SASTRA
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MAJOR-PROJECT FINAL REVIEW

COMPUTATIONAL STUDY ON THE DEPLOYMENT DYNAMICS OF LENTICULAR COMPOSITE BOOM

GUIDED BY

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B TECH. AEROSPACE ENGINEERING

SCHOOL OF MECHANICAL ENGINEERING

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OUTLINE

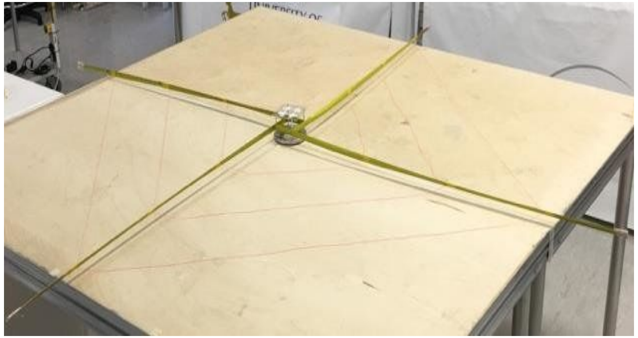
- Introduction
- Problem Statement
- Objective
- Literature Review
- Methodology
- Results and Discussion
- Conclusion
- References

Credit: NASA

INTRODUCTION

- Booms are structures that are used in space vehicles used to position equipment in optimal location for various functions like data collection, communication.
- Booms are more advantageous when they are **deployable.**
- Thin walled **high strain composite** booms can replace the existing metallic structures.
- The boom is extremely lightweight for its length and has a great deployed-to-stowed length ratio.
- **Lenticular** booms are preferred over other cross sectional shapes.
- This can minimize the attitude control interactions.

Credits: NASA

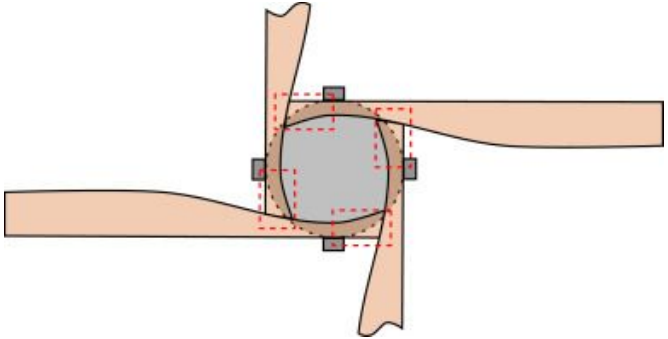


Credits: JAXA

PROBLEM STATEMENT

- Folding and deploying of long metallic structural booms from small spaces of a spacecraft is quite difficult.
- Composite structures with lenticular cross section have been tried to overcome this.
- However, they do not work efficiently under certain dimensional constraints.

Credit: NASA



MOTIVATION:

The technological development is at its peak. Therefore it is necessary to develop and analyse the most efficient solutions for composite structures.
The Aditya L1 mission also employs carbon fibre booms as magnetometer boom.

Credit: ISRO

OBJECTIVE :

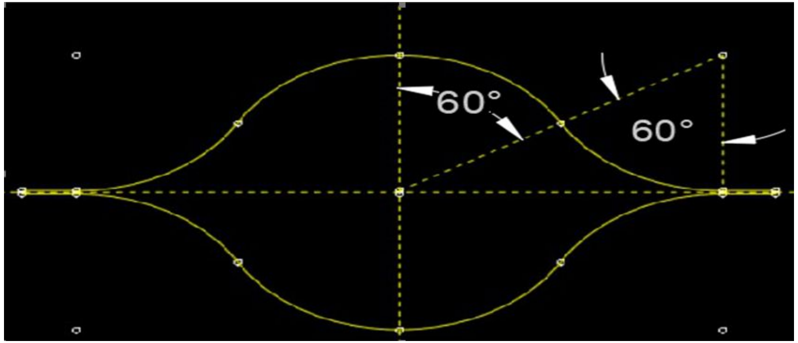
- To computationally analyze the deploying mechanism on various lenticular booms.
- To explore the dynamics of the process.
- This would be done by varying the cross sectional parameters which are curvature radius, length and stowing drum radius.

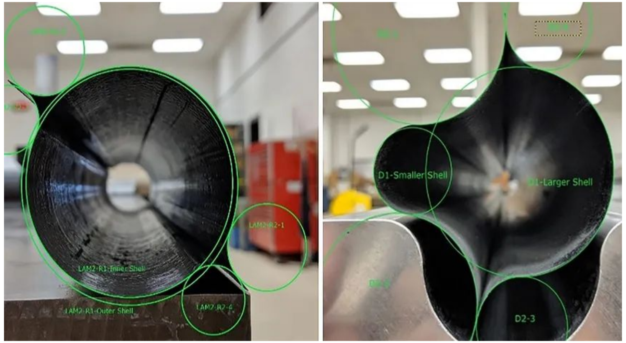
Why High-Strain Composites?

- High Strain Composite (HSC) are a class of composite material structures designed to perform in a high deformation setting.
- High strain composite structures transition from one shape to another upon the application of external forces.
- A single HSC Structure component is designed to transition between two or more different shapes.

What is a Lenticular cross-section?

- Lenticular shape is similar to that of biconvex lens with 60° as subtended angle.
- Lenticular booms depicts effective strain energy characteristics when compared with other cross sections such as circular or semi circular structure.
- This was also verified with the analysis with various other closed cross sectional geometry with different subtended angles.





Credit: *NASA*

APPLICATIONS

- ❖ The outcomes will contribute to development of the Wrapped Rib Antenna (WRA). WRA is the state of art technology in the field of large deployable mesh antennas.
- ❖ It has potential use in GEO/LEO spacecraft cargo space optimization

Credits: ISRO

LITERATURE REVIEW

- ★ Fundamentals of STEM mechanics (2000)
- ★ Development Dynamic of composite booms with integrated slotted Hinges.
- ★ Folding Analysis for thin walled deployable composite boom — Acta Astronautica (2019)
- ★ Design, modelling, analysis and development of deployable tubular metallic booms for space application (2020)
- ★ Effects of Long-Term Stowage on the Deployment of Bistable Tape Springs (2021)
- ★ Effects of Fibre non Linearity and matrix type on the realization of foldable structures (2021)
- ★ Deployment analysis of composite thin-walled lenticular tubes with effect of storage time and temperature (2023)
- ★ Folding, stowage, and deployment of composite thin-walled lenticular tubes (2023)

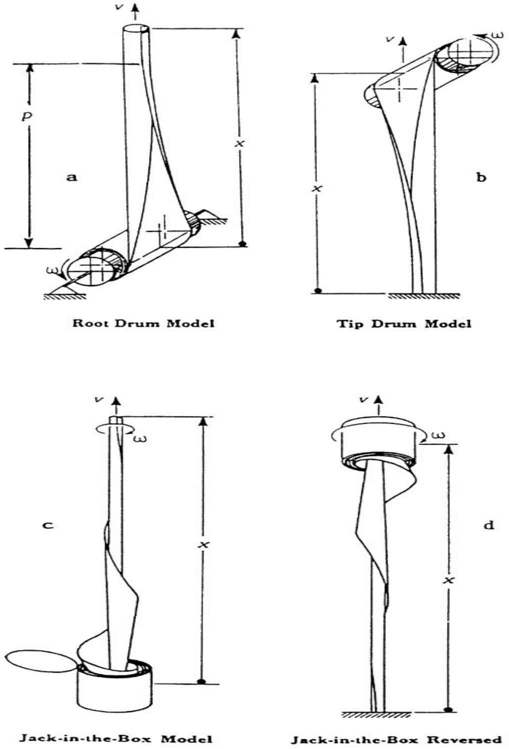
FUNDAMENTALS OF STEM MECHANICS

F.P.J. Rimrott and G.Fritzsche, 2000

OBJECTIVE: Understanding and analysing Deployable slit overlapped tubing (STEM) characteristics and material suitability

METHODOLOGY: Formulae for analysing coiling capability, ploy region, shear centre, self extension velocities were applied considering the 4 different types of stem extension techniques.

CONCLUSION: Few fundamental characteristics of STEM were analysed due to space limitations of the typical STEM structure.



From ref. 1

DEVELOPMENT DYNAMICS OF COMPOSITE BOOMS WITH INTEGRAL SLOTTED HINGES

H.M.Y.C. Mallikarachchi and S. Pellegrino, 2009

OBJECTIVE: The dynamic deployment behaviour of stored energy in deployable structures made of composites.

WORK CARRIED OUT:

- Experimental analysis through various tests
- Simulation and computation through matlab and ABAQUS

MATERIAL USED: Plain-weave carbon fibre fabric (1k tons of T300 fibres) impregnated with HexPly 913 epoxy resin.

CONCLUSION:

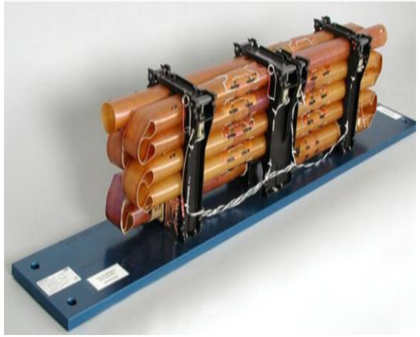
From ref. 2

- Dynamic behavior is classified into three phases:
  - Deployment phase
  - Incomplete latching and large rotation phase
  - Vibration phase
- The most critical phase is the second phase with strain in fully loaded configuration for 45 deg folded boom is 30% lower than peak value
- The presence of gravity effects had significant effects on the second phase of the boom.

EFFECTS OF LONG TERM STOWAGE OF DEPLOYMENT OF BISTABLE SPRINGS

Alex Brinkmeyer, Sergio Pellegrino and Paul M. Weave, 2016

From ref. 3



OBJECTIVE: To analyse the effects of temperature and deformation history on dimensional stability and deployment accuracy.

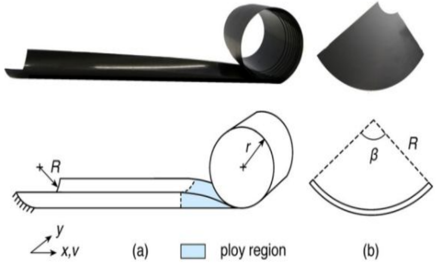
WORK CARRIED OUT:

- Geometry and stowage was modeled.
- Stability is found using analytical model & verified using lamination parameters.
- Deployment study for various stowage types & compared with experimental tests

MATERIALS: Thin-Ply T800H, an ultrathin unidirectional carbon fiber prepreg.

CONCLUSION:

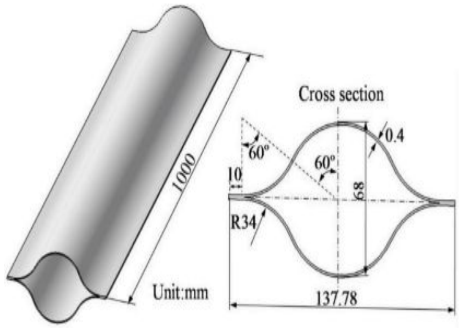
- Stowing the structure at higher temperatures or for longer periods of time increases the dynamic deployment time of the structure.
- Reduction in stored energy is used to eliminate dynamic latching effects.
- Such a structure needs minimal energy for deployment, simplifying the design and leading to smaller and lighter actuators.



FOLDING ANALYSIS FOR THIN WALLED DEPLOYABLE COMPOSITE BOOM

Jiang-Bo Bai , Di Chen , Jun-Jiang Xiong , R. Ajit Shenoi, 2019

From ref. 4



TESTS CARRIED OUT:

- Large deformation function tests for Tensile, Compressive & Folding Behaviours.
- Geometrically non-linear explicit behaviours using Finite Element Method.

MATERIAL USED: Carbon Fibre T300/5228A Prepreg

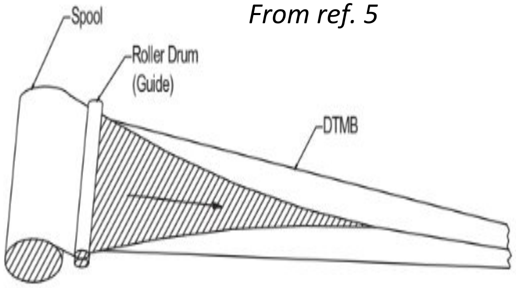
CONCLUSIONS:

- Carbon Fibre deforms and recovers Elastically
- Their load displacement curves are non-linear
- Maximum Stress of the DCB in large folding deformation are much less than their ultimate strengths.

DESIGN, MODELLING, ANALYSIS AND DEVELOPMENT OF DEPLOYABLE TUBULAR METALLIC BOOMS FOR SPACE APPLICATIONS

Gaurav Sharma, S.N. Omkar, H.N. Suresha Kumar, S. Narendra, 2020

From ref. 5



OBJECTIVE: Modelling of DTMB considering the non-linearity of the material.

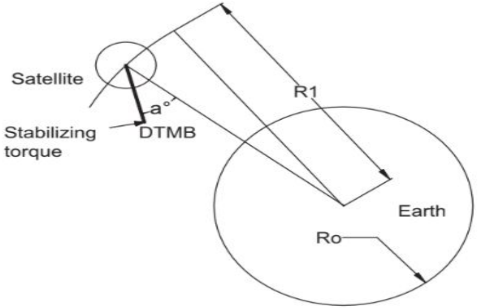
TESTS CARRIED OUT:

- ➢ Design Analysis
- ➢ Stress analysis
- ➢ Length of the transition zone (using analytical method)

MATERIAL USED: Be-Cu with constant Young's Modulus, Yield Strength & Poisson's ratio

CONCLUSIONS:

- ➢ The stress curves are constant for experimental and computational analysis
- ➢ Load deflection curve is not consistent.



EFFECTS OF NON LINEARITY AND MATRIX TYPE ON THE REALIZATION OF FOLDABLE STRUCTURES

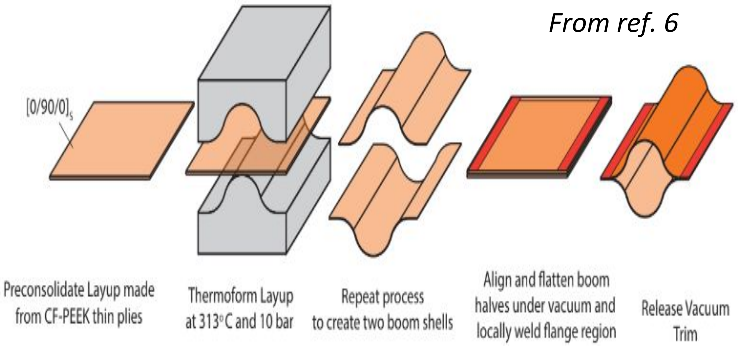
Arthur Schlothauer, Dominik Cueni, Georgios A. Pappas, Paolo Ermanni, 2021

OBJECTIVE: Quantification of non linear effects & their influence on overall structural design & layup choice.

TESTS CARRIED OUT:

- ➢ Non linearity model
- ➢ Modelling and comparison of CF PEEK with CF epoxy
- ➢ Layup design for HSC
- ➢ Designing Thermoplastic HSC boom

From ref. 6



MATERIAL USED: Autoclave cured T700 Carbon Fibre

CONCLUSIONS:

- ➢ Non linearity has an enhancing effect to performance of structures that have tight packaging constraints
- ➢ Low transverse tensile stress due to high transverse strength.
- ➢ Asymmetric layups can enhance highest packaging efficiencies.

DEPLOYMENT ANALYSIS OF COMPOSITE THIN-WALLED LENTICULAR TUBES WITH EFFECT OF STORAGE TIME AND TEMPERATURE

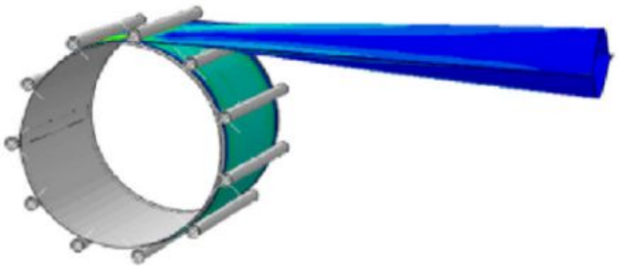
Jinfeng DENG, Ning AN, Qilong JIA, Xiaofei MA, 2023

OBJECTIVE: Analyse the characteristics of coiling mechanics of CLCT and understand the deployment dynamics.

TESTS CARRIED OUT:

- Coiling
- Controlled Deployment
- Free Deployment

From ref. 7



MATERIAL USED: T300/5228A Carbon Fibre

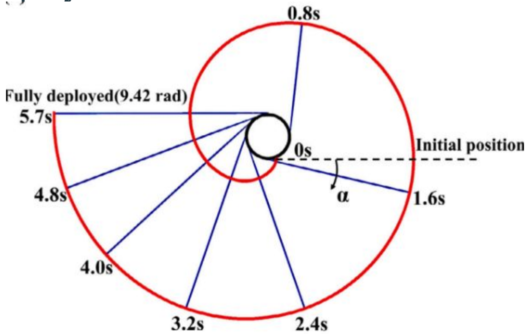
CONCLUSIONS:

- The strain energy plots were analysed and also very with the experiment data.
- The shape recovery factor and the rotational moment was studied during the deployment process.
- It was found that the free deployment induces more dynamics when compared to that of controlled deployment.

FOLDING, STOWAGE AND DEPLOYMENT OF COMPOSITE THIN-WALLED LENTICULAR TUBES

Ruiwen Guo, Xin Jin, Qilong Jia, Ning AN, Qilong JIA, Xiaofei MA, Jinxiong Zhou, 2023

OBJECTIVE: To understand the effect of storage time on the deployment behaviour.



From ref. 8

TESTS CARRIED OUT:

- Deployment Experiment (before and after stowage)
- FEM model analysis

MATERIAL USED: T300/5228A Carbon Fibre

CONCLUSIONS:

- From the results, it was concluded that after being stowed for a period the deployment becomes slower.
- For a period of 6 months, the deployment time was increased by 8.2% and for a period of 10.5 months the increase in time was found to be 15%.
- The long-term storage effect was accounted for in the numerical analyses with the use of a viscoelastic fiber-reinforced composite material model.

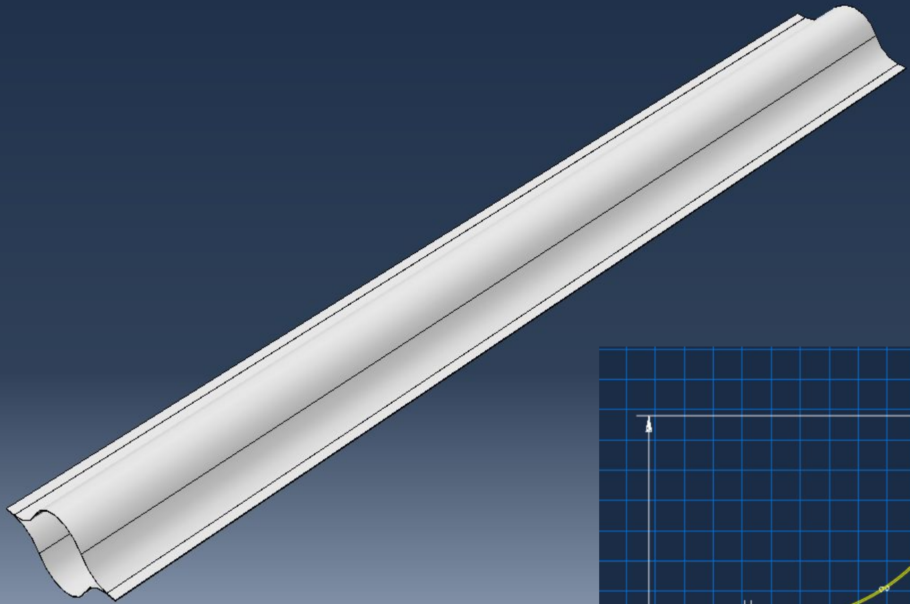
LITERATURE SURVEY - Critical observations

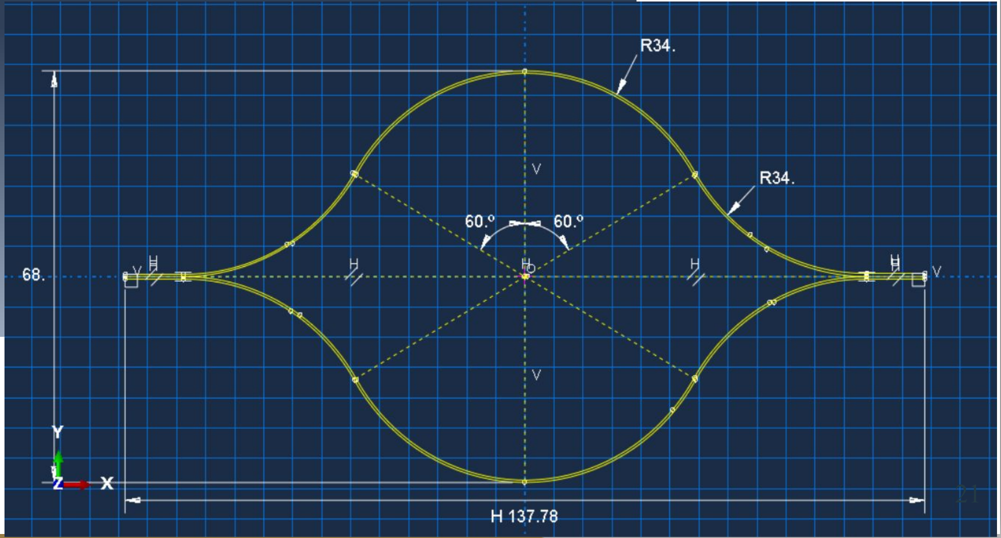
- ★ Different types of coiling and deploying methods of STEM
- ★ Understood the dynamic behaviour of booms with slotted hinges and gravity effects
- ★ Stowing the structure at higher temperatures or for longer periods of time increases the dynamic deployment time of the structure.
- ★ Reduction in stored energy is used to eliminate dynamic latching effects.
- ★ Maximum stress developed on the DCB during tensile and folding test are much lesser than its ultimate Strength
- ★ Carbon fibre coils and deploys elastically
- ★ Folding of Metallic booms creates permanent deformation of the structure which makes the load deflection curve inconsistent.
- ★ Non linearity characteristics contributes to higher packing efficiency.
- ★ Epoxy matrix shows higher thermal characteristics when compared to PEEK matrix
- ★ For a period of 6 months, the deployment time was increased by 8.2% and for a period of 10.5 months the increase in time was found to be 15%.

METHODOLOGY

- ❖ Models of various Lenticular structures were designed in **ABAQUS (Ver.2024).**
- ❖ The parameters varied were radius of curvature of the composite sheet by fixing ply configuration.
- ❖ The analysis would be done for a model length of 1 m, 1.5m and 2m.

MODELLING	Designing of different Booms with various combinations of cross sectional parameters and stowing drum
MATERIAL	Defining the material properties of Carbon fibre Composite (T300/5228A)
LOAD & CONSTRAINTS	Contact between surfaces: Surface to surface contact and self contact Constraints: Rigid body constraint, Coupling
MESHING	Optimal Mesh size
RESULT	Validation study,Winding of plate, Static Test, Coiling of Boom





*All dimensions in mm

Parameters

Radii of Curvature : 34 mm 12 mm 7 mm

Length of the boom : 1 m 1.5 m 2 m

Radius of the Central drum : 80 mm 300 mm

Material properties

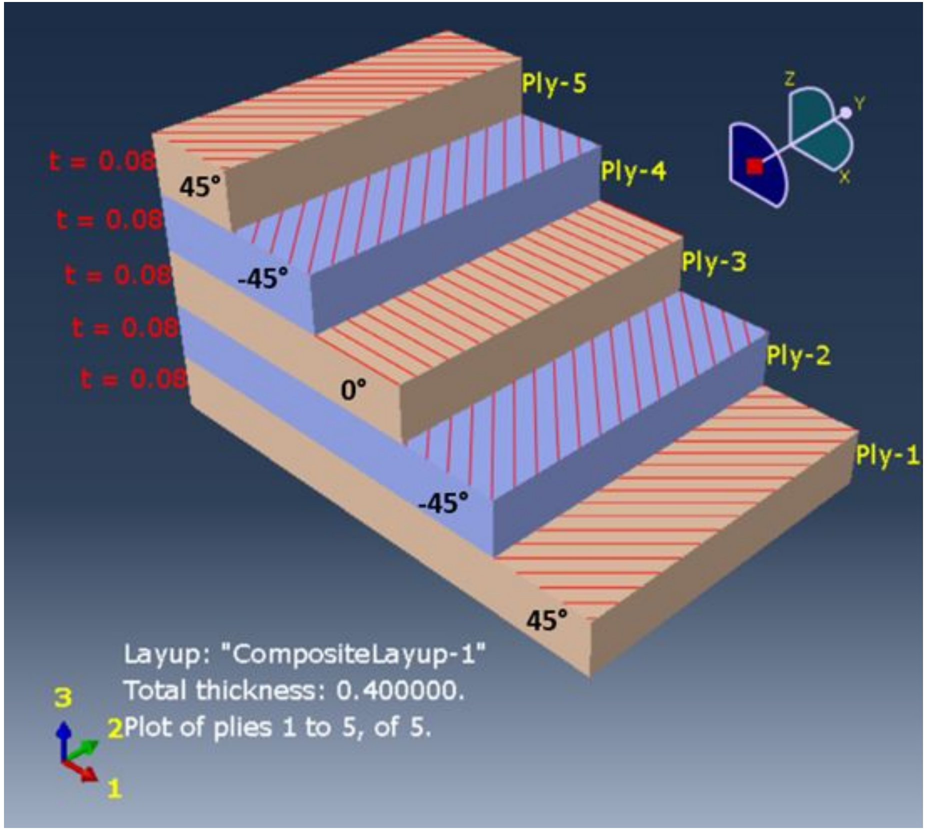
DENSITY : 1.6e-9 tonne/mm^3

E_1	E_2	E_3	μ_{12}	μ_{13}	μ_{23}	G_{12}	G_{13}	G_{23}
80080	6670	6670	0.34	0.34	0.036	2930	2930	2500

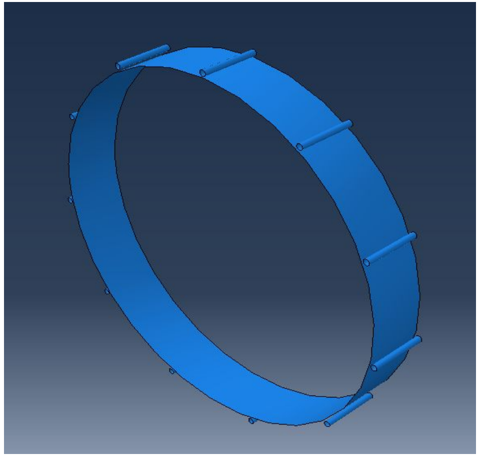
E - Young's Modulus *(MPa (Megapascal))*
µ - Poisson's ratio
G - Rigidity Modulus *(MPa)*

**Values were taken from base paper*

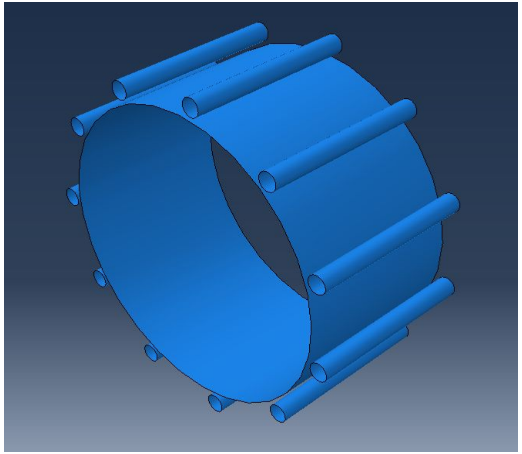
Ply orientation : 45°/-45°/0°/-45°/45°



Assembly



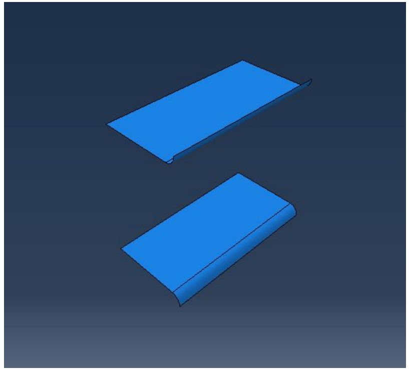
Radius = 300 mm
20 Shafts



Radius = 80 mm
11 shafts

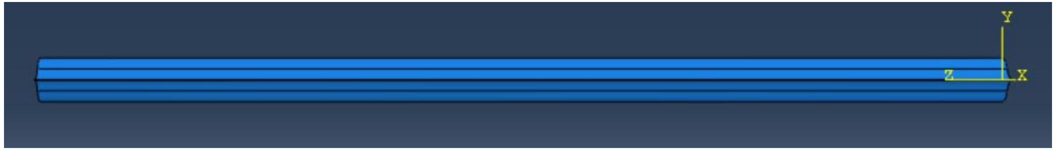
Central Drum along with the shafts

Assembly



Flattening plates

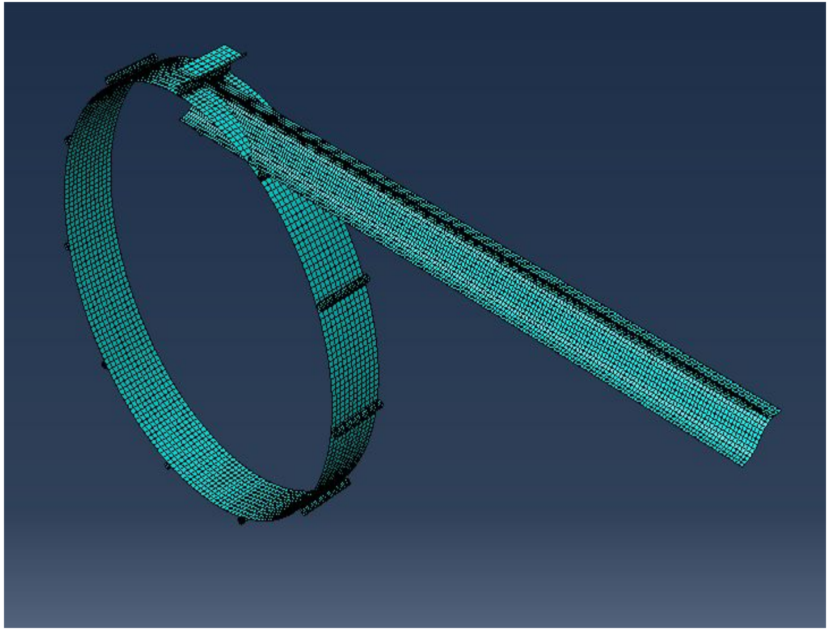
1 m

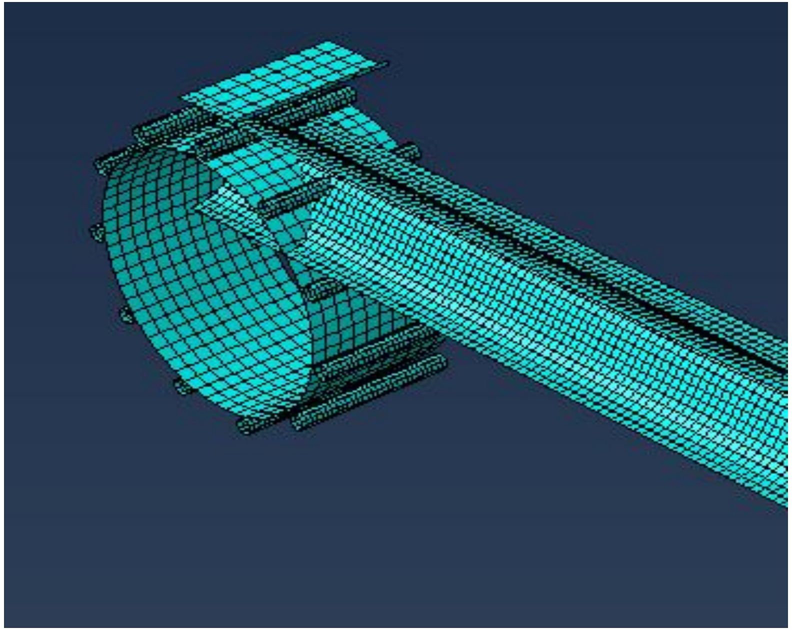


1.5 m

2 m

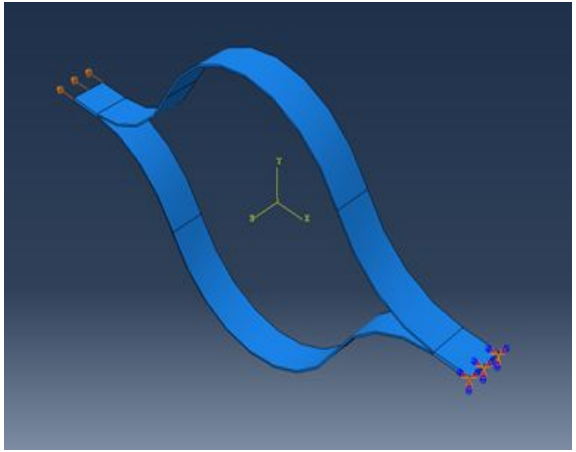
Assembly



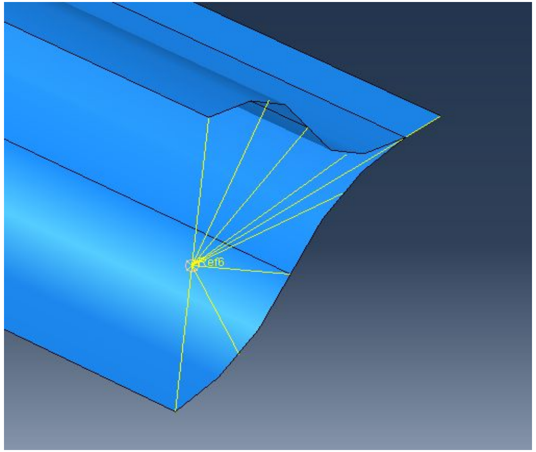


Meshing

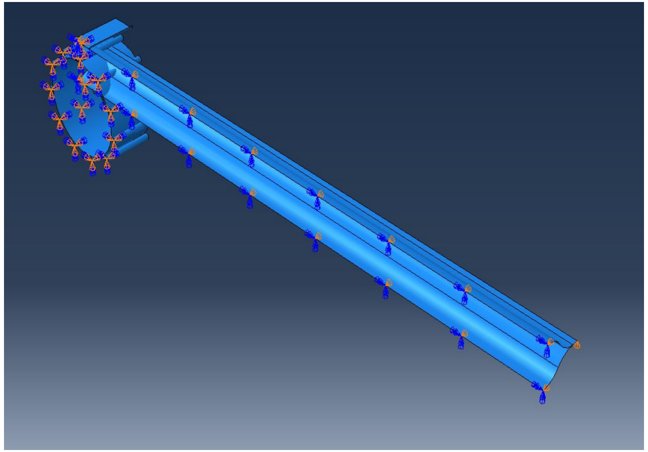
Load & Boundary conditions



Displacement load & Encastre



Coupling

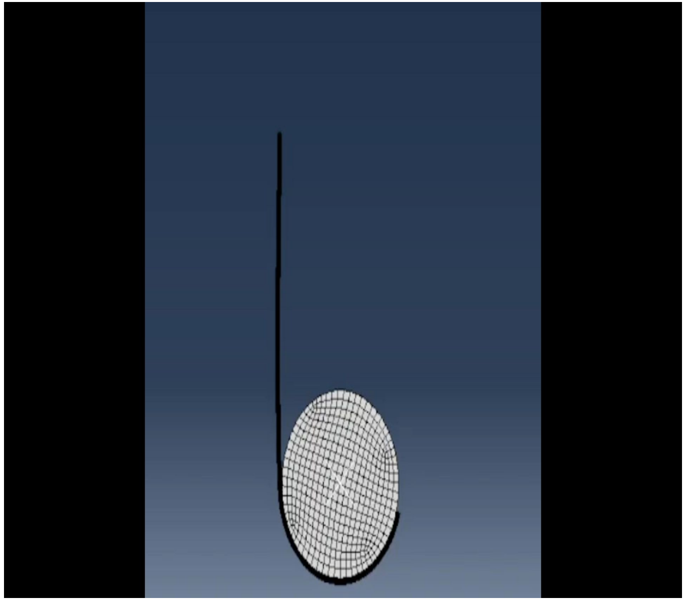


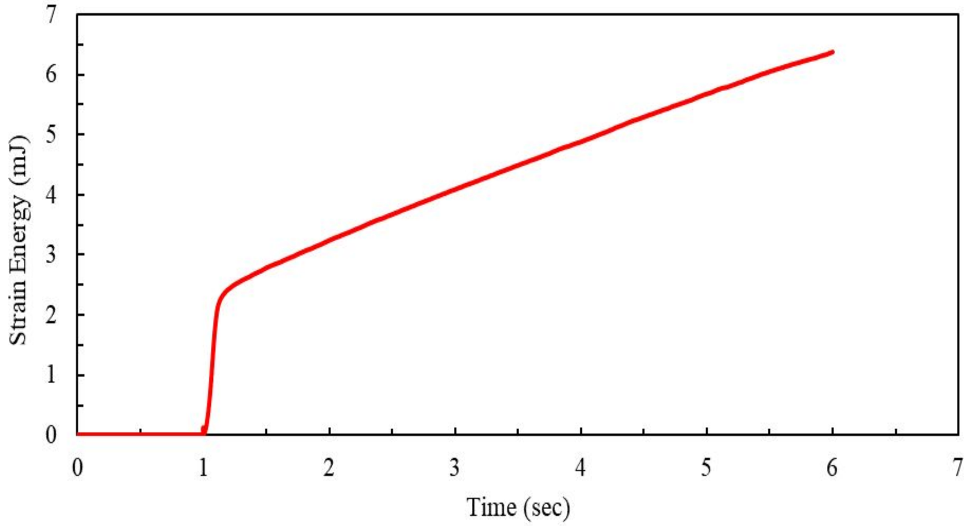
Rotational displacement

RESULTS AND DISCUSSION

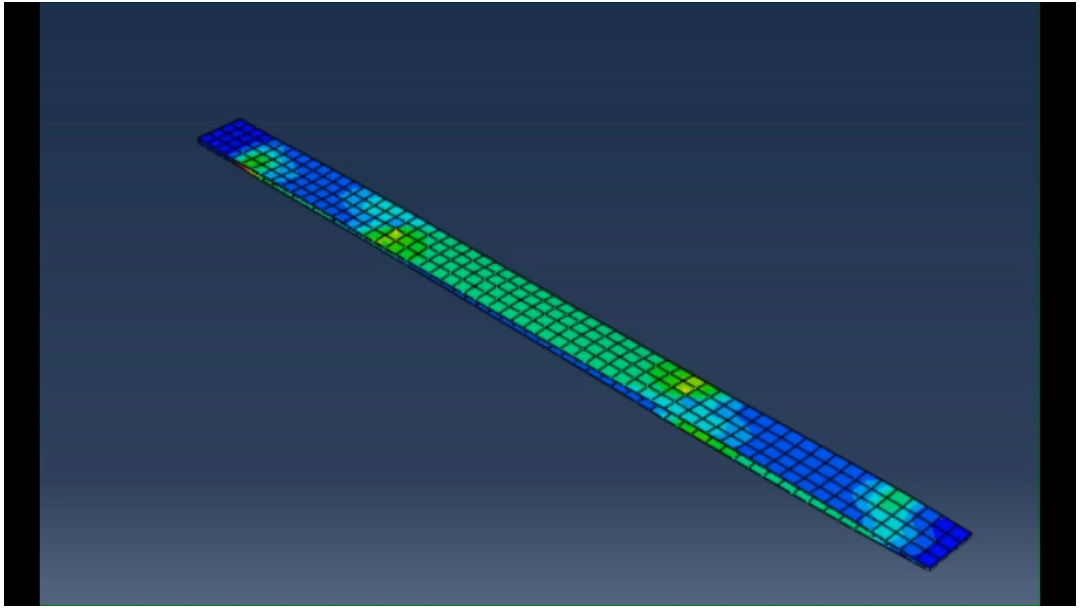
1. Initial Study
2. Static Test
3. Dynamic Test

1. INITIAL RESULTS

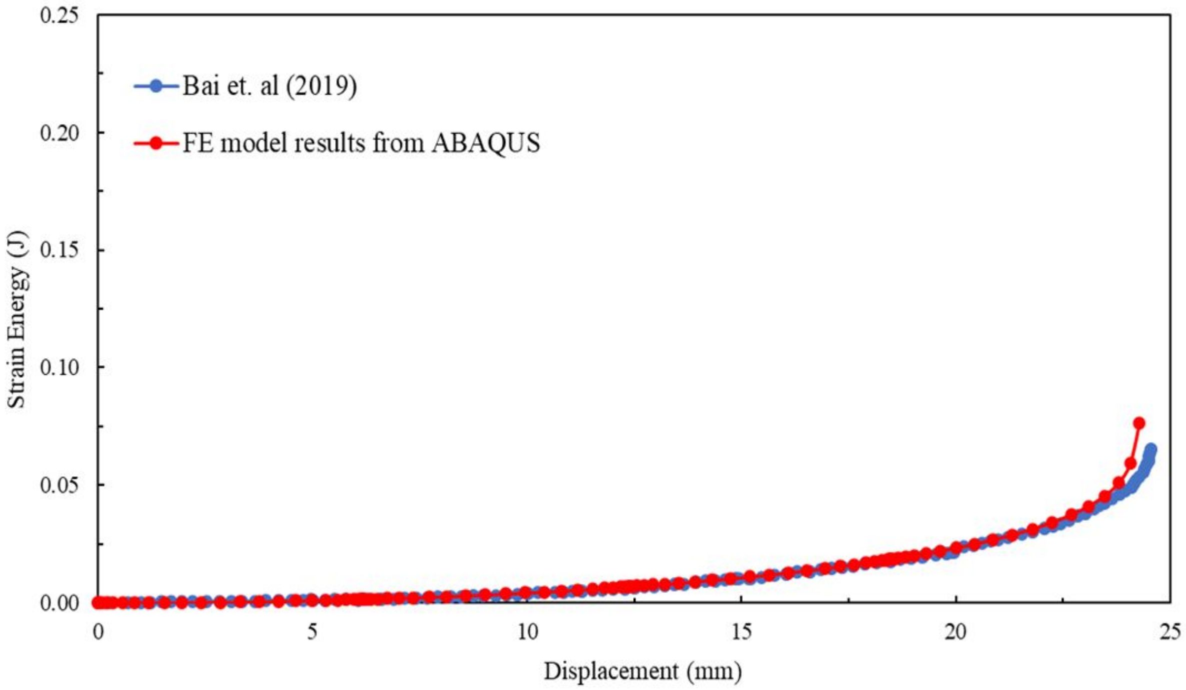




2. PRELIMINARY STATIC TEST



2.1 Validation Study



2.2 Theoretical Validation

$$U = \frac{Et^3}{12}\left\{\frac{L_1}{r_1^2} + 2\frac{L_2}{r_2^2}\right\}$$

$$L = r\theta$$

$$\begin{aligned} E &= 80080\,MPa \\ L_1 &= 71.20943\,mm \\ L_2 &= 35.604732\,mm \\ r_1 &= r_2 = 34\ mm \\ t &= 0.4\,mm \end{aligned}$$

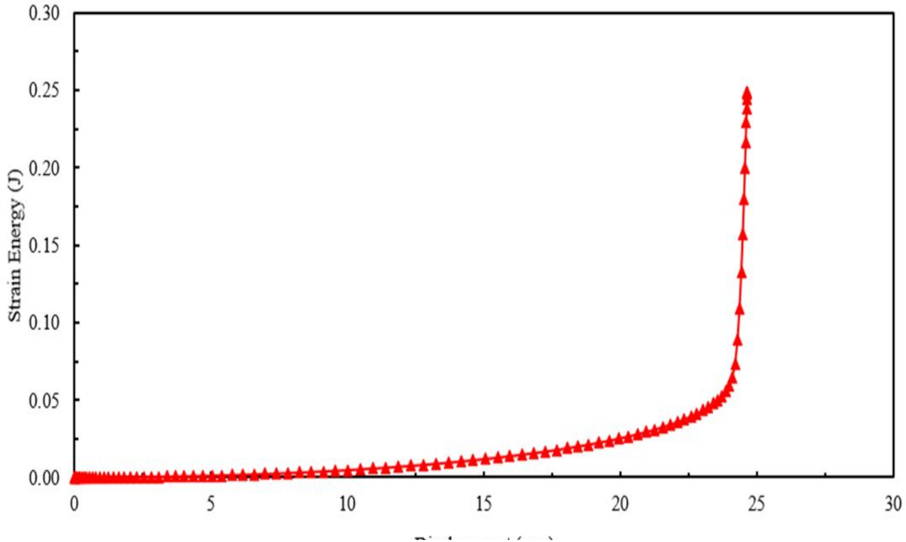
$$U = \frac{(80080)(0.4)^3}{12}\left\{\frac{71.21}{34^2} + \frac{(2)35.60}{34^2}\right\}$$

$$U = 52.06\,mJ$$

From Bai et. al. (2019), U = 50 mJ

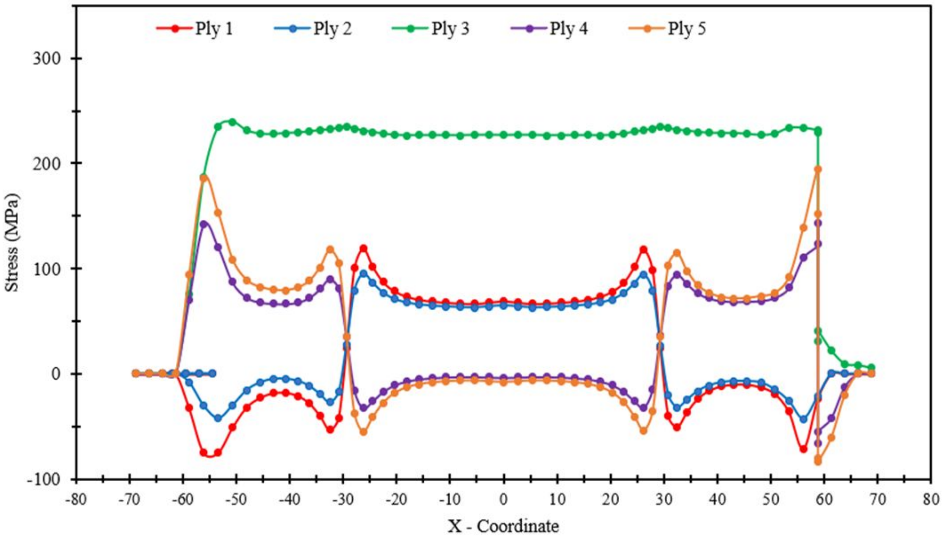
Variation from theoretical results = 4 %

2.3 Strain Energy



- At the point of flattening strain energy is around 0.05 J
- Sudden rise in strain energy is noticed due contacts between the upper and lower surfaces
- The maximum strain energy stored in the model was found to be 0.2488 J

2.4 Stress Distribution

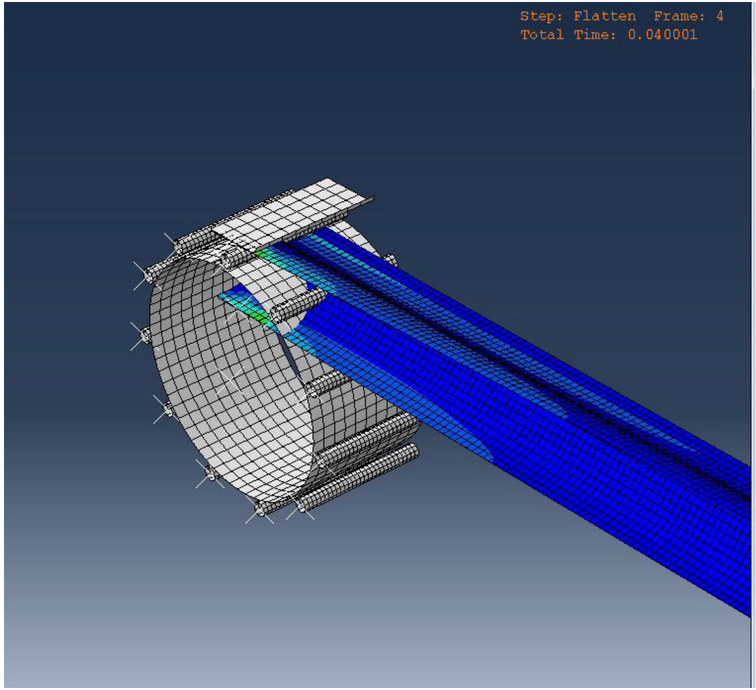


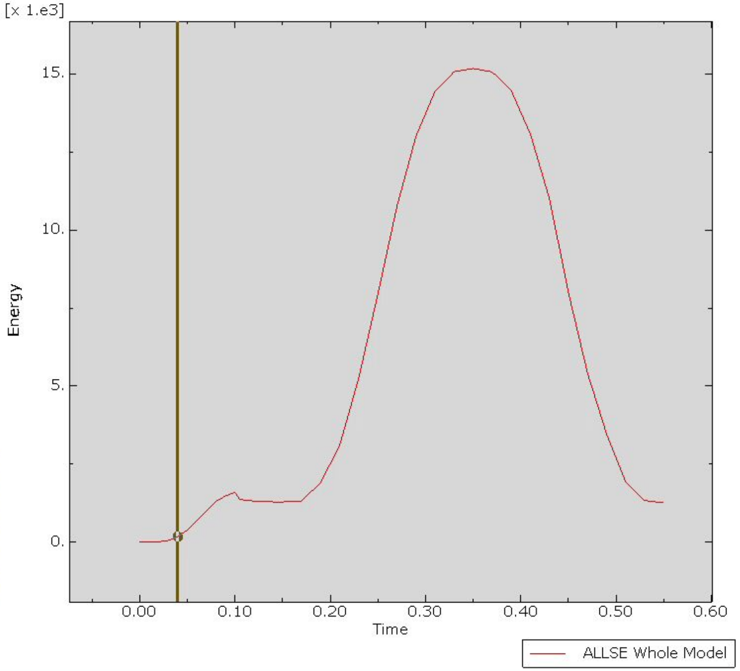
- Plies 1 and 2 are found to be subject to compressive stresses at the mid-arc and tensile stresses at the arcs to the flanges.

- Compressive stresses at the arc sections closer to the flanges and tensile stresses at the mid-arc area are observed to predominate in the fourth and fifth plies.

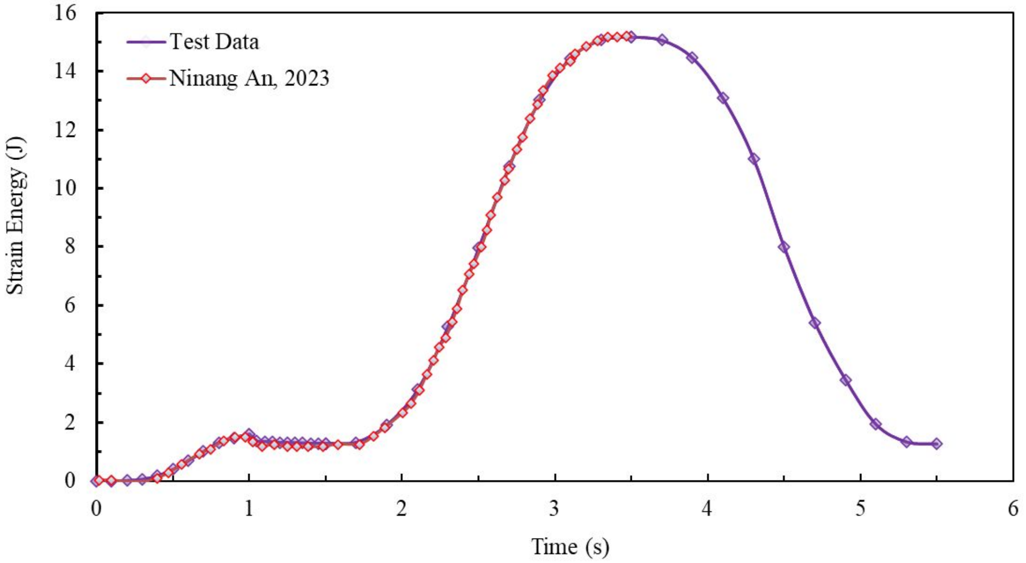
- The stresses are at their highest in the third plies, where the fibers are oriented at an angle of 0 º

3. DYNAMIC TEST



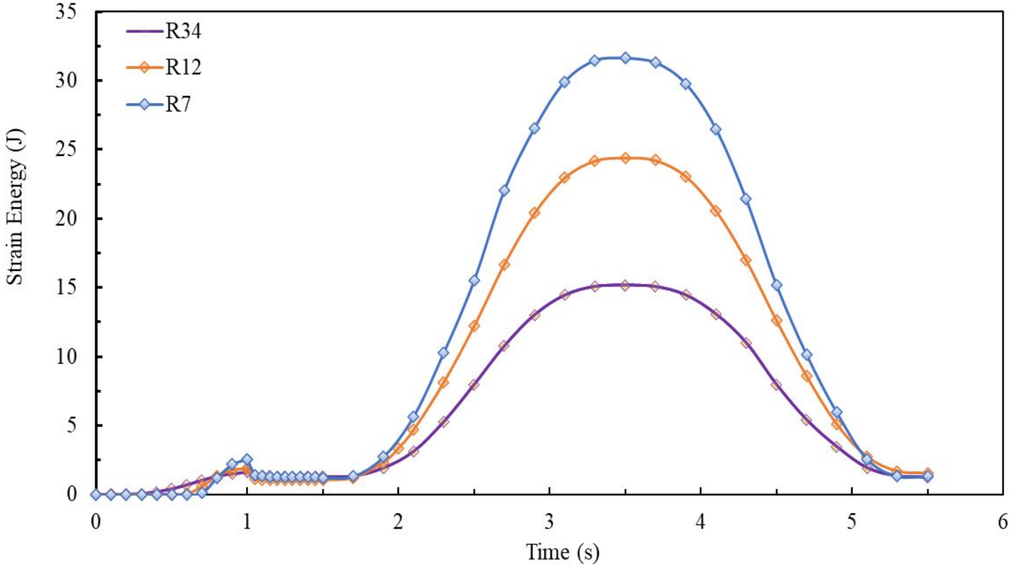


3.1 Strain Energy Validation



- The strain energy variation with respect to time was validated with Ninang An et.al.
- As observed from the plot, the values obtained from the simulation perfectly matched with that of Ninang An et.al.

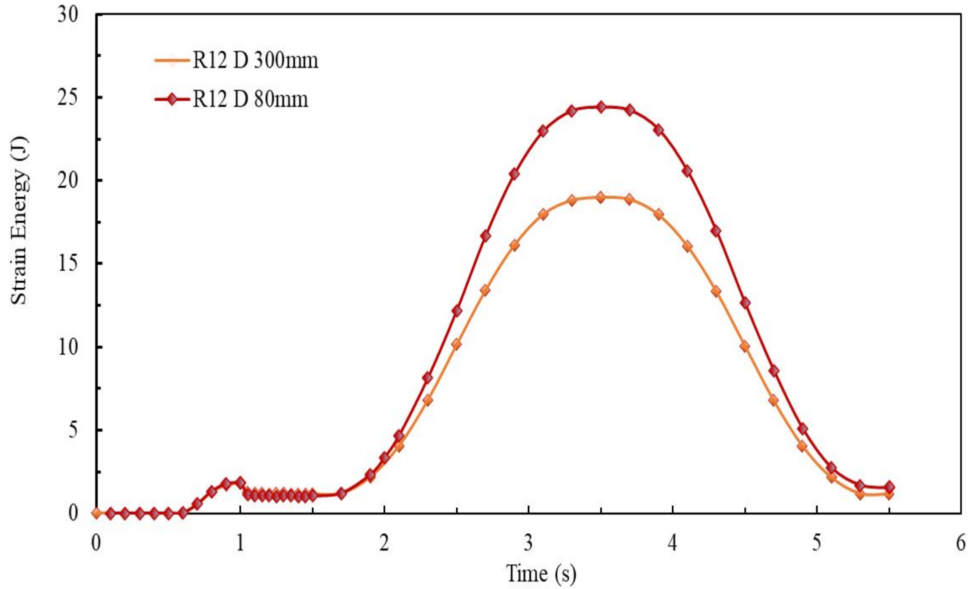
3.2 Strain Energy for different Radii of curvature



1 m length boom over 80 mm drum with different radii of curvature

- As the compression starts R34 model picks up strain energy at higher rates than the other models
- At the time of complete compression R7 model has highest strain energy
- As the winding process starts R7 model attains higher strain energy.
- When the model is deployed completely R7 and R12 have almost same residual strain energy.

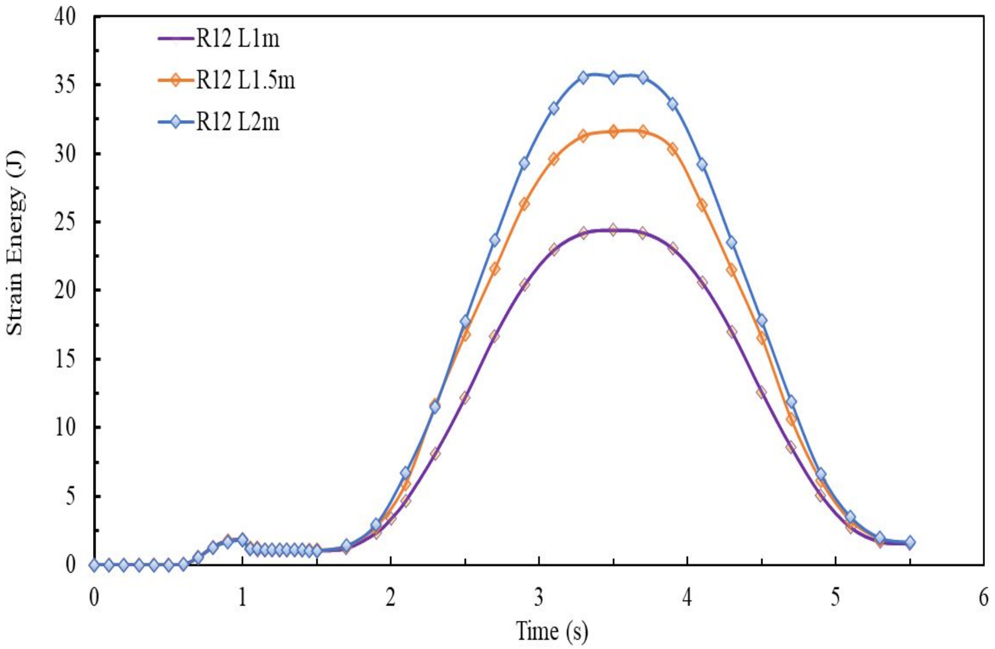
3.3 Strain Energy for different drum radii



1 m length boom of radius 12 mm with over drums with 80 mm and 300 mm radii

- Keeping the radii of curvature of the boom model same, the central stowing drum radius was changed.
- Case 1- D 80mm and Case 2- D 300mm
- During the initial compression and contact phase of the simulation the strain energy values of both cases were the same.
- During the winding phase Case 1 had higher strain energy than Case 2 due the higher strains produced in the model

3.4 Strain Energy for different Boom Length



Radius 12 mm over 80 mm drum with different lengths

- The strain energy during the initial compression phase did not vary when the boom model length changed.
- As the winding phase begins, the strain energy of all models increases, with the 2m model having the highest strain energy.
- At the end of the simulation, all models have approximately the same residual strain energy.

CONCLUSION

- From the preliminary static test it was found that the strain energy increases during the tensile deformation and also it can be noticed that the stress distribution is symmetric about the vertical axis.
    - The strain attained peak at the point of flattening and the stress is maximum at the points of inflection, that is where the concave and convex arcs meet.
    - From the flattening process it can be understood that the **Strain energy obtained increases with decrease in radius of curvature.**

- The strain energy plot is segmented into four different processes such as Flattening, Contact, Coiling and Deployment. At the time of complete winding strain energy is maximum for the boom model.
    - With the **decrease in radii of curvature of the boom, the strain energy stowed in the model increases**. R7 model has the highest maximum strain energy (37.62 J).
    - When the **stowing drum radius was decreased from 300 mm to 80 mm, the strain energy of the boom model increased by 28.4%.**
    - A **significant increase in strain energy was observed when the model length was doubled**. 1m boom had an energy magnitude of 24.40 J at the time of complete coiling while the 2m model had strain energy of 35.56 J.

- Presented our work in Conference- at the 36th National Convention and Seminar of Aerospace Engineers by The Institution of Engineers (India) in Bengaluru
  Paper details:
  Advaith Gopan, Ragini Manoharan, Aangeerasaa Sriram, Balamurali S, Hariharan Sankara Subramanian, Dr. Sreehari VM, ***"Computational Analysis on the Tensile behavior of Collapsible Tubular Composite Booms"***, 36th National Convention of Aerospace Engineers and National Seminar on Space – Boundless Opportunities – Transforming Lives, 1st & 2nd of September, 2023

- Balamurali S, Aangeerasaa S, **Ragini Manoharan, Advaith Gopan,** Sreehari VM, Hariharan Sankara Subramanian, ***"Analysis on varying cross-sectional parameters of Lenticular Deployable Composite Booms"*** (Corrected manuscript is ready, **to be communicated to International Journal**)

FUTURE SCOPE

1. Experimental study need to be carried out for comparing with computational results
2. Frequency Analysis

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THANK YOU

APPENDIX

RESEARCH GAP

- ❖ The present applications lacks in compactness of the structure
- ❖ Therefore, in this work we are trying to analyse the variation of performance parameters over various dimensions and thereby would arrive with the optimum dimensions of the LDCB to be applied for different applications.