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Impact resistance of metal skin-carbon fiber reinforced polymer laminate structures for the production of lightweight vehicles body frame

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Abstract. The research presented in this paper deals, in the first part, with the material characterization of an innovative class of material, made of steel skin and sheet molding compound core, the last one realized with vinyl-ester resin and chopped carbon fibers. Utilizing the results of the material characterization, the case of an automotive B-pillar is taken into account in order to test and prove the reliability of the utilization of this innovative typology of material, instead of the standard steel. The steel skin – SMC hybrid laminate structures are realized by means of stamping process under warm forming condition, in order to favorite the curing of the SMC layers. The result presented along the paper will show that the steel skin – SMC material not only have better specific resistance that those of both standard and high strength steel but also better crashworthiness properties, in comparison to the considered steel. Based on the results of the numerical simulations, a useful way thought which to estimate the crash worthiness property is proposed in this paper and the results will show how the B-pillar realized with steel skin – SMC has a higher impact resistance, in comparison the steel one with the same weight and reduced thickness.

1. Introduction

In the nowadays automotive industry, the vehicles weight reduction is becoming a critical issue, driven by environmental growing concerns as well by the shortage of fossil combustibles. However, the utilization of lightweight material has shown not always to comply with the requirements of high mechanical properties required for some parts of the vehicles body frame, such as in case of comparing the mechanical properties of aluminum and steel. To this aim, lightweight hybrid structures made of steel skin and carbon fiber reinforced polymer core are a concrete innovative option for the lightening of vehicles body frame and, if well designed and manufactured, can also improve the mechanical properties of the relevant components. In the literature, different authors presented results concerning the material characterization of the sheet molding compound parts, both from the material and from the numerical point of view, among them. Kim et al. [1] studied the basic of the SMC process by means of numerical simulations, taking into account both deformation and curing phases of

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the process. Katayama et al. [2] developed a CAE model for the prediction of the stiffness in parts with ribs made of SMC, showing how the material flow prediction is more complex in presence of ribs. Evan et al. [3] studied the mechanical properties of carbon fiber molding compounds, showing how they can be processed by utilizing the conventional SMC glass fiber process. In addition to that, Lauter et al. [4] studied a manufacturing method for the realization of a vehicle B-pillar structure by utilizing a metal skin – CFRP (carbon fiber reinforced polymer) made of layups of unidirectional fibers reinforced prepregs. Moreover, Liu et al. [5] studied feasible design method for the fabrication of lightweight vehicles by utilizing fabrics of carbon fibers.

In addition, concerning the impact test for the determination for the crash worthiness of composite material, some contributions are available in the literature, among them: Meo et al. [6] developed a numerical simulation for the analysis of the influence of low-velocity impacts on the aircraft sandwich panels. Bandi et al. [7] developed a design method for the realization of crashworthy structures where the energy abortion is chosen a-priori as a project input. Finally, Lewis et al. [8] proposed an interesting method to correlate impact strength, calculated from the results of the impact test, and the fracture toughness. The present research work is subdivide into two different parts. In the first part, the materials composing the steel skin – sheet molding compound (SMC) laminate structure, the SK5 steel and the original SMC, are tested by means of simple tension test. In addition, since also the adhesive utilized between steel skins and SMC core is vital for the load transfer, also a shear strength test has been conducted. Finally, the mechanical properties of the steel skin – SMC laminate structure has been tested by means of 3-points bending test. In the second part of the paper, focusing the attention on a vehicle B-pillar simplified shape, an impact test resistance simulation has been set-up considering both the original steel and the laminate structure made of steel skin and SMC core. From the results of the numerical models, the principle stress components are exported and utilized for the calculation of the strain energy density by utilizing the Beltrami equation. The comparison between the amount of strain energy density for each element of the mesh and the critical strain energy density allows calculating the number of elements those have reached, or passed, the critical value hence to compare the crashworthiness of steel and laminate steel skin – SMC products. Following this procedure it is possible to estimate the overall amount of damaged element out of the total and compare the impact resistance of the steel skin – SMC laminate structure with that of the original steel.

2. Material characterization and model constants determination

In order to enhance the strength of the original SK5 steel, quenching and tempering operation at 780°C 120°C, respectively, have been carried out. This procedure allows obtaining higher yield strength values at the expenses of part of the elongation to fracture. The rationale behind this choice is given by the fact that, as it will be shown in this section, the SMC workpiece manifests a brittle behavior characterized by a high value for the break stress thus, a high strength steel shall promote a more uniform behavior of the composite steel-SMC structure.

The simple tension test has been conducted at the speed of 2mm/min utilizing the INSTRON 3367 test machine, with a maximum load of 3tons. The size of the specimen, the ASTM E8 type 1, are reported in Figure 1 whereas the fitting of the plastic part of the stress-strain curve, operated by utilizing the Swift model, is shown in Figure 2.

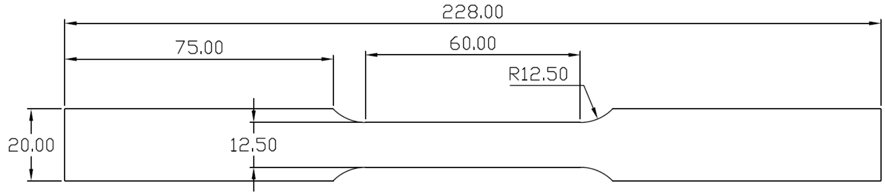

Figure 1. SK5 simple tension test specimen

In addition to that, the material properties derived from the material characterization of the SK5 steel are reported in Table 1.

Table 1. Material properties for the SK5 steel

Parameter	Description
Young's modulus	190GPa
Yield strength	1450MPa
UTS	1796MPa
Density	7.8744 kg/dm^3

Concerning the material testing for the SMC, simple tension test have been carried out by utilizing the specimen shown in Figure 3a, whose size are reported in in Figure 3b.

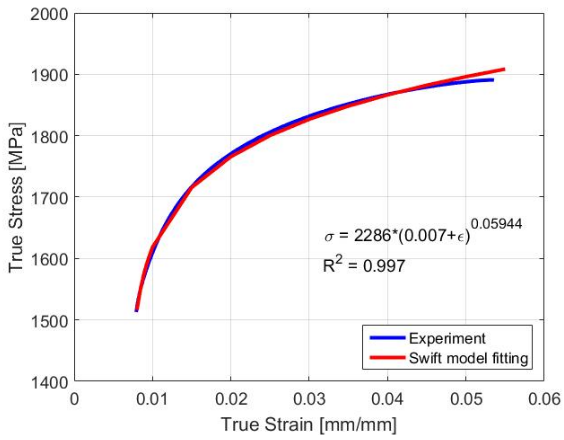

Figure 2. SK5 simple tension test specimen

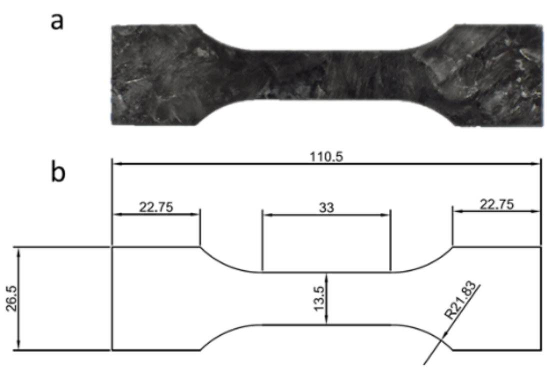

Figure 3. (a) SMC specimen and (b) dimensions

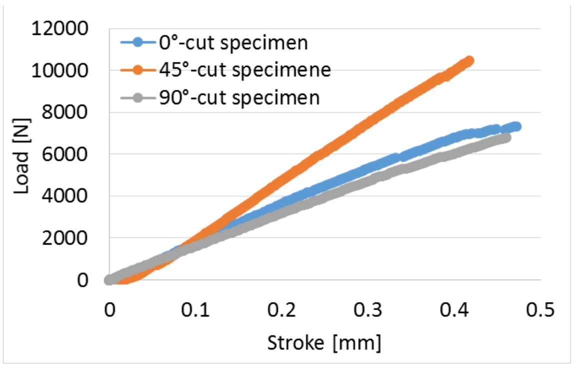

Figure 4. Load-stroke for SMC specimens along 0°, 45° and 90° directions

The simple tension test specimens have been derived from a single plate realized by compressing three pre-cured SMC layers, each one with the initial thickness of 2.5±0.5mm, by means of stamping process. In order to favorite the curing of the SMC, both top and bottom die have been heated up to 130°C and the plate has been kept under pressure for 2 minutes after the stamping process in order to assure a complete curing. At the end of the stamping process, the SMC plate has a thickness of 3.2±0.05mm. In order to account for possible anisotropies in the material, due to the random orientation of the carbon fibers in the sheet molding compound process, simple tension specimens have been cut along 0°, 45° and 90° directions in the stamped plate and the results, in terms of load-stroke curves, are presented in Figure 4. The density of the SMC has been calculated in 1.8431kg/dm^3 and the material properties, relevant for the three tested directions, are reported in Table 2.

Table 2. Material properties for the SMC

Parameter	Young's modulus [GPa]	Break stress [MPa]
0°-cut specimen	20.91	184.19
45°-cut specimen	29.30	259.65
90°-cut specimen	18.79	169.35

The last material property to be tested is the shear strength of the adhesive utilized to bond the steel skins to the SMC core, which is of vital importance for the load transfer between these two different materials. However, the adhesive can also represent a weak point in the laminate structure since it represent a discontinuity in the stress field between the two materials and can generate strong stress concentrations. The utilized adhesive is a vinyl-ester polymer, whose composition is shown in following Table 3.

Table 3. Chemical composition of the vinyl-ester adhesive

Component	Percentage	Component	Percentage
Epoxy	35 ~ 43%	Toning agent	0.5 ~ 1%
Hardener	6 ~ 8%	Additive	4.5 ~ 6.5%
Filler	29 ~ 39%	Thinner	5 ~ 7%
Accelerator	1.5 ~ 2.5%	Glass bead	4 ~ 6%

The shear strength test specimens have been realized by applying a 0.1mm layer of adhesive on a 0.4mm thick metal skin and, on the top of it, a 3.2mm piece of SMC has been placed, as reported in Figure 5, where also the fracture area after the test is shown.

Figure 5. Shear strength specimen and fracture area after the test

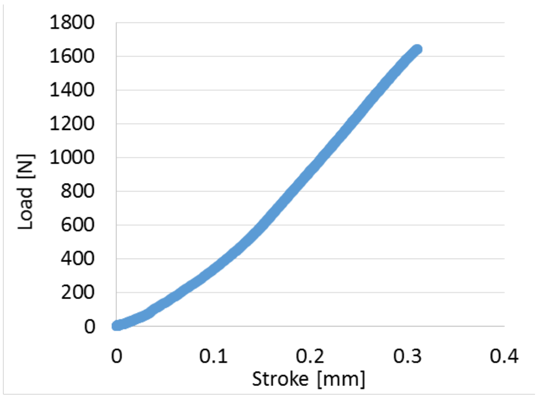

Figure 6. Load-stroke curve of the adhesive shear strength test

The bonding area measures 13mmx13mm and the bonded pieces have been blocked into the right position during the curing time (20minute) and the cooling down time (12 hours).

The load-stroke curve relevant for the shear strength of the utilized adhesive is shown in following Fig. 5 where a slightly non-linear behavior can be seen from the results and where the break load is identified in 1642.7N.

Finally, in order to test the material properties of the laminate structure made of steel skins and SMC core, bending test on specimens with size shown in Figure 7 have been carried out. In Figure 8 both the experiment settings and the specimen after failure are presented.

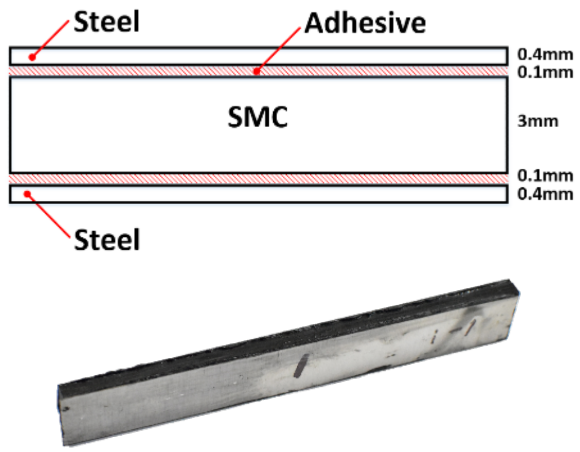

Figure 7. Steel skin – SMC specimen and relevant dimensions

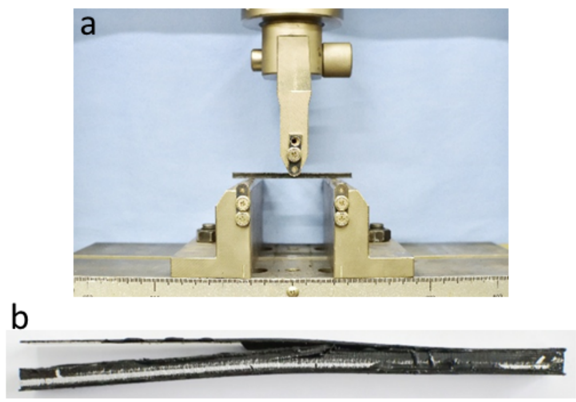

Figure 8. Steel skin – SMC 3-points bending test setting and (b) specimen after failure

The 3-point bending tests have been conducted on the Universal Test Machine TO-100-IC, which has a load limit of 10tons, with a test speed of 2mm/min. The load-stroke and engineering stress-strain curves, relevant for the bending test of the steel skin – SMC specimens are shown in Figure 9 and Figure 10, respectively, where the results are presented with those of the only SMC, showing an improvement in both Young's modulus and break stress.

By gathering together all the results, it is possible to draw a first conclusion concerning the specific strength of the steel skin – SMC laminate structure, in comparison with standard steel. Considering a generic steel, with an yield strength of 600MPa and the SK5 steel utilized in this paper, which as a yield strength of 1350MPa, the specific strength is identified in 0.76MPa/(g/cm^3) and 1.72 MPa/(g/cm^3), respectively, whereas that of the steel skin – SMC hybrid material is calculated in 2.28MPa/(g/cm^3), showing the improvement of the proposed material in comparison to standard one.

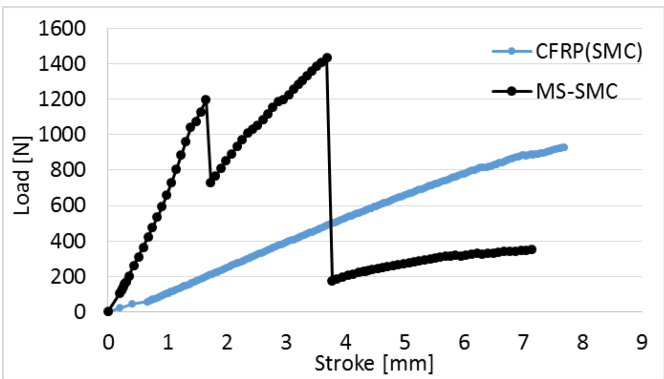

Figure 9. Load-stroke curves for steel skin – SMC and only SMC

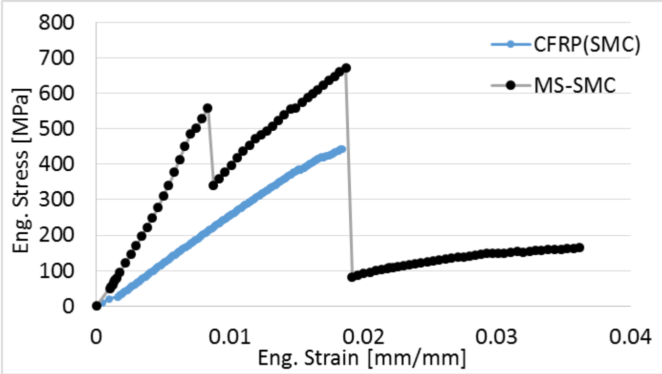

Figure 10. Load-stroke curves for steel skin – SMC and only SMC

3. Numerical model implementation

In order to prove the crashworthiness properties of laminate structures made of steel skin and SMC core, a numerical simulation has been implemented in ABAQUS/Explicit simulating the impact of an object of cylindrical shape on the top of the simplified B-pillar. In order to be able to compare the results in a fair way, the thickness of the B-pillar realized with steel has been set to 1.5mm whereas that of steel skin – SMC to 4mm, resulting in both products to have the same weight. The implementation of the simulation is shown in Figure 11 and Figure 12, for the steel product and for the laminate product, respectively.

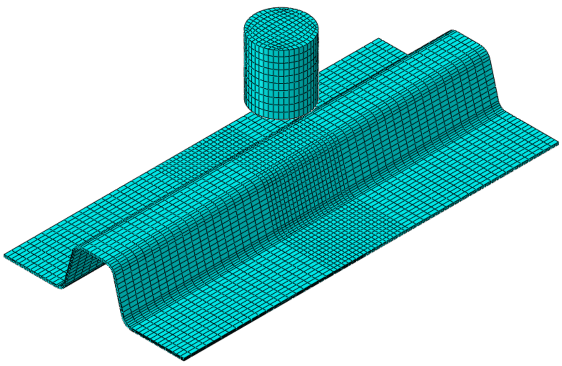

Figure 11. ABAQUS impact resistance simulation (steel)

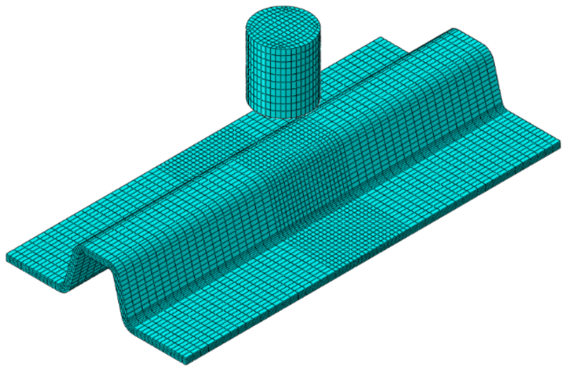

Figure 12. ABAQUS impact resistance simulation (laminate steel skin - SMC)

In the numerical model, the C3D8R element with reduced integration has been utilized and both models have been meshed with a fine mesh size of 2.5mm side and a coarse mesh size of 5mm side. Concerning the boundary conditions applied to the model, the link between the B-pillar and the rest of the body frame of the vehicle has been simulated by imposing four fully constrained zones on the four corners of the low areas of the part, in order to simulate the relevant rivets, as shown in Figure 13, where the fixed nodes have been highlighted in red.

The cylinder, which represents the impactor is, moved, till the impact with the B-pillar surface, with a constant speed of 27.8m/s and has a mass of 400kg, which represent a total amount of 155kJ transferred to the part.

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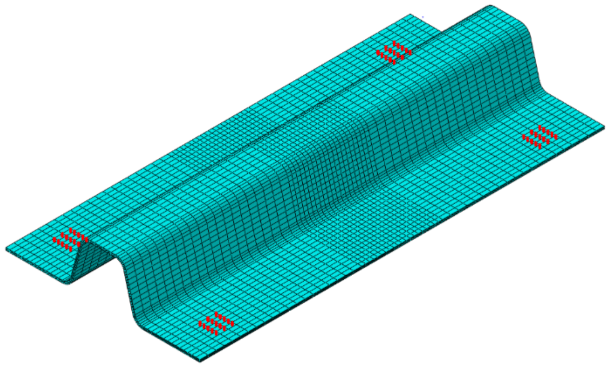

Figure 13. Constraint boundary conditions

4. Results and discussion

As a first result of the numerical simulations, the von Mises yield stress distribution, results of both steel and laminate products, in shown in Figure 14a and Figure 14b, respectively.

The more spread stress field in the laminate structure, with a lower maximum value for the von Mises equivalent stress, is a first confirmation of the capability of this laminate structure material to better redistribute the stresses when loaded. The steel part instead presents an higher value for the von Mises equivalent stress and the area where the load is redistributed is small, which is a typical behaviour for high strength steel, as the case of the hardened SK5.

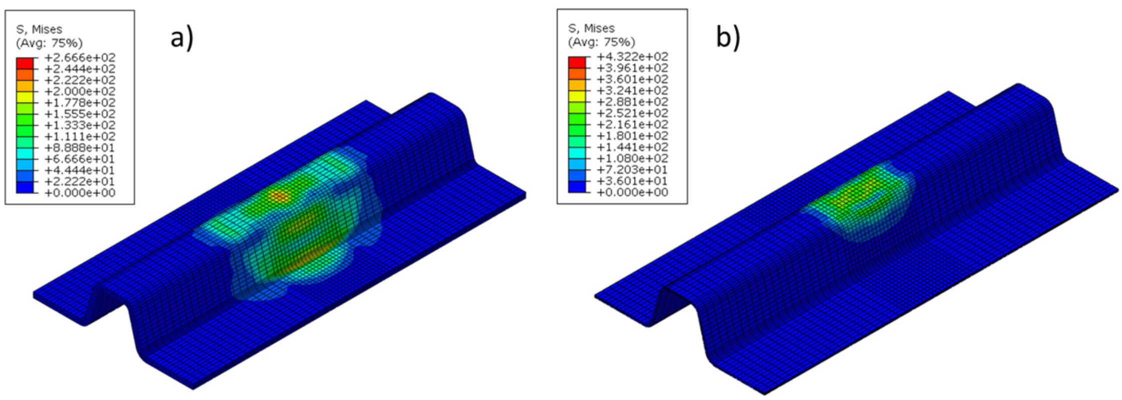

Figure 14. (a) von Mises stress distribution for the laminate steel skin – SMC B-pillar and (b) for the SK5 steel B-pillar

In order to have a more clear comparison between the crashworthiness properties of the laminate steel skin – SMC laminate structure and those of the SK5 steel, the strain energy density has been calculated by utilizing the Beltrami Eq. (1).

$$U_t = \frac{1}{2E}\left[\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2v\left(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_1\sigma_3\right)\right] \qquad (1)$$

By exporting, from both simulations, the principle stress tensor and inputting the relevant components into Eq. (1), it is possible to determine the total amount of strain energy density in the fine mesh portion of the B-pillar. In addition to that, by considering the critical value for the strain energy density, Eq. (2), the amount of failed elements can be determined and used for the comparison of the crashworthiness properties. In Eq (2), σ_R stands for the break stress under bending loading conditions for the relevant material. The flexural strength of the SK5 has been derived from the previously presented result of the uniaxial tension test in order to carry out a proper comparison with the flexural strength determined for the laminate structure in the 3-points bending test.

$$W_c = \frac{1}{2E}\sigma_R^2 \tag{1}$$

For comparison, in Table 2, the data of the total strain energy density on all the elements in the fine mesh portion of the B-pillar are reported along with the number of failed elements.

Table 1. Strain energy density results comparison

Parameter	Steel skin – SMC	SK5 steel
Total strain energy density	394.40485	119.6991
Flexural strength	671.6MPa	300MPa
Young's modulus	63.93GPa	190GPa
Critical strain energy density	3.53	0.24
N° of failed elements	0	64
Volume of failed elements	0mm^3	1000mm^3
% of failed elements	0%	1.05%

As a consequence of the higher specific strength of the laminate material in comparison to the original steel, also the crashworthiness properties of the steel skin – SMC laminate structures have shown to be higher than those of the SK5 steel. Especially, the capability of the laminate structure to better redistribute the stresses consequent to the impact is one of the main reason to explain why, being same the weight, no failed element have been detected in the steel skin – SC product simulation whereas 1.05% of the elements in the steel one have shown to fail.

5. Conclusion

The preliminary results shown in this paper, concerning the material characterization and the crashworthiness properties of laminate structures made of steel skin and SMC core, have proved the capability of this new typology of replacing standard ones, made of traditional material, such as steel.

In addition to that, the reduced density makes the laminate structure to be of very interest for the automotive industry, where the weight reduction is a key aspect in the design of the vehicles of the future. Finally, the utilization of an energy criterion for the comparison of the crashworthiness properties between different materials has proved to be a quick and practical approach, easy to implement in all the FEM structural program.

Although the results presented in this paper are based on material characterization and preliminary application on test-products, the positive outcome of the research encourages further effort in this

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direction for a better understanding of fundamental, processing and possible applications for this new class of hybrid laminate materials.

References

[1] Kim N S 1992 *Conf. Kor. Soc. Tech. Plast.* **3** 177–199
[2] Katayama T, Shinohara M, Hakotami M, Kitade A abd Kono D 2001 *J. Mat. Proc. Tech.* **119** 237–243
[3] Evans A D, Qian C C, Turner T A, Harper L T and Warrio N A 2016 *Comp. Part A* **90** 1–12
[4] Lauter C, Niewel J, Siewers B, Zanft B and Tröster T 2015 *Int. Conf. Exp. Mech.* **2690** 1–7
[5] Liu Q, Lin Y, Zong Z, Sun G and Li Q 2013 *Comp. Str.* **97** 231–238
[6] Meo M, Morris A J, Vignjevic R and Marengo G 2003 *Comp. Str.* **62** 353–360
[7] Bandi P, Schmiedeler J P and Tovar A 2013 *J. Mech. Des.* **135** 1–11
[8] Lewis G and Mladsi S 2000 *Biom.* 755–781