# NUMERICAL ANALYSIS AND OPTIMIZATION OF CFRTP HAT-STIFFENED STRUCTURE

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## Abstract

Carbon fiber reinforced plastics (CFRP) are increasingly used in the primary structural components of vehicles and aircraft on count of their high specific moduli and strength. However, the applications of conventional continuous fiber composites are limited by the high manufacturing costs and complex shape formability issues. In contrast, discontinuous carbon fiber reinforced thermoplastics are well suited for high-cycle and complex shape molding, being viewed as favorable materials for mass-produced vehicles [1]. What's more, the use of discontinuous fiber composites not only avoids winkle formation at curved parts but also enables thickness variation, improving possibility of more flexible lightweight design. Consequently, randomly oriented strands, chopped carbon fiber tape reinforced thermoplastics (CTT), and similar materials have recently attracted increased attention [2-4]. Besides, the mass application of CFRTP in automotive industry has been regarded as potential solution to reduce resource shortage and environmental pollution.

In the present study, numerical studies were conducted to investigate the flexural behavior of CFRTP hat-stiffened structure, which was frequently encountered in aeronautical and automotive applications. A finite element model was established to investigate the fracture process in comparison with experimental results, and using the results of the model to optimize hat-stiffened structure. The results showed good agreement between numerical analysis and experiment both in linear and fracture processes, and optimal CFRTP hat-stiffened structures using different optimization methods were compared and showed the superiority of optimization method in the present study. The method presented in this paper, makes it possible for engineers to improve their designs with an integrated consideration between product performance and design parameters.

## 1. Introduction

Carbon fiber reinforced plastics (CFRP) are increasingly used in primary structural components of automobiles and aircrafts because of their high specific modulus and strength. However, the application of conventionally used continuous-fiber composites in mass-produced devices has been limited by high manufacturing costs and their low formability to complex shapes. In comparison, discontinuous carbon fiber reinforced thermoplastics (DCFRTP) are considered to be more favorable for mass production of vehicles because of their relatively high applicability in high-cycle molding and complex-shape molding [1]. Consequently, randomly oriented strands (ROS), chopped carbon fiber tape reinforced thermoplastics (CTT), and other similar materials have attracted a lot of recent attention [2-9]. Complex-shaped structures (e.g., L-shaped or hat-shaped ones) are frequently encountered in aeronautical and automotive applications. Most works adopted braided or fabric composites structures in axial crash studies, there has been few investigations for random-chopped composite hollow beam in out-of-plane crash study [10-13].

This work aims to investigate the flexural behavior and design optimization of CFRTP hat-shaped hollow beam. FE model using Hashin's failure criteria was used for damage propagation process, and then optimal structure of hat-shaped hollow beam was found under flexural loading using multi-material solution and free-shape optimization. Finally, multi-objective optimization was conducted to find the optimal hat-shaped hollow beam under flexural, torsional and roof collision loadings.

## 2. Finite element analysis

### 2.1. Numerical model

The UT-CTT hat-shaped hollow beam was designed by using 3D finite element model in Altair Hypermesh 14.0 as shown in Fig. 1. The thickness of the hat-shaped structure and the panel was both 2mm. The cylindrical loading bar and cylindrical support bars have rigid body property. And, the cylindrical loading bar was assigned with a constant speed $V_z$= 1 mm min$^{-1}$ in the vertical direction and detected the reactive force influenced by the deformation of the hollow beam, whereas the cylindrical support bars were fixed. Contacts between cylindrical bars and the hat-shaped hollow beam were treated as surface-to-surface contacts while tie constraint was used to represent the contacts between hat-shaped and panel structure since the ultrasonic welding is perfect in the experiment. The element size in the contact sections was chosen to be small for obtaining a more accurate stress distribution, being increased in the other parts to reduce computation time. The failure behavior of all elements was defined to comply with Hashin's failure criteria, and corresponding equations are presented as follows where 1 and 2 are in-plane fiber and matrix directions, respectively, and 3 is the out-of-plane direction. Two different kinds of material properties were used as indicated in Table 1.

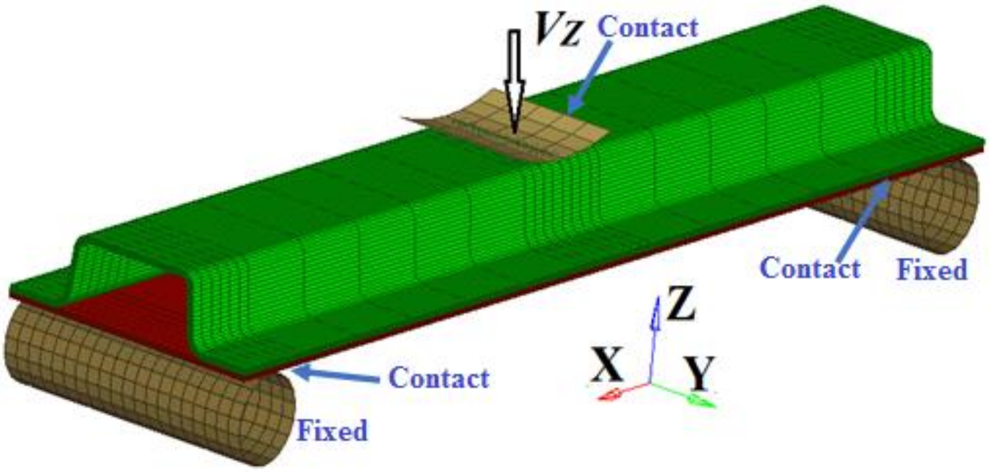

**Figure 1.** FE model of hat-shaped hollow beam.

**Table 1.** Mechanical properties of UD and UT-CTT.

| Parameters | | UT-CTT | UD |
|---|---|---|---|
| Density(g/mm$^3$) | | 1.5e-3 | 1.5e-3 |
| Elastic Modulus(GPa) | $E_1$ | 34.0 | 101 |
| | $E_2$ | 34.0 | 4.5 |
| | $E_3$ | 7.33 | 4.5 |
| Shear Modulus(GPa) | $G_{12}$ | 16.7 | 1.5 |
| | $G_{13}$ | 1.08 | 1.5 |
| | $G_{23}$ | 1.08 | 1.5 |
| Poisson ratio | $\mu_{12}$ | 0.34 | 0.34 |
| Longitudinal tensile strength(MPa) | $X_T$ | 403 | 1573 |
| Transverse tensile strength(MPa) | $Y_T$ | 403 | 21 |
| Longitudinal compressive strength(MPa) | $X_C$ | 280 | 461 |
| Transverse compressive strength(MPa) | $Y_C$ | 280 | 70 |

## 2.2. Results and discussion

Fig. 2 shows the load-displacement curve of experimental results [14]. The crack initiates at the corners of the top wall due to stress concentration caused by the increasing compression, which can be characterized by the severe local fragmentation of fiber and matrix, and then the cracking region spreads towards the symmetric axis at the top wall and towards the overlap area at the side wall. Simultaneously, the corners of the top wall begin to crush, and the top and side wall start buckling. Finally, the crack starts growing in the overlap area and bottom panel, with progressive failure occurs, the formation of a plastic hinge can be inhibited and as a result the load is decreased slowly.

As shown in Fig. 3, damage propagation in FEM using Hashin's failure criteria shows similar trends with that in experiment, especially in initial linear deformation. Meanwhile, the stress distribution in the longitudinal direction of the hat-shaped hollow beam also shows same damage propagation mode which can be visualized in a contour figures.

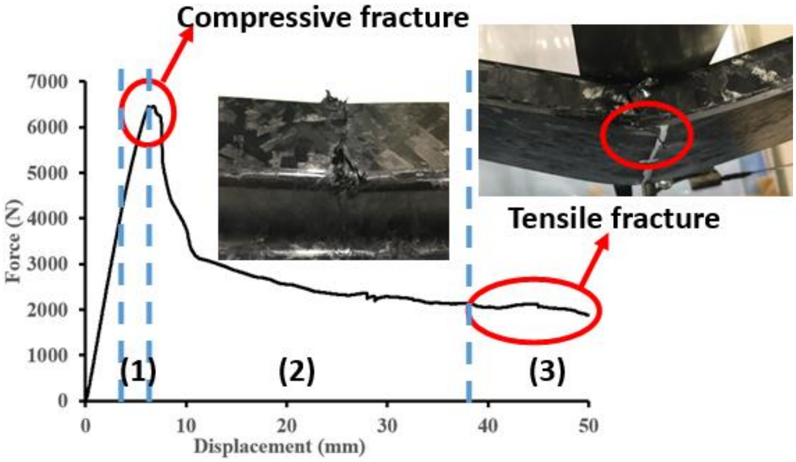

**Figure 2.** Load-displacement curve of experimental results.

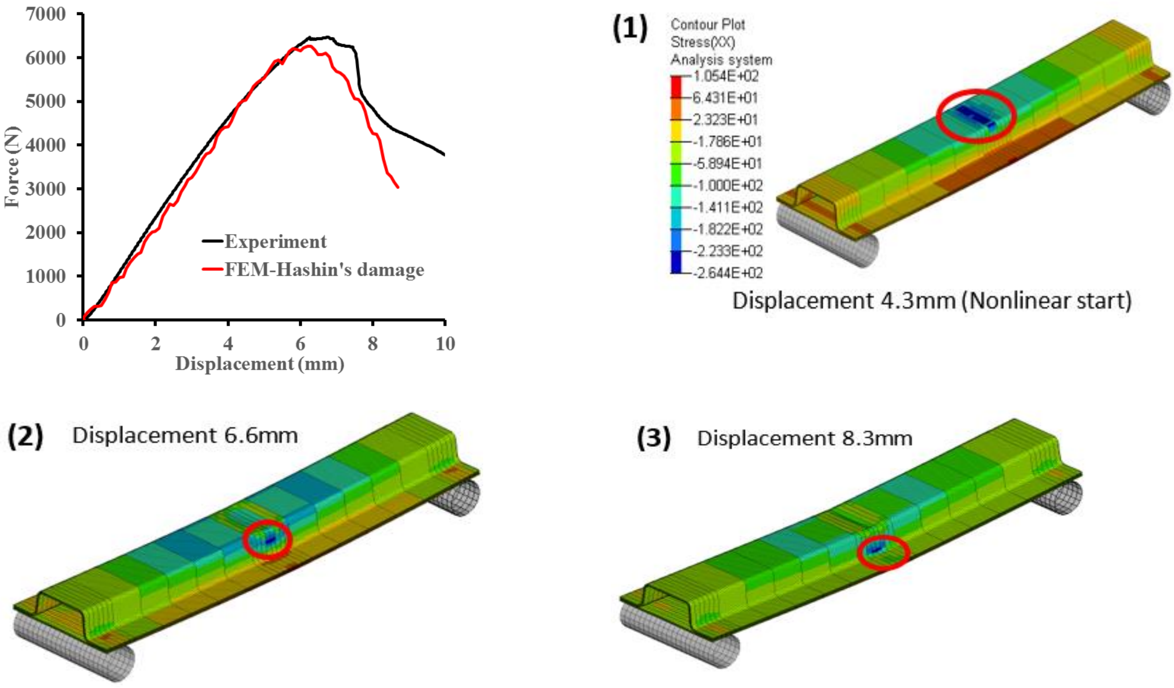

**Figure 3.** Load-displacement curves and stress distribution in FEM.

## 3. Design optimization

### 3.1. Optimization under flexural loading

In the present study, finite element model of hat-shaped hollow beam made by UT-CTT was established. The thicknesses of all plates were 2mm and the total weight was 276g, and the maximum deflection was 3.878mm (The flexural stiffness was 1418N/mm). For comparison, finite element model of steel hat-shaped hollow beam with 780MPa-high-tensile-strength was also established. The thicknesses of all plates were 0.55mm and the total weight of the steel hat-shaped hollow beam was 397g, and the maximum deflection was 3.228mm (The flexural stiffness was 1704N/mm).

Two different kinds of material properties UD and UT-CTT were chosen to obtain the highest flexural stiffness by material selection process. In addition, the effect of the increasing ratio of UD plies in the panel was investigated for improving the flexural stiffness. After parametric study, UT-CTT hat-shaped structure and the thickness 1.6 mm and 0.4mm of UD and UT-CTT plies in panel part were chosed, resulting in the highest flexural stiffness 1558N/mm.

The design requirement for CFRTP hat-shaped hollow beam was to minimize the weight while keeping same stiffness with that of steel one. The surface nodes, the position of which can be varied along the thickness direction, were marked in Fig. 4. The movement of these surface nodes were chosen as design variables. There was a lower bound on the thickness for each movable surface node for actual design. In the present study, the maximum movements of the 6050 movable surface nodes was limited to 2 mm along normal direction (grow direction and shrink direction).

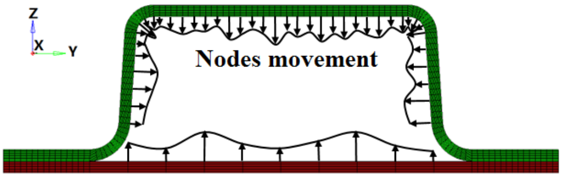

**Figure 4.** Schematic illustration of free-shape optimization.

Fig.5 depicted the optimized geometry of hat-shaped hollow beam. The different colors represented thickness variation along Z direction. For hat-shaped structure, the maximum thickness of central curved parts of the optimized model increased from 2 mm (original thickness) to 3.538 mm whereas the minimum thickness of two end parts of hat-shaped decreased to 1.185mm. For panel structure, the minimum thickness of two end parts of panel structure decreased to 1.051mm. The total weight of optimized model was 247g, which means the structural weight reduction was 38% with same flexural stiffness comparing with the weight of steel one.

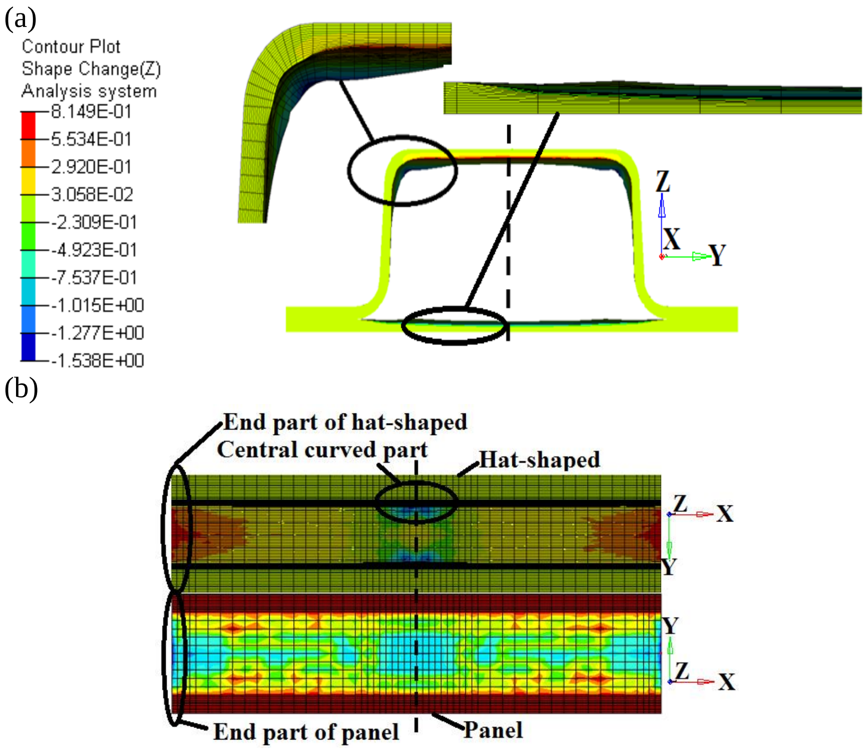

**Figure 5.** The free-shape optimization result. (a)Side view (b)Top view.

## 3.2. Multi-objective optimization

Robustness to load from the multi-directions is one of the features required for the automobile frame structure. In order to evaluate the possibility of mass-production application of CFRTP, the hat-shaped hollow beam was designed under three different loadings assuming the roof collision, the flexural and torsional condition as show in Fig. 6. The value 200N of force was used to evaluate stiffness for each FE model.

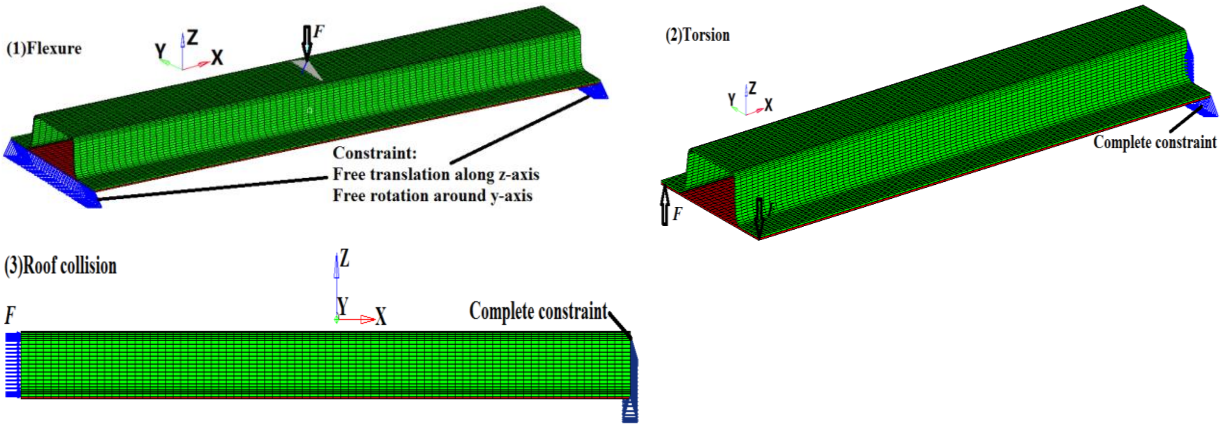

**Figure 6.** FE models of hat-shaped hollow beam under flexural, torsional and roof collision loadings.

The thickness of steel hat-shaped and panel part are both 1 mm while the initial thickness of UT-CTT ones are 3 mm. The evaluated indexes in FEM study are mass and compliance of the model. Compliance is defined as a relation of an inverse proportion with stiffness. The weight of steel model is 746g UT-CTT model is 425g, however, the stiffness of the UT-CTT model under three conditions are not more than that of steel one.

Therefore, applicability of a hybrid structure composed of UT-CTT and UD material was used to improve stiffness and achieve more light-weight structure. Though mechanical properties of UD in longitudinal direction are superior as three times higher than UT-CTT, the mechanical properties in transversal direction are only one-eighth of UT-CTT. Hence, it is reasonable that UD is used as a reinforcement of UT-CTT.

The size optimization was used to find the optimal thickness of each ply of UT-CTT and UD. The design variables are the thickness of each ply of UT-CTT and UD, the lower and upper thickness of each ply are 0.1mm and 0.5mm, the constraint function is the compliance of hybrid material structure is less than that of steel one, and the objective function is minimization of mass. By size optimization, the thickness of each part and each ply was adjusted to optimal parameter as shown in Fig. 7 and Fig. 8. Weight reduction of 43% was achieved in keeping the same stiffness with that of steel one under the three loading conditions. Table 2 shows the comparison of compliance and mass before and after optimization.

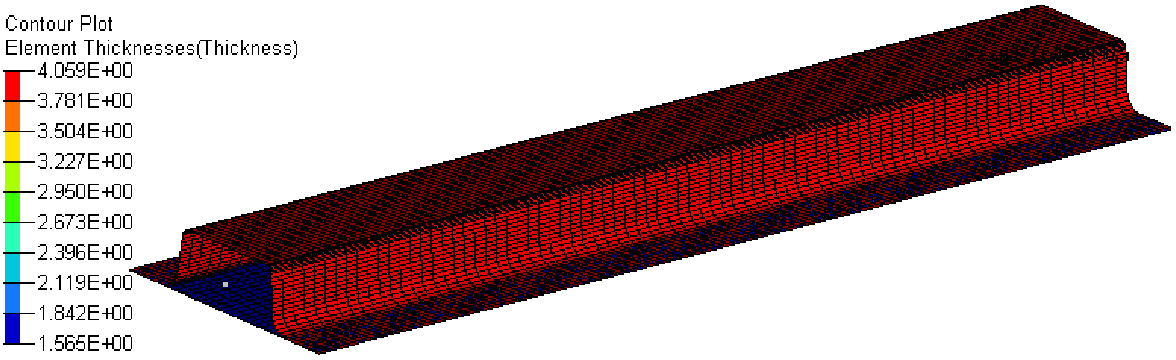

**Figure 7.** The optimal total thickness of each part.

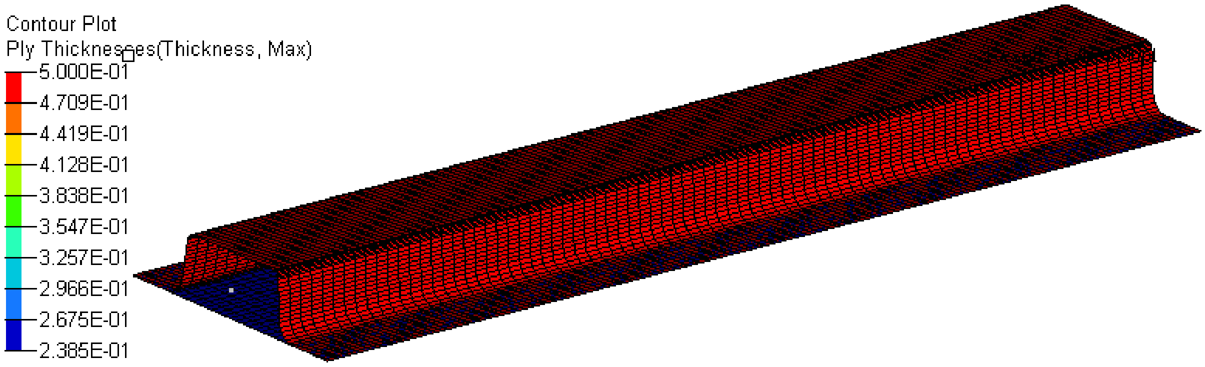

**Figure 8.** The maximum ply thickness of UT-CTT and UD.

**Table 2.** Comparison of compliance and mass before and after optimization.

| | Material | Compliance(mm/N) | | | Mass(g) |
|---|---|---|---|---|---|
| | | Flexure | Torsion | Roof collision | |
| Before optimization | Steel | 7 | 186 | 0.2 | 746 |
| | UT-CTT | 9.6 | 91 | 0.31 | 425 |
| Hybrid material | UT-CTT+UD | 7.7 | 137 | 0.2 | 425 |
| After size optimization | UT-CTT+UD | 7 | 161 | 0.18 | 425 |

## 4. Conclusions

The fracture behavior and design optimization of hat-shaped hollow beam, which is made of hat-shaped structure and panel was investigated numerically.

1) The progressive failure mode of UT-CTT hat-shaped hollow beam was observed in static bending tests, and the numerical result of 3D finite element model based on Hashin damage criteria was in good agreement with experimental results.

2) Weight reduction of 38% by CFRTP can be achieved through lightweight design using multi-material solution and free-shape optimization for UT-CTT hat-shaped hollow beam under flexural loading.

3) Weight reduction of 43% was achieved in keeping the same stiffness with that of steel one under the three loading conditions including flexural, torsional and roof collision loadings.

Therefore, it can make conclusion that the numerical method proposed here can offer one of effective design aids for bending fracture behavior, and the work contributes to show potential application of UT-CTT for mass-produced vehicles by taking full advantage of the merit “thickness variation”.

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## References

[1] Wan Y, Ohori T and Takahashi J. Mechanical properties and modeling of discontinuous carbon fiber reinforced thermoplastics. In: *Proceedings of the 20th international conference on composite materials*, Copenhagen, Denmark, 19-24 July 2015.
[2] LeBlanc D, Landry B, Levy A, et al. Compression moulding of complex parts using randomly-oriented strands thermoplastic composites. In: *Proceedings of the international SAMPE symposium and exhibition*, Seattle, USA, 2-5 June 2014.
[3] Selezneva M and Lessard L. Characterization of mechanical properties of randomly oriented strand thermoplastic composites. *J Compos Mater* 2016; 50: 2833-2851.
[4] Feraboli P, Peitso E, Deleo F, et al. Characterization of prepreg-based discontinuous carbon fiber/epoxy systems. *J Reinf Plast Compos* 2009; 28: 1191-1214.
[5] Lee H, Tang S, Ohori T, et al. Applicability of FEM to complex shape parts made by ultra-thin chopped carbon fiber tape reinforced thermoplastics. In: *Proceedings of 14th Japan international SAMPE symposium and exhibition*, Kanazawa, Japan, 6-9 December 2015.
[6] DeWayne D and Fukumoto S. Compression molding of long chopped fiber thermoplastic composites. In: *Proceedings of the CAMX conference*, Orlando, USA, 13-16 October 2014.
[7] Feraboli P, Peitso E, Cleveland T, et al. Modulus measurement for prepreg-based discontinuous carbon fiber/epoxy systems. *J Composite Mater* 2009; 43: 1947-1965.
[8] Selezneva M, Roy S, Lessard L, et al. Analytical model for prediction of strength and fracture paths characteristic to randomly oriented strand (ROS) composites. *Compos Part B Eng* 2016; 96: 103-111.
[9] Eguemann N, Giger L, Roux M, et al. Compression moulding of complex parts for the aerospace with discontinuous novel and recycled thermoplastic composite materials. In: *Proceedings of the 19th International conference on composite materials*, Montreal, Canada, 28 July-2 August 2013, pp. 6718-6725.
[10] T. Matsuo, M. Kan, K. Furukawa, et al. Numerical modeling and analysis for axial compressive crushing of randomly oriented thermoplastic composite tubes based on the out-of-plane damage mechanism. *Compos Struct* 181 (2017) 368–378.
[11] Q Liu, HL Xing, Y Ju, et al. Quasi-static axial crushing and transverse bending of double hat shaped CFRP tubes. *Compos Struct* 117 (2014) 1–11.
[12] HC Kim, DK Shin, JJ Lee. Characteristics of aluminum/CFRP short square hollow section beam under transverse quasi-static loading. *Compos Part B Eng* 51 (2013) 345–358.
[13] OT Topac, B Gozuluklu, E Gurses, et al. Experimental and computational study of the damage process in CFRP composite beams under low-velocity impact. *Compos Part A* 92 (2017) 167–182.
[14] Xiao BH, Guo QT, Ohsawa I, Fujita M and Takahashi J. Manufacture and performance evaluation of hat-stiffened structure made by chopped carbon fiber tape reinforced thermoplastics. In: *Proceedings of the 18th European Conference on Composite Materials,* Athens, Greece, 24-28 June 2018.