DESIGN, ANALYSIS AND DEVELOPMENT OF SPECIAL PURPOSE TOOLS FOR COMPOSITE MANUFACTURING EFFICIENCY IMPROVEMENT

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Abstract

Advanced materials are widely used in high performance structures that profit from their high strength; high stiffness and low weight .Composite products are realized using different manufacturing processes to meet the functional, production rate, size and shape of the part. Now days most of the industries are mainly focusing on improvements in manufacturing techniques to reduce efforts as well as material wastage. Wet layup, compression molding, resin transfer molding, filament winding, pultrusion are the some of the well established process in composites. The present work mainly focused on some of the improvements in layup process and filament winding process. In layup process improvements, design and development of special purpose tool for noodle preparation (i.e. Radius fillers) for composite T, I, H sections is carried out. Comparison made on the existing and proposed design for the feasibility. In filament winding process improvements, design and development of special purpose mandrel for complex shaped filament wound composite parts is carried out based on the industrialization concept. Later part of work extended to the study of impact of winding angle on the filament wound composite part using NASTRAN software.

Keywords: *Layup, Noodle preparation (i.e. Radius fillers), Filament winding, Mandrel, Winding angle, NASTRAN.*

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1. INTRODUCTION

Continuous advances in the composite manufacturing technique have lead to significant market acceptance. But current challenge is to reduce human efforts as well as material wastage. A general composite manufacturing process is labor incentive, requires high skilled operators and uses expensive non degradable material. The effort to produce economically attractive composite components desire several innovative manufacturing techniques. Presently, industries mainly focusing on improvements in the composite manufacturing techniques which can cause cost effective as well reduction in human efforts. Especially for composites, that the improvement in manufacturing technology alone is not enough to overcome the cost hurdle. It is essential that there be an integrated effort in design, material, process, tooling, quality assurance and manufacturing processes.

Most of the aircraft and marine structures are manufactured by layup process using prepreg. During manufacturing of structural members like T, I, H sections forms cavity at the interface between web and flanges due to flexibility disadvantages of prepreg. These cavities cause induced cracks or premature cracks when member subjected to loading. Composite radius filler “a noodle” of present work better meets the challenges faced with such structural members. To meet these requirements, it is necessa9ry to think on performing unique operation for multiple parts, proposal for new tool to optimizing the process to reduce the operational cost and improving the quality. Lot of works carried out in last few years on the Radius fillers from the most of the aircraft industries. Stanely W. Stawski [1] investigated radius fillers are manufactured using laminated board made up of plurality of the composite materials having substantially unidirectional fibers. Panagiotis E. George, Kirik B.Kajita, Barry P.Van west [2, 3] proposed a plurality of woven fabrics used to form composite radius fillers. Stanely W. Stawski [4] introduced another new idea about radius fillers i.e. inflatable radius fillers.

Filament winding is another composite manufacturing technique especially for cylindrical and spherical parts. Most of the uniform thickness parts are manufactured using conventional mandrel. But some special cases like complex shaped inner part profile and an asymmetric parts leads to machining which causes a material wastage, cost incentive and lower production rate using conventional mandrel. To overcome these problems, it’s necessary to think on the special purpose mandrel for such parts.

As literature says, there are different types of mandrels are used based on the geometry of the part to be produced. For special cases like inner step profile, asymmetric parts, Kevin Davis, James A. Yorgason introduced about inflatable mandrel. Which have disadvantages over highly complex parts [5]. Jhon C. Brooks investigated inflatable, collapsible mandrel for constructing a filament wound pressure vessels [6]. But typically plain mandrel, segmented mandrel and molded mandrel are widely used by the industries now days.

In this paper suitable type of mandrel is chosen among plain, segmented and moldable mandrel based on the industrialization concept.

Last part of this paper extended to the impact of winding angle the strength of the filament wound composite tube. P.Satheeshkumar reddy, Ch. Nagaraju, T.Hari Krishna worked on design and analysis of filament wound composite tube under pure and combined loading using ANSYS tool [7]. Balya Bora investigated characteristics of filament wound composite tube under combined loading condition. Winding angle, level of orthotropy and various ratios of loading condition are main concern of that study [8-9]. The present work gives impact of winding angle on stresses and strains of the part and also concentrated on the winding angle optimization. This analysis is performed using NASTRAN.

2. LAYUP PROCESS IMPROVEMENT

Layup process is usually preferred for thin walls. Most of the structural members like T, I, H stiffened composite panels are manufactured using prepreg layup process.

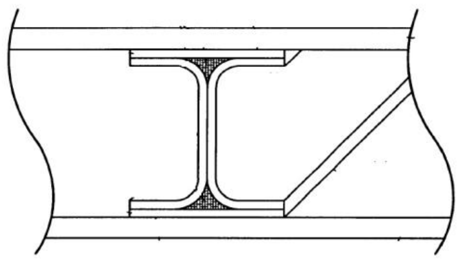


Fig- 1: Typical Composite T stiffener showing "Radius filler"

Composite T, I. H sections are made by binding two 'C' or 'U' channel tools together to form a web with flanges. These channels generally comprises of prepreg plies of different orientation. Due to flexibility disadvantages of forming sharp corners by its own from the prepreg, tool are designed in predetermined radius form at the sharp edge as shown in Fig-2. Laid prepreg plies are bent according to the predetermined radius form.

When the two 'C' or 'U' tools are joined at the webs after layup, a 'dimple' occurs along the flange because of these radii. When such structures undergo various types of loading condition, distortion occurs due to gap at the interface between web and flange. Usually structures should have stiff enough to resist the loads. So, voids or dimples formed during the manufacturing composite stiffeners are filled by using 'a NOODLE' (i.e. Radius filler).

Hence, noodles are necessary for composite spars and ribs to fill the gap formed at the interface between the flanges and web. These radius fillers or "noodle" must have structural adequate, easy processing and less expensive to produce. Such designs of noodles often force to undergo post manufacturing using special purpose tool. Manufacturing of these fillers slows the production flows, increases the cycle time and increases the cost.

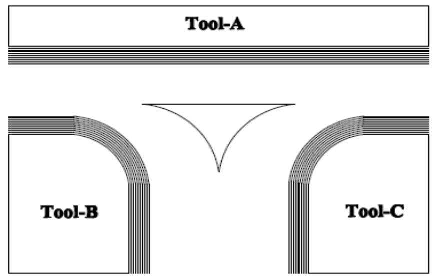


Fig-2: Composite T- Stiffener processing.

2.1 Noodle Preparation Technique

Most of composite manufacturing industries have their own way of processing noodles. Using hydraulic, pneumatic, automated, other mechanisms are used to form these radius fillers. Usually spars and ribs are larger in length, such structural members requires discontinuous fillers are required in order to avoid discontinuity in members. Present noodles pressing tools have less capacity in length parameter. So, present work concentrated on disadvantages over conventional systems and also focused on other parameters like operational time, production rate and improvements in quality.

2.1.1 Design of Noodle Pressing Tool

Concept of Pneumatic compaction system:

New concept of pneumatic compaction system is proposed for noodle pressing. The output from the proposed design is identified the following need:

- Increase in the length of the noodle.
- Development of special purpose tool replaces conventional tools.
- Optimization of process parameters like operational cost, production time and improvements in the quality.

In this system (as shown in Fig-3), pressure is applied on the mold tool pneumatically. Air is supplied to the inflatable tube which is located inside the rectangular frame. The tube get expands and pressure is applied by means of flat plate on the rolled prepreg. Based on the noodle shape and size, mold tool is designed. Once plate come in contact with the mold tool, rolled prepreg is turned into a required shape. Max pressure on the mold tool is assumed to be 2 bars. For air intake and out take air values are fixed at the top of the frame. External air connections are connected to the air values. Mold tools are designed in such way that, mold is movable using roller bearings for material loading and unloading.

2.1.2 CATIA Model.

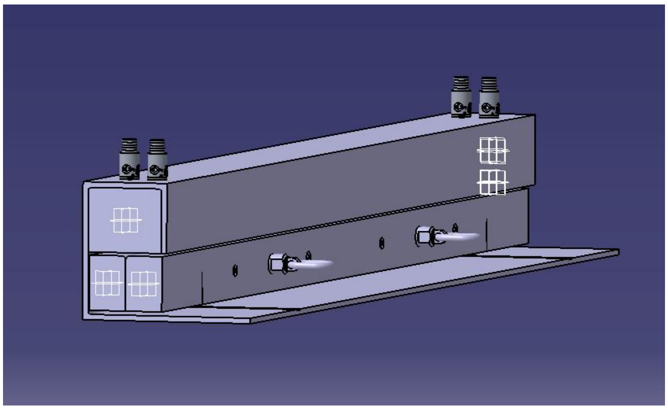


Fig-3 CATIA Model for pneumatic compaction system

Specifications:
Max capacity: 2 bar pressure.
Length of the system: 2000mm
Width of the system: 300mm

Table – 1: Parts specifications

Parts	Dimension (mm)	Material	Feasibility
Rectangular Frame	250x150x12	Mild steel	Good in strength
Die pattern	130x100	Aluminum	Flexibility in changing the pattern
Inflatable tube	130x100x10	Rubber	Ease for Expansion
Press plate	130x7	Composite	Light weight, Less hanging effect
Air values	STD	STD	Less cost and Available as Std part.
Roller Bearings	D=58, d=28, B=16	STD	Max capacity and easy for movement.
Handles	STD	STD	Easy to hold.

2.2 Comparison between Existing and Proposed Design

At present, hydraulic hot press is used for the noodle pressing. As discussed earlier, length of the noodle stick manufactured using existing system is only 0.5 meters. But most of the structural members have a length more than 2 meters. In order to meet 2 meter lengthened T section, 4 no of 0.5meter noodles are required. Hence, it takes more production time as well effects on cost and quality. Using pneumatic compaction system structural properties like structural integrity, distortion and structural strength are improved. Proposed design focused on increase in the length of the noodle stick. So can adversely reduces the production time and cost.

Comparison made between existing and proposed design by considering time factor to manufacture 2 meter length noodle stick.
As per hydraulic hot press, (for 0.5m)
Tool preparation time = 15min.
Prepreg cutting time = 2min.
Rolling of prepreg = 2min.
Heating up of tool = 15min at 60°C.
Other processing time = 5min.

Total time taken for manufacturing 0.5m noodle stick = 40min. But tool preparation time and heating time is not included for the further processing. Therefore total time taken to prepare a 2meter noodle stick = 40+9+9+9 = 67 minutes. For pneumatic compaction system, it only takes 40minutes to prepare 2 meter lengthened stick.

3. FILAMENT WINDING PROCESS IMPROVEMENT

Filament winding is special type of composite manufacturing technique especially for cylindrical and spherical parts. Simple process of wrapping a mandrel with fibers becomes complicated when the composite part is comprised of a compound-curved shape, inner step profile in the part and asymmetric parts. Such geometries of filament wound composite parts problematic for mandrel extraction. Internal mandrels for complex shaped composites require extensive design considerations to ensure the mandrel can be removed after the composite is cured. This makes mandrels very expensive to develop, difficult to fabricate, and time-consuming to remove from a cured, complex composite part.

When composite parts like stepped cylindrical profile and asymmetric parts are fabricated on a conventional mandrel, additional machining to be done on the part to get desired part profile. Typically it is not advisable for machining in order to get desired profile in the part because as it leads to cost incentive, decrease in the strength due to fiber discontinuities also lowers the production rate. It is more desirable to remove the mandrel without affecting the part. Hence winding the part to net shape by introducing a stepped mandrel and other accessories will reduce the cost.

This paper focused on the mandrel solutions for such parts considering different conceptual design related to plain mandrel, segmented mandrel and molded mandrel. Mandrel solution is given on basis of industrialization concept considering mandrel deflection, material consumption and winding time calculations related to filament winding process. Industrialization is another best tool for design feasibility.

3.1 Types of Mandrel

Any changes in the pattern or part in filament winding process needs an alternative solution for the mandrel. Solution for such parts gives rises to distinguished mandrel design. There are three different types of mandrels are studied for the feasibility.

3.1.1 Plain Mandrel

Plain mandrels are nothing but conventional mandrel having uniform diameter. These mandrels are limited to shapes with a uniform inner diameter and symmetric parts. But some complex parts like inner step profile, non uniform and non symmetric parts suggests to additional Machining operations. Manufacturing of such parts involves resin impregnated fibers wound on the rotating mandrel until maximum part thickness is achieved. Later proper machining is accomplished in order to get a required part profile. Salient features of plain mandrels are easy in extracting the mandrel from the part as mandrel having uniform diameter.

3.1.2 Segmented Mandrel

Segmented metal mandrels are accounted in order to achieve an inner step profile of the part. These types of mandrel are consisting of core mandrel and split mandrel. Core mandrel and split mandrel together assembled to get exact part profile and then assigned for winding. Grooves provided on the core mandrel helps to fit together with split mandrels. Split mandrels are of converging and diverging shapes. These converging and diverging split mandrels are arranged in succession. This arrangement benefits for easy removable of mandrel from part. Initially core mandrel is disassembled from the split mandrel. However, these are difficulty to remove if the end openings are small.

3.1.3 Molded Mandrel

Moldable mandrels are the specially employed for unshaped wound parts comprises of moldable material along with plain mandrel. Molded mandrels have mold patterns on the plain mandrel which is exact replica of the inner part profile. Exact part profile can be achieved using this type of mandrel. Moldable mandrels may be constructed in any conventional molding procedure which is pre processing technique comprises of sand particles and polyvinyl acetate in 100:9 ratio. Extraction of mandrel from the part is done using water. Hence it’s also called as water soluble mandrel.

3.2 Part Description

As shown in the Fig 3-1 is considered for the selection of proper class of mandrel. Industrialization is another best tool for design feasibility. Fig 3-1 represents complex shaped part have inner step profile as well outer curved shape manufactured from filament winding process. Mandrel deflection, material consumption and winding time are considered.

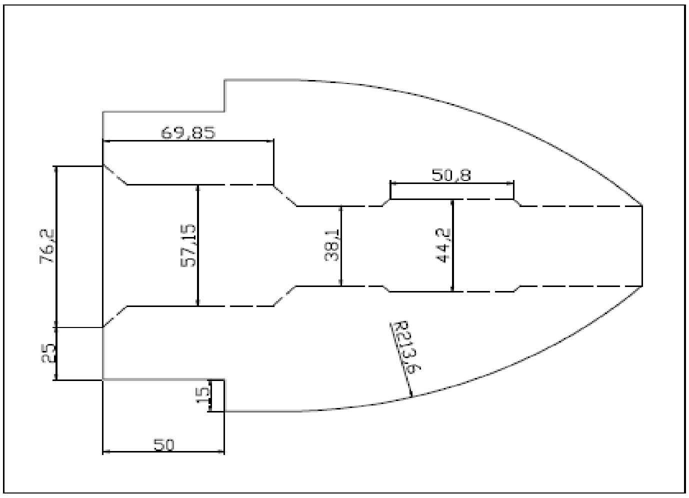


Fig-4: Complex shaped filament wound composite part

3.3 Selection of Mandrel

There are three different types of mandrel are used for filament wound composite tubes. Only plain mandrel and molded mandrel are considered for the industrialization.

3.3.1 Mandrel Deflection

In this section, mandrel deflection is calculated for plain and molded types by considering various lengths. Based on the results obtained from above calculation feasible mandrel is chosen.

Length of the mandrel is varied from 1 to 6m.
Below table shows mandrel deflection results for plain and molded type.

Table – 2: Mandrel deflection results

Length of the mandrel (m)	Deflection (mm)	
	Plain mandrel	Molded mandrel
1	0.35	0.29
2	0.97	0.57
3	4.94	3.52
4	15.96	11.93
5	38.09	30.58
6	78.87	65.52

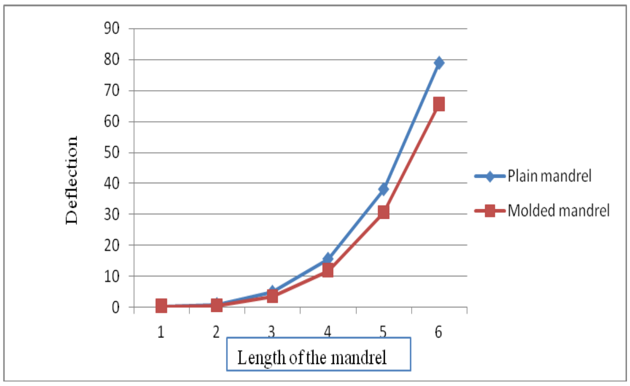


Fig-5: Deflection v/s Length of the mandrel

3.3.2 Material Consumption

Material required to manufacture a part shown in the Fig – 4 using plain mandrel and molded mandrel is calculated. Material consumption is another parameter for selection of mandrel. Length of mandrel is varied and corresponding material consumption is intended.

Material weight = volume of wounded material x Density of material used. Below table represents a comparison between the plain mandrel and molded mandrel considering material consumption parameter.

Table – 3: Material Consumption results

Length of the mandrel (m)	Material consumption (Kg)	
	Plain Mandrel	Molded mandrel
1	33.33	7.81
2	66.61	29.88
3	99.92	59.78
4	133.22	89.68
5	166.53	119.58
6	199.84	149.84

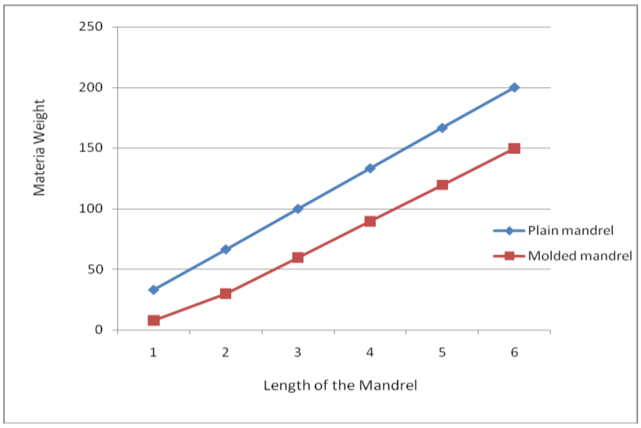
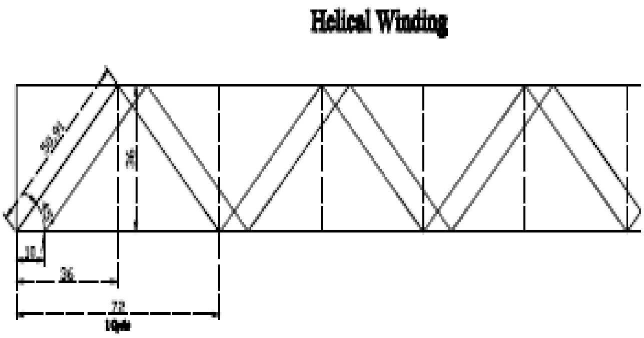


Fig -6 : Material consumption v/s Length of the mandrel

3.3.3 Winding Time

Mandrel selection using winding time calculation is another new concept in this paper. The time taken to complete winding for given part (Fig -4) effects on the production and processing. Time taken to complete the winding is different for different types of mandrel. Here for given part, Hoop and helical winding patterns are considered.



For Plain mandrel:
Mandrel diameter = 36mm
Length of the mandrel = 6m.

From geometry:

$\text{Sin } \theta = \frac{Oppo}{Hypo}$ $\quad\quad$ $\text{Tan } \theta = \frac{0.036}{Y}$

$\text{Sin } 45 = \frac{0.036}{hypo}$ $\quad\quad$ Y = 0.036 m.

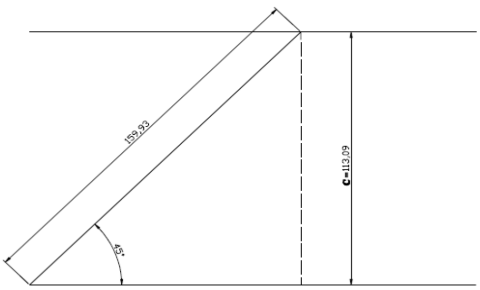
Hypo = X = 50.91mm

For one revolution = 72mm of length is covered.
Total winding length in 6m mandrel is =4800mm
No of revolution required for full length of winding = (4800/72) = 66.66 revolutions.
Speed of the mandrel =100 rpm.
Time taken for one pass $= \frac{66.66}{100}$
= 0.666min. = 39.96 seconds.
Length of the strand covered for 72mm length of the mandrel = 159.93 mm.

$$X = \frac{(\text{Circumference of the mandrel})}{\text{Sin } 45}$$

$$X = \frac{113.09}{\text{Sin } 45}$$

X = 159.93mm



$$\text{No of passes} = \frac{(\text{Surface Area of mandrel})}{\text{Area of the mandrel}}$$

$$= \frac{\pi dl}{(\text{Length of the strand x width of the strand })}$$

$$= \frac{\pi x 0.036 x 0.072}{\left(\frac{2\pi x 0.018}{\sin 45}\right) x\ 0.010)}$$

= 5.091 passes. (Approximately = 6)

Time taken to complete one layer of 45° winding = 6 x 39.96
= 240 sec.
= 4minutes.

Similarly, for hoop winding
i.e. ±88°;

From geometry,

Sin θ = $\frac{Oppo}{Hypo}$ Tan θ = $\frac{0.036}{y}$

Sin 88 = $\frac{0.036}{Hypo}$ 1.257 = $\frac{0.036}{\tan\theta}$

Hypo = X = 36.02mm. Y =1.257 mm

Width of the strand = 10mm
I.e. Y = 10+1.257 = 11.257mm

For one revolution, 11.257mm of winding length is covered.
Total winding length = 4800mm.

No of revolution required full length of winding = $\frac{4800}{11.257}$

=426.40 revolutions.

Speed of the mandrel = 100rpm. = $\frac{426.57}{100}$

= 4.26 minutes.

Total time taken to wind one complete layer of 88° winding = 4.26 minutes.

Each layer thickness calculations:
Bandwidth of the fiber strand = 10mm
No of strands = 12
No of fiber filaments in each strand = 50
Fiber diameter range from = 3 to 20 micrometers.

Each layer thickness = $\frac{(No\ of\ strands\ x\ No\ of\ fiber\ filaments\ in\ each\ strand\ x\ fiber\ dia)}{Fiber\ bandwidth}$

Each layer thickness = $\frac{(12\ x\ 50\ x\ 20\ x\ 10\ E{-}3)}{10}$

= 1.2mm

Winding patterns for given part is alternate 3 layers of helical winding and 2 layers of hoop winding.
Total part thickness is = 57 mm

No of layers required to achieve part thickness is = 69
(Total 24 Hoop and 36 helical windings are compulsory)

Time for Helical winding = 36 x 4 = 144 minutes.
Time for Hoop winding = 24 x 4.28 =102.72 minutes.
Total time taken to complete 4800m winding is 246.72 minutes. I.e. 4.106 hours.

Based on the no of layers and winding patterns total winding time is formulated and below table represents the winding time for plain mandrel and molded mandrel for different lengths of mandrel.

Table- 4: Winding time results

Length of the mandrel (m)	Winding time (in hours)	
	Plain Mandrel	Molded mandrel
1	0.411	0.096
2	0.821	0.368
3	1.642	0.983
4	2.463	1.657
5	3.284	2.358
6	4.106	3.078

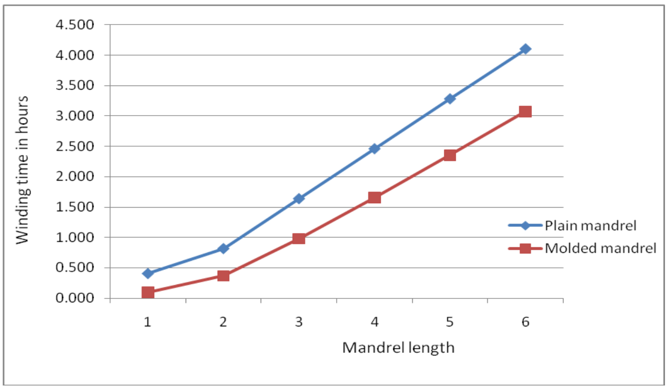


Fig -7 Winding time v/s mandrel length

4. ANALYSIS OF FILAMENT WOUND TUBE

Analysis performed on the filament wound composite tube using HYPERMESH and NASTARN software is the one of the leading parts of these studies. In the most of these studies the effects of winding angle on the strength of filament wound composite tubes are investigated. These investigation results are compared with ANSYS results and briefly explained about FEA simulation of filament wound composite tube using NASTRAN.

4.1 Modeling of Composite Tubes

Structural analysis is performed in order to investigate the behavior of layered orthotropic tubes with different materials. Level of orthotropy is also performed considering same winding angle with different materials. Internal pressure loading conditions are considered. The model is prepared with MAT8 and PCOMP card property in NASTRAN. As shown in Fig – 6 this model is constraint at one node at the end of the tube in all degrees of freedom in order to prevent instability in finite element analysis and internal pressure is applied at the inner surface of the tube. Dimension of the tube used in this study are given in Table-3.

Table -5: Dimension of the tube

Length of the tube	400mm
Average radius	60.565mm
Tube thickness	1.13mm
No of layers	6
Each layer thickness	0.1883mm

4.2 Results and Discussion

In this analysis, Carbon/Epoxy, E-Glass/Epoxy tubes are subjected to internal pressure of 12.6MPa. All deformation and stresses in corresponding directions are collected. Result validation is done, by performing similar analysis to the experimental and ANSYS results performed in literature [10]. NASTRAN and ANSYS results are very close to the experimental results, although some scattering involved in the experimental results. It's important to note that FEA results observed for composite analysis is stiffer than the experimental. Experimental results and material properties are taken from the [10].

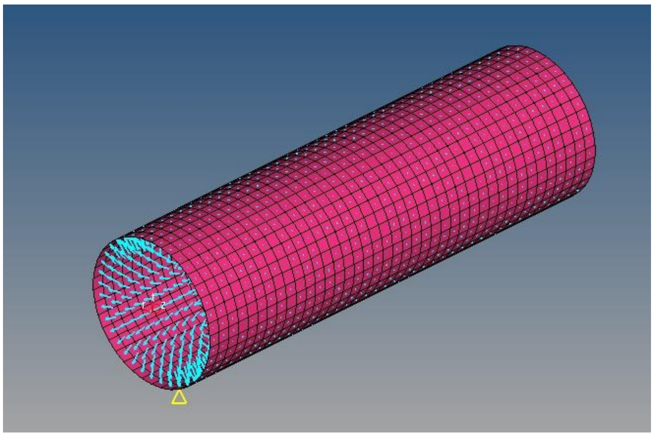
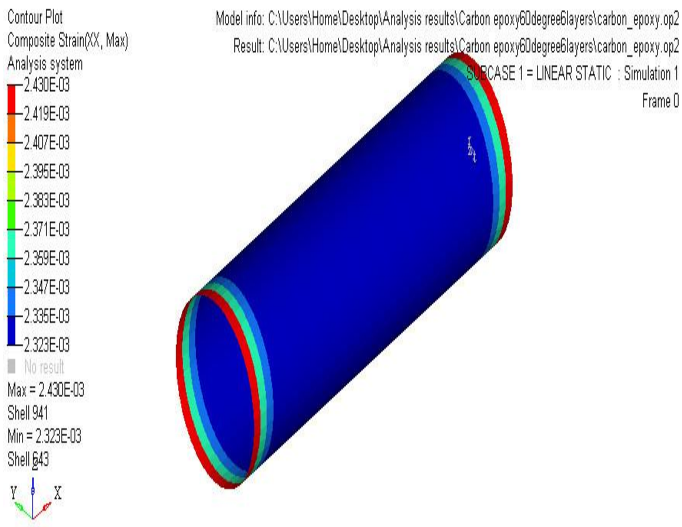


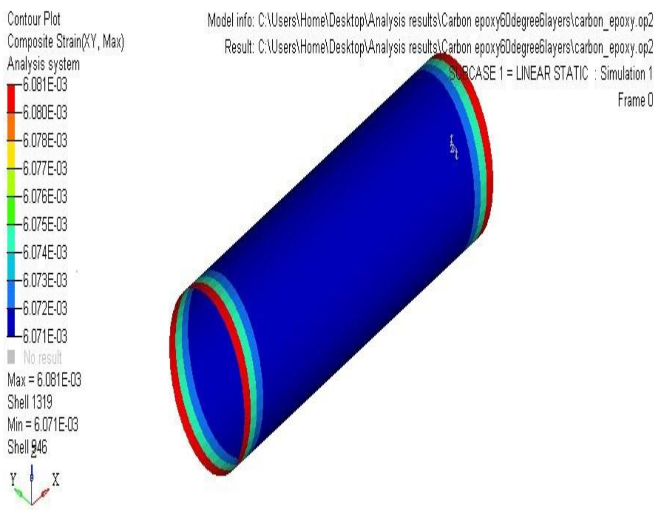
Fig-8: FEA Model of filament wound composite tube using HYPERMESH.

Table -6: Validation results

Test Type	Material	Experimental results[	FEA results using ANSYS	FEA results using NASTRAN
Internal pressure of 12.6 MPa	Carbon/ Epoxy	Axial Strain = 2.290E-3	Axial Strain= 2.023E-3	Axial Strain= 2.430E-3
		Hoop Strain= 7.665E-3	Hoop Strain= 6.251E-3	Hoop Strain= 6.6081E-3



(a)



(b)

Fig – 9(a) (b) NASTRAN Results

In the first analysis, 6 layers, ±60̊ wound, C/Ep tube subjected to pure internal pressure of 12.6MPa. Stresses and strains are obtained for each layer. Then in order to investigate the effect of winding angle on stresses and strains in each layer, the same analysis is performed for ±75̊ wound, 6 layer, C/Ep tube. Finally in order to investigate the effect of level of orthotropy , the same procedure is performed for 6 layer, ±60̊ wound, Eg/Ep tube.

Stress and strain levels are represented as shown in Fig -10 to Fig- 14

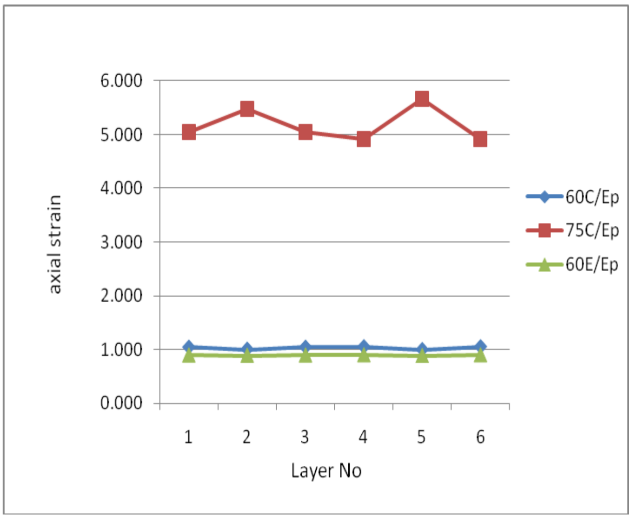


Fig -10 : Axial strain vls Layer No

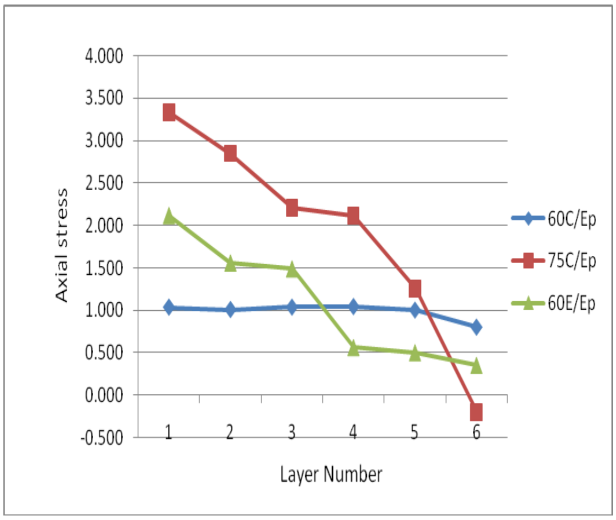


Fig – 13 :Axial stress v/s Layer No

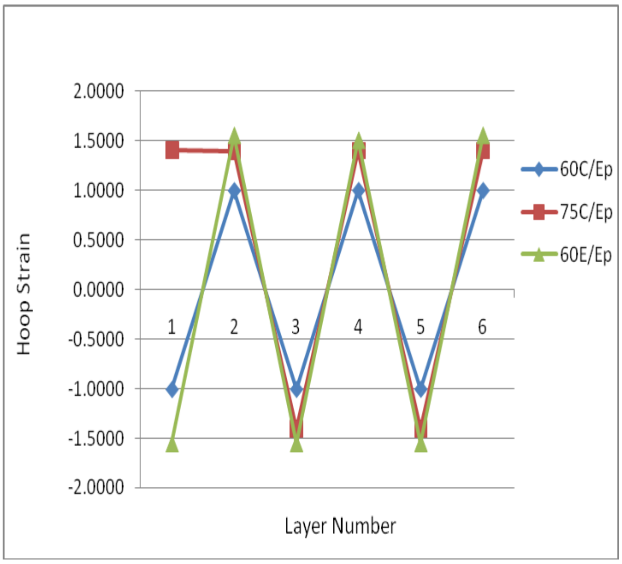


Fig -11 : Hoop strain v/s Layer No

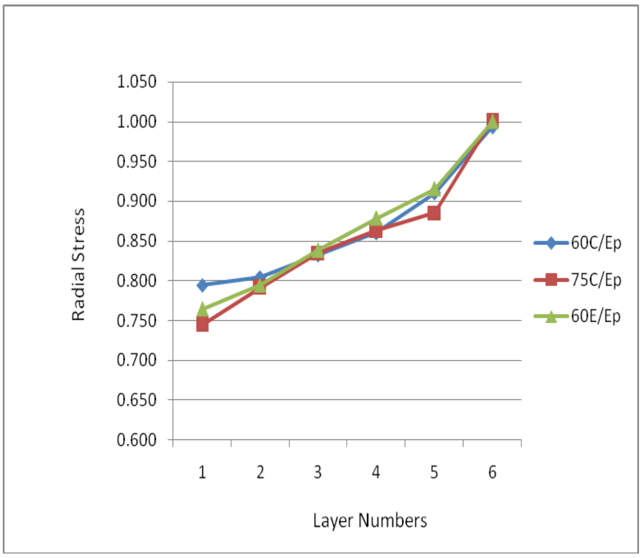


Fig – 14 : Radial stress v/s Layer No.

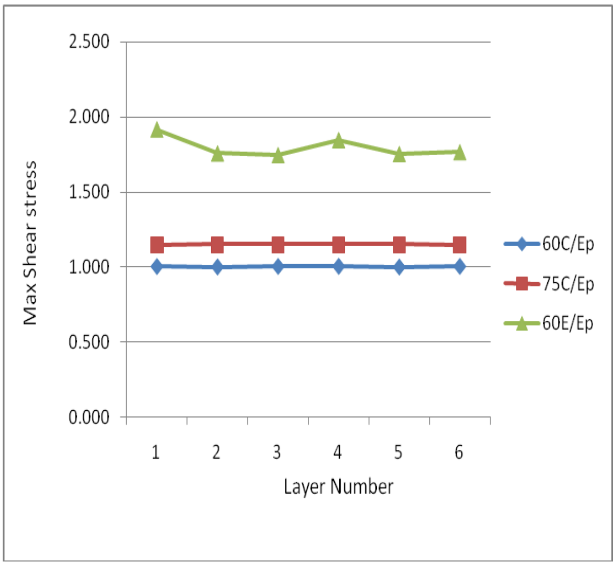


Fig – 12 : Shear stress v/s Layer No

In second type of analysis, composite tube comprises of multiple of layers wound at different angles subjected to internal pressure loading is considered. Three different winding angles are considered. In previous analysis only effects of repeating winding angles and level of orthotropy is studied. Three different winding patterns for three different tubes are chosen for the analyses. An internal pressure loading condition is considered.

Table 3.8 Different winding patterns for Tube 1, 2 and 3.

Layer No	Tube 1	Tube 2	Tube 3
1	25	25	90
2	-25	-25	-90
3	45	55	45
4	-45	-55	-45
5	90	90	25
6	-90	-90	-25

Following results obtained and represented from Fig 15 to Fig - 18

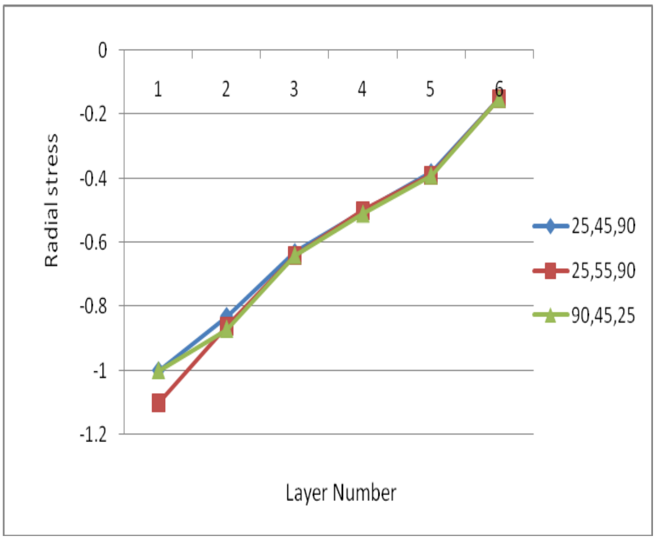


Fig – 15: Radial stress v/s Layer No

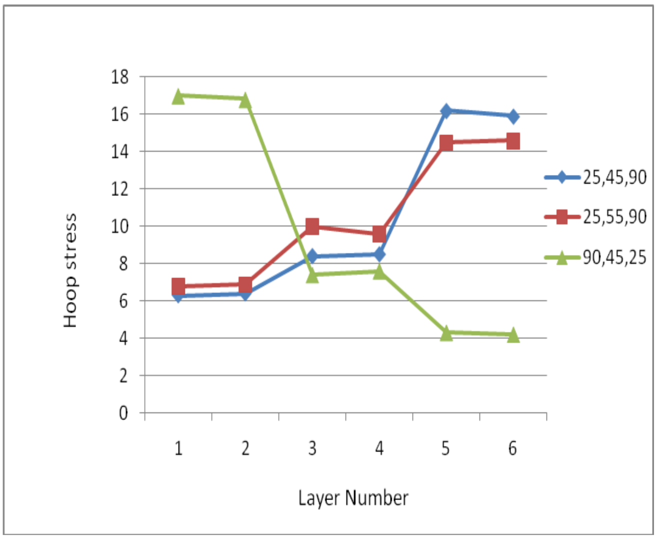


Fig – 16: Hoop stress v/s Layer No.

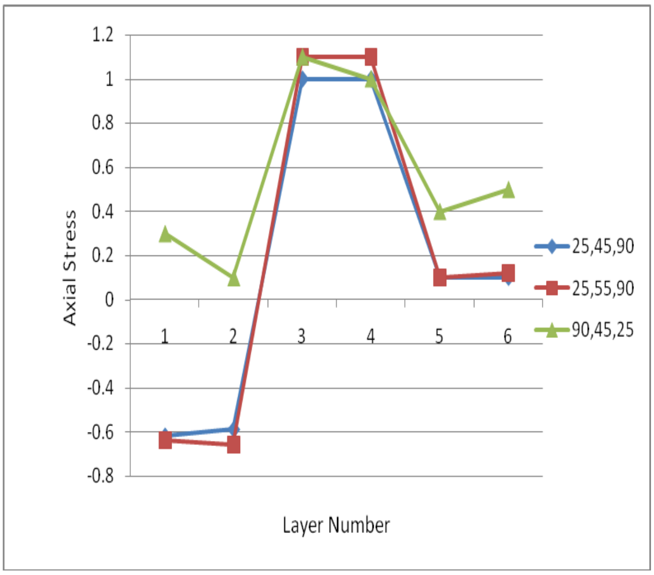


Fig -17 : Axial stress v/s Layer No

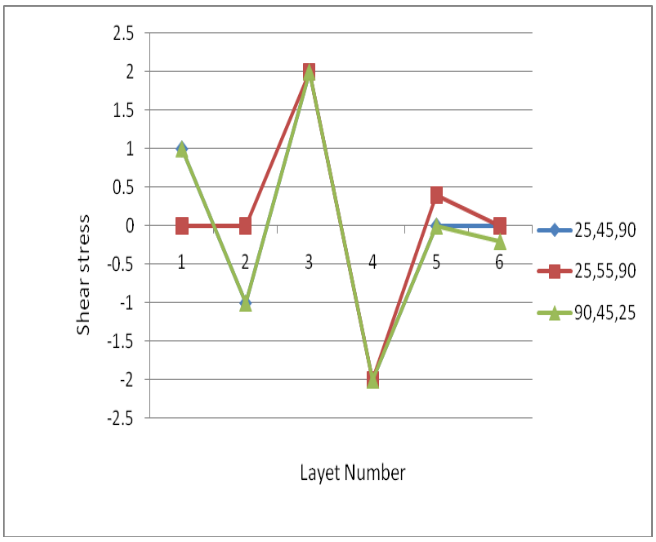


Fig -18 : Shear stress v/s Layer No.

5. CONCLUSION

Most of the composite manufacturing industries have continuously seeking for the advanced or/and improved manufacturing techniques in order to meet global market acceptance. In this scope of the work, layup process improvement related to noodle pressing tool has carried out. Proposed tool has improved manufacturing capabilities like length of the noodle stick which adversely effects in the production rate and most importantly focused on structural integrity and distortion factors. Also some of the factors also discussed related to quality. Another development related to filament winding has proposed. pain mandrel, segmented mandrel, molded mandrel are considered for the complex shaped parts and selection of mandrel is carried out based on the industrialization concept. Mandrel deflection, material usage and winding time are performed for the feasibility. Based on result as shown in (Fig – 5, 6, 7) molded mandrel is chosen for given part. Third part of this paper is worked on effect of winding angle on the filament wound composite tube using NASTRAN software. Results as shown in Fig 9 to Fig 18.

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