_{fail}^{TB-SMC}$ and the UHM-100-800 configuration presented the lowest value. However, by analysing the ratio between the TB-SMC failure strain and the fibre failure strain $\epsilon_{fail}^{TB-SMC}/\epsilon_{fail}^{f}$, as done in Figure 2d one can better quantify the exploitation of the fibre strength within the TB-SMC, for each plate configuration: this suggests that the configuration with the UHM fibres (UHM-100-800) achieved a better exploitation of the fibre strength than the corresponding configuration with HM fibres, due to a more efficient stress transfer mechanism promoted by the stiffer fibres in the former. However, the lower fibre strength of the UHM fibres (3000 MPa) compared to the HM fibres (4640 MPa), is limiting the TB-SMC strength value of the UHM material.



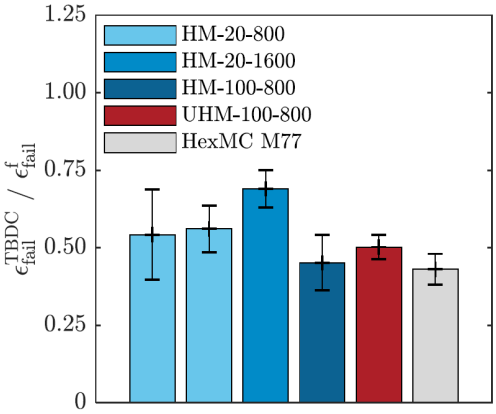

(a) Experimental stiffness values.




(b) Experimental strength values.




(c) Experimental failure strain of the different material configurations.

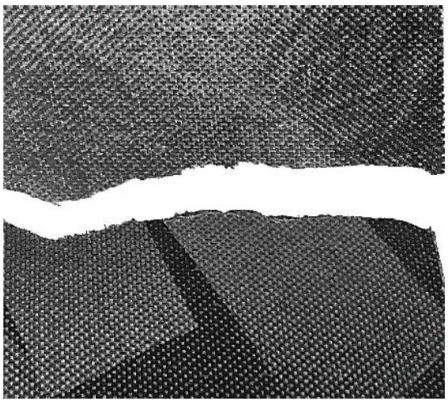



(d) Ratio between the experimental and respective fibre failure strain.

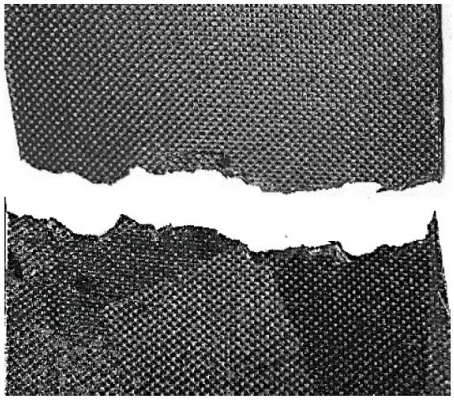
Figure 2: Experimental tensile test results of the different TB-SMC configurations tested (Vf = 57 %), and comparison against the commercially available HexMC-M77 [18]; the error bars represent one standard deviation

### 3.2 Fracture surfaces

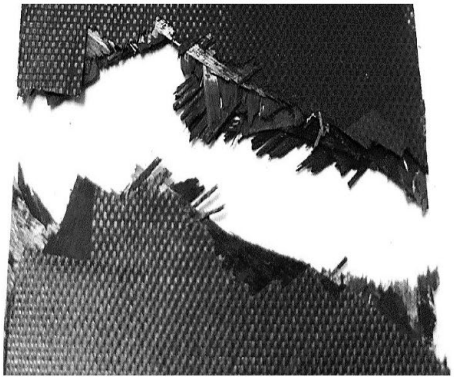
The fracture surfaces of a representative specimen taken from each plate configuration are shown Figure 3. The fracture surfaces for the thin tape configurations (Figures 3a and 3b) show no evidence of tape-pull out, and a clear evidence of tape fracture. For the thicker tape configurations (Figures 3c and 3d), a mixture of tape-pull out and tape fracture was observed, reflecting the less efficient stress transfer that occurs for thicker tape configurations.



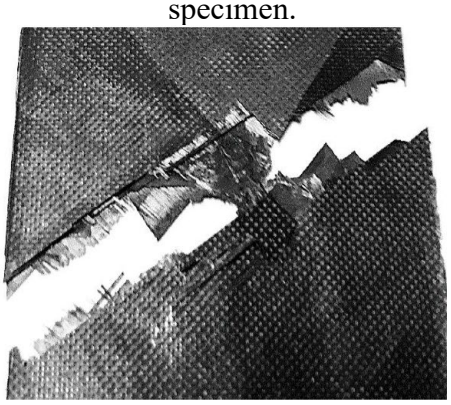
(a) Fracture surface of a HM-20-800 specimen.



(b) Fracture surface of a HM-20-1600 specimen.



(c) Fracture surface of a HM-100-800 specimen.



(d) Fracture surface of a UHM-100-800 specimen.

Figure 3: Fracture surfaces of specimens from the different plate configurations.

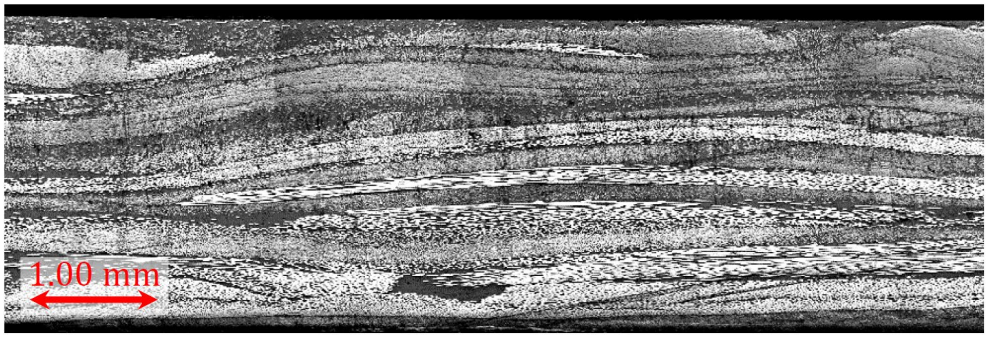
### 3.3 Comparison with other material systems

Figure 4 compares micrographs of four different materials systems: Figures 4a and 4b are cross-sections of two commercially available TB-SMC materials systems [18, 19]; the microstructures of these materials are very irregular, with the carbon fibre tows presenting significant through-the-thickness waviness and large resin rich regions. Figure 4c corresponds to a cross-section of a conventional continuous-fibre composite [20], with its conventional regular and well-structured microstructure. Finally, Figure 4d shows the cross-section of a HM-20-1600 specimen developed in this paper; the microstructure of this material system presents very little amount of tape waviness, and is visually more similar to the microstructure of the quasi-isotropic material system in Figure 4c, than to the commercially available TB-SMCs in Figures 4a and 4b.

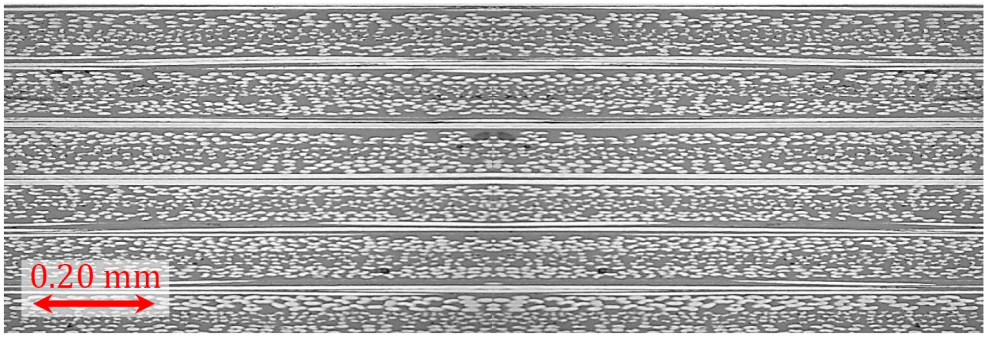
The mechanical properties of the HM-20-1600 and UHM-100-800 configurations (which are the material systems that performed the best from the ones tested in this work) are compared to other carbon-fibre based material systems specified in Table 3; these include TB-SMC systems presented in the literature [9, 21, 22], the HexMC R-M77 [18] and the AMC R8593 [23] commercially available TB-SMC material systems, and a widely-used aerospace-grade CF/epoxy continuous QI laminate.



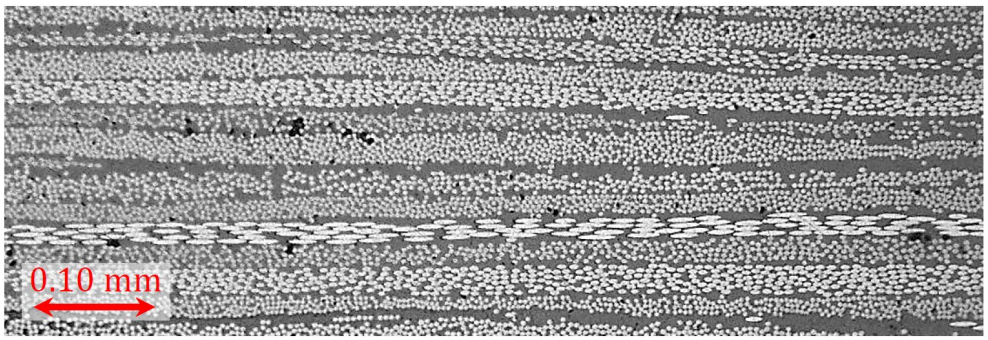

(a) Micrograph of the cross-section of a HexMC-M77 [18] specimen.




(b) Micrograph of the cross-section of a SMC [19] specimen.

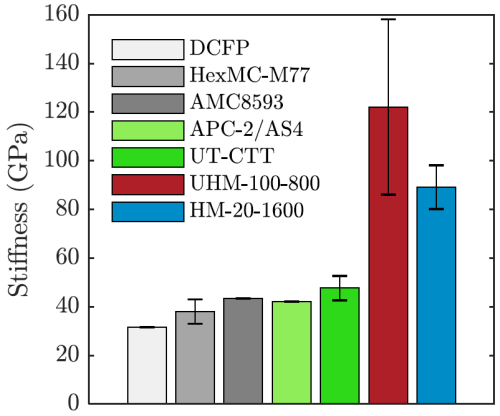



(c) Micrograph of the cross-section of a quasi-isotropic continuous-fibre specimen [20].

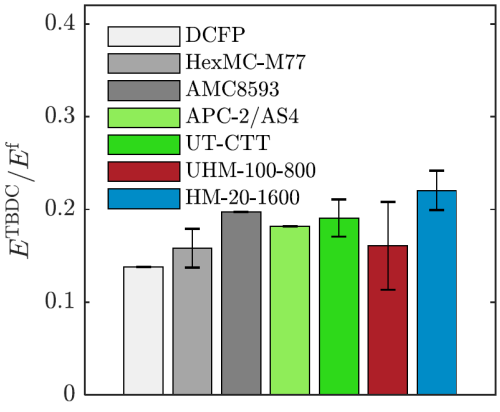



(d) Micrograph of the cross-section of a HM-20-1600 specimen.

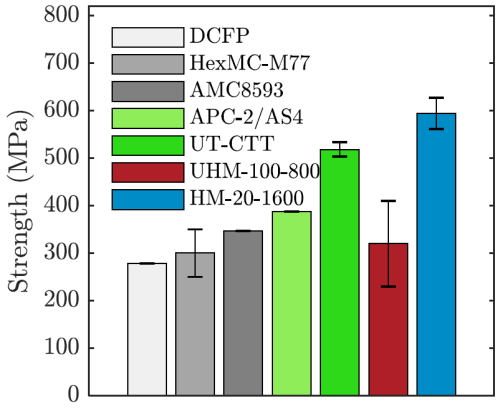
Figure 4: Micrographs of cross-sections of different material systems.



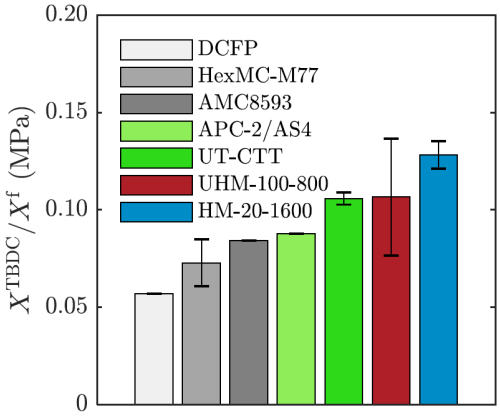

(a) Comparison between the stiffness of different TB-SMCs.




(b) Ratio between the measured stiffness of the TB-SMC and the respective fibre stiffness.




(c) Comparison between the strength of different TB-SMCs.




(d) Ratio between the measured strength of the TB-SMC and the respective fibre strength.

Figure 5: Comparison of the mechanical properties between the HM-20-1600 material proposed in this study, and discontinuous material systems reported in the literature (specified in Table 3). All mechanical properties have been linearly normalised to $V_f$ = 57 % for comparison purposes.

Table 3: Configurations of the different CFRP systems compared in Figure 5.

| Material ID | Material system description | $V_f$ (%) | Ref. |
|---|---|---|---|
| DCFP | T700 carbon fibre/epoxy, manufactured with modified DCFP | 45 | [21] |
| HexMC-M77 | Carbon epoxy material system for compression moulding | 57 | [18] |
| AMC8593 | PAN-based carbon epoxy material system (moulding compound) | 47 | [23] |
| APC-2/AS4 | Carbon/PEEK CYTEC APC-2/AS4 material system | 61 | [22] |
| UT-CTT | Ultra-thin (50 µm) carbon fibre/thermoplastic system | 55 | [9] |
| AS4 8552 | Continuous fibre quasi-isotropic laminate | 60 | [24] |
| UHM-100-800 | Thin (100 µm) and UHM carbon fibre/epoxy system | 54 | |
| HM-20-1600 | Ultra-thin (20 µm) and HM carbon fibre/epoxy system | 46 | |

Figure 5a shows that the HM-20-1600 material system has a significantly higher average stiffness when compared to all other TB-SMC material systems. In Figure 5c the strength comparison of the selected TB-SMC material systems shows that, once again, the HM-20-1600 material system turned out to be the one that presents the highest average strength of all TB-SMC-type materials.

Figures 5b and 5d show how the ratio between the stiffness/strength of the TB-SMC ($E^{TB-SMC}/E^{f}$) and the fibre stiffness/strength ($X^{TB-SMC}/X^{f}$) differs for each material system. These results clearly show that the proposed HM-20-1600 configuration is the one that better exploits the fibre properties, due to enhanced stress transfer mechanism enabled by the ultra-thin and stiff tapes.

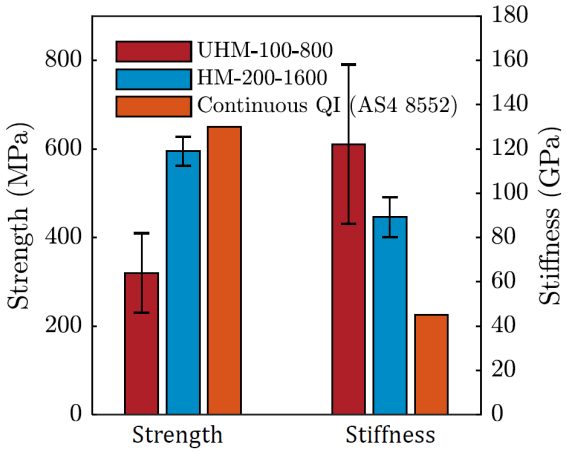



Figure 6: Comparison between the mechanical properties of the HM-20-1600 and UHM-100-800 configurations and a continuous fibre QI laminate (specified in Table 3).

The mechanical properties of the UHM-100-800 and HM-20-1600 configurations are compared to those of a quasi-isotropic laminate of continuous fibres (AS4 8552 [24]) in Figure 6. Remarkably, the strength of HM-20-1600 discontinuous material is practically the same as the one of the continuous fibre laminate. Moreover, due to the high modulus fibres used in both discontinuous configurations, the measured stiffness values are much higher than that of the continuous fibre laminate.

# 4. DISCUSSION

## 4.1 Effect of microstructure on mechanical properties

This work shows that, using ultra-thin tapes, TB-SMCs with a more regular microstructure are achieved (compared to conventional TB-SMCs with conventional tows), as shown in Figure 4d. This leads to improvements in stiffness (as previously suggested in the literature [1, 8-9], and corroborated by the slightly higher Young's modulus of the HM-20-800 material compared to the HM-100-800 in Figure 2a) as the tapes present less out-of-plane orientations, and hence lower reductions of in-plane stiffness due to tow/tape waviness [3]. Furthermore, this more regular microstructure is also less prone to weak spots within the material (such as resin pockets) which generally trigger premature failure, and hence also contributes to the significant increase in the ultimate strength of the material, observed in Figure 2b (compare HM-20-800 with HM-100-800).

In addition to the effect on the material's microstructure, the use of thin and stiff tapes also leads a more efficient stress transfer between the tows, and hence to a better exploitation of the mechanical properties of the fibres, as shown by the HM-20-1600 and UHM-100-800 configurations in Figure 2d.

## 4.2 Improvement over existing materials

### *4.2.1 Stiffness*

The stiffness improvement achieved with the ultra-thin and stiff tape based TB-SMCs is essentially due to the higher stiffness of the HM and UHM fibres. However, there are small differences between the stiffness of the HM-20-800 and HM-100-800 plate configurations, with the later presenting lower stiffness values (see Figure 2a). This may be due to the wavier disposition of the thicker tows in comparison to the thinner tows, leading to higher stiffness knockdowns, which is in agreement with the numerical predictions done by Li and Pimenta [5].

### *4.2.2 Tensile strength*

The average strength value of 600 MPa, obtained with the HM-20-1600 plate configuration (see Figure 2b), represents an increase of 100 % when compared to the strength of the commercially available materials and of ≈ 20 % when compared to the UT-CTT material [9], which was the TB-SMC system with the highest strength previously reported in the literature. The enhancement of the stress-transfer mechanisms enabled by the use of ultra-thin and stiff tapes delays the on-set of tow pull-out (governed by toughness criterion) and promotes failure by tape fracture, as evidenced by the fracture surfaces of Figures 4a and 4b.

The comparison between the mechanical properties of the best proposed configurations (HM-20-1600 and UHM-100-800) against those of a continuous QI laminate in Figure 6, shows that is possible to match the strength of a continuous fibre laminate and surpass its stiffness using a composite with a discontinuous microstructure. This highlights the great potential that this new class of high-performance discontinuous composites offer, as they are able to bridge the gap in mechanical properties that typically exists between continuous and discontinuous fibre composites, while still retaining the advantages of design flexibility and manufacturability of discontinuous composites, as discussed in the next section.

### *4.2.3 Design flexibility and manufacturability*

It has been suggested in the literature [1, 8] that the strength of TB-SMCs increases with plate thickness (for a constant tow thickness); this is corroborated by the slightly higher strength and failure strain of the HM-20-1600 configuration when compared to the HM-20-800 configuration (see Figures 2b, 2c and 2d). This effect can be explained by two factors: firstly, thicker specimens have a smaller fraction of tows/tapes at the surface of the specimen, and these surface tows/tapes cannot transfer stresses as effectively as those well-embedded in the through-the-thickness direction; secondly, thicker specimens have a larger average number of tows in the through-the-thickness direction, which increases the homogeneity of mechanical properties in comparison with thinner specimens [3]. Consequently, there is a limitation for the minimum thickness that can be accepted in components manufactured with TB-SMC systems with conventional tow thicknesses. This limitation can be relaxed significantly through the use of ultra-thin tapes, as shown by the results in Figures 2 and 5:

- Firstly, the mechanical properties of the plates manufactured with ultra-thin tapes were considerably higher than those of conventional TB-SMCs (see Figures 2 and 5), even though the plate thickness of the former was below 0.5 mm.

- Secondly, the similar properties observed with the two HM-20-800 plates tested at different directions (see Figure 2) suggest that using ultra-thin tapes to make TB-SMCs enables the manufacture of shell-type structures, with wall thicknesses lower than 0.2 mm, with in-plane isotropy.

Consequently, TB-SMCs manufactured with ultra-thin tapes offer much more design flexibility than conventional TB-SMCs, and allow for production of shell-type structures with very thin walls (which is useful e.g. for body-in-white parts of cars). Figure 6 shows that TB-SMCs made of ultra-thin tapes of HM fibres combine (i) a similar strength and even higher stiffness than those of aerospace-graded composites with (ii) the improved manufacturability and design flexibility of a discontinuous and random microstructure. The latter can be realised by creating SMC-type intermediate materials (similar to HexMC [18] and carbon-SMC [19]) but using ultra-thin (spread) tapes of (ultra-)high modulus fibres and fast-curing matrices; these intermediate materials could then be directly used in compression moulding, with several advantages over conventional continuous-fibre composites:

- Allowing for the production of parts within a matter of minutes and out-of-the-autoclave, and with minimal manual work;

- Allowing for the production of complex 3D geometries (rather than 2D shells) with local embedded reinforcements where they are needed most (rather than relying on ply-drops and bonded stiffeners, as often done with continuous-fibre composites).

- Possibility of using UHM fibres to manufacture parts/components with complex geometries; this is enabled by the discontinuous architecture of TB-SMCs, and is not easily achievable with continuous-fibre architectures.

- Reducing significantly the amount of waste generated by material cut-offs.

# 5. CONCLUSIONS

This work has successfully proposed and demonstrated a pathway to increase the stiffness and ultimate tensile strength of tow-based discontinuous composites. The main conclusions are summarised below:

- Quasi-isotropic TB-SMCs manufactured with ultra-thin (20 μm) and high-modulus (450 GPa) carbon-fibre tapes reached a tensile strength of 600 MPa and stiffness of 90 GPa for a $V_f$ of 57 %. This represents a strength increase of 100 % when compared to the strength values of commercially available TB-SMC materials, and of 20 % when compared to the TB-SMC material system with the highest strength previously reported in the literature.

- This work demonstrates that TB-SMCs manufactured using ultra-thin and high-modulus carbon-fibre tapes can reach the tensile strength of conventional aerospace-grade QI laminated CFRP, and overcome their stiffness.

- The use of thin and stiff tapes in the manufacture of TB-SMCs leads to this significant improvement in mechanical properties by enhancing the stress transfer mechanisms within the material and suppressing matrix/interface dominated failure mechanisms. This allows for a better exploitation of the mechanical properties of the fibres, which has been demonstrated by the features of the fracture surfaces of these TB-SMCs, which were dominated by fibre-failure rather than by tape pull-out.

- Test results suggest that there is a reduction in tensile strength for specimens with a small ratio between the specimen thickness and tape thickness. This indicates that TB-SMCs with ultra-thin tapes can be used to manufacture components with very thin walls, removing several design barriers and offering more design flexibility over conventional TB-SMCs (based on tows with conventional thicknesses).

This work shows the potential of ultra-thin and stiff TB-SMCs as a high-performance and highly-manufacturable material, able to comply with the stiffness and strength requirements of primary structural applications and suitable for a wider range of part geometries and more automated manufacturing processes when compared to continuous-fibre composites. These materials can potentially change the way in which composite materials are used in several industries (automotive, aerospace, sport and others), and at the same time open the use of high-performance composite materials to new industries with different manufacturability constraints.

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