Vijayvignesh N S. International Journal of Engineering Research and Applications
www.ijera.com
ISSN: 2248-9622, Vol. 11, Issue 9, (Series-II) September 2021, pp. 46-53

RESEARCH ARTICLE OPEN ACCESS

Design and Material Optimization of Glass Fibre Reinforced Polymer (GFRP) Internally Stiffened Tubular Decks

[1]Vijayvignesh N S
[1]M.E. Manufacturing Engineering, Anna University, MIT Campus,
MIT Road, Radha Nagar, Chromepet, Chennai, Tamil Nadu 600044, India.

ABSTRACT:-
Composites have become an inevitable alternative to conventional materials when the challenge of enhancing the abilities is to be addressed. Polymer based composites is being highly sought after as they are capable of solving the existing problem in a better cost efficient manner and due to its flexibility in their manufacturability. In this paper, the existing GFRP tubular decks performance has been improved by proposing a newer, non-standard internal stiffening design along with a change in material that is validated and visualized using the Abaqus CAE Softwareand the engineering reason behind the improved performance based on the obtained analysis results has also been discussed in this paper along with the future scope of the work that has been currently done.

Keyword:-Composites, GFRP, Internal Stiffening Design, Abaqus Simulations, 3 point bending test

Date of Submission: 01-09-2021 Date of Acceptance: 14-09-2021

I. INTRODUCTION

The composite material is the combination of two or more materials with distinct physical and chemical properties. This makes the properties and structural performances of mixed resultant materials superior to those materials acting independently.The significant properties of composite materials are high strength-to-weight and stiffness-to-weight ratios; hence they are used in applications which require reduced weight without any compromise on its strength and stiffness.A polymer matrix composite also known as fibre reinforced plastics (FRP) or reinforced plastics is composite with two or more materials in which matrix material must be fibre (i.e. thermosets or thermoplastics).

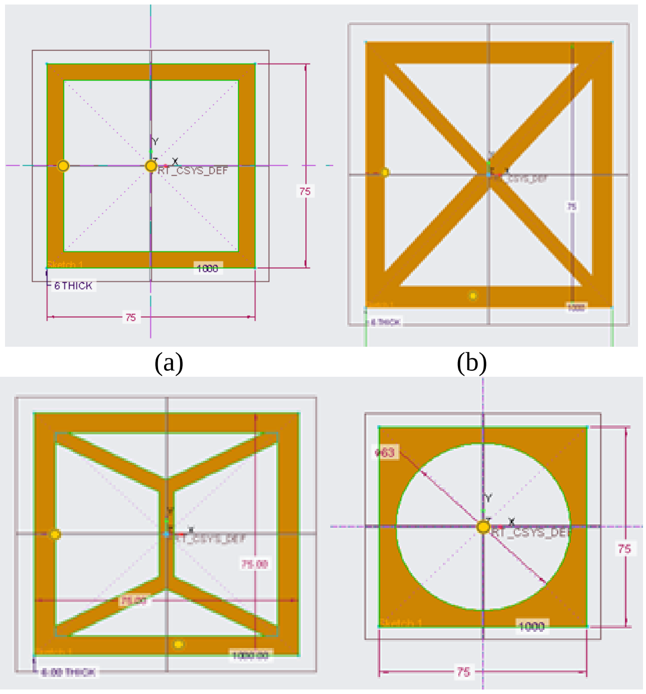
Glass fibre is made up of numerous fine fibres of glass. The glass fibres are made by drawing molten glass through small openings in the die. Then they are elongated, cooled, wound on a roll. The glass fibres are initially treated with silanecompounds to remove the ‘size’ coatings used to protect the glass fibres as they have poor abrasion resistance. The main categories of glass fibres are, E-type (calcium alumina-boro-silicate glass) are most commonly used, S-type (magnesia alumina-silicate glass) offers higher strength and stiffness but at a higher cost whose properties are given in Table 1.The glass fibres have high tensile strength, higher dimensional stability, good thermal conductivity and higher heat resistance. It accounts for more than 95% of fibre reinforcement in composite industries significantly due to its higher performance to price ratio.

Table 1: Properties of E-Glass and S-Glass Fibers

Type	E-Glass	S-Glass
Tensile Strength (MPa)	3500	4600
Tensile Modulus (MPa)	73	85
Density (kg/m^3)	2480	2580
Relative Cost	Low	High

II. DESIGN OPTIMIZATION

As for the comparative study purpose, a plane square tubular deck without any internal stiffening is chosen as a base design so as visualize how different our results are as compared to various internal stiffened designs. From a set of various standard internal stiffened designs, choosing top three designs namely X, Y and O cross sections [1] as illustrated in Figure 1. The cross-sectional dimensions are fixed as 75 x 75 mm, 6 mm thick and has span of 1000 mm.



(a) (b)

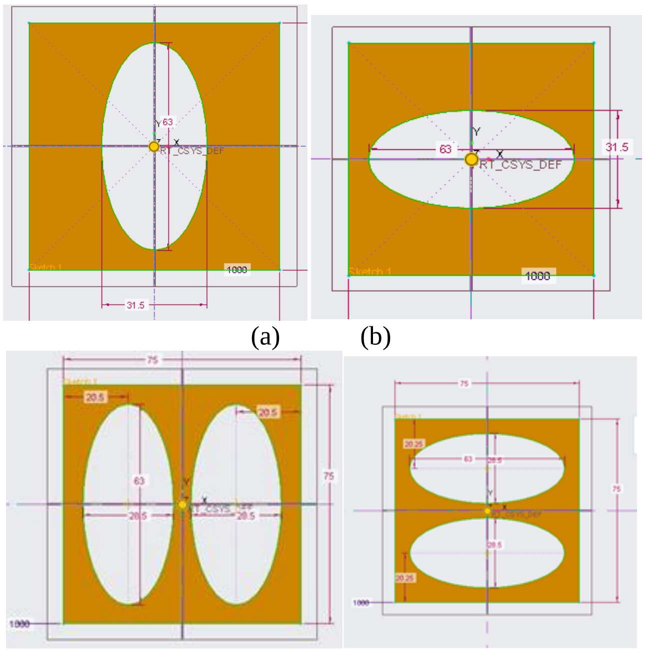
(c) (d)

Figure 1: (a)Plane Cross-Section (b)X Cross-Section (c)Y Cross-Section (d) O Cross-Section

Upon 3 point bending analysis as per ASTM D790 of the standard internal stiffening designs the 'O Cross-Section' has proven to have the better flexural modulus. This is because the curvature allows for uniform stress distribution along its contour making the component to able to withstand higher loads with lesser deformation and crack propagation. What exists as a linear distribution along a flat surface is now a radial distribution along a curved surface and hence the observed result.

With this engineering understanding it led to introducing a newer design that is of elliptical cross-section [8] due to the reason even when they are subjected to different loads in the two different directions, they can provide different bending stiffness and moment capacity around two axes of symmetry without significantly reducing the confining effect over its surrounding elements or components. Also the contour of the ellipses is much longer than that of the circular cross-section; hence the scope for the stress distribution could possibly occur over a longer region thereby reduction in localised stress and hence better performance.

Despite all these engineering understanding, geometrical reasoning and logical explanation there could be many number of orientations of the said ellipse as the internal stiffening design, the real challenge still lies in finding out which orientation of ellipse in the internal stiffening design proves to have higher flexural modulus. Some of the most common orientations have been analysed using Abaqus CAE software under 3 point bending test and based on the results we could extrapolate and predict the results of other orientations. Those orientations that are tested are being illustrated in Figure 2.



(a) (b)

(c) (d)

Figure 2: (a) Single Vertical Ellipse Cross-Section (b) Single Horizontal Ellipse Cross-Section (c) Double Vertical Ellipse Cross-Section (d) Double Horizontal Ellipse Cross-Section

III. MATERIAL OPTIMIZATION

The need for material optimization comes into play so as to introduce a material [4] that has much higher mechanical capability than the existing material but also taking into consideration that the new material being introduced does not require a tedious processing as that would lead to a newer and a bigger challenge in terms of capital investment, machining parameters, modelling considerations and inability to perform a comparative study. Hence E-Glass 21Kx43 Gevetex has been chosen as the newer material that has similar processing as compared to existing Pultruded GF-800 material whose properties are given in Table 2.

Table 2: Mechanical Properties of Pultruded GFRP GF-800 and E-Glass 21Kx43 Gevetex

Mechanical Properties	**Pultruded GF-800**	**E-Glass 21Kx43**
E_1 (GPa)	45.95	49.43
E_2 (GPa)	14.56	15.32
E_3 (GPa)	14.56	15.32
G_{12} (GPa)	4.50	7.88
G_{13} (GPa)	4.50	7.88
G_{23} (GPa)	5.51	8.92
v_{12}	0.25	0.27
v_{13}	0.25	0.27
v_{23}	0.30	0.31

Note:-

E_1 - Young's modulus in fibre direction
E_2& E_3- Young's modulus in transverse directions(Y & Z axes respectively)
G_{12}, G_{13}, G_{23}-In-plane shear stress (X-Y, X-Z,Y-Z planes respectively)
v_{12}, v_{13}, v_{23} - Poisson's ratio (X-Y, X-Z, Y-Z planes respectively)
GPa- Giga Pascal (10^9 Pascal)

IV. PLY ORIENTATION

Ply orientation defines the angle at which the glass fibres are oriented in each layer of the composite that are stacked up to form the final product. Ply orientation plays a major role in deciding the stress distribution in the composite material once loaded and the capability for more stress distribution allows for the composite product to bear higher loads or in other words, reduction in deflection of the composite product for the same load with efficient ply orientation.

The ply orientation $[0/90/0/90/+45/-45]_S$as illustrated in Figure 3, has been chosen [5] because of the reason that for bending stress induced in the composites the initial orientation of [0/90/0/90] allows for higher resistance to stress penetration and the internal orientation [+45/-45] allows for greater dispersion of the stress over a larger directional span which along with the radial curvature of the newly chosen design has proven to be a greater advantage leading to better outcomes.

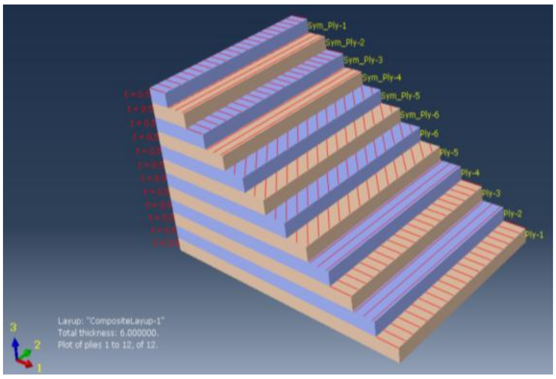
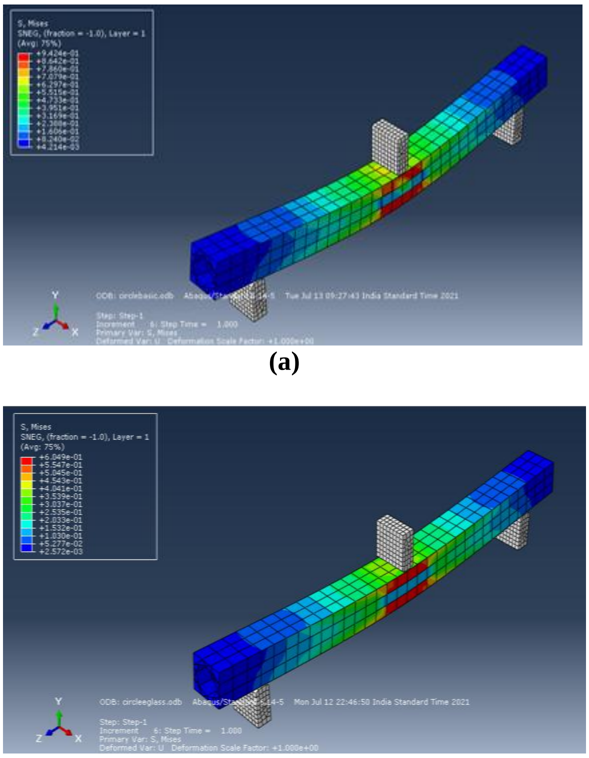


Figure 3: Ply Stack Layup

V. ANALYSIS RESULTS

The initial step in the analysis [2-6] is the justification of newer material that is to ensure that it performs better than the existing material which is visualized from the result obtained using Abaqus CAE software under ASTM D790 3 point bending test with a displacement of 10 mm given in the negative Y-direction as illustrated in Figure 4.This test was done upon the most efficient O Cross-Sections from the standard internal stiffening designs as the medium of comparison has to arise from an already proven efficient design which indirectly means to justify the better performance of all other designs.

The 3 points of loading was designed using a ‘Rigid’ element based on the standard assumption that support structures and the tool executing loading are perfectly rigid and do not develop any stress that can cause an effect in the composite product. The supports are also restricted all their degrees of freedom considering that both the support structures and toll at the point of loading do not undergo any bending, slipping, shearing or torsion.

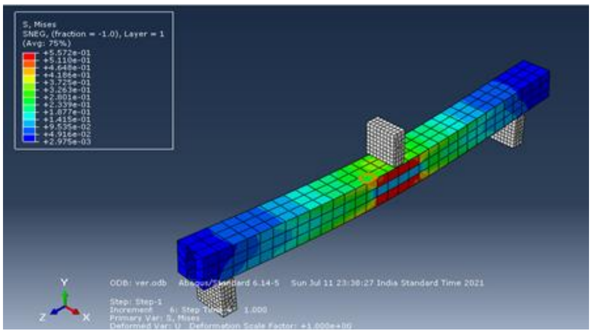


(a)

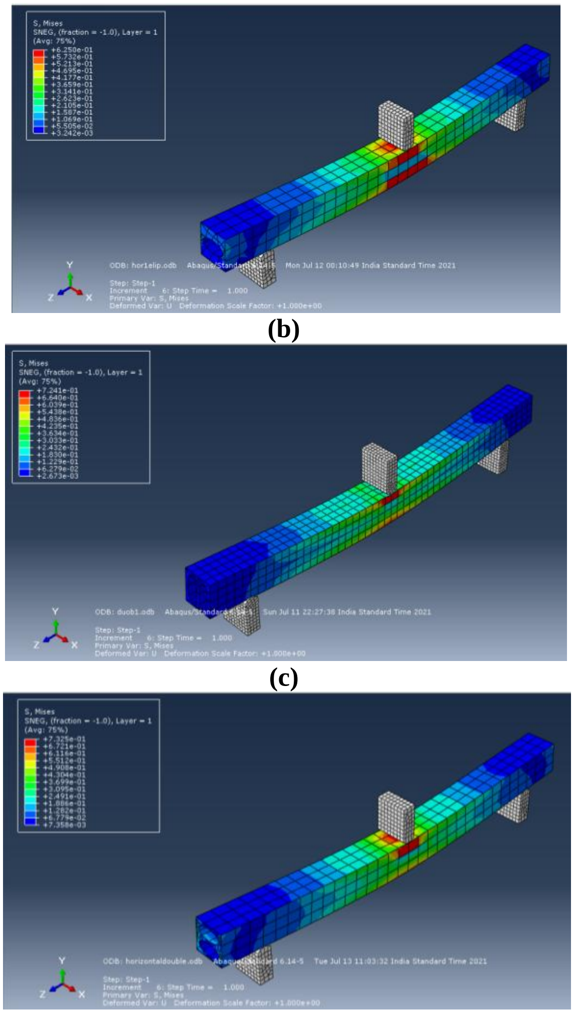
(b)

Figure4: (a) 3 point bending test on O Cross-section with GF-800 material
(b) 3 point bending test on O Cross-section with E-Glass material

It is evident from the result that for a given displacement the stress induced in the E-Glass 21kx43 Gevetex material is 604.9 MPa is less than that of Pultruded GFRP GF-800 material which is 942.4 MPa which means that the E-Glass material has higher flexural modulus than the GF-800 material. Now with this as the base result the analysis has been performed on different orientations of elliptical internal stiffening design whose results are as illustrated in Figure 5 and tabulated in Table 3.



(a)



(b)

(c)

(d)

Figure 5: Abaqus Simulation Results of (a) Single Vertical Ellipse Cross-Section (b) Single Horizontal Ellipse Cross-Section (c) Double Vertical Ellipse Cross-Section (d) Double Horizontal Ellipse Cross-Section

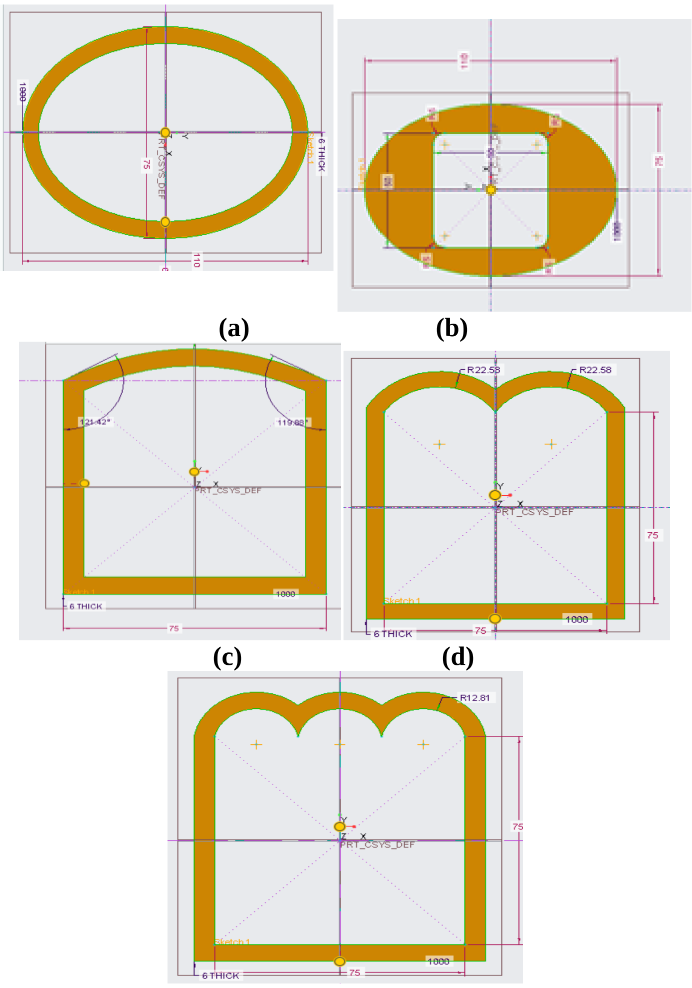
Table 3: Analysis Numerical (Stress) Results

Internal Stiffening Design	**Stress (MPa)**
Plain Square	1293
Vertical Single Ellipse	557.2
Horizontal Single Ellipse	625
Vertical Double Ellipse	724.1
Horizontal Double Ellipse	732.5

From the tabulated results it’s observed that vertical single ellipse internal stiffening has proved to have greatest flexural modulus. This can be explained by the fact that the stress distribution is at a radial distance from the point of generation and also the rate of change of the position along the contour is higher as compared to that of horizontal single ellipse internal stiffening design. The same reason holds good for double ellipse design also but the reason why the vertical double ellipse has higher stress as compared to vertical single ellipse is because as the stress distribution takes place the contours closer to each other having their own share of stresses gets added up but less than the total because of the instantaneous changes taking place in the directions of their distribution.

VI. SIMPLER DESIGN FOCUS

From the results obtained so far, we understand that the curved surfaced internal stiffening designs have higher flexural modulus. Hence, instead of creating a beam with internal stiffening it might be beneficial in terms of capital, materials and manufacturing by creating a beam that has a curvature feature [9] which is in direct contact with the load. However, again an iteration of few designs has to be created to observe and identify the pattern and explain the phenomenon based on the simulation results. Thus the designs taken under consideration are as illustrated in Figure 6.



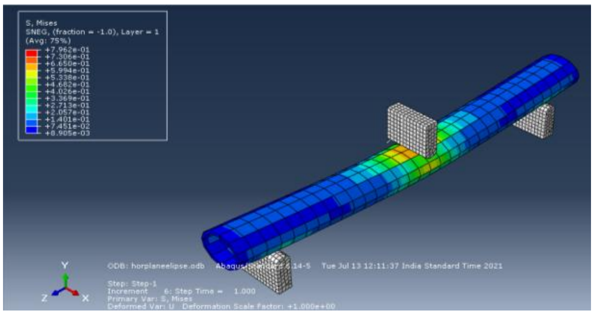
(a) **(b)**

(c) **(d)**

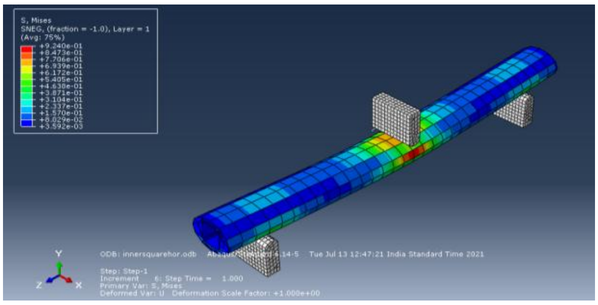
(e)

Figure 6: (a) Elliptical Cross-Section
(b) Square Inscribed Elliptical Cross-Section
(c) Single Curved Top
(d) Double Curved Top
(e)Triple Curved Top

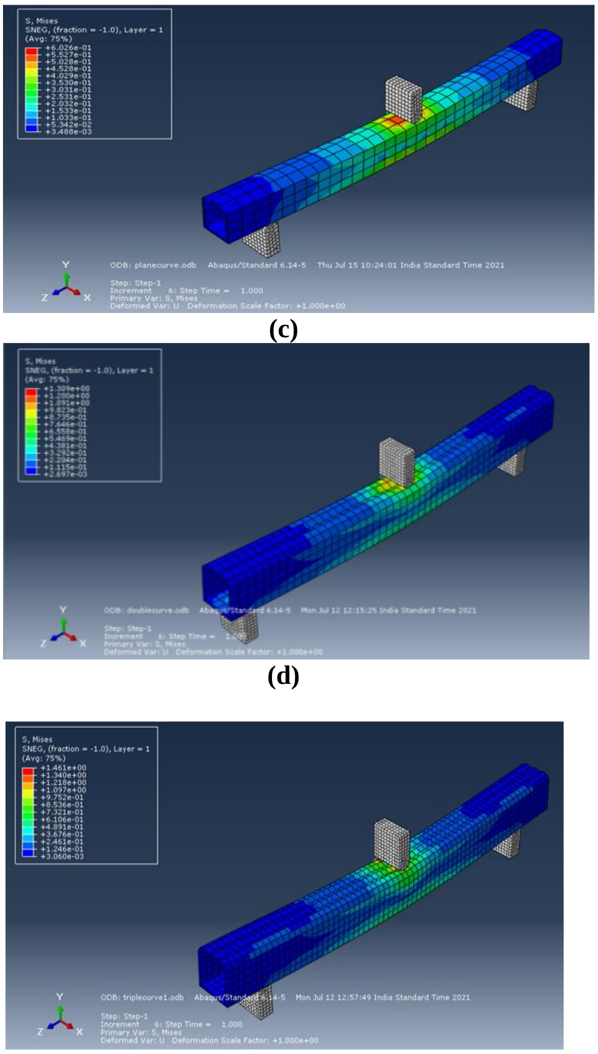
The Abaqus Simulation results for the designs proposed above are illustrated below in Figure 7 and tabulated in Table 4.



(a)



(b)



(c)

(d)

(e)

Figure 7: Abaqus Simulation Results of
(a) Elliptical Cross-Section
(b) Square Inscribed Elliptical Cross-Section
(c) Single Curved Top
(d) Double Curved Top
(e)Triple Curved Top

Table 4: Simulation Results (Stress)

Design	**Stress (MPa)**
Elliptical Cross Section	796.2
Square Inscribed Elliptical Cross-Section	924
Single Curved Top	602.6
Double Curved Top	1309
Triple Curved Top	1461

Based on the results, we can understand that the Single Curved Top has lesser stress generation for the same amount of displacement which is closer to the value obtained for the best internal stiffened design. However, since the loading is conducted within the elastic region the results seem better, if the loading is further increased beyond the yield point this design fails earlier. Hence, such designs are to be used for low loading applications as in that regime they prove to be beneficial both functionally and economically.

When we consider a newer set of designs that vary in the amount of curvatures at the top surface we find that as the number of curve increases the stress developed for the same constant displacement at the centre of the beam. This can be explained based on the intensity of corrugations developed in the curved structure. As this intensity increases the ability to resist deformation increases but as these compressed laminae find lesser space to deform further on account of the applied load the stress developed is higher and at a certain peak load such structures fail suddenly without much plastic deformation.

VII. CONCLUSION

Although simulations can do much better things like creating a predictive model about unknown phenomena before direct investigation via prototyping that could save a huge amount of time and money, downsize the total available number of variables or parameters and even validate those operations that are done experimentally to find out the authenticity of the conduction of the physical work but every simulation software have their very own set of limitations.

Here, in this case, Abaqus could efficiently solve the kind of conditions that has been assigned to the model in this paper which can also be conducted experimentally but in real time scenario the laying up of the reinforcement fibre doesn't have to be continuous, they could be short fibres or particulate fibre or a combination of both or altogether they can be built up in such a way that represents a non-directional curve like a hypotrochoidwherein the stress developed in the fibres spreads in an unconditional manner whose effects can be further analysed and compared with the results as obtained in this paper to validate and also to check for various mechanical properties that would further continue the research thread that has been introduced which was again an continuation of the previous works.

REFERENCES

[1]. Yeou-Fong Li, HabibArmelMeda, Walter Chen;The Design and Analysis of Internally Stiffened GFRP Tubular Decks — A

Sustainable solution. Journal of Sustainability, December 2018 MDPI doi:10.3390/su10124538.

[2]. G. J. Turvey, Lancaster University, UK; Testing of pultruded glass fibre-reinforcedpolymer (GFRP) composite materials and structures. Woodhead Publishing Limited, 2013,Page; 440 – 508. Research Article – Book Chapter doi:10.1533/9780857098641.3.440.

[3]. HaohuiXin, Yuqing Liu, Ayman S. Mosallam , Jun He, Ao Du ; Evaluation on material behaviors of pultruded glass fiber reinforced polymer (GFRP) laminates. September 2017 Composite Structures, Elsevier Publications, doi:10.1016/j.compstruct.2017.09.006

[4]. Yeou-Fong Li, Tseng-Hsing Hsu, Fu-Chr Hsieh; A Study on Improving the Mechanical Behaviors of the Pultruded GFRP Composite Material Members, January 2019. Journal of Sustainability, MDPI doi:10.3390/su11030577.

[5]. M. Meng, H.R. Le, M.J. Rizvi, S.M. Grove; 3D FEA Modelling of Laminated Composites in Bending and Their Failure Mechanisms October 2014, Composite Structures, Elsevier Publications doi:10.1016/j.compstruct.2014.09.048.

[6]. I Uyar, B Gozluklu, D Coker; Dynamic delamination in curved compositelaminates under quasi-static loading, June 2014 Journal of Physics, IOP Publishing,

[7]. doi:10.1088/1742-6596/524/1/012042.

[8]. Joy Pederson; Finite Element Analysis of Carbon Fiber Composite Ripping Using ABAQUS, December 2008, MS Mechanical Engineering Thesis, Clemson University Source:https://tigerprints.clemson.edu/all_theses/512.

[9]. Bing Zhang, Gui-SenFeng, Yan-Lei Wang, Cong-Cong Lai, Chen-Chen Wang, Xia-Min Hu, Elliptical FRP-Concrete-Steel Double-Skin Tubular Columns under Monotonic Axial Compression, Hindawi, Advances in Polymer Technology, doi:10.1155/2020/7573848, Volume 2020

[10]. Matthew Rudas, TarekQasim, and Mark B. Bush, Failure of curved brittle layer systems from radial cracking in concentrated surface loading, Journal of Materials Research doi:10.1557/JMR.2005.0343, Vol. 20, No. 10, Oct 2005, Page: 2809 - 2820

[11]. Xing Wang, Yu Jiang, Yonghui Huang , Yue Huang , Fan Wang; Finite Element Failure Analysis of GFRP Laminates in Plate-Cone Reticulated Shell, June 2020, Advances in Polymer Technology, MDP doi:10.1155/2020/2809302.

[12]. 11.Youyou Zhang, AymanMosallam, Yuqing Liu, Yun Sun, HaohuiXin, Jun He; Assessment of Flexural Behavior of Pultruded GFRP Laminates for Bridge Deck Applications, May 2019, Journal of Advances in Materials Science and Engineering, Hindawi doi:10.1155/2019/6751636.

[13]. Jian Zhang, XinxinYue, JiajiaQiu, Lei Chen, Wei Shen; A Bracket-Stiffened Two-Planar Overlapped Tubular KT-Joint for Offshore Jack-Up Fatigue Analysis, March 2021, Journal of Advances in Civil Engineering, Hindawi doi:10.1155/2021/8890075.

[14]. Ibrahim KhyaamArshad; Determination of Elastic Constant of Pultruded Fiber Reinforced Polymer Closed Sections, April 2015, Bachelor of Engineering in Civil Engineering Thesis, Coventry University.

[15]. Dikshant Singh Saini, DebasisKarmakar, Samit Ray-Chaudhuri; A review of stress concentration factors in tubular and non-tubular joints for design of offshore installations, August 2016, Journal of Ocean Engineering and Science, Elsevier Publication, doi:10.1016/j.joes.2016.06.006.