MATERIALE PLASTICE
https://revmaterialeplastice.ro
https://doi.org/10.37358/Mat.Plast.1964

Multi-disciplinary Optimizations on Flexural Behavioural Effects on Various Advanced Aerospace Materials: A validated investigation

RAJ KUMAR GNANASEKARAN[1]*, BALASUBRAMANIAN SHANMUGAM[2], VIJAYANANDH RAJA[1], SAKTHIPANDI KATHIRESAN[3]
[1]Assistant Professor, Department of Aeronautical Engineering, Kumaraguru College of Technology, Coimbatore 641 049, Tamil Nadu, India
[2]Associate Professor, Department of Mechanical Engineering, Kumaraguru College of Technology, Coimbatore 641 049, Tamil Nadu, India
[3]Department of Physics, SRM TRP Engineering College, Triuchirappalli 621105, Tamil Nadu, India

Abstract: *Generally, the importance of bending test has been employed to analyse the induction level of internal resistance of its larger face size of the test specimens. Comparatively, stress induction is quite larger at the perpendicular face, where the bending load has been initiated its point of contact. Therefore the estimation of the location of maximum stress induction on bending test specimen must be analysed for the purpose to estimate the breaking point of test specimen, which supported a lot in the lifespan estimation of a component. In this work, three different composites are selected under the category of primary composites and thereby underwent the bending testing for the purpose of material refinement to tackle compressive load based applications. Three-Point flexural tests are conducted on the primary composites. The internal molecules bonds at peak loads are visualized through SEM approach. Thus, the perfect initial and boundary conditions for computational structural analyses are found out. Ansys Workbench is an advancement tool, which is used in this work for composite generation and structural simulations. All the computational tests are effectively executed with the help of advanced coupling facility between different working environments. Finally, the numerical results are compared with experimental results and then suitable material is based on high load withstand capacity. Additionally, the conventional analytical approaches are used to validate the flexural outcomes. Further, the advanced finite element analyses are expanded to advanced composites materials such as nano-composites, shape memory alloys based composites, and sandwich composites. From the above all studies, the superior material is finalized based on the outcomes of this multi-inclusive investigations.*

Keywords: *composite materials, flexural loads, Sandwich composite, shape memory alloys, nanocomposite, rectangular beam structure*

1.Introduction

In recent year, the fundamental studies on advances composites materials have been emerged essentially to validate and ensembles to outline the application of those composites. Generally, the bending load on the horizontal member creates the fundamental outputs of deflection and slope in the vertical direction of the test specimen. Because of this geometrical nature, these horizontal members can able to withstand perfectly at axial loading conditions. While come to lateral loading, the possibility of failure occurrence is very high because of its geometrical orientation. Therefore, the bending load and its effects have to be watched carefully in order to provide high lifetime to the member. To tackle this complicated bending behaviour, the preliminary studies are mandatory to obtain the critical conditions on the materials which provide the handling methodology under peak loading environment. Henceforth, this comparative work is aimed to clearly analyze the flexural property of the advanced materials through different complicated methodologies. In which the principal composite materials such as glass fiber

*email: rajkumar.g.aeu@kct.ac.in

reinforced polymer (GFRP), kevlar fiber reinforced polymer (KFRP), and carbon fiber reinforced polymer (CFRP) are contributed the vital role in the preliminary calculations and its validations. The standard flexural stress derivative, conventional deflection derivative, flexural test machine, scanning electron microscope (SEM) images and finite element analyses (FEA) are greatly involved in the estimation of structural parameters. Through verification and validation, the reliability of the structural outcomes are confirmed and thus the FEA is extended to compute the flexural behaviour of advanced materials such as shape memory alloys based composites, sandwich composites, and nanocomposites [1].

The targeted applications of this work for the selected samples are mostly related to aerospace, marine and automobile filed. To fulfil the structural requirements of specified applications, the structural analyses on these advanced materials need to be carried out. Comparatively, the composite materials and its depended materials are more capable to engage the dynamic structural loads of complicated and emerging applications. Under structural perspective, different loads are available but tensile loads, flexural loads, and impact loads plays predominant role. In this work, the bending test is taken for the comparative studies on various advanced GFRP, KFRP and CFRP composite materials and thereby the ultimate and fracture stresses are estimated. The reason involved in the selection of bending load is, it can provide abnormal environmental conditions on the test specimen. The definition of abnormal is the structural output effects on test specimen are created in a drastic manner with respect to normal input conditions. In general, the beam elements are majorly affected from bending load, which is predominantly acting in the lateral direction to the beam element. The beam elements are geometrically oriented in the longitudinal but due to the abnormal lateral loading the deflection has been developed in high manner. Because of these issues, the probability of failure occurrence in the lateral direction is quite high. Therefore, the detailed study about the bending load and its effect on beam element are mandatory to get the details of ultimate stress, facture point, allowable stress, etc., also to attain high lifetime of a beam elements on real-time implemented areas, by avoiding the failure fractures. In the aerospace and marine applications, the beam elements are used predominantly in the primary devices such as wing, propeller, hydro rotor, etc. Hence, the rupture study of bending test on beam element can support a lot in the emerging engineering applications [1].

C. Elanchezhian et al., [1] investigated the tensile, flexural and impact properties of GFRP and CFRP materials through Charpy test machine under the guidance of ASTM D256 experimentally. In which, the authors were used epoxy resin as primary load withstanding adhesive agent also used the hand layup method based construction. Especially, the flexural test used in this article was more supported to execute the current research work, in which working environments, the details about experimental set-up, dimensions of the test specimens, were predominantly supported in this current research. Finally, the ultimate flexural load was obtained as 1785 N for CFRP material and 475 N for GFRP material. Tao Yang [2] et al., clearly analyzed the flexural load and its fatigue properties on CFRP materials with the support of standard experimental set-ups. In which, the CFRP composite’s laminates were prepared through prepreg based fiber and epoxy resin based matrix. The flexural test of this study was conducted in quasi static based three-point flexural test machine, wherein three samples were underwent the bending tests. The ultimate flexural load, ultimate flexural stress, maximum deflection, and flexural modulus were obtained. In addition, the maximum flexural load was obtained as 1000.789 N, maximum flexural stress was found out as 1097.866 MPa and the maximum deflection at mid-span was determined as 8.912 mm. Dominik Banat [3] numerically tested the bending properties on various rectangular beams, which were made up of both CFRP and GFRP with the support of ANSYS APDL. In which the authors were used the SOLID185 and SHELL181 elements with eight layered composite laminates. The anisotropic properties were also correctly provided to the appropriate composite materials. The bending loads were provided between the ranges of1 to 100 kN and the corresponding deflections were recorded, which were varied from 1 to 60 mm. Through this investigation, the reactions of composite rectangular beam at various peak loading conditions have been noted and thereby considered in the current investigations. Prashanth Turla [4] et al., experimentally studied the flexural properties on CFRP, GFRP and hybrid composites in accordance with ASTM D790. In which, Formasa T6 6K based carbon fiber was used as primary agent in CFRP and E-Glass 12000 Tex was used as reinforcement element in GFRP, LY 556 depended Epoxy resin was used as adhesive elements for all the composites and finally 5200 specified Hardener was also added in these preparations. In this work, filament winding machine, hand layup based manufacturing process, and three-point flexural test machine, were employed for construction and flexural testing respectively. Finally, the authors were obtained the ultimate flexural strength and flexural loads for all the aforesaid composites: The maximum flexural stresses and loads were estimated: 475.27 MPa and 804 N, 304.81 MPa and 500.4 N, 542.94 MPa and 850.6 N for the GFRP, CFRP and hybrid composite respectively. Suresh et al., [5] enhanced the mechanical properties of CFRP with additions of graphite, in which the authors were tested the three important mechanical properties such as flexural properties, impact characteristics, and tensile properties. Three samples were prepared and thereby underwent the abovementioned mechanical tests, wherein first sample was a pure CFRP based test specimen, second sample was a CFRP with 5% graphite paper and third sample was a CFRP with 10% of graphite paper. While come to composite's preparation, the hand layup and compression moulding processes were involved, in which the bi-directional based 3K Carbon - 200 Gsm fibers were used as reinforcement, epoxy resin was used as adhesive, and MEKP accelerator was used in these comparative analyses. Finally, the flexural outputs were obtained following as: 115 MPa and 2.95 mm, 140 MPa and 2.6 mm, 165 MPa and 3.1 mm for 0 %, 5% and 10 % respectively. A. F. Ávila [6] et al., tested the bending performance of carbon fiber based nanocomposite with graphene and four kind of samples were prepared such as CFRP with a different weight percentage of the graphene such as 0, 0.5, 0.1 and1.5%. Among these graphene CFRP nanocomposites, CFRP with 0.5% of graphene was performed well in the perspective high resistivity towards bending stress, i.e., 1200 MPa. At the sample preparation stage, 12 layers were used for the laminate construction, in which woven carbon fiber was used as reinforcement and DGBA based epoxy resin with HY956 was incorporated to act as an adhesive element and thus hand layup process was used for this construction of nanocomposite. Hassan Ijaz [7] et al numerically analyzed the flexural properties of sandwich composites and thereby validated the FEA results with previous completed experimental works, in which polypropylene honeycomb and GFRP were played predominant role in this comparative investigation. In this FEA analysis, 3D brick elements were used in the discretization process and thereby there-point, four-point flexural analyses were executed on the sandwich composite materials. In this work, CAST3M based CEA software was used for the computational simulation over these sandwich composites and the validations were executed with the support of literature survey.

In this multi-disciplinary optimization, advanced computational structural analyses are predominantly involved in the structural optimization. Because of the working nature of computational simulations, the validations are principally needed in this optimization so, in this work, three point bending test and FEM are planned to impose. The ultimate aim of this validation is to corroborate the computational structural analysis with the help of standard analytical calculation and experimental testing. Comparatively, the reliable output attainment is quite complicated in computational simulation compared than other approaches for complicated applications. The boundary and initial conditions of this computational works are fully relays on this experimental outcome and literature survey observations. Totally, two different validation studies are planned to conduct in this present investigation that is, validation of/through experimental results and validation through analytical results [8].

2. Materials and methods

2.1. Experimental test results and discussions

The bending test contributes a great role in the ultimate property estimation on composite materials. The experimental tests are conducted with the help of three point bend fixture test machine. The complete representations of test specimens are revealing in Figures 1 to 3. The test specimens such as GFRP and CFRP based platforms are constructed as per ASTM D7264 and the dimensional details are span is 100 mm, breadth is 20 mm, and the width is 7 mm. Totally, twenty bi-directional layers are used in the test specimen construction, in that carbon, glass fibers plays a complete role as reinforcing element and epoxy resin contributes a top role as adhesive element [9]. The combined views of both glass and carbon fibers based composite test specimens are shows in Figure 2. Figure 3 ha been used to reveal the loaded test specimen on the three-point flexural test machine.

Figure 1. Weight estimation of Carbon fiber for fabrication

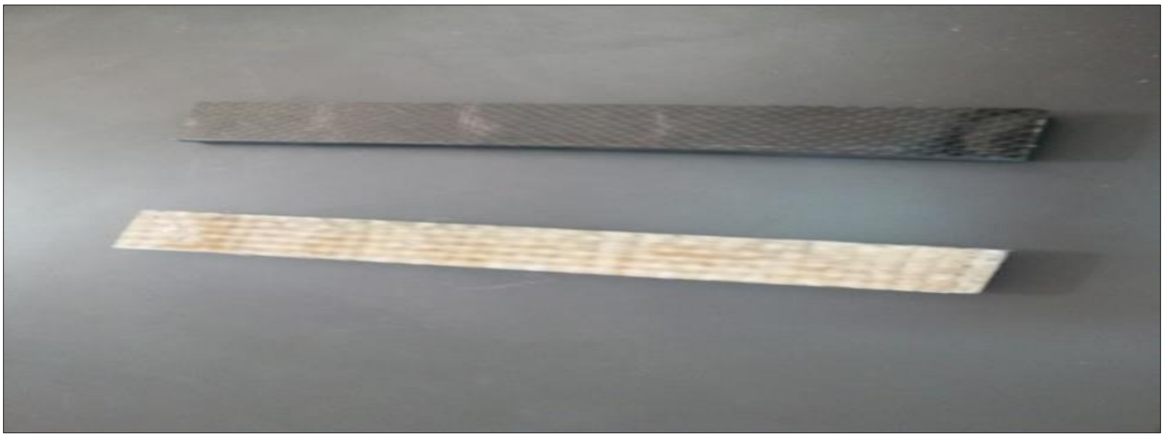


Figure 2. The top view of developed composite test specimens

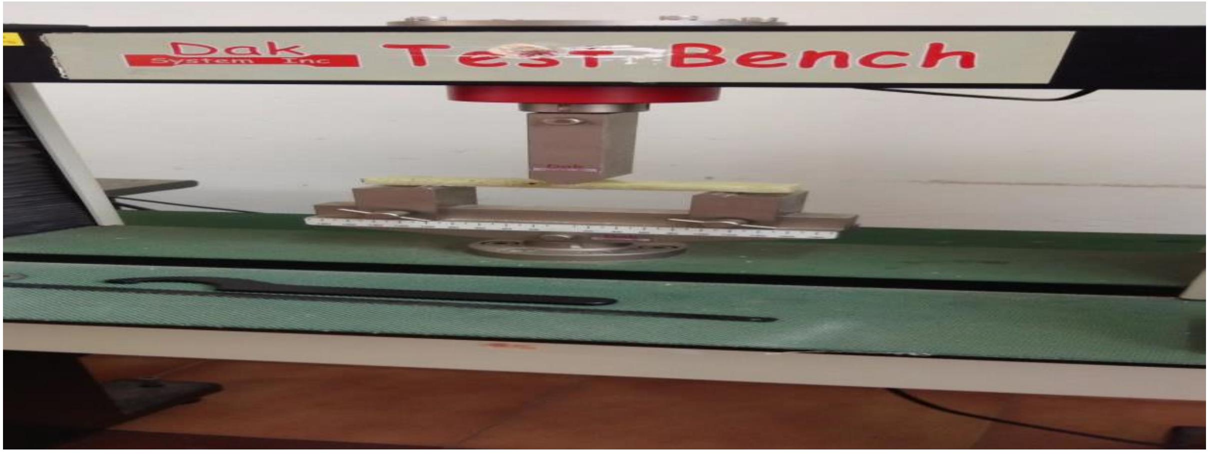


Figure 3. A typical front view of test machine loaded with test specimen

Experimental tests are conducted as per the conventional procedures and environments for different composite materials. Two different composite families are underwent flexural test through three point test methods and thereby the results are captured. The entire results are in Figures 4 to 9. Apart from the bending test results, other characterization such as stress versus elongation graph, frictional stress, deformation, the scanning electron microscope are also carried out to understand the molecular level modification and effect at the peak loading conditions. The SEM image of CFRP is revealed in Figure 6 and the SEM image of GFRP is revealed in Figure 9.

2.1.1.Bending test results for CFRP

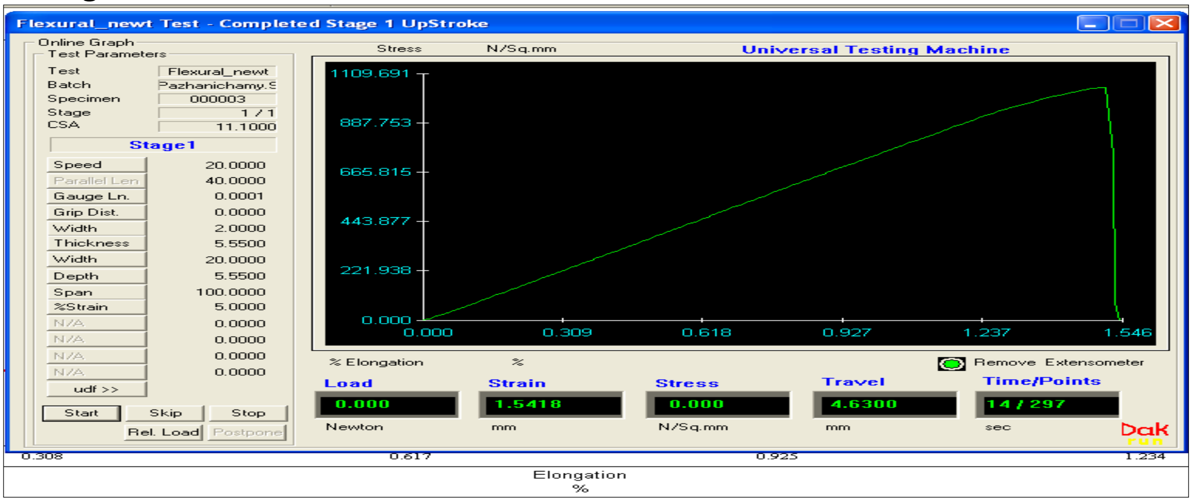
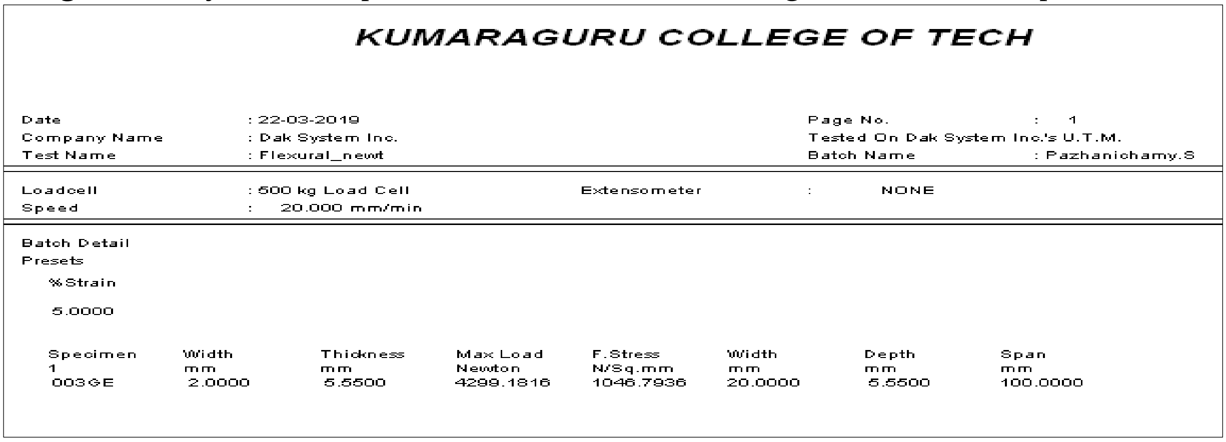


Figure 4. A systematic representation of stress versus elongation for a CFRP specimen



KUMARAGURU COLLEGE OF TECH

Date : 22-03-2019 Page No. : 1
Company Name : Dak System Inc. Tested On Dak System Inc.'s U.T.M.
Test Name : Flexural_newt Batch Name : Pazhanichamy.S

Loadcell : 500 kg Load Cell Extensometer : NONE
Speed : 20.000 mm/min

Batch Detail
Presets
%Strain
5.0000

Specimen	Width	Thickness	Max Load	F.Stress	Width	Depth	Span
1	mm	mm	Newton	N/Sq.mm	mm	mm	mm
003GE	2.0000	5.5500	4299.1816	1046.7936	20.0000	5.5500	100.0000

Figure 5. The final experimental outcomes of a carbon specimen under bending test

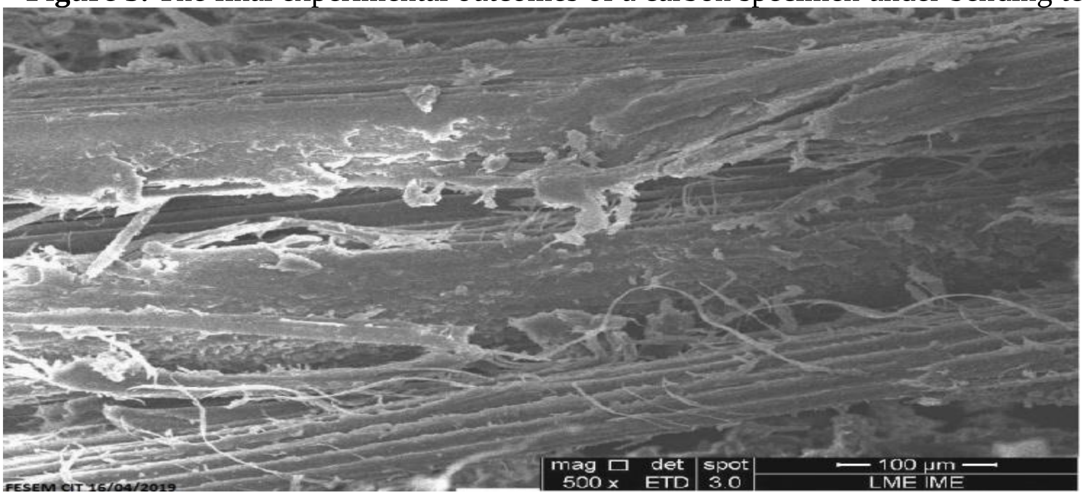


Figure 6. A distinctive projection of internal structure of a CFRP under bending test

2.1.2.Bending test results for GFRP

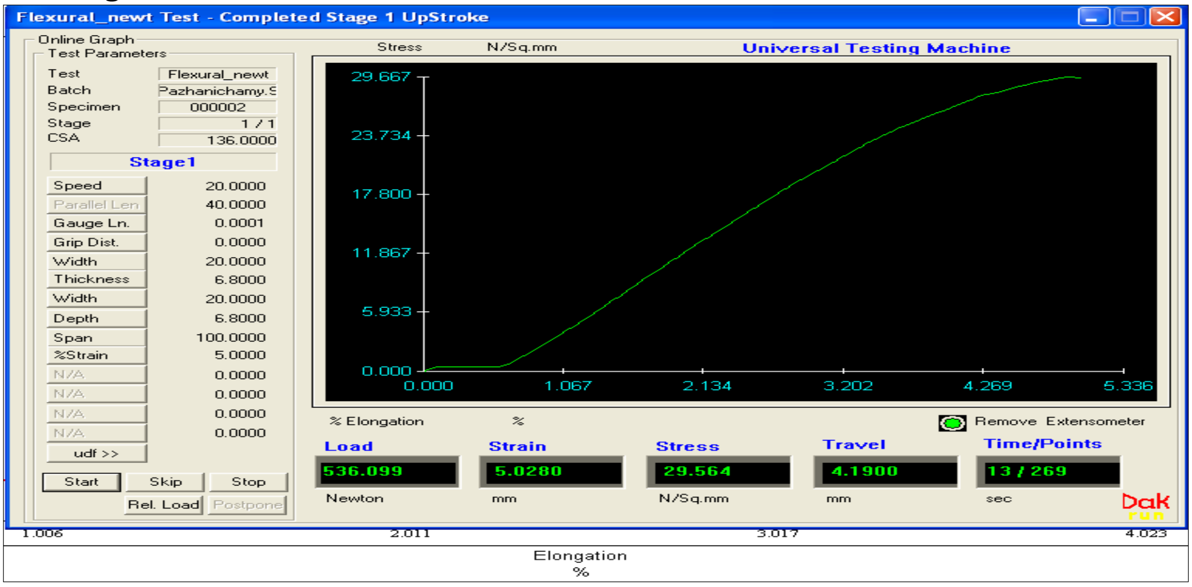


Figure 7. A systematic representation of stress versus elongation for a GFRP specimen

KUMARAGURU COLLEGE OF TECH

Date	: 22-03-2019	Page No.	: 1
Company Name	: Dak System Inc.	Tested On Dak System Inc.'s U.T.M.	
Test Name	: Flexural_newt	Batch Name	: Pazhanichamy.S

Loadcell	: 500 kg Load Cell	Extensometer	: NONE
Speed	: 20.000 mm/min		

Batch Detail
Presets
%Strain
5.0000

Specimen 1	Width mm	Thickness mm	Max Load Newton	F.Stress N/Sq.mm	Width mm	Depth mm	Span mm
002GE	20.0000	6.8000	537.0891	29.6189	20.0000	6.8000	100.0000

Figure 8. The final experimental outcomes of a glass specimen under bending test

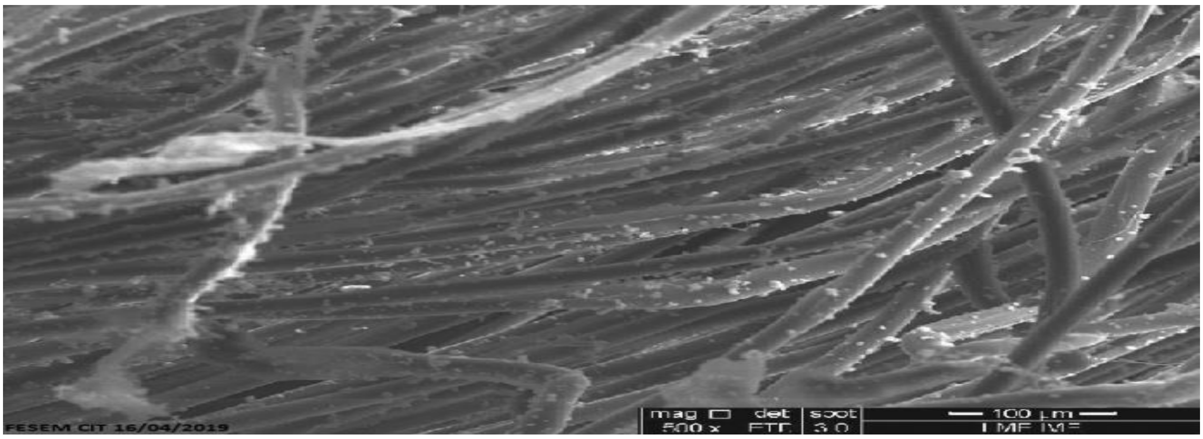


Figure 9. A characteristic projection of internal structure of a GFRP under bending test

2.1.2.1. Validation – I

In this validation study, GFRP plays a vital role as base material, in which the ultimate structural parameters are estimated and verified between experimental results and conventional analytical formulae, which are given in the Eq. (1) [1-10]. From the huge calculations, it has been concluded that the predominant contribution in the resistance of the flexural load is dependent on in-plane modulus. Therefore, the same modulus is used in this equation. The comparative results obtained for this validation are given in the Table 1. The percentage of error is calculated as 00.011%.

$$F = \frac{EI}{L^3} * 48 * (y_{max}) \quad (1)$$

$$537.0891 = \frac{4.966 * 10^9 * 0.020 * (0.0068)^3}{0.1^3} * 4 * (y_{max}) \Rightarrow (y_{max}) = 4.3 \text{ mm}$$

Table 1. Comparative data of experimental test and analytical approach of GFRP

Material Name	Structural Output	Experimental Result	Analytical Results
GFRP	Maximum deflection (m)	0.0042	0.0043

2.2.Computational structural analyses [FEA] – methodology – II

Computational structural analyses are executed through FEA a tool, which is fully dependent on preloaded numerical codes. In this work, ANSYS Workbench based computational studies are involved, wherein composite preparation and structural analysis tools are incomparably contributed. Before entering the computational outputs, the formulations of this flexural investigation are very important. The construction of a computational model, the generation of a finite element model, the explanation of analyses imposed on the computational model, and the boundary conditions implemented on the finite element model are the important processes comprised in this multi-inclusive investigation [11].

2.2.1.Numerical model

The computational model is the fundamental platform of the modern research. In simple, the conceptual design of the object is called as numerical model, in which the three dimensional data must be evaluated in a correct as well as good manner. While in the case of fundamental property investigation, the ASTM provides the uniform design parameters to support the construction of numerical model based on its nature of the test and its material’s properties. The nature of this work is aimed to analyze the flexural property of various composite materials in multi-disciplinary perspectives [12-15]. Therefore, this work is finalized to use the design parameters from ASTM D7264 where the dimensions are length span as 100 m, width as 20 mm, and thickness as 7 mm. To execute the multi-dimensional analyses on fibers of the composites, the number of layers are restricted with 20.

2.2.2.Discretization

Computationally, the discretization is the conversion process from physical model into finite element model, wherein the points and lines of physical models are converted into nodes and elements of the FE models for computation purpose. Therefore, to resemble the original physical model in a perfect manner, the fine discretization process is very important. Hence, the variety of mesh generation processes have been emerging, in which un-structural, structural, 3-D, 2-D elements are importantly plays a vital role. This work uses the structural 3-D brick elements for the construction of discretization. The quality of these mesh constructions attained at the above level of 90%, which is because of the implementation of structural formation. Figure 10 is reveals the discretized structure of specimen.

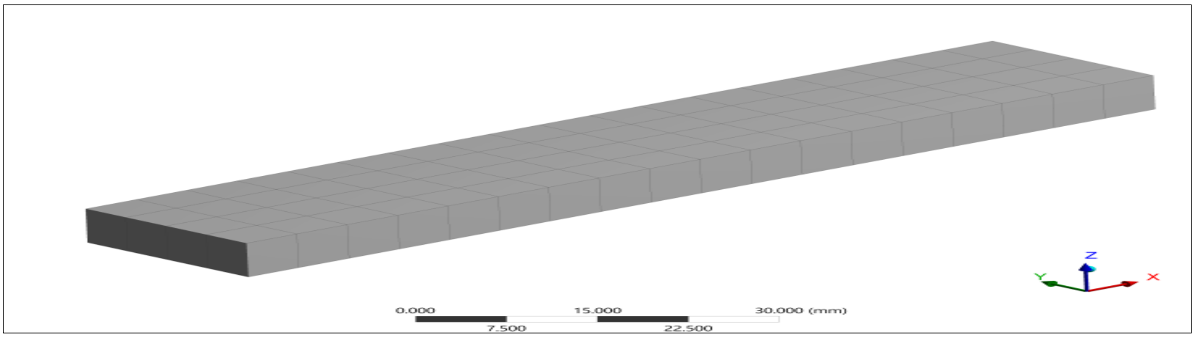


Figure 10. An isometric view of discretized structural grids

2.2.3.Boundary conditions

The boundary conditions have been used for the initialization process of computational problems through workstations. The proper boundary conditions are those that have the capability to perfectly demonstrate the computational simulation. In FEA, the major boundary conditions are supports given to the test specimen, external loads acts on the object, environmental conditions such as thermal loads, vibrational loads, etc. Apart from these boundary conditions, the principal initial conditions are additionally contribute to the perfect execution of computational simulation, which are orthogonal properties of all the composite materials, mechanical properties of core materials (Foam, Honeycomb, SWCNTs, MWCNTs, shape memory alloys), mechanical and general properties of matrix, geometrical properties of the test specimen. In this work, the roller support is given at both the bottom edges of the rectangular composite structure, and the concentrated load is projected at the mid span of the simply supported composite beams. The properties of all the fibers, core and materials are collected from the standard literature survey [16 - 20] and material library of the FEA tool. The entire details of implementation of boundary conditions are revealed in Figure 11.

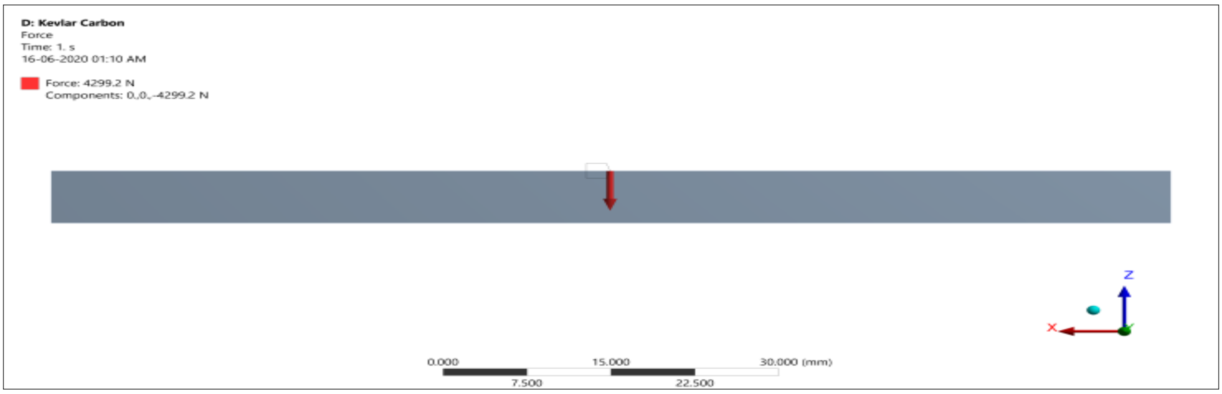


Figure 11. A typical front view of loaded test specimen - boundary condition

2.2.4.Governing equations

In general, mathematical modeling consists of governing equations defined in a field and boundary conditions provided at the boundaries of the area. The composites are the primary platform which has two more important equations need to be included in order to provide required and acceptable outputs. The important equations are 3-D Hooke's law equation and strain-displacement relationships. Finally, fifteen sub-equations are predominantly used in these FEA based stress calculations, which are force balance equations that have been derived from second law of Newton, stress versus strains relationships developed from various conventional approaches, and strain versus deformation relations are generated from the conventional approaches [20].

2.2.5.FEA results for the purpose of validations

Under this section, the primary composites of this work such as CFRP, GFRP, and KFRP are tested under both ultimate loading conditions such as 4299.1866 N and 537.0891 N. The deformation analysis of epoxy with carbon woven wet (230 GPa) based CFRP composite is reveals in Figure 12 and the stress variations on the E-glass woven fiber with epoxy resin based composite is shows in Figure 13.

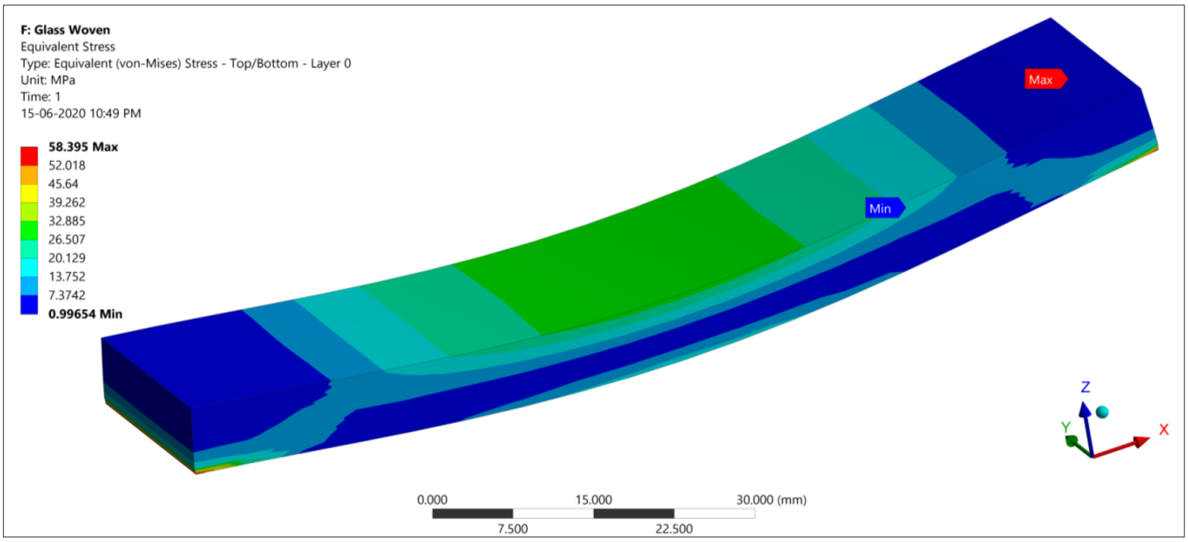


Figure 12. Deformed structure of CFRP composite specimen

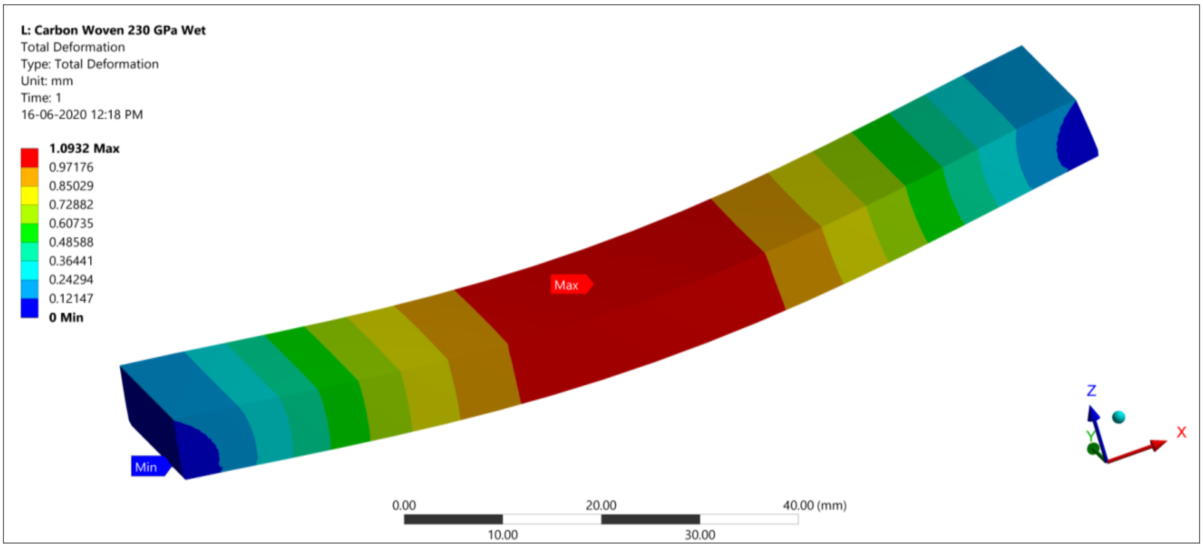


Figure 13. Distribution of Equivalent Stress of GFRP composite test specimen

Similarly, all the other primary composites were underwent the flexural test and thus the comparative results were revealed in the Figures 14 to 23

2.2.6.Validations of the imposed methodologies

In this entire work, three important validations are carried out, in which the conventional analytical formulae, FEM based theoretical approach and experimental tests are involved. Through these validations, the targeted outputs of this work such as the provision of ultimate stress and deformations of the various advanced composite materials are furthermore fine tuned. The confirmed ultimate outputs such as various stresses, strain energy, strains, and deformations are more usable in the real-time composite implemented applications such as aerospace, and marine. The ultimate outputs are clearly gives the view about working conditional parameters and thereby the lifetime of an implemented components may have the chance to increase. The CFRP based composite is involved as principal material, wherein exactly carbon woven (230 GPa) wet is used as reinforcement and epoxy resin is used as adhesive bond. The standard FEM based analytical result with the only consideration of in-plane modulus of CFRP is compared with deflection of computational outcome. The fracture flexural load extracted from experimental test and the design parameters of test specimens are obtained from ASTM D7264. The validation procedures were listed below: For CFRP, At Element – I,

$F_1 = \frac{-W}{2} = \frac{-4299.1816}{2} = -2149.5908$ N ; $M_1 = \frac{-WL}{8} = \frac{-4299.1816*0.1}{8} = -53.73977$ N.m ; $F_2 = \frac{-W}{2} = \frac{-4299.1816}{2} = -2149.5908$ N ; $M_2 = \frac{WL}{8} = \frac{4299.1816*0.1}{8} = 53.73977$ N.m; E = 59.16 GPa, $I = \frac{b*(t)^3}{12} = 2.8492313 * 10^{-10} m^4$, Length of the element-1 is equal to 0.05 m.

$$\begin{Bmatrix} F_1 \\ M_1 \\ F_2 \\ M_2 \end{Bmatrix} = \frac{EI}{L^3} * \begin{bmatrix} 12 & 6L & -12 & 6L \\ 6L & 4L^2 & -6L & 2L^2 \\ -12 & -6L & 12 & -6L \\ 6L & 2L^2 & -6L & 4L^2 \end{bmatrix} \begin{Bmatrix} y_1 \\ \theta_1 \\ y_2 \\ \theta_2 \end{Bmatrix} \quad (2)$$

$$\begin{Bmatrix} -2149.5908 \\ -53.73977 \\ -2149.5908 \\ 53.73977 \end{Bmatrix} = 168560.52075 * \begin{bmatrix} 12 & 0.3 & -12 & 0.3 \\ 0.3 & 0.01 & -0.3 & 0.005 \\ -12 & -0.3 & 12 & -0.3 \\ 0.3 & 0.005 & -0.3 & 0.01 \end{bmatrix} \begin{Bmatrix} y_1 \\ \theta_1 \\ y_2 \\ \theta_2 \end{Bmatrix}$$

At Element – II,

$F_2 = \frac{-W}{2} = \frac{-4299.1816}{2} = -2149.5908$ N ; $M_2 = \frac{-WL}{8} = \frac{-4299.1816*0.1}{8} = -53.73977$ N.m; $F_3 = \frac{-W}{2} = \frac{-4299.1816}{2} = -2149.5908$ N; $M_3 = \frac{WL}{8} = \frac{4299.1816*0.1}{8} = 53.73977$ N.m; Length of the element-2 is equal to 0.05 m,

$$\begin{Bmatrix} F_2 \\ M_2 \\ F_3 \\ M_3 \end{Bmatrix} = \frac{EI}{L^3} * \begin{bmatrix} 12 & 6L & -12 & 6L \\ 6L & 4L^2 & -6L & 2L^2 \\ -12 & -6L & 12 & -6L \\ 6L & 2L^2 & -6L & 4L^2 \end{bmatrix} \begin{Bmatrix} y_2 \\ \theta_2 \\ y_3 \\ \theta_3 \end{Bmatrix} \quad (3)$$

$$\begin{Bmatrix} -2149.5908 \\ -53.73977 \\ -2149.5908 \\ 53.73977 \end{Bmatrix} = 168560.52075 * \begin{bmatrix} 12 & 0.3 & -12 & 0.3 \\ 0.3 & 0.01 & -0.3 & 0.005 \\ -12 & -0.3 & 12 & -0.3 \\ 0.3 & 0.005 & -0.3 & 0.01 \end{bmatrix} \begin{Bmatrix} y_2 \\ \theta_2 \\ y_3 \\ \theta_3 \end{Bmatrix}$$

The FEM equation is,

$$\begin{Bmatrix} -2149.5908 \\ -53.73977 \\ -4299.1816 \\ 0 \\ -2149.5908 \\ 53.73977 \end{Bmatrix} = 168560.52075 * \begin{bmatrix} 12 & 0.3 & -12 & 0.3 & 0 & 0 \\ 0.3 & 0.01 & -0.3 & 0.005 & 0 & 0 \\ -12 & -0.3 & 24 & 0 & -12 & 0.3 \\ 0.3 & 0.005 & 0 & 0.02 & -0.3 & 0.005 \\ 0 & 0 & -12 & 0.3 & 12 & -0.3 \\ 0 & 0 & 0.3 & 0.005 & -0.3 & 0.01 \end{bmatrix} \begin{Bmatrix} y_1 \\ \theta_1 \\ y_2 \\ \theta_2 \\ y_3 \\ \theta_3 \end{Bmatrix}$$

Boundary conditions are, $y_1 = y_3 = 0$; The finalized displacement equations, in which deflection and slope are played a predominant role,

$$1685.605521\theta_1 - 50568.1562\theta_3 y_2 + 842.8026604\theta_2 + 0\theta_3 = -53.7398$$
$$-50568.1562\theta_3\theta_1 + 4045452.5y_2 + 0\theta_2 + 50568.1562\theta_3 = 4299.1816$$
$$842.8026604\theta_1 + 0 * y_2 + 3371.210442\theta_2 + 842.802604\theta_3 = 0$$
$$0 * \theta_1 - 50568.1562y_2 + 842.802604\theta_2 + 1685.605521\theta_3 = 53.7398$$

By simplifying the above equation, one can get the following results are:

$$y_1 = 0;\ \theta_1 = -1.26094 * 10^{-10}\text{rad};\ y_2 = -0.00106272\ \text{m};\ \theta_2 = 5.20955 * 10^{-19}\text{rad};\ y_3 = 0;\ \theta_3 = 1.26094 * 10^{-10}\text{rad}$$

Thus by the validated FEM, this authors proposed the following equation for the estimation of ultimate flexural load in flexural test based numerical simulation as well as analytical estimations for all kind of materials. In which, Young's Modulus (E) is difficult parameter for this equation therefore, the explanation of the use of "E" is important, which has been completed with the support of in-plane modulus.

$$\text{Ultimate Flexural Load (F)} = \frac{EI}{L^3} * 24 * (y_{max}) \qquad (4)$$

The maximum deflection based investigation executed in the first validation and the percentage of error is obtained as 2.78 %. The comparative analysis of theoretical calculation and FEA structural data were listed in Table 2.

Table 2. Comparative analysis of Theoretical calculation and FEA results

Material Name	Structural Output	Analytical FEM result	Computational FEA result
CFRP	Maximum deflection (m)	0.00106	0.00109

Next, the maximum deflection induced on the beam elements is considered as primary parameter of this validation. The predominant approaches contributed are three-point bending test and FEA simulation results. The comprehensive results are listed in Table 3.

Table 3. Comparative analysis of Experimental test and computational simulations

Material Name	Structural Output	Experimental result	FEA simulation result
CFRP	Maximum deflection (m)	0.0015	0.0011

Most of the error percentages are attained within the acceptable limit. Therefore, it is strongly proved that computational procedures involved in the FEA simulations are correct and that can able to provide high robustness in FEA outcomes. Thus, the same procedures are extended to other advanced composites.

3. Results and discussions

The computational structural analyses are carried out with the full support of aforementioned boundary conditions. This computational work contained two different cases, one among its primary composite materials based numerical simulation and other is advanced composite materials based numerical simulation. Under primary material, the three predominant fibers such as glass fiber, carbon fiber and kevlar fiber and its classifications are included and thus, totally 11 materials are analyzed for verification and validations. Under the category of advanced composite materials, the nanocomposites, shape memory alloy based composites and sandwich based composites are imposed and its classifications are analyzed for the purpose of multi-inclusive investigation. After the successful completion of structural investigations on primary composites and its validations, the structural investigations on advanced composite materials are analysed with the same computational procedures. Under sandwich composites, the honeycomb (HCB), PVC foam, and SAN foam are used as major core elements. In shape memory alloy based composites, the NiTi, Cu-Al-Ni (CAN), and Cu-Zn-Al (CZA) are used as major core elements. Under Nanocomposites, the single walled carbon nanotube (SWCNT), and multi walled carbon nanotube (MWCNT) are imposed as major mixtures. In this extensive investigation, the deformation and stress analyses are involved as major analysing parameters and thereby the suitable flexural resist material is shortlisted.

3.1. Primary composite materials (Comparative Numerical results of CFRP and KFRP)

Firstly, the comprehensive analyses are dealt for CFRP and KFRP composites, in which the following parameters involved in the selection of best composites under the flexural load of 4299.1816 N are deformation, shear, normal and equivalent stresses. The comparative results were revealed in Figures 14 and 15.

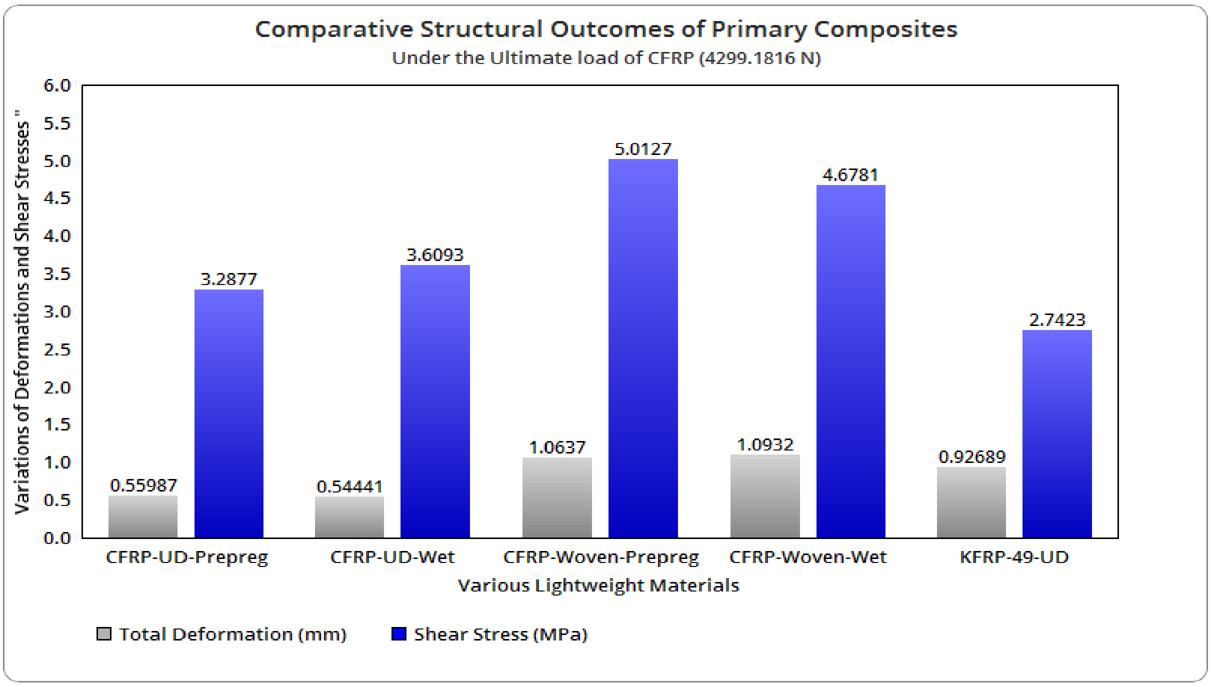


Figure 14. Comparative structural primary outcomes of primary composites

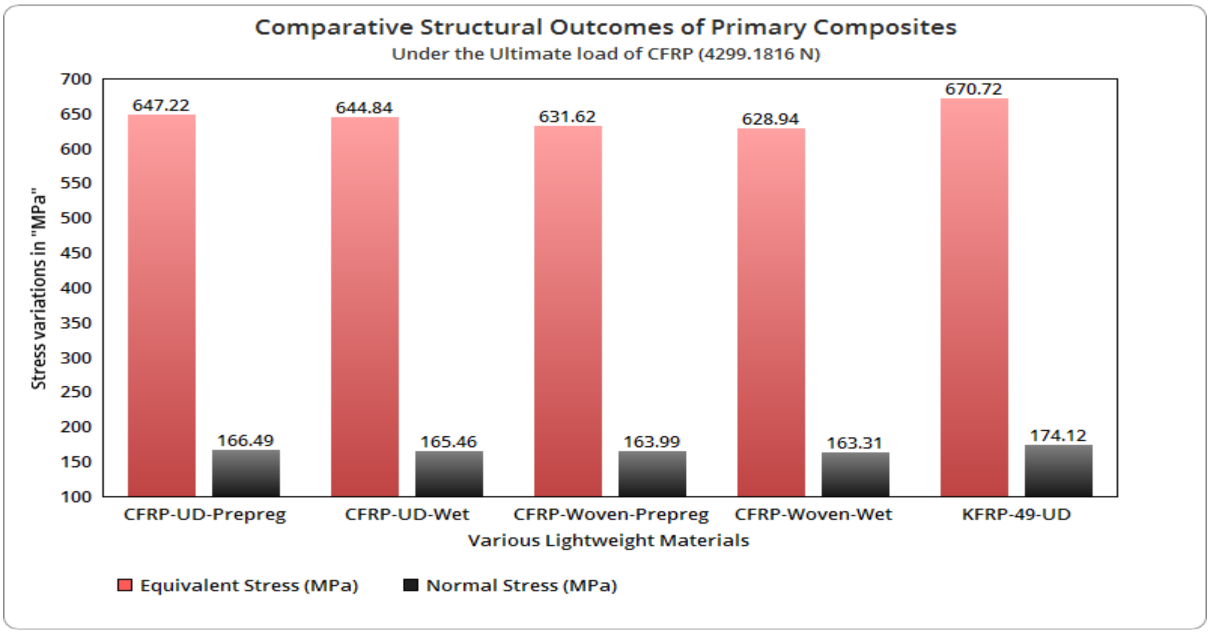


Figure 15. Comparative stresses outcomes of primary composites

From the primary results, it is understood that Epoxy-Carbon-Woven family based composites are reacted less stress inductions thus the Epoxy-Carbon-Woven-Wet and Epoxy-Carbon-Woven-Prepreg are picked as best performers.

3.2. Primary composite materials (Comparative numerical results of GFRP and KFRP)

Secondly, the comparative structural investigations are executed for both GFRP and KFRP under the flexural load of 537.0891 N. All the primary aerospace based glass fibers and kevlar fiber are implemented in this comparative analysis and the comparative results are reveals in Figures 16 and 17.

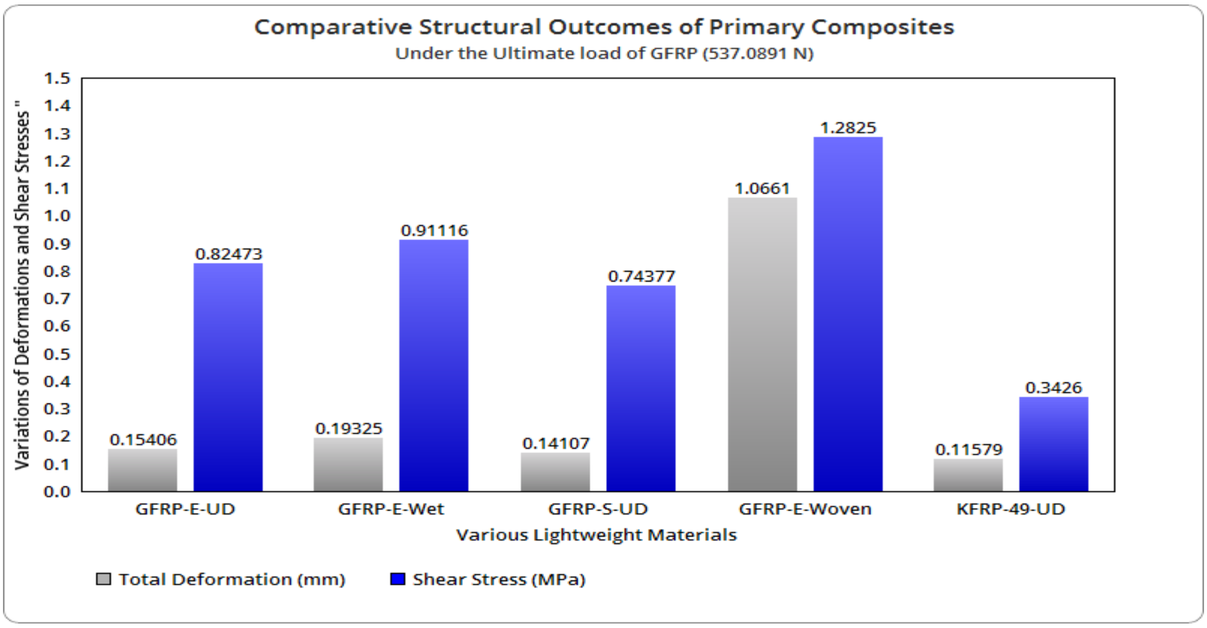


Figure 16. Comparative structural primary outcomes of primary composites

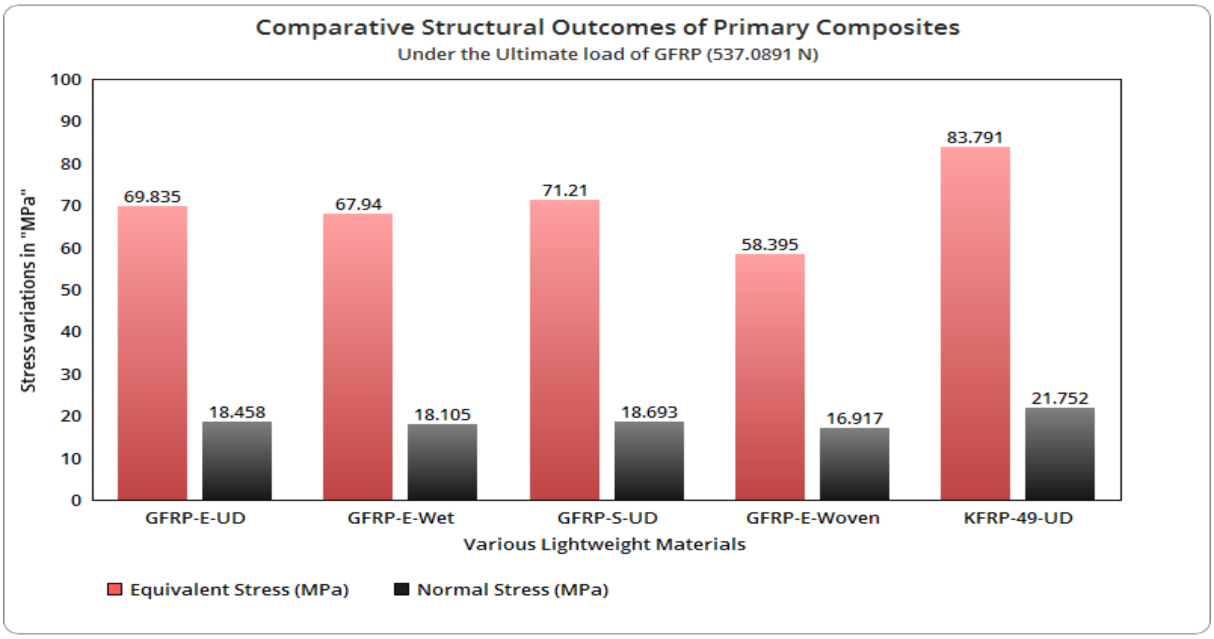


Figure 17. Comparative stresses outcomes of primary composites

From this investigation, it has been conferred that Epoxy-E-Glass based GFRP composites are reacted better than other composites. Also, recommended that Epoxy-E-Glass-UD fiber based composite is most suitable for high stiffness based real-time applications and Epoxy-E-Glass-Woven based GFRP composite is fit to provide to low internal stresses than others.

3.3. Advanced composite materials

In the advanced materials, two kinds of structural outputs are considered for the comparison, which are deformation analysis and stress examination under different ultimate flexural loading conditions.

3.3.1. Comparative computational results of CFRP and its associate composites

The carbon fiber interlinked advanced fibers such as sandwich cores, shape memory alloys based metals, and carbon nanotubes based layers are imposed and thereby the carbon fiber based enhanced composites are formed. The created just now mentioned advanced composites are implemented the various computational tests and thereby the comparative outcomes are reveals in Figures 18 to 20.

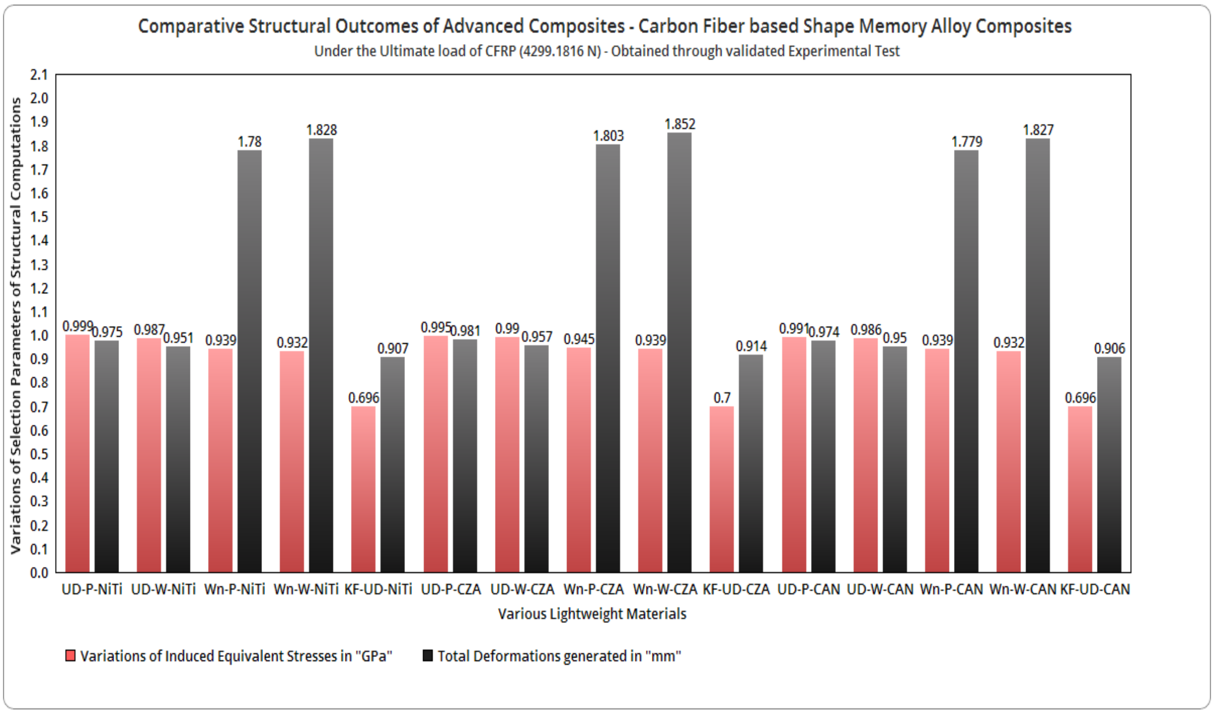


Figure 18. Comparative structural outcomes of shape memory alloy based CFRP composites

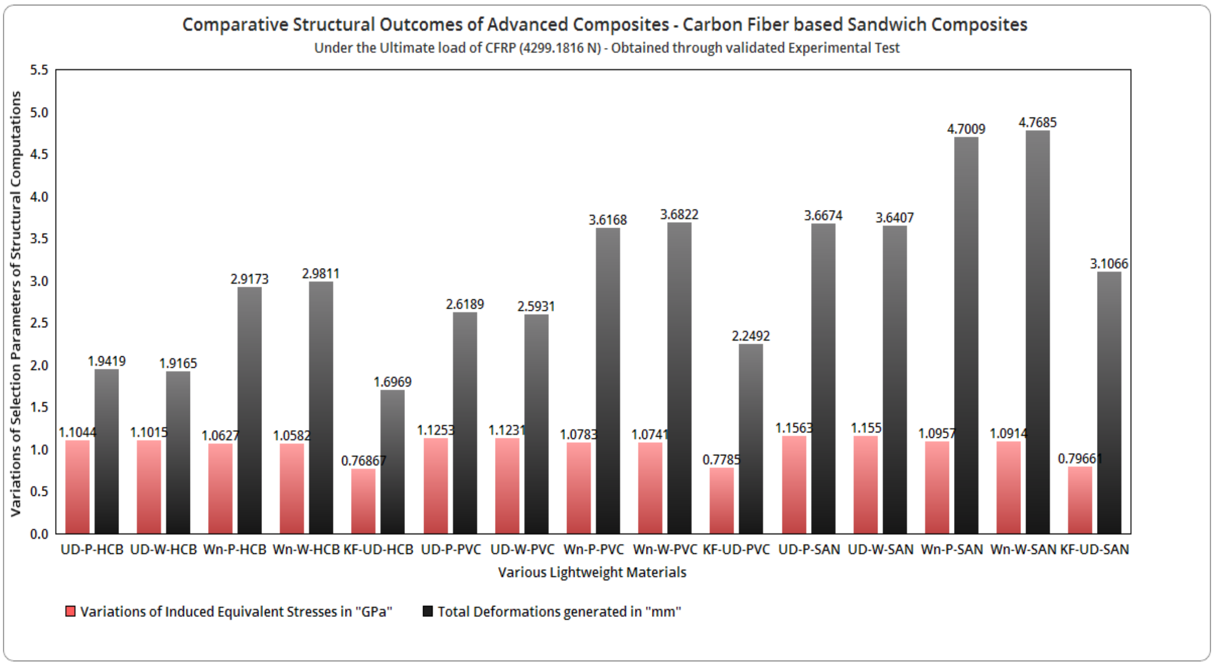


Figure 19. Comparative structural outcomes of sandwich structured based CFRP materials

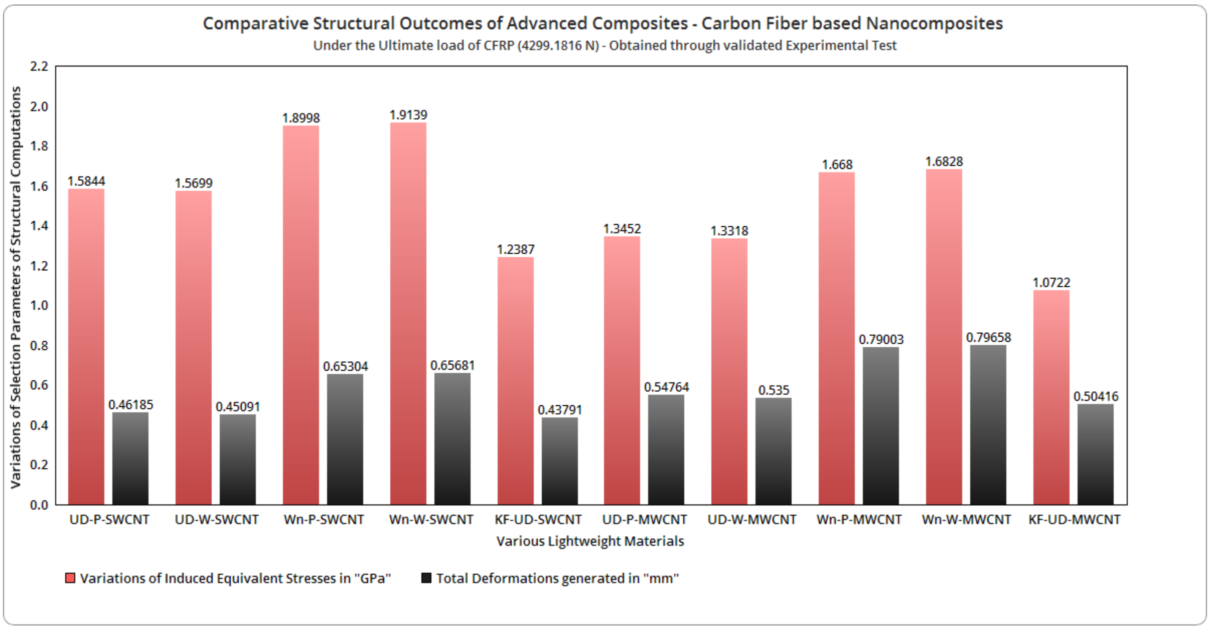


Figure 20. Comparative structural outcomes of various carbon nanotubes loaded with CFRP

Firstly, the flexural load of 4299.1816 N is commonly applied all the sub-categories and thereby the following outcomes are achieved: The kevlar fiber is fit serve as associate member for all the imposed core structures of this work. The NiTi based shape memory alloy, the honeycomb based sandwich core, and the SWCNTs are perfect combiners to withstand high loads under group of Carbon Fiber families.

3.3.2.Comparative computational results of GFRP and its associate composites

As similar as carbon fiber associate case, this glass fiber also interlinked with same advanced fibers such as sandwich cores, shape memory alloys based metals, and carbon nanotubes based layers are imposed and thereby the glass fiber based enhanced composites are formed. The formed 32 advanced composites are underwent the various computational tests and thereby the comparative outcomes are reveals in Figures 21 to 23.

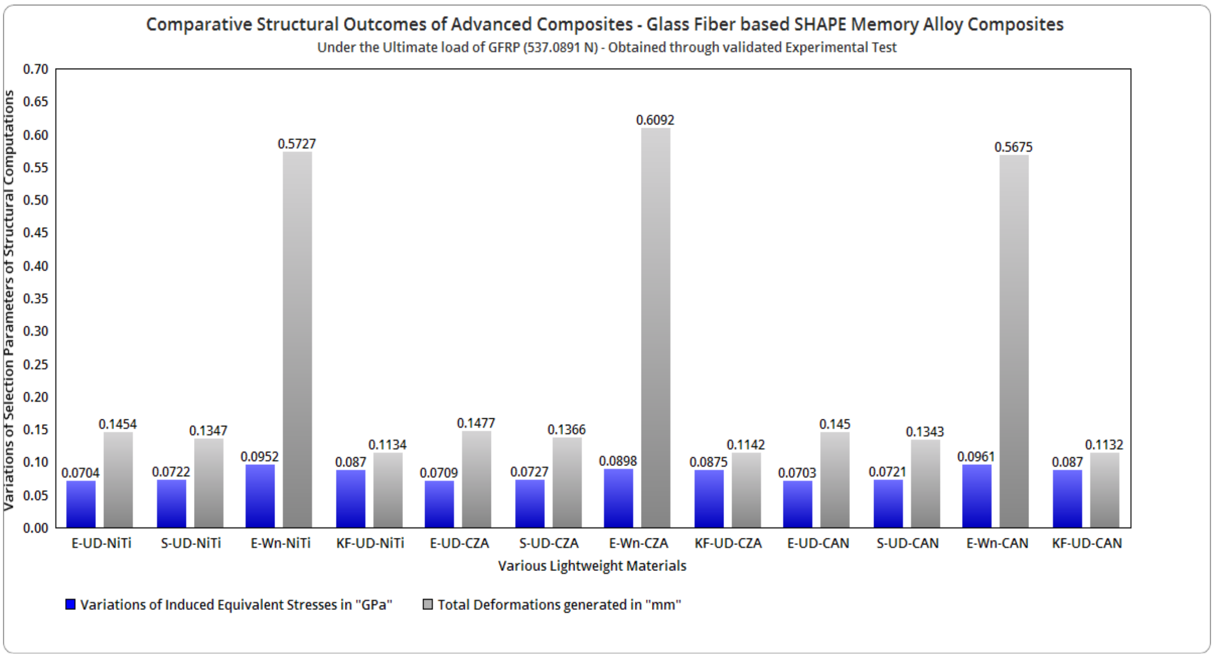


Figure 21. Comparative structural outcomes of shape memory alloy based GFRP composites

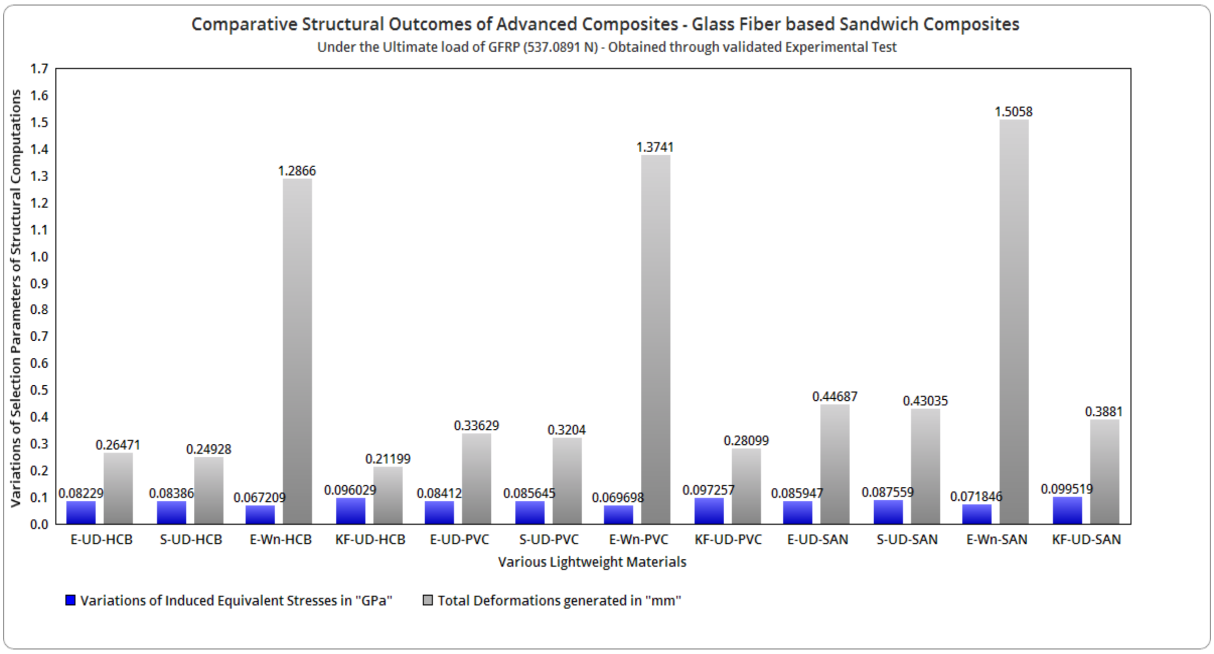


Figure 22. Comparative structural outcomes of sandwich structured based GFRP materials

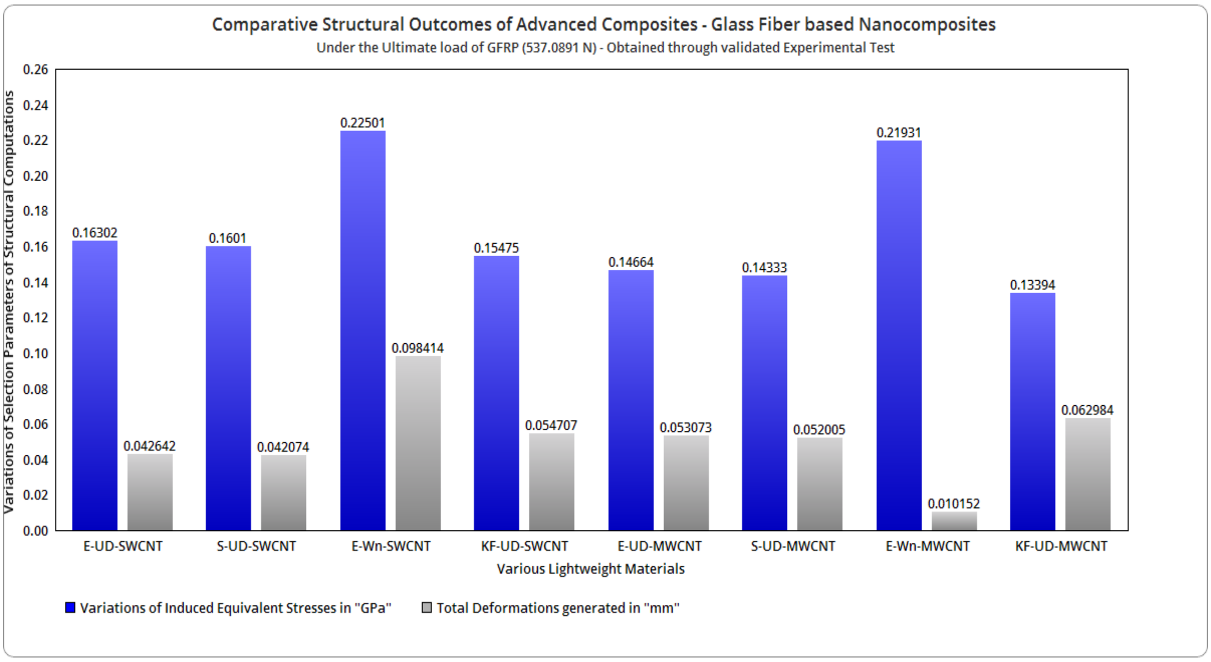


Figure 23. Comparative structural outcomes of various carbon nanotubes loaded with GFRP

Secondly, the GFRP and its allied materials are underwent the flexural test, in which it is found that S-UD is performed better than other materials under the combination of carbon nanotubes. In advanced cases, E-GFRP-UD-SAN foam, E-Glass-Woven-MWCNT and E-Glass-Woven-SWCNT were performed better than other materials, in which E-Glass-Woven-MWCNT is utmost good in GFRP advanced based composites. However, while coming to overall comparison KFRP materials are better than both CFRP and GFRP materials, especially, KFRP-PVC foam is a supreme performer than others.

3.4. Validation of advanced composites

From the advanced analysis, it can be understood that the advanced composite materials are achieved enhanced results than primary materials. Thus, the sensitivity test needs to be conducted on advanced results to increase its robustness. In this regard, the conventional theoretical method based validation is executed based on the Eq. (5). The maximum flexural stress induced in the advanced composite under flexural test is,

$$\sigma_{max} = \frac{PL(t_{fiber} + 2\, t_{core})}{4 * b t_{core}\, (t_{fiber} + t_{core})^2} \quad (5)$$

In this validation, the CFRP and GFRP based nanocomposites are underwent the flexural test, in which the literatures survey provided that decision on the finalization of the thickness of the core materials. The Epoxy S-glass UD with SWCNT based theoretical estimation and FEA numerical simulations of maximum flexural stress variations are dealt firstly. The equivalent stress variations on GFRP based nanocomposite test specimen is reveals in Figure 24.

$$\sigma_{max} = \frac{537.0891 * 100 * (6.12 + 2 * 0.68)}{4 * 20 * 0.68(6.8)^2} \Rightarrow \sigma_{max} = 159.71 \text{ Mpa}$$

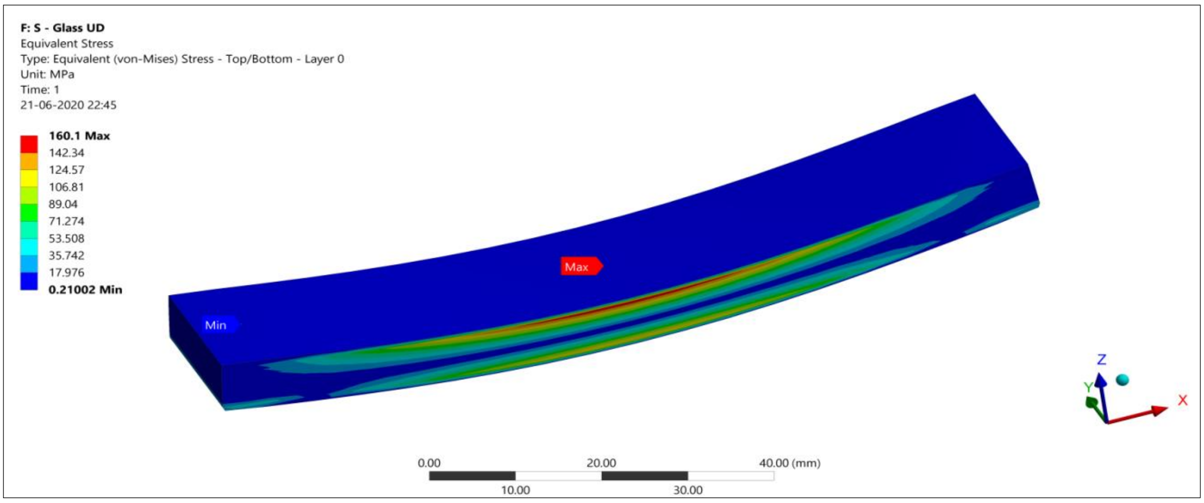


Figure 24. The equivalent stress variations on Epoxy S-Glass UD with SWCNTs

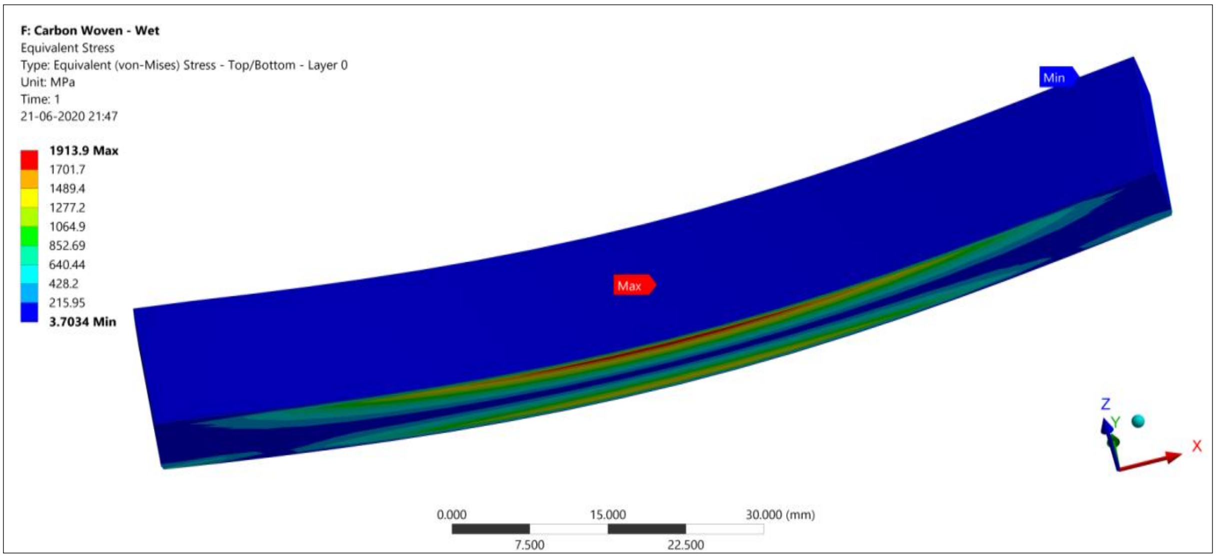


Figure 25. The equivalent stress variations on Epoxy Carbon-Woven-Wet with SWCNT

The estimated maximum stress is compared with each other and thereby the error percentage is determined as 0.24 %. The error is a tiny one so the same conventional formula is extended for higher flexural load based case that is CFRP based nanocomposite. In the second validation, the Epoxy-Carbon-

Woven-Wet and SWCNT are played the predominant role. The theoretical stress value is computed using the procedure given below. In addition to that, the FEA simulation result of equivalent stress of CFRP-Nanocomposite is shows in the Figure 25. Finally, the comprehensive data of theoretical estimations, FEA simulation results and error percentages are provided in Table 4.

$$\sigma_{\max} = \frac{4299.1486 * 100(4.995 + \ 2 * 0.555)}{4 * 20 * 0.555(5.55)^2} \Rightarrow \sigma_{\max} = \ 1919.12 \text{ MPa}$$

Table 4. Comparative analysis of advanced composite materials

Material Name	Structural Output	FEA Simulation results	Analytical Results	Error Percentage (%)
GFRP-Nanocomposite	Maximum Equivalent Stress (MPa)	160.1	159.71	0.24
CFRP-Nanocomposite		1913.9	1919.13	0.27

4.Conclusions

The ultimate flexural behaviour is one of the primary evaluation techniques involved in the construction of primary components. In this work, the same flexural tests are imposed on the advanced composites to get the clear view about the flexural behaviour with respect to the corresponding materials. Initially, the three point flexural tests are conducted on GFRP and CFRP composites, which provided the initial as well as boundary conditions to the other engineering approaches. The conventional analytical formulae are involved in the estimations of maximum deflections and maximum flexural stresses. The primary validations are computed in between these two aforementioned approaches, wherein the estimated percentages of errors are within the acceptable limit. In addition to that, the advanced FEA simulation is also implemented in the flexural test, wherein the test specimens are prepared as per relevant ASTM design data. All the structural outputs are computed on primary composite materials and thereby the estimated error lied between 0.2 to 10 percentages. Thus, the implemented engineering approaches on the estimations of flexural tests are verified. The advanced FEA simulation is extended to advanced composites materials such as nanocomposites, shape memory alloy based composites and sandwich composites. In the advanced levels, 72 material combinations are underwent the flexural tests with the help of CAE tools, in which the structural FEA tool and composite preparation tool are primarily contributed platforms. From the 72 cases, it can be concluded that the advanced composites are better than primary composites. Especially, stress level of CFRP-UD-Prepreg-PVC foam is reduced 14.44 times than CFRP-UD-(230 GPa)-Prepreg. Further, stress level of E-GFRP-UD-SAN foam is reduced 3.18 times more than that of E-GFRP composite. In addition, it is found that KFRP composite and allied materials are best performer than other composites and their allied materials. The NiTi based shape memory alloy, the honeycomb based sandwich core, and the SWCNTs are perfect combiners to withstand high loads under groups of Carbon and Glass Fiber families.

References

1.C. ELANCHEZHIAN, B. VIJAYA RAMNATH, J. HEMALATHA, Mechanical behaviour of glass and carbon fibre reinforced composites at varying strain rates and temperatures, Procedia Materials Science 6 (2014) 1405 – 1418
2.TAO YANG, MEIHONG HE, XUEJUAN NIU, YU DU, Experimental Investigation of the Three-point Bending Fatigue Properties of Carbon Fiber Composite Laminates, AMS-Original Article, Volume 1, Issue 1, 2016, pp 2-6, DOI: 10.18686/ams.v1i1.1
3.DOMINIK BANAT, Load-carrying capacity of the GFRP and CFRP composite beams subjected to three-point bending test – numerical investigations, Mechanics and Mechanical Engineering, 2019, 23, pp. 277–286, https://doi.org/10.2478/mme-2019-0037

4.PRASHANTH TURLA, S. SAMPATH KUMAR, P. HARSHITHA REDDY, K. CHANDRA SHEKAR, Processing and Flexural Strength of Carbon Fiber and Glass Fiber Reinforced Epoxy- Matrix Hybrid Composite, International Journal of Engineering Research & Technology, ISSN: 2278-0181, Vol. 3 Issue 4, pp. 394 – 398, 2014.
5.D. SURESH, A. SIVAKUMAR, Enhancement of Mechanical Properties in Carbon Fibre Reinforced Epoxy Composite with and without graphite powder, International Journal of Innovative Technology and Exploring Engineering, Volume-8 Issue-12, 2019.
6.SHIH-YAO KUO, LE-CHUNG SHIAU, KE-HAN CHEN, Buckling analysis of shape memory alloy reinforced composite laminates, Composite Structures, 90 (2009) 188–195.
7.HASSAN IJAZ, WAQAS SALEEM, MUHAMMAD ZAIN-UL-ABDEIN, TAREK MABROUKI, SAEED RUBAIEE, ABDULLAH SALMEEN BIN MAHFOUZ, Finite Element Analysis of Bend Test of Sandwich Structures Using Strain Energy Based Homogenization Method, Advances in Materials Science and Engineering, Volume 2017, Article ID 8670207, 10 pages, https://doi.org/10.1155/2017/8670207
8.UDHAYA PRAKASH R, RAJ KUMAR G, VIJAYANANDH R, SENTHIL KUMAR M, RAM GANESH T, Structural analysis of aircraft fuselage splice joint, IOP Conference series: Materials Science and Engineering Journal, ISSN 1757-899X, Volume149 Number 1, 012127
9.RAJAGURUNATHAN. M, RAJ KUMAR. G, VIJAYANANDH. R, VISHNU. V, RAKESH KUMAR. C & MOHAMED BAK. K, The Design Optimization of the Circular Piezoelectric Bimorph Actuators Using FEA, International Journal of Mechanical and Production Engineering Research and Development, Vol. 8, Special Issue 7, Oct 2018, 410-422
10.RAJ KUMAR. G, SENTHIL KUMAR. M, VIJAYANANDH. R, K. RAJA SEKAR, MOHAMED BAK. K & VARUN. S, The Mechanical Characterization of Carbon Fiber Reinforced Epoxy with Carbon Nanotubes, International Journal of Mechanical and Production Engineering Research and Development, Vol. 9, Special Issue 1, Jan 2019, 243-255.
11.VIJAYANANDH R, VENKATESAN K, RAMESH M, RAJ KUMAR G, SENTHIL KUMAR M, Optimization of Orientation of Carbon Fiber Reinforced Polymer Based on Structural Analysis, International Journal of Scientific & Technology Research, ISSN 2277-8616, 8 -11, 2019.
12.NAVEEN KUMAR K, VIJAYANANDH R, BRUCE RALPHIN ROSE J, SWATHI V, NARMATHAR, VENKATESAN. K, Research on Structural behaviour of Composite Materials on different Cantilever Structures using FSI, International Journal of Engineering and advanced Technology, Vol. 8, Issue 6S3, 2019, pp: 1075 - 1086, DOI: 10.35940/ijeat.F1178.0986S319
13.RAJ KUMAR. G, VIJAYANANDH. R, MOHAMMAD BAK. K, SHYAM CHANDER. R & ARAWINTH. R, Experimental Testing on Mechanical Properties Effect of Aluminum Foam, International Journal of Mechanical and Production Engineering Research and Development, ISSN(E): 2249-8001, Vol. 8, Special Issue 7, 2018, 1047-1059
14.G RAJ KUMAR, R VIJAYANANDH, M SENTHIL KUMAR, S SATHISH KUMAR, Experimental Testing and Numerical Simulation on Natural Composite for Aerospace Applications, ICC 2017, AIP Conf. Proc. 1953, 090045-1–090045-5; https://doi.org/10.1063/1.5032892, 978-0-7354-1648-2.
15.K. VENKATESAN, K. RAMANATHAN, R. VIJAYANANDH et al., Comparative structural analysis of advanced multi-layer composite materials, Materials Today: Proceedings, Volume 27, Part 3, 2020, Pages 2673-2687, https://doi.org/10.1016/j.matpr.2019.11.247.
16.K. VENKATESAN, S. GEETHA, R. VIJAYANANDH, G. RAJ KUMAR, P., JAGADEESHWARAN, R. RAJ KUMAR, Advanced structural analysis of various composite materials with carbon nano-tubes for property enhancement, AIP Conference Proceedings 2270, 030005 (2020), pp. 030005-1 to 030005-6, https://doi.org/10.1063/5.0019367
17.P. MIRRUDULA, P. KAVIYAPRIYA, M. MALAVIKA, G. RAJ KUMAR, R. VIJAYANANDH, M. SENTHIL KUMAR, Comparative structural analysis of the sandwich composite using advanced numerical simulation, AIP Conference Proceedings, 2270, pp. 040005-1 to 040005-5, 2020, https://doi.org/10.1063/5.0019370

18.S. INDIRA PRASANTH, K. KESAVAN, P. KIRAN, M. SIVAGURU, R. SUDHARSAN, R. VIJAYANANDH, Advanced structural analysis on E-glass fiber reinforced with polymer for enhancing the mechanical properties by optimizing the orientation of fiber, AIP Conference Proceedings 2270, pp. 040006-1 to 040006-5, 2020, https://doi.org/10.1063/5.0019378
19.S.BHAGAVATHIYAPPAN, M. BALAMURUGAN, M. RAJAMANICKAM, R. VIJAYANANDH, G. RAJ KUMAR, M. SENTHIL KUMAR, Comparative computational impact analysis of multi-layer composite materials, AIP Conference Proceedings, 2270, pp. 040007-1 to 040007-5, 2020, https://doi.org/10.1063/5.0019380.
20.VIJAYANANDH RAJA et al., Material Optimizations on UAV's axial flow compressor blade by using FSI Approach, AIAA SCITECH 2022 Forum, January 3-7, 2022, San Diego, CA & Virtual, https://doi.org/10.2514/6.2022-1090.

Manuscript received: 5.06.2021