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Numerical Investigation on the Effect of Composite Corrugated Cores in Lightweight Sandwich Panels under Planar Impact Loading

Majid Jamal-Omidi[1]*, Mahmood Zabihpoor[1], Mehdi Vaezi[1], Ali Choopanian Benis[1]

[1]Faculty of Aerospace Engineering,
Malek Ashtar University of Technology, Tehran, IRAN

*Corresponding Author

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Abstract: Lightweight sandwich structural components have been widely used in different industries as highly effective energy absorbers. This research aims to provide a comparative study on the role of the composite corrugated sheet as a core in sandwich panels under low velocity impact loading. To reach this goal, the crashworthiness characteristics of three sandwich panels with different corrugated cores, which consist of identical mass and mechanical properties, are evaluated under vertical and transverse loading. The finite element computation is done using LS-DYNA under planar loading conditions. To validate the numerical process, first, the dynamic compression behavior of the square corrugated core sandwich panel made of aluminum alloys in comparison to existing experimental data is analyzed and the appropriate compliance has been observed. Then the effect of composite material and core shape on the crashworthy behavior of sandwich panels is explored. The research results reveal that the material type and geometric configuration of corrugated core have a considerable effect on the mean crushing load and the energy absorption of sandwich panels. It is found that the triangular configuration has a higher capability in load carrying and energy absorption than the square and/or the sinusoidal configuration. The failure modes of the crushed corrugated sandwich panels also significantly influenced by the type of corrugation cores. The present results supply valuable information on low velocity impact response that can be helpful for increasing crashworthy performance and development of such lightweight structures.

Keywords: CFRP, corrugated core, energy absorption, sandwich panel, vertical and transverse loading

1. Introduction

Mechanical properties such as high specific strength and bending stiffness and the outstanding impact strength, energy absorption, lightweight, and thermal insulation make sandwich structures an attractive choice for designers in high-tech industries like aerospace, automotive and marine.

The sandwich panel is a structure made of three layers consisting of a lightweight internal core and two external thin and strong face layers. Depending on the type of application, different shapes and materials are utilized for face layers and core. The faces are often manufactured of metal or composite materials, and the core can be classified based on its material or architecture, like honeycomb core, foam or solid core, corrugated core, and lattice core. Core-to-face bonding integrity is normally done using adhesive bonding or welding. The type of cores is highly influential to predict the crashworthy behavior of sandwich constructions. Torre and Kenny [1] experimentally studied the crashworthiness

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*Corresponding author: j_omidi@mut.ac.ir, m.jamalomidi@gmail.com response of two types of sandwich structures made of glass fiber/polyester face sheets with a foam core and glass fiber/phenolic face sheets bonded to a corrugated core with the same skin material filled by foam. The results indicated that the corrugated sandwich structure capable to absorb much more impact energy in comparison to the traditional ones. Yamashita and Gotoh [2] investigated the mechanical response of bare aluminum honeycomb under transverse quasi-static compression. The relation between crush behavior and cell shape as well as foil thickness was numerically studied by using the DYNA3D code. The results showed that the smaller cell angle and thicker foil wall recommended improving crush strength. Yokozeki et al. [3] proposed corrugated laminates made from carbon/epoxy composites as an ideal material in morphing wing technologies. They performed tensile and flexure tests in longitudinal and transverse directions to assess the stiffness and strength of corrugated sheets. Furthermore, they analytically established a simple model to predict the initial stiffness of corrugated composite laminates. Cote et al. [4] studied the properties of stainless steel corrugated and diamond lattice cores in sandwich panels. They experimentally extracted mechanical properties of the longitudinal and transverse shear as well as out of plane compressive of corrugated cores and evaluated the results with the theoretical and numerical study. The results also showed that these cores absorb less energy than square honeycomb in compression and transverse shear, however, the shear strength and energy absorption in the longitudinal shear of the corrugated core is comparable to square honeycomb. Aktay et al. [5] predicted the crush performance of sandwich structures made of aluminum and NomexTM honeycomb core using PAM-CRASH code. They used two modelling techniques included micromechanics and homogenised models, and observed that the micromechanical model had a better agreement with experimental data in the design of the honeycomb core. Castanie et al. [6] suggested a core damage criterion to study the post-impact compressive strength on sandwich panels made of plain-weave carbon fabric/epoxy skins and Nomex Honeycomb as a core. They used nonlinear springs to model the core behavior and Mindlin plate elements to model the linear elastic behavior of the skins. Ruijun GE et al. [7] examined the elongation of corrugated composite skins made of glass/epoxy laminates by numerical simulation with ANSYS software, and the results evaluated experimentally. The results demonstrated that corrugated skin has larger deformation capability in comparison to the flat one, so this structure can be a suitable candidate for morphing wing design. Biagi and Bart-Smith [8] studied the mechanical behavior of corrugated core sandwich beams made of SAE340 stainless steel under in-plane compression. The numerical analysis by ABAQUS finite element software and analytical approach was performed on beams, and the results were compared with experimental data. The results illustrated an accurate prediction of the maximum failure load and failure mode for more cases. In addition, the study concluded that the resistance of the corrugated sandwich beams is dependent on the local and global boundary conditions. Rejab and Cantwell [9] investigated the compression response and subsequent fracture modes in sandwich panels with triangular corrugated cores experimentally and numerically (ABAQUS software). Three different materials included aluminum alloy, glass fiber reinforced plastic, and carbon fiber reinforced plastic is used to make sandwich panel specimens. They assessed the role of the cell wall thickness and the unit cell numbers on the local collapse and overall deformation of structures. The results showed that the triangular corrugated core becomes a trapezium form in the deformation process. Kılıcaslan et al. [10] studied the low velocity impact response of multi-layer corrugated sandwich structures composed of aluminum face sheets, trapezoidal corrugated aluminum core and aluminum sheet interlayers experimentally and numerically (using LS-DYNA software). The results of the work showed that the main mechanisms of deformation are due to the buckling/folding of corrugated cores and bending of interlayer and face sheets. Hou et al. [11] explored the impact response of sandwich structures made of aluminum alloys with trapezoidal and triangular corrugated cores experimentally and by the means of finite element simulations (using ANSYS and LS-DYNA software). They evaluated geometrical factors on the crushing behavior of corrugated cores in order to find the optimized shape for crashworthiness criteria. Hou et al. [12] performed the experimental and numerical study on the multi-layered trapezoidal corrugated core sandwich structures made of the aluminum alloy under the quasi-static crushing loading. They reported the major effect of the cell shapes and numbers of core layers on energy absorption and failure modes. Kılıcaslan et al. [13] investigated the axial crushing behavior of single and double layer sandwich panels with corrugated cores made of aluminum alloy by experimental and numerical methods under quasi-static and dynamic rates. They observed the interaction of loading rate and deformation mechanism and reported that the stress of corrugated core increased in case of loading rate increased from quasi-static to dynamic. Nouri Damghani et al. [14] performed analytical modeling and numerical simulation (using ANSYS/LS-DYNA) to study the effects of core density on the low velocity impact response of sandwich structures with the corrugated foam-filled core made of aluminum alloys. The results showed that densifying the foam core cause increasing energy absorption and improves impact resistance. Boonkong et al. [15] studied the energy absorption specification and failure modes of aluminum sandwich panels with the corrugated core experimentally and by the means of developing the finite element modeling (ABAQUS/Explicit software) at low velocity. They also explored the crashworthiness behavior of these structures due to the impactor size, the material types of the substrate, and the angle of impact. Wang et al. [16] performed the medium velocity impact experiments on sandwich panels with aluminum alloy face sheets and the five different core materials including polystyrene foam, polypropylene honeycomb, cork, low density balsa wood, and high density balsa wood. The test results showed that core materials play a significant role in the impact response of sandwich structures. They concluded that polystyrene foam is a promising main material when the primary design parameters are focused on energy absorption and resistance of penetration. Furthermore, numerical modelling using LS-DYNA software was carried out as an experimental supplement. Liu and Turner [17] performed quasi-static and dynamic strain rate compression tests on the corrugated composite sandwich panels made of carbon fiber/epoxy and reported the rate-dependency behavior for the examined composite cores. Nouri Damghani and Mohammadzadeh Gonabadi [18] explored the influence of core geometry on energy absorption and impact resistance of corrugated sandwich panels made of aluminum alloy using a drop hammer tester. The results showed the highlighted role of the height of the panel and core geometry in the load-carrying capability of sandwich structures. It was observed that the increase in panel height enhanced energy absorption ability, and the square core has higher impact resistance in comparison to the triangular core. Rong et al. [19] employed ABAQUS software to investigate the effect of corrugated cores with various geometric shapes in the dynamic response of sandwich panels under the local impact. The face sheets and the core were made of carbon fiber-reinforced polymer (CFRP) material and aluminum alloy, respectively. They concluded that geometric shapes have a significant role in energy absorption capability at minor energy levels. However, for the high energy impact, no significant effect was observed with changes in the geometric shape of the cores.

Yan et al. [20] performed the numerical and experimental study on corrugated sandwich panels with the empty core and aluminum foam-filled core under the low velocity impact. Both the face sheets and the core were made of 304 stainless steel. Numerical simulations were done using ABAQUS/Explicit software. The results revealed that aluminum foam fillers played an important role in the impact responses of corrugated sandwich panels. Also, a significant increase in crashworthiness performances of the foam-filled corrugated sandwich panel was reported compared to empty ones. Rong et al. [21] explored the influence of core materials on the crashworthiness responses of corrugated sandwich structures under the low velocity impact experimentally and numerically (ABAQUS/Explicit software). The panels were composed by CFRP face sheets with aluminum alloy core, stainless steel core, and CFRP core. The results revealed the significant effect of the core material fracture properties on structural performance and found that the core with stainless steel material improved significantly the ability to absorb energy and load-carrying capacity compared to other ones.

Based on the studies performed, it was observed that few studies have focused on evaluating the role of the composite corrugated sheets as a core on the impact behavior of sandwich panels, which is directly associated with structural safety. In this regard, this research is aimed to explore the low velocity planar impact response of corrugated core sandwich panels made of composite materials using LS-DYNA finite element code. To ensure the accuracy of the simulation process, first, numerical modelling results of the corrugated core sandwich panel made of aluminum alloys is assessed with existing experimental data. Then, a range of corrugated composite-based sandwich structures with multi-layer composite faces are simulated and analyzed under vertical and transverse loading conditions, and the effect of using square, triangular and sinusoidal corrugation cores on the crashworthiness performance of composite sandwich panels are examined. The results indicate that the corrugated composite core in sandwich construction can considerably increase the energy absorption efficiency.

2. Finite Element Analysis

2.1 Finite Element Modelling-Validation

In this section, the planar impact response of the 2024 aluminum alloy sandwich panel with a square-shaped 5052-O aluminum corrugated core, shown in Fig. 1, is used to validate the numerical simulation process. The overall dimensions of the plate and the square core are 70 mm × 80 mm and 10 mm × 10 mm, respectively. Explicit solver in LS-DYNA is utilized for numerical analysis. The mesh convergence evaluation is carried out with four different sizes, i.e., 2 mm × 2 mm, 1.5 mm × 1.5 mm, 1 mm × 1 mm, and 0.5 mm × 0.5 mm respectively. It is found that the size of 1 mm × 1 mm can fully satisfy the simulation accuracy. The material model 3 (MAT_PLASTIC_KINEMATIC) is selected to model the face sheets and core. This model is a bi-linear elastic-plastic model and its formulation is based on the combination of isotropic and kinematic hardening. Also, the loading plate and lower platform are defined using the rigid body material model MAT20, which attributes non-deformable characteristics to them, with steel material property. The mechanical properties of the structural components of the sandwich panel and impactor are given in Table 1.

The face sheets and core is constructed from Belytschko-four-node shell element, and a perfect bonding is assumed between the face sheets and core. The impactor is modeled as a rigid plate with a thickness of 10 mm and a diameter of 120 mm. The lower platform is fully constrained and modeled using 2300 constant stress solid elements and 2886 nodes. The panel is put on a rigid platform and is impacted by a rigid impactor. It is also assumed that no slippage occurs between the rigid platform and the lower face sheet.

Different type of contact formulations is utilized in the simulation process. The automatic surface-to-surface contact model is applied to the contact between the loading plate and the sandwich panel. The automatic single surface contact model is used for simulating the self-contact of the core during deformation. In addition, two contact types including the automatic one-way surface-to-surface contact and the tied contact formulation is employed to assess the performance between the face sheets and the core structure. The geometric modeling of the aluminum sandwich panel, upper rigid plate, and the rigid floor is shown in Fig. 2. The panel is compressed downwards at a speed of 1 m/s.

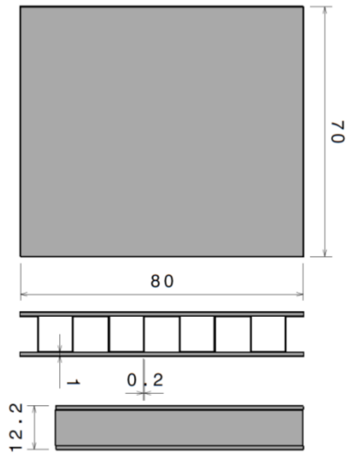

Fig. 1 - Geometrical details of metallic sandwich panel with square corrugated core (unit: mm)

Table 1 - Mechanical property of materials [11]

Property	Unit	Aluminum 2024 (face sheets)	Aluminum 5052-O (core)	Steel (Impactor)
ρ	kg/m^3	2700	2685	7830
E	GPa	72.4	69.6	210
ET	GPa	28	2.5	-
σ_y	MPa	75.8	65.5	-
υ	-	0.33	0.33	0.3

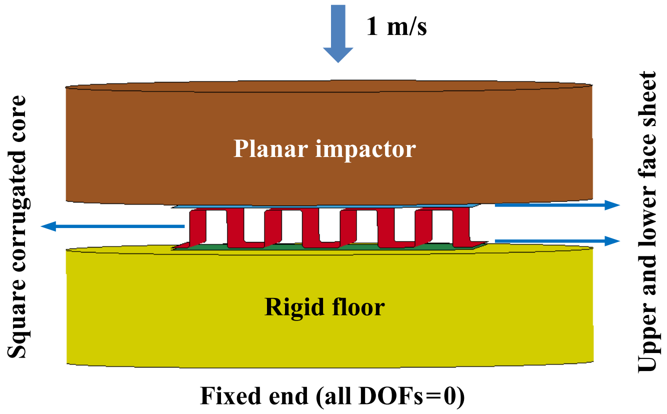

Fig. 2 - Finite element geometric model of the corrugated core sandwich panel and applied conditions

The result of load-displacement curve for the corrugated sandwich panel in comparison to the available experimental data is displayed in Fig. 3. The simulation results show good quantitative and qualitative agreement with experimental ones. As shown in the figure, the simulation result based on the use of tied contact is closer to experiments data, so this formulation is considered in the simulation process. Differences in results can be attributed to the lack of modelling of the details of the adhesive layer between the face plates and the core in the simulation process relative to the actual condition. The comparison of the deformed shape of the corrugated sandwich panel is displayed in Fig. 4. As can be seen in the figure, the deformed pattern is similar to the results of experimental deformation modes.

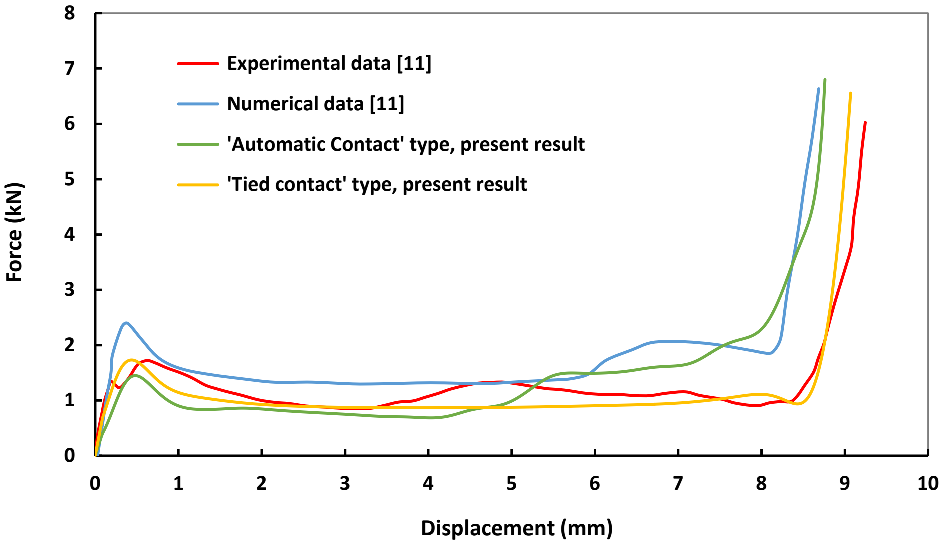

Fig. 3 - Comparison of the load-displacement curve between the present results and available data [11]

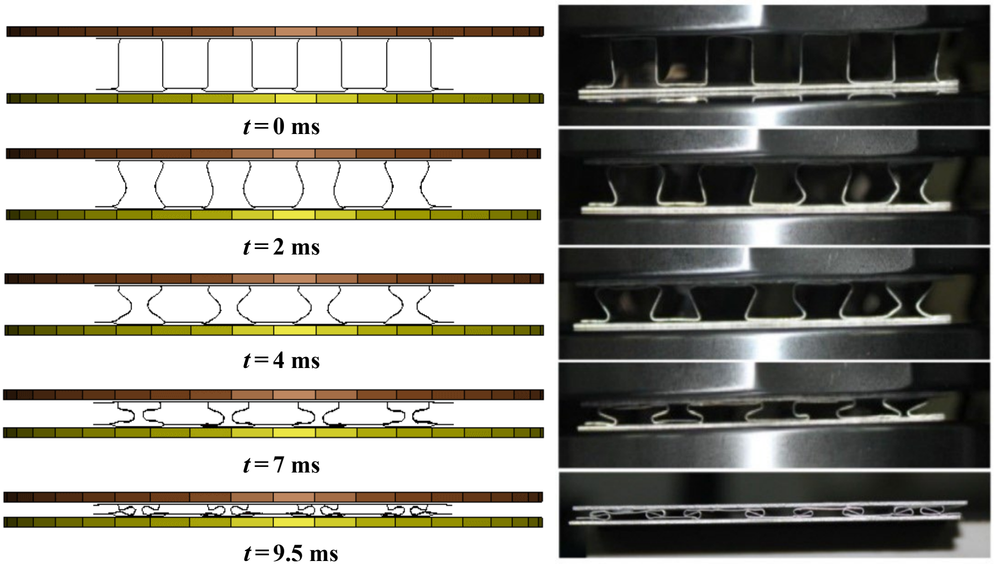

Fig. 4 - The resulting deformation patterns for simulation based on the tied contact formulation between the face sheets and the core structure and experiment [11]

2.2 Finite Element Simulation of Composite Corrugated Core Sandwich Panel

In this section, finite element analysis on carbon-fabric/epoxy sandwich panel with corrugated core has been investigated under vertical and transverse crushing. The material parameters of carbon/epoxy are given in Table 2. In addition, the non-physical parameters of the material model MAT54 is listed in Table 3. This material model uses Chang-Chang failure criterion to predict damage of each ply progressively.

Three types of corrugation cores including square, triangular, and sinusoidal with the same density and mechanical properties are designed and chosen for the study. The corrugated core geometry with different configurations is displayed in Fig. 5. It should be noted the cores are designed so that the panels have a similar mass. The mass amounts of the sandwich panels with square, triangular, and sinusoidal cores are 22.14 gr, 22.13 gr, and 21.80 gr, respectively. Information on the number of elements and nodes involved with suitable element type and mesh size is given in Table 4. In addition, the detail of interaction between components is summarized in Table 5. In the research process, the effect of using corrugated composite cores on the crashworthiness parameters and energy absorption capability of the sandwich structures is explored. The sandwich structure parameters used in the investigation is shown in Table 6.

Table 2 - Mechanical and strength property of carbon/epoxy composite [22,23]

Property	Value	Unit	Material model
Mass density, *RO*	1500	kg/m^3	MAT54
Young's modulus - longitudinal direction, *Ea*	55.9	GPa	
Young's modulus - transverse direction, *Eb*	54.4	GPa	
Shear modulus, *Gab* / *Gbc* / *Gca*	4.2	GPa	
Poisson's ratio, PRba	0.042	-	
Longitudinal compressive strength, *XC*	704.0	MPa	
Longitudinal tensile strength, *XT*	911.3	MPa	
Transverse compressive strength, *YC*	698.2	MPa	
Transverse tensile strength, *YT*	770.1	MPa	
Shear strength, *SL*	131.6	MPa	

Table 3 - Non-physical parameters for MAT54

Variable	Description
AOPT	EQ.3.0: locally orthotropic material axes determined by rotating the material axes about the element normal by an angle (MANGLE) from a line in the plane of the element defined by the cross product of the vector v with the element normal.
V1	Define components of vector v for AOPT = 3.
SOFT	Softening reduction factor for material strength in crashfront elements (default = 1.0).
YCFAC	Reduction factor for compressive fiber strength after matrix compressive failure (MAT_054 only). The compressive strength in the fiber direction after compressive matrix failure is reduced to: XC = YCFAC * YC (default:YCFAC = 2.0).
CRIT	Failure criterion (material number): EQ.54.0: Chang matrix failure criterion (as Material 22).
SOFT 2	Optional “orthogonal” softening reduction factor for material strength in crashfront elements (default = 1.0).
SOFTG	Softening reduction factor for transverse shear moduli GBC and GCA in crashfront elements (default=1.0).

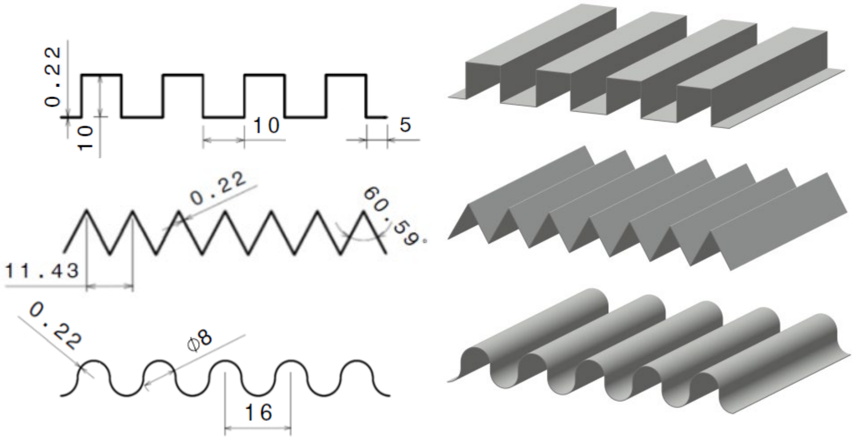

Fig. 5 - Geometrical details of square, triangular and sinusoidal corrugated core (Unit: mm)

Table 4 - The total number of elements and nodes for structural components

Component	Element	Node	Element type	Element size
Square core	11130	11360	Belytschko-Tsay	1 mm × 1 mm
Triangular core	11760	11999		
Sinusoidal core	10446	10666		
Face sheets	5250	5396		
Impactor/rigid floor	2300	2886	Constant stress solid	10 mm × 10 mm

Table 5 - Interactions between parts in finite element model

Components	Interaction type
Face sheets/core	Tied nodes to surface
Impactor/sandwich panel	Automatic surface to surface

Table 6 - The sandwich configuration for impact analysis

Face sheet/core material	Face sheet ply orientation	Face sheet thickness (mm)	Core ply orientation	Core thickness (mm)
Carbon-fabric/epoxy	[(0/90)/(±45)/(0/90)/(±45)/(0/90)]	1.1	[(0/90)]	0.22

2.2.1 Vertical Loading

The finite element results on a sandwich panel with composite skins which stiffened with square corrugated composite core subjected to vertical loading with a velocity of 1 m/s is displayed in Fig. 6. The failure strength and modes of the composite sandwich panel is computed based on the MAT 54 formulation, using the Chang-Chang failure theory. These results are also compared with that of aluminum square corrugated core sandwich structure having the same geometry, boundary, and loading conditions. The results indicated that the CFRP offers the best impact resistance and energy absorptions, in comparison with the metal materials. The deformed shape of the CFRP square corrugated core sandwich structure at different crushing stages is displayed in Fig. 7.

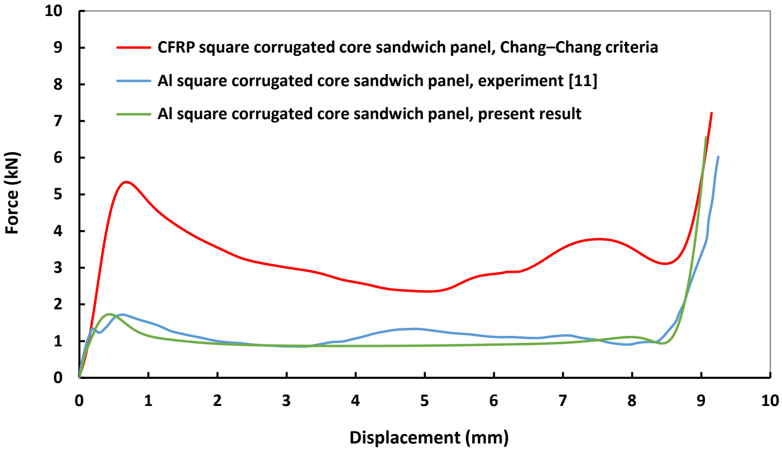

Fig. 6 - The load-displacement curves of the square corrugated core sandwich panel

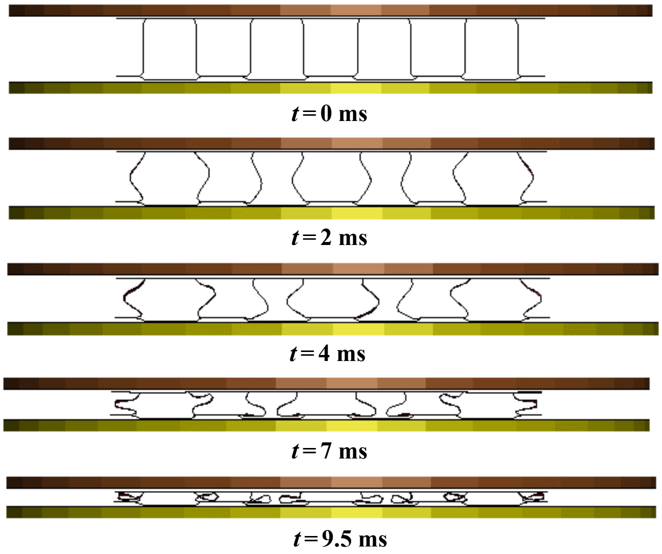

Fig. 7 - Deformed shape of the CFRP sandwich panel with square corrugated core due to impact response

The load-displacement curves for three composite sandwich panels with corrugated CFRP cross-ply cores are shown in Fig. 8. The results indicate that triangular corrugated core support a higher load than the square and sinusoidal corrugated cores. This indicates the role of the cross-section configuration of the corrugated core during the impact loading process. A similar crashworthiness performance on sandwich panels made of aluminum alloys with square and triangular corrugated cores under impact loading has been reported in the study by Hou et al. [11].

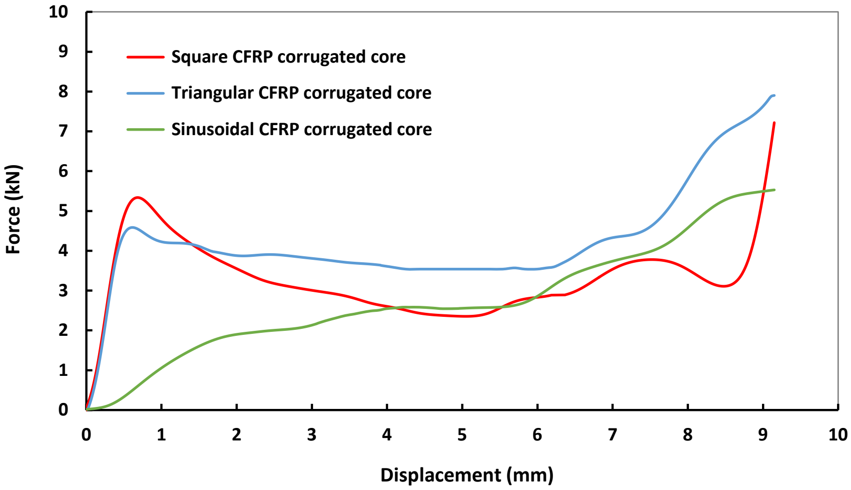

Fig. 8 - The load-displacement curves for the corrugated core sandwich plane

The results for initial load, mean crushing load, energy absorption and specific energy absorption are summarized in Table 7. The initial crushing loads by the CFRP square corrugated core found higher 1.16 and 2.10 times than triangular and sinusoidal cores, respectively, while the triangular corrugated core shows an increase of 1.19-1.62 times in the mean crushing load compared to square and sinusoidal cores. It should be noted that the mean crush load plays an effective role in assessing the crashworthiness and energy absorption ability of sandwich structures. The results also indicate that changing the geometry of the corrugation causes a considerable increase in energy absorption. It is observed that the triangular CFRP corrugated core supports the energy absorption higher than two types of corrugations, especially compared to sinusoidal corrugated cores.

The deformed shape of the triangular and sinusoidal CFRP corrugated core sandwich panels at different states of the crushing simulation is shown in Figs. 9 and 10. As shown in Figs. 7, 9 and 10, the failure mode significantly influenced by the type of corrugated core. It should be noted that the CFRP corrugated core sandwich panels generally exhibited a brittle type of behavior, involving extensive crushing. The failure processes in the CFRP corrugated cores indicate that the initial failure is dominated by cell wall buckling [9].

Table 7 - The comparison of crashworthiness indicators between three configuration specimens due to vertical impact response

Core geometry	Initial load (kN)	Mean crushing load (kN)	Energy absorption (J)	Specific energy absorption (J/kg)
Square	5.34	3.21	25.7	1160.80
Triangular	4.60	3.83	30.7	1387.26
Sinusoidal	2.58	2.37	19.0	871.56

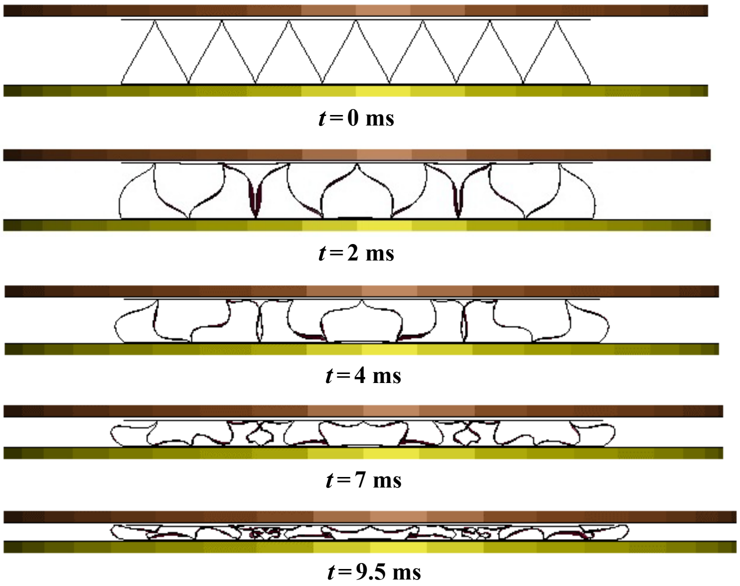

Fig. 9 - Deformed shape of the CFRP sandwich panel with triangular corrugated core due to impact response

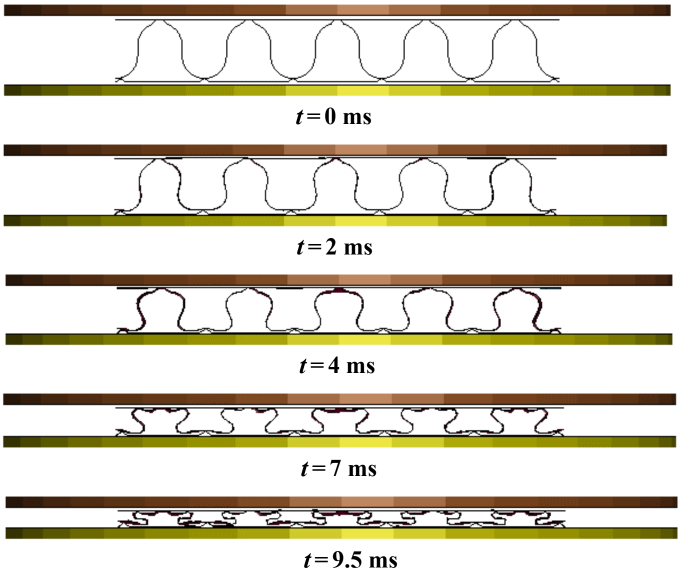

Fig. 10 - Deformed shape of the CFRP sandwich panel with sinusoidal corrugated core due to impact response

2.2.2 Transverse Loading

In this section, finite element analysis on CFRP sandwich panel with corrugated core has been investigated under transverse crushing. The geometry as well as the appropriate boundary condition for the sandwich panel under transverse loading is shown in Fig. 11. In this situation, the rigid platform motion is restrained completely, while the lateral impactor is only able to move in the transverse direction. In addition, in order the stability of the sandwich panel on the rigid platform, the rows of ending elements of the face sheets and the core are completely fixed.

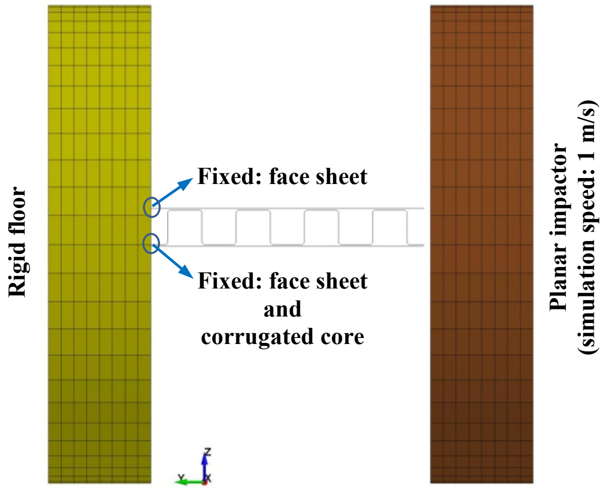

Fig. 11 - Geometrical model and loading and boundary condition of the sandwich panel under the transverse impact

The results on the sandwich panels with three types of corrugation cores including square, triangular and sinusoidal subjected to transverse loading is shown in Fig. 12. A comparison between the crashworthiness indicators of the different types of core subjected to transverse loading is listed in Table 8. The results indicate that CFRP triangular corrugated core support loads higher than two other types of corrugation cores.

The deformed shape of sandwich panels with different corrugated cores is shown in Figs. 13 to 15, and the results indicate that the modes of failure are affected by the core configurations. In addition, the results show a significant capacity to extend and deform flexibly of corrugated configuration in sandwich structures.

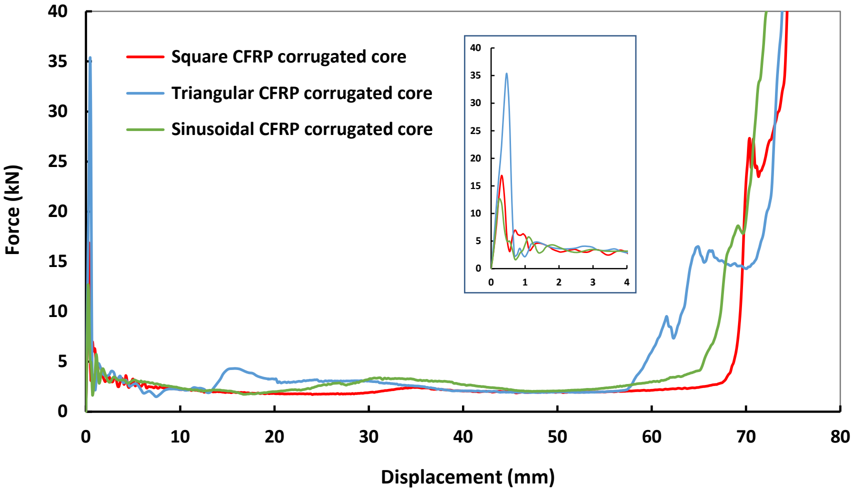

Fig. 12 - The load-displacement curves of the sandwich panels under transverse loading

Table 8 - The comparison of crashworthiness indicators between three configuration specimens due to transverse impact response

Core geometry	Initial load (kN)	Mean crushing load (kN)	Energy absorption (J)	Specific energy absorption (J/kg)
Square	16.2	2.18	131	5916.90
Triangular	35.4	2.90	174	7862.63
Sinusoidal	12.6	2.62	157	7201.83

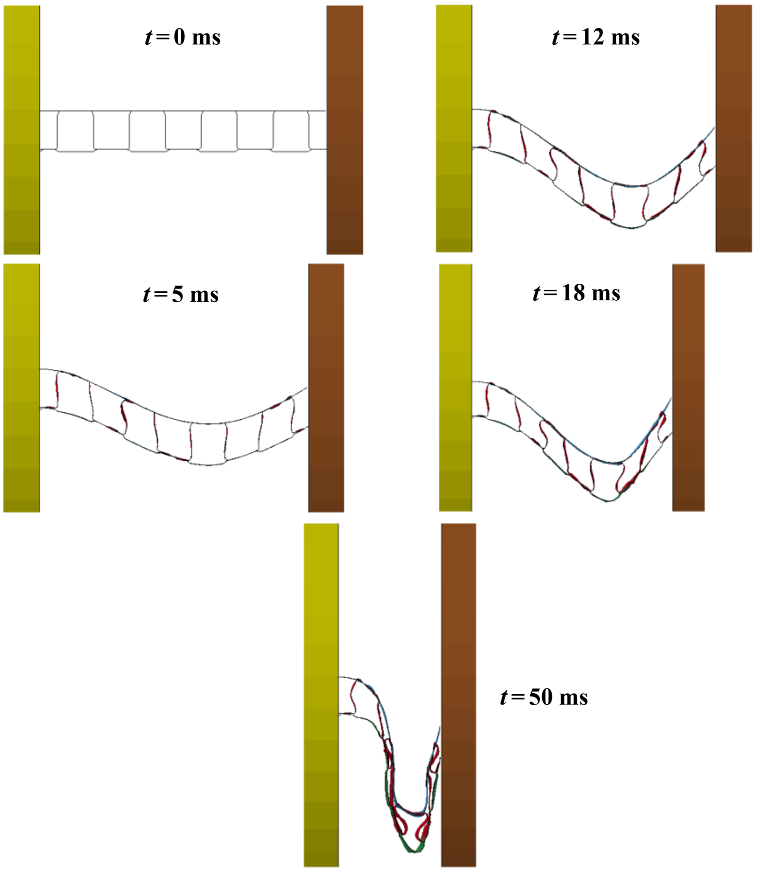

Fig. 13 - Deformed shape of the CFRP sandwich panel with square corrugated core due to impact response

3. Conclusions

Composite sandwich panels are widely used in engineering applications due to their lightweight and high strength/stiffness to weight ratio. In recent years, the use of these structures with the aim of creating crashworthy structures has attracted the interest of many researchers. In this regard, this research aims to study the energy absorption capabilities of rectangular composite sandwich panels with square, triangular and sinusoidal corrugated core using the LS-DYNA code. To verify the feasibility of the plan, first, computed results from the simulation model on aluminum sandwich panel has been compared and validated with the results obtained by the corresponding available experimental data. Then, a range of corrugated composite-based sandwich structures is simulated and the influence of core type on impact response of carbon-fabric/epoxy laminated panels has been examined under vertical and transverse load that contain the following results:

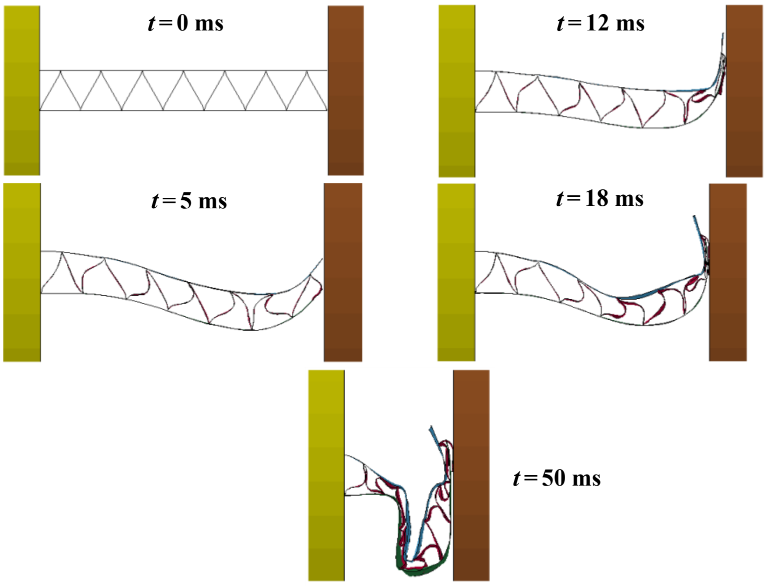

Fig. 14 - Deformed shape of the CFRP sandwich panel with triangular corrugated core due to impact response

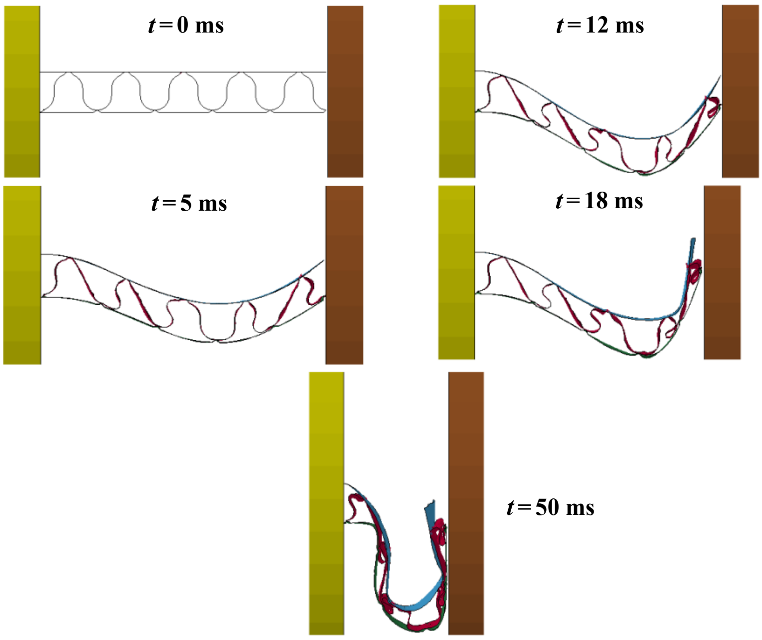

Fig. 15 - Deformed shape of the CFRP sandwich panel with sinusoidal corrugated core due to impact response

- The load-displacement results on aluminum and carbon-fabric/epoxy sandwich panels with corrugated core show that in same conditions, the required load for CFRP cores is higher than metal's one. This is expected and mainly due to the advantages and benefits of composite materials.
- The geometric configurations of the corrugated cores have a considerable effect on the crashworthy response and energy absorption performance of sandwich panels.
- The CFRP sandwich panel with the triangular corrugated core exhibited considerably higher loads and higher energy absorption capacity than the square and sinusoidal cores under vertical and transverse loads.

- The mean crushing load and the corresponding energy absorbing ability of these structures increases by changing the corrugation geometry. Considerable enhancement in the mean crushing load is obtained by using the triangular core compared to two other cores.
- Failure modes of the corrugated core composite sandwich panels are significantly influenced by the type of corrugated cores. The results show a significant capacity to extend and deform flexibly of sandwich panels based on the different geometric configuration of the core.

Generally, the numerical analysis revealed that composite sandwich panels with the triangular corrugated core are a suitable structure for engineering applications under impact loading.

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Conflicts of interest

The authors declare that they have no competing interests.

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References

[1] Torre, L., & Kenny, J. M. (2000). Impact testing and simulation of composite sandwich structures for civil transportation. Composite Structure, 50, 257–267.
[2] Yamashita, M., & Gotoh, M. (2005). Impact behavior of honeycomb structures with various cell specifications - numerical simulation and experiment. International Journal of Impact Engineering, 32, 618–630.
[3] Yokozeki, T., Takeda, S., Ogasawara, T., & Ishikawa, T. (2006). Mechanical properties of corrugated composites for candidate materials of flexible wing structures. Composites Part A: Applied Science and Manufacturing, 37, 1578–1586.
[4] Cote, F., Deshpande, V. S., Fleck, N. A., & Evans, A. G. (2006). The compressive and shear response of corrugated and diamond lattice materials. International Journal of Solids and Structures, 43, 6220–6242.
[5] Aktay, L., Johnson, A. F., & Kroplin, B. H. (2008). Numerical modeling of honeycomb core crush behavior. Engineering Fracture Mechanics, 75, 2616–2630.
[6] Bruno Castanie, Y. A., Bouvet, Ch., & Barrau, J. J. (2008). Core crush criterion to determine the strength of sandwich composite structures subjected to compression after impact. Composite Structures, 86, 243–250.
[7] Ruijun, G. E., Wang, B., Mou, C., & Zhou, Y. (2010). Deformation characteristics of corrugated composites for morphing wings. Frontiers of Mechanical Engineering in China, 5, 73–78.
[8] Biagi, R., & Bart-Smith, H. (2012). In-plane column response of metallic corrugated core sandwich panels. International Journal of Solids and Structures, 49, 3901–3914.
[9] Rejab, M. R. M., & Cantwell, W. J. (2013). The mechanical behaviour of corrugated-core sandwich panels. Composite Part B: Engineering, 47, 267–277.
[10] Kılıçaslan, C., Guden, M., Odaci, I. K., & Tasdemirci, A. (2013). The impact responses and the finite element modeling of layered trapezoidal corrugated aluminum core and aluminum sheet interlayer sandwich structure. Materials and Design, 46, 121–133.
[11] Hou, S., Zhao, S., Ren, L., Han, X., & Li, Q. (2013). Crashworthiness optimization of corrugated sandwich panels. Material and Design, 51, 1071–1084.
[12] Hou, Sh., Shu, Ch., Zhao, Sh., Liu, T., Han, X., & Li, Q. (2015). Experimental and numerical studies on multi-layered corrugated sandwich panels under crushing loading. Composite Structures, 126, 371–385.
[13] kilicaslan, C., Odaci, I. k., & Guden, M. (2016). Single- and double-layer aluminum corrugated core sandwiches under quasi-static and dynamic loadings. Journal of Sandwich Structures and Materials, 18, 667–692.
[14] Nouri Damghani, M., & Mohammadzadeh Gonabadi, A. (2016). Analytical and numerical study of foam-filled corrugated core sandwich panels under low velocity impact, Mechanics, Materials Science & Engineering Journal, 7,176–200.
[15] Boonkong, T., Shen, Y. O., Guan, Z. W., & Cantwell, W. J. (2016). The low velocity impact response of curvilinear-core sandwich structures. International Journal of Impact Engineering, 93, 28–38.
[16] Wang, H., Ramakrishnan, K. R., & Shankar, K. (2016). Experimental study of the medium velocity impact response of sandwich panels with different cores. Material and Design, 99, 68–82.
[17] Liu, T., & Turner, P. (2017). Dynamic compressive response of wrapped carbon fibre composite corrugated cores. Composite Structures, 165, 266–272.

[18] Nouri Damghani, M., & Mohammadzadeh Gonabadi, A. (2017). Numerical and experimental study of energy absorption in aluminum corrugated core sandwich panels by drop hammer test, Mechanics, Materials Science & Engineering, 8, 52–60.

[19] Rong, Y., Liu, J., Luo, W., & He, W. (2018). Effects of geometric configurations of corrugated cores on the local impact and planar compression of sandwich panels, Composite Part B: Engineering, 152, 324–335.

[20] Yan, L. L., Yu, B., Han, B., Zhang, Q. C., Lu, T. J., & Lu, B. H. (2020). Effects of aluminum foam filling on the low-velocity impact response of sandwich panels with corrugated cores. Journal of Sandwich Structures & Materials, 22, 929–947.

[21] Rong, Y., Luo, W., Liu, J., Shen, Zh., & He, W. (2020). Effect of core materials on the low-velocity impact behaviour of trapezoidal corrugated sandwich panels. International Journal of Crashworthiness, 25, 505–516.

[22] Jiang, H., Ren, Y., Gao, B., & Xiang, J. (2017). Numerical investigation on links between the stacking sequence and energy absorption characteristics of fabric and unidirectional composite sinusoidal plate. Composite Structures, 171, 382–402.

[23] Tomblin, J., Sherraden, J., Seneviratne, W., & Raju, K. S. (2002). A-basis and B-basis design allowables for epoxy-based prepreg toray T700SC-12K-50C/#2510 plain weave fabric. AGATE-WP3.3-033051-131.