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Design And Analysis Of Cng Pressure Vessel Using Natural Fibre Composites

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Abstract: Bio composites comprise one or more phases derived from a biological origin; these may be reinforcements (cotton, hemp, flax, sisal, jute, and kenaf or recycled wood and paper) or organic matrices, for example, polylactic acid (PLA) and soybean resins. Use of natural fibers has been in existence for many generations, however, the discovery and subsequent commercialization of synthetics such as glass, aramids, and carbon fibers in early and mid-twentieth century resulted in the reduced preference for natural fibers in a number of applications. However recent advancement in manufacturing methods and a shift towards environmental protection shifted the focus back to biodegradable composite. This paper deals with the generation of MATLAB script files that assists the user in the design of a biodegradable composite CNG pressure vessel to operate within safe conditions. The inputs of the program are the material properties, ply strength, applied loading, cure and room temperature and fiber orientation. Classical Laminate Analysis (CLA) is a widespread theory in engineering for analyzing the stress/strain behavior of orthotropic laminates under mechanical and hygrothermal loading. CLA is an orthotropic adaptation of Kirchoff's thin plate theory. The output of the program is extension, coupling and bending stiffness matrices, equivalent elastic constants, thermal, moisture, mechanical and total strain vector, total strains and stresses at ply Interfaces and mid planes. The calculation also predicts the minimum reserve factors with the occurrences of failure at various points in the ply interface.

Keywords: Bio Composite, MATLAB, Laminate, Fiber orientation, Hygrothermal, Stiffness matrices, Strain vector, Ply interfaces

1. INTRODUCTION

A. *Composite*

A composite material is a material produced from two or more constituent materials with notably dissimilar chemical or physical properties that, when merged, create a material with properties, unlike the individual elements. The individual components remain separate and distinct within the finished structure, distinguishing composites from mixtures and solid solutions. The development of bio composites, produced using a biopolymer matrix and a reinforcement from renewable resources, is currently an extensive research area due to the promising mechanical properties, recyclability after service, and biodegradability of these materials [20]. These composites have potential applications in different fields such as automotive, packaging, and household goods. Clearly, the application of natural fibres is being driven not only by environmental reasons, but also by economical ones [1]. Natural fibre-reinforced composites, in fact, can be used as low-cost materials having at the same time different structural properties. The use of natural fibres has many advantages. Natural fibres are renewable, biodegradable, and less abrasive to tooling. Furthermore, they can be formed into light composites leading to weight reductions and, especially in automotive field, to fuel saving [2]. Among natural fibres, lignocellulosic fibres are investigated as promising substitutes of the synthetic fibres in polymeric composites and several studies have examined drawbacks and advantages of the most significant lignocellulosic fibres and their related polymeric composites.

B. *Classical lamination theory (CLT)*

It is a commonly used predictive tool, which evolved in the 1960s, which makes it possible to analyse complex coupling effects that may occur in composite laminates. It is able to predict strains, displacements and curvatures that develop in a laminate as it is mechanically and thermally loaded. The method is similar to isotropic plate theory, with the main difference appearing in the lamina stress-strain relationships. As with any analytical technique, some assumptions must be made in order to make the problem solvable. These assumptions lay the foundation for the theory and enable prediction of composite laminate behaviour. By modifying the original CLT formulation to include variations in material properties as a function of temperature as well as chemical shrinkage contributions, we can predict the behaviour of a multi-directional laminate based solely on the behaviour of a unidirectional sample of the same material system [16].

A simple method used for consideration of chemical shrinkage in calculating residual stresses with CLT is to measure the stress-free temperature experimentally and consider the measured temperature in the calculations instead of curing temperature, and by this way the chemical strains would not be entered into the calculations [14].

C. *ABD matrix*

The cross-sectional forces and moments can be determined by summation of the integrated stress components over each individual ply. The result is the so-called ABD-matrix, which relates cross-sectional forces and moments to mid-plane strains and curvatures. The ABD matrix thus obtained is a 6x6 matrix that serves as a connection between the applied loads and the associated strains in the laminate. The ABD-matrix characterizes the mechanical behavior of the laminate, as it relates the cross-sectional loads to strains and curvatures of the mid-plane.

D. *Bio fiber composite CNG tank*

Compressed natural gas is stored at less than 1 percentage of the volume it occupies at standard atmospheric pressure. Typically, they are stored and distributed in hard steel containers at a pressure of 20 – 25 Mpa (2,900-3,600 psi). Cylindrical or spherical shaped containers are typically employed because circular hoops can withstand internal pressure by pure tension in the tank material instead of bending. If the shape were not circular, then there would be bending stresses in the tank wall and it would not be able to withstand as much pressure without breaking. From a purely technical standpoint the value that bio composite cylinders provide to conventional steel cylinders are many. As a result of 50 to 60 percentage lighter cylinders, vehicle divers are benefiting from an improvement in payload, better performance, saving in vehicle maintenance, an overall reduction in CO2 emissions, low eco-toxicity and their biodegradability after end cycle of the product.

PROBLEM IDENTIFICATION

The main issue in adopting CNG pressure vessel in vehicle is that of reduction in boot space, addition of weight and its cost. Typically, such pressure vessels are fabricated in steel. But with the advent of composite based structure the weight of the tank can be significantly reduced and the cost is minimal. But such pressure vessels are not eco friendly and cannot be recycled once its end cycle is reached. Bio composites have excellent biodegradability and its eco friendly in nature, Natural fibres are less expensive, thereby reducing the cost of the composite laminate. The mechanical properties of bio composites are lower than that of traditional composites. So special design considerations have to be followed to achieve the desired properties.

E. *Objective of the project*

- Design a MATLAB program that allows the user to swiftly set analysis parameters in pre - defined text files.
- Calculates the A, B and D matrixes for a specified stacking sequence and given material properties.
- Finds equivalent “isotropic” material properties of the laminate and useful derived terms for buckling analysis.
- Calculate the total stresses and strains at mid ply locations and ply interfaces, and residual stresses due to volumetric expansion.
- Computes the minimum reserve factors for fiber dominated, matrix dominated and shear failure, and points out in which ply this failure is predicted to occur.
- Optimization algorithm that computes the constant through thickness moisture content that flattens a laminate that has warped upon post curing cool down.
- Optimization for natural fiber incorporation
- Plots graphs of total stresses and strains at local and global axes

F. *Literature Summary*

- Application of various factors in the calculation of burst strength of the composite over wrapped pressure vessel (COPV)
- Various effect arising due to failure of CNG cylinders
- Effectiveness of glass fibre composite natural gas tanks
- Complex calculation and simulation methods available for composites laminate

2. MATERIALS AND METHODS

A. *Flax fiber*

One of the strongest natural fibers is the flax fiber. Flax fiber is extracted from the bast beneath the surface of the stem of the flax plant. Flax fiber is soft, lustrous, and flexible; bundles of fiber have the appearance of blonde hair, hence the description "flaxen" hair. It is stronger than cotton fiber, but less elastic. Their structure is very complex and can be compared to a composite structure. In fact, the flax fibers are constituted by a series of polyhedron shape elementary fibers overlapped over a considerable length; they are held together by an interphase that mainly consists of hemicellulose and pectin [12].

Each elementary fiber consists of a very thin primary cell wall, a secondary cell wall (dominating the cross section), and an open channel at the fiber center called “lumen”. Typical dimeter for an elementary flax fiber are around 10–15 µm; on the other hand, technical flax fibers have a diameter that varies between 35–150µm [10].

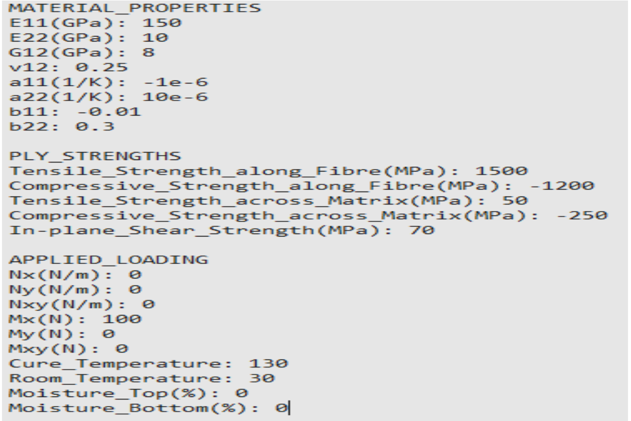
Coarser grades are used for the manufacturing of twine and rope, and historically, for canvas and webbing equipment. Flax fiber is a raw material used in the high-quality paper industry for the use of printed banknotes, laboratory paper (blotting and filter), rolling paper for cigarettes, and tea bags.

B. *Poly lactic acid (PLA)*

Polylactic acid is a thermoplastic polyester with backbone formula (C3H4O2) formally obtained by condensation of lactic acid C(CH3)(OH)HCOOH with loss of water. It can also be prepared by ring-opening polymerization of lactide [–C(CH3)HC(=O)O–]2, the cyclic dimer of the basic repeating unit [13].

DESIGN AND ANALYSIS STUDY

The entire calculation of the laminates is sub divided into separate MATLAB modules. A main linker program is then used to link these sub modules. Three separate input files are used to enter the various properties. Material properties, various applied loading, cure and room temperature, moisture values are entered as image shown in Fig 1



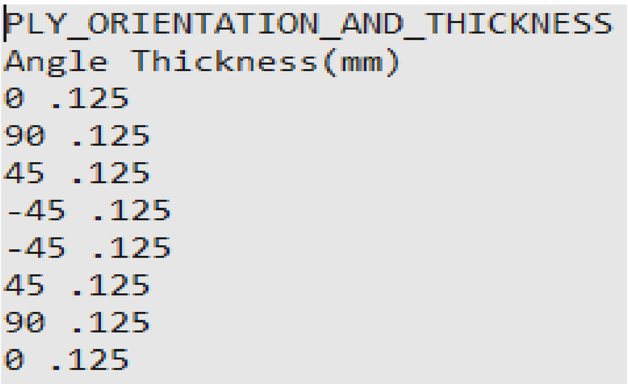
```
MATERIAL_PROPERTIES
E11(GPa): 150
E22(GPa): 10
G12(GPa): 8
v12: 0.25
a11(1/K): -1e-6
a22(1/K): 10e-6
b11: -0.01
b22: 0.3

PLY_STRENGTHS
Tensile_Strength_along_Fibre(MPa): 1500
Compressive_Strength_along_Fibre(MPa): -1200
Tensile_Strength_across_Matrix(MPa): 50
Compressive_Strength_across_Matrix(MPa): -250
In-plane_Shear_Strength(MPa): 70

APPLIED_LOADING
Nx(N/m): 0
Ny(N/m): 0
Nxy(N/m): 0
Mx(N): 100
My(N): 0
Mxy(N): 0
Cure_Temperature: 130
Room_Temperature: 30
Moisture_Top(%): 0
Moisture_Bottom(%): 0
```

Fig. 1. Pre-processing information file for mechanical properties

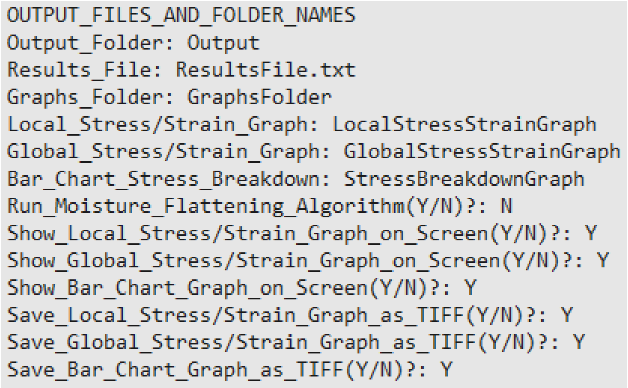
The orientation of individual ply and its corresponding thickness are entered in the second file as shown in Fig 2. The inputs are provided serially beginning from the bottom layer till the top layer.



```
PLY_ORIENTATION_AND_THICKNESS
Angle Thickness(mm)
0 .125
90 .125
45 .125
-45 .125
-45 .125
45 .125
90 .125
0 .125
```

Fig. 2. Pre-processing information file for ply orientation and thickness

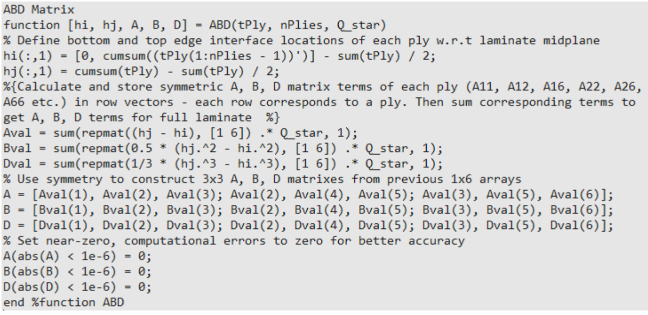
Various algorithms to be used and the options to generate the required graphs can be preset using the third input file as shown below in Fig 3.



```
OUTPUT_FILES_AND_FOLDER_NAMES
Output_Folder: Output
Results_File: ResultsFile.txt
Graphs_Folder: GraphsFolder
Local_Stress/Strain_Graph: LocalStressStrainGraph
Global_Stress/Strain_Graph: GlobalStressStrainGraph
Bar_Chart_Stress_Breakdown: StressBreakdownGraph
Run_Moisture_Flattening_Algorithm(Y/N)?: N
Show_Local_Stress/Strain_Graph_on_Screen(Y/N)?: Y
Show_Global_Stress/Strain_Graph_on_Screen(Y/N)?: Y
Show_Bar_Chart_Graph_on_Screen(Y/N)?: Y
Save_Local_Stress/Strain_Graph_as_TIFF(Y/N)?: Y
Save_Global_Stress/Strain_Graph_as_TIFF(Y/N)?: Y
Save_Bar_Chart_Graph_as_TIFF(Y/N)?: Y
```

Fig. 3. Pre-processing information file for option settings

The programing logic is designed such that the provided input values are taken and a series of steps are followed one after the other to achieve the required results. Based on the input values provided the ply stiffness matrix is calculated. The obtained result is transformed to produce the ply transformation stiffness matrix. From this obtained value, the ABD matrix is generated as per the script file shown in Fig 4. Induced loads are then calculated from the obtained matrix. Various CLT calculations are then followed to calculate strain to stress, global to local, residual strain stress, the major strain values etc.



```
ABD Matrix
function [hi, hj, A, B, D] = ABD(tPly, nPlies, Q_star)
% Define bottom and top edge interface locations of each ply w.r.t laminate midplane
hi(:,1) = [0, cumsum((tPly(1:nPlies - 1))')] - sum(tPly) / 2;
hj(:,1) = cumsum(tPly) - sum(tPly) / 2;
%{Calculate and store symmetric A, B, D matrix terms of each ply (A11, A12, A16, A22, A26,
A66 etc.) in row vectors - each row corresponds to a ply. Then sum corresponding terms to
get A, B, D terms for full laminate  %}
Aval = sum(repmat((hj - hi), [1 6]) .* Q_star, 1);
Bval = sum(repmat(0.5 * (hj.^2 - hi.^2), [1 6]) .* Q_star, 1);
Dval = sum(repmat(1/3 * (hj.^3 - hi.^3), [1 6]) .* Q_star, 1);
% Use symmetry to construct 3x3 A, B, D matrixes from previous 1x6 arrays
A = [Aval(1), Aval(2), Aval(3); Aval(2), Aval(4), Aval(5); Aval(3), Aval(5), Aval(6)];
B = [Bval(1), Bval(2), Bval(3); Bval(2), Bval(4), Bval(5); Bval(3), Bval(5), Bval(6)];
D = [Dval(1), Dval(2), Dval(3); Dval(2), Dval(4), Dval(5); Dval(3), Dval(5), Dval(6)];
% Set near-zero, computational errors to zero for better accuracy
A(abs(A) < 1e-6) = 0;
B(abs(B) < 1e-6) = 0;
D(abs(D) < 1e-6) = 0;
end %function ABD
```

Fig. 4. ABD MATLAB script file

From these generated stress and strain values the Flat plate calculation is done. It Iterate different values of constant moisture through laminate to find moisture content that flattens warped laminate post cure. Various induced loads are then generated. In order to plot the various graphs like local, global and stress bar charts, separate script modules are used.

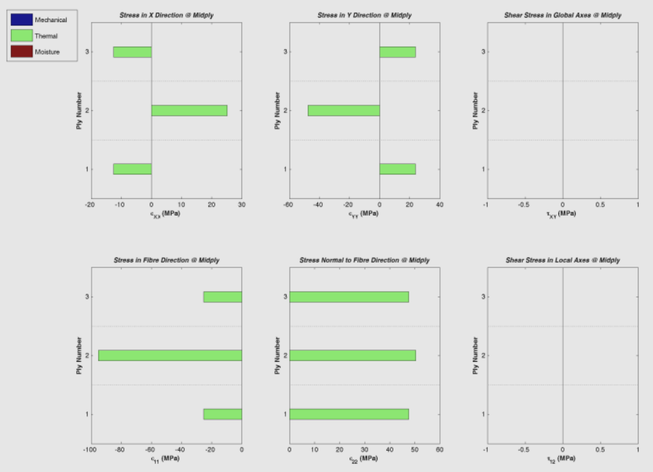


Fig. 5. Stress breakdown graph thermal

The stress breakdown graph shown in Fig 5 depicts stress breakdown into the three ie mechanical, thermal and moisture components through the thickness of every ply in the laminate.

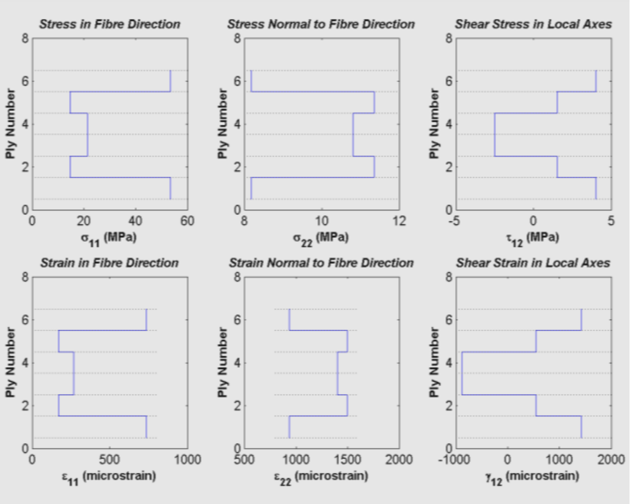


Fig. 6. Local stress strain graph

Local stress strain graph shown in Fig 6 depicts the stresses and strains in horizontal and normal direction to the fibre. Shear strain generated in the local axes is also plotted.

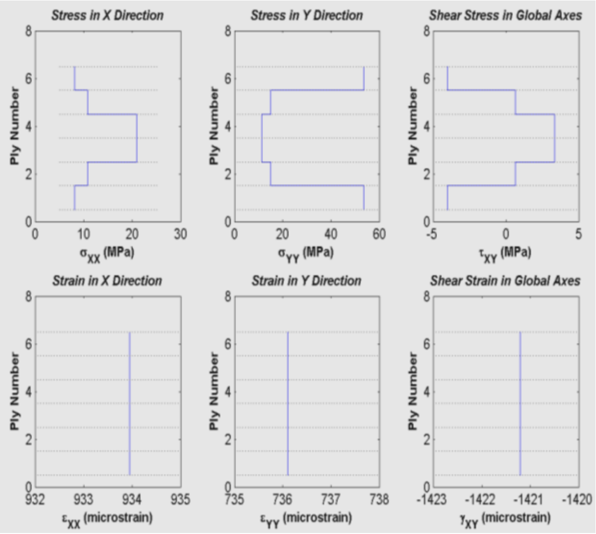


Fig. 7. Global stress strain graph

Global stress strain graph shown in Fig 7 depicts the stresses and strains in X and Y direction to the fibre. Shear strain generated in the global axes is also plotted.

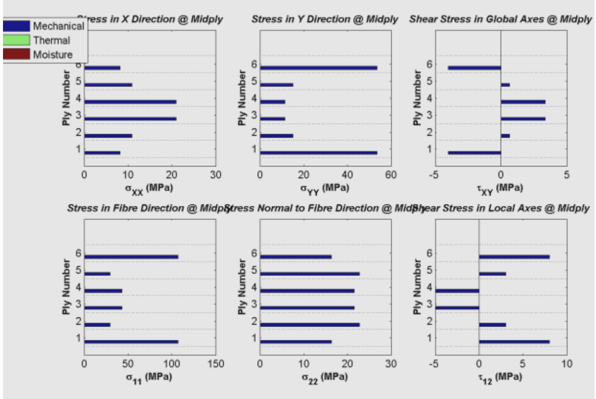
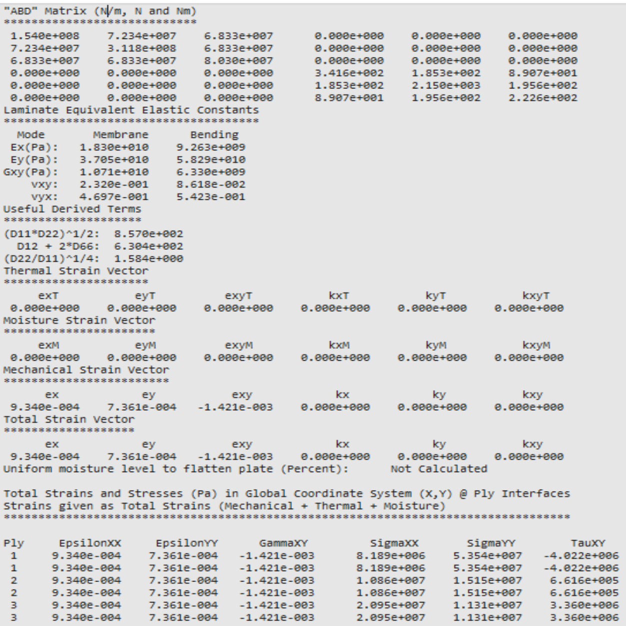


Fig. 8. Stress breakdown graph mechanical

Stress breakdown graphs show in Fig 8 shows the extend of mechanical, thermal and moisture on the laminate ply. Moisture curvatures are plotted only when the flat plate algorithm is activated based on the commands given in the input control file.

The result file generated as shown in Fig 9 summarises the laminate characteristics, A,B,D matrixes and equivalent "isotropic" properties of the laminate. Useful derived terms for buckling analyses, loading parameters and resulting strain vectors in terms of membrane strains and bending curvatures, the moisture content required to flatten the laminate post cure, the total stress/strain results at ply interfaces and mid-ply locations in local 1-2 and global X-Y-axes are also generated. The reserve Factors for simple fibre, matrix or shear failure criteria are also generated. Minimum reserve factors for fibre dominated, matrix dominated and shear failure, and points out in which ply this failure is predicted to occur. This is a very useful data while determining the safe operating condition of a newly proposed laminate. This prediction helps to analyse the fracture point in details and choose alternative methods to avoid the failure.



```
"ABD" Matrix (N/m, N and Nm)
****************************
 1.540e+008    7.234e+007    6.833e+007      0.000e+000    0.000e+000    0.000e+000
 7.234e+007    3.118e+008    6.833e+007      0.000e+000    0.000e+000    0.000e+000
 6.833e+007    6.833e+007    8.030e+007      0.000e+000    0.000e+000    0.000e+000
 0.000e+000    0.000e+000    0.000e+000      3.416e+002    1.853e+002    8.907e+001
 0.000e+000    0.000e+000    0.000e+000      1.853e+002    2.150e+003    1.956e+002
 0.000e+000    0.000e+000    0.000e+000      8.907e+001    1.956e+002    2.226e+002
Laminate Equivalent Elastic Constants
*************************************
  Mode        Membrane       Bending
 Ex(Pa):   1.830e+010    9.263e+009
 Ey(Pa):   3.705e+010    5.829e+010
Gxy(Pa):   1.071e+010    6.330e+009
    vxy:   2.320e-001    8.618e-002
    vyx:   4.697e-001    5.423e-001
Useful Derived Terms
********************
(D11*D22)^1/2:  8.570e+002
  D12 + 2*D66:  6.304e+002
(D22/D11)^1/4:  1.584e+000
Thermal Strain Vector
*********************
     exT           eyT          exyT          kxT           kyT          kxyT
 0.000e+000    0.000e+000    0.000e+000    0.000e+000    0.000e+000    0.000e+000
Moisture Strain Vector
**********************
     exM           eyM          exyM          kxM           kyM          kxyM
 0.000e+000    0.000e+000    0.000e+000    0.000e+000    0.000e+000    0.000e+000
Mechanical Strain Vector
************************
      ex            ey           exy           kx            ky           kxy
 9.340e-004    7.361e-004   -1.421e-003    0.000e+000    0.000e+000    0.000e+000
Total Strain Vector
*******************
      ex            ey           exy           kx            ky           kxy
 9.340e-004    7.361e-004   -1.421e-003    0.000e+000    0.000e+000    0.000e+000
Uniform moisture level to flatten plate (Percent):      Not Calculated

Total Strains and Stresses (Pa) in Global Coordinate System (X,Y) @ Ply Interfaces
Strains given as Total Strains (Mechanical + Thermal + Moisture)
**********************************************************************************

Ply     EpsilonXX     EpsilonYY     GammaXY         SigmaXX       SigmaYY        TauXY
 1      9.340e-004    7.361e-004   -1.421e-003      8.189e+006    5.354e+007   -4.022e+006
 1      9.340e-004    7.361e-004   -1.421e-003      8.189e+006    5.354e+007   -4.022e+006
 2      9.340e-004    7.361e-004   -1.421e-003      1.086e+007    1.515e+007    6.616e+005
 2      9.340e-004    7.361e-004   -1.421e-003      1.086e+007    1.515e+007    6.616e+005
 3      9.340e-004    7.361e-004   -1.421e-003      2.095e+007    1.131e+007    3.360e+006
 3      9.340e-004    7.361e-004   -1.421e-003      2.095e+007    1.131e+007    3.360e+006
```

Fig. 9. Result file auto generated

Consequently, quite a lot of information can be extracted from this results file either for a particular ply or for the complete laminate

3. CONCLUSION

From the various graphs and simulation results obtained we can conclude that natural fibre composites can be proposed for manufacturing CNG pressure vessels. Based on the application and requirements the number of layers have to be increased when compared to traditional composite laminate. With the increase in the number of layers the thickness of the tank increases and the properties of conventional tanks can be matched. Also, it has been observed that as the thickness increases, the effect of thermal and moisture in the mid-ply laminates is considerably low.

The proposed simulation tool proves that it can reduce considerable effort and cost while designing bio composite pressure vessels. After testing the various reserve factors, the designer can easily propose various combination and design the most economical vessel suitable to the application requirement.

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