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# STRESS ANALYSIS OF THIN-WALLED LAMINATED COMPOSITE BEAMS

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**ABSTRACT**

An educational software which can aid students in stress analysis of thin wall open sections made of composite material has been developed. The software enables students to easily calculate stresses of thin wall open section and evaluate the stresses in each ply. Results obtained through this software have been validated against ANSYS V14. The software is intended to be used as a resourceful tool for effective teaching and learning process on thin-walled structures, aircraft structures and composite structures courses.

**Keywords:** stress analysis, educational software, thin wall open section, composite structures.

## INTRODUCTION

Composite materials are known due to their properties such as excellent fatigue resistance, high specific strength and stiffness, good corrosion resistance, excellent fire resistance and lower thermal expansion. Due to that, many industries like aerospace and defense, marine, automotive, and sports choose to use composite materials instead of other materials. The complexity of composite materials has attracted researchers to study their behavior and up until now, complete composite behavior is still unknown. This is because; the anisotropic properties of composite materials complicate the prediction of structural behavior.

In universities, engineering students who are specializing in Aerospace discipline are required to take courses such as Structural Mechanics, Aircraft Structures and Composite Structures. However, these courses especially Aircraft Structures and Composite Structures involve calculations that are lengthy, tedious and hence time consuming which makes the students loose interest in these courses.

Available software such as MDSolids has its limitation because it is deals only with basic Mechanics of Materials, and the students will not be able to learn advanced topic on structures using this software. An extensive literature shows that software named TWProfile [1] is the only commercial software available in the market that can perform analysis of thin-walled sections made of composite materials. The software determines structural properties and stresses as defined by Vlasov theory.

Previously, Nurhuda and Mohamed Ali [2] had done a great work in developing educational software for thin-walled sections of isotropic and composite materials. The students of IIUM have extensively used for the Aircraft Structures course. The software is able to evaluate direct stress due to bending, shear flow due to shear and maximum shear stress due to torsion for I, C, T, and Z cross section beams. This software when applied for composites, just reports the average stresses instead of a detailed ply by ply analysis which is useful for design.

Advance finite element software like ANSYS and ABAQUS are very helpful to understand the behavior of either isotropic or composite beams under various loading. However, the original software are very expensive and students must study how the software works from modelling, meshing processes and applying loads correctly in order to get good results and understand the results thoroughly. The process to familiarize them with the finite element software itself is very challenging and stressful.

In this work, software is developed using MATLAB which is capable to evaluate stresses in each ply for I-, C- and T- section composite beams under axial and bending loads. MATLAB is chosen instead of other programming software not only because it is familiar software among students and lecturers, but also because it is widely used in aerospace and automotive industries. Hence, it is expected that this software will be very useful to students and lecturers and also will ease the teaching and learning processes by acting as a complementary tool to traditional teaching and learning methods.

## METHODOLOGY

A thin-walled open section made of composite material subjected to axial force and bending moments in two planes is considered for analysis. As the theory for stress analysis of thin-walled open section made of composite material is well established in the literature, the theory and methods of calculation have been referred from [3] except where it is stated otherwise.

An FRP laminate may have individual plies oriented at different angles, relative to the reference (loading) axes, to produce the desired stiffness and strength in the required directions. The properties of the laminate depend very much on the individual ply properties and the stacking sequence of the plies.

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**Determination of elastic constants of laminate**

The procedure for computing the stiffness, compliance and equivalent elastic constants is the same for any laminate configuration and it is as follows:

1. From the given elastic properties $E_1$, $E_2$, $G_{12}$ and $\nu_{12}$ of each ply, determine the reduced stiffness terms $Q_{11}$, $Q_{22}$, $Q_{33}$ and $Q_{12}$ using the following equation

$$\begin{aligned} Q_{11} &= E_1/(1-\nu_{12}\nu_{21}) \\ Q_{22} &= E_2/(1-\nu_{12}\nu_{21}) \\ Q_{33} &= G_{12} \\ Q_{12} &= \nu_{21}E_1/(1-\nu_{12}\nu_{21}) \end{aligned} \tag{1}$$

2. Using the obtained $Q_{ij}$ terms, the transformed reduced stiffness terms $\bar{Q}_{ij}$ for a given ply angle can be calculated using the equation given below in a boxed matrix form:

| | $Q_{11}$ | $Q_{22}$ | $Q_{12}$ | $Q_{33}$ |
|---|---|---|---|---|
| $\bar{Q}_{11}$ | $m^4$ | $n^4$ | $2m^2n^2$ | $4m^2n^2$ |
| $\bar{Q}_{22}$ | $n^4$ | $m^4$ | $2m^2n^2$ | $4m^2n^2$ |
| $\bar{Q}_{33}$ | $m^2n^2$ | $m^2n^2$ | $-2m^2n^2$ | $(m^2-n^2)^2$ |
| $\bar{Q}_{12}$ | $m^2n^2$ | $m^2n^2$ | $m^4+n^4$ | $-4\,m^2n^2$ |
| $\bar{Q}_{13}$ | $m^3n$ | $-mn^3$ | $mn^3-m^3n$ | $2(mn^3-m^3n)$ |
| $\bar{Q}_{23}$ | $mn^3$ | $-m^3n$ | $m^3n-mn^3$ | $2(m^3n-mn^3)$ |

(2)

While the $Q_{ij}$ matrix relates the stresses to the strains in the material axes *1-2*, the transformed reduced stiffness terms $\bar{Q}_{ij}$ relate the stresses to the strains in the reference or loading axes *x-y* as shown in Equation (3).

$$\begin{bmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\end{bmatrix} = \begin{bmatrix}\bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{13}\\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{23}\\ \bar{Q}_{13} & \bar{Q}_{23} & \bar{Q}_{33}\end{bmatrix} \begin{bmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\end{bmatrix} \tag{3}$$

$$\begin{bmatrix}\epsilon_x\\ \epsilon_y\\ \gamma_{xy}\end{bmatrix} = \begin{bmatrix}\epsilon_x^0\\ \epsilon_y^0\\ \gamma_{xy}^0\end{bmatrix} + zk\begin{bmatrix}k_x\\ k_y\\ k_{xy}\end{bmatrix} \tag{4}$$

3. For each ply in a laminate, determine the following values (refer Figure-1):
   $t_p$: ply thickness, associated with $A_{ij}$ term
   $\bar{z}_p$: ply centroidal value
   $t_p\bar{z}_p$: associated with $B_{ij}$
   $(t_p\bar{z}_p^{\,2} + t_p^3/12)$: associated with $D_{ij}$ term

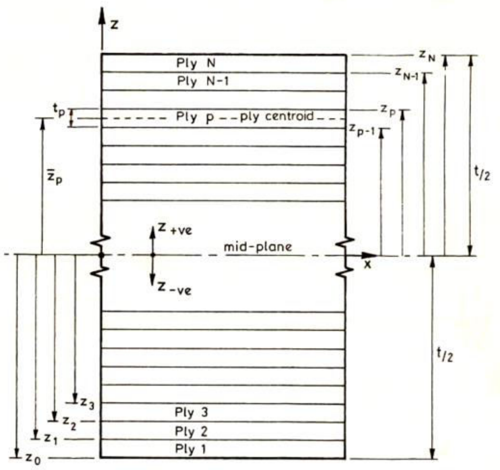


**Figure-1.** A layered laminate [5].

$$\begin{aligned} A_{ij} &= \sum_{p=1}^{N} t_p\left(\bar{Q}_{ij}\right)_p \\ B_{ij} &= \sum_{p=1}^{N} -t_p\bar{z}_p\left(\bar{Q}_{ij}\right)_p \\ D_{ij} &= \sum_{p=1}^{N} \left(t_p\bar{z}_p^{\,2} + t_p^{\,3}/12\right)\left(\bar{Q}_{ij}\right)_p \end{aligned} \tag{5}$$

The complete laminate constitutive equation gives the relationship between load intensity and deformation, taking into account forces and moments acting on a point on the laminate. Below is the laminate constitutive equation in a boxed matrix notation form:

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| | $\varepsilon_x^o$ | $\varepsilon_y^o$ | $\gamma_{xy}^o$ | $k_x$ | $k_y$ | $k_{xy}$ |
|---|---|---|---|---|---|---|
| $N_x$ | $A_{11}$ | $A_{12}$ | $A_{13}$ | $B_{11}$ | $B_{12}$ | $B_{13}$ |
| $N_y$ | $A_{12}$ | $A_{22}$ | $A_{23}$ | $B_{12}$ | $B_{22}$ | $B_{23}$ |
| $N_{xy}$ | $A_{13}$ | $A_{23}$ | $A_{33}$ | $B_{13}$ | $B_{23}$ | $B_{33}$ |
| $M_x$ | $B_{11}$ | $B_{12}$ | $B_{13}$ | $D_{11}$ | $D_{12}$ | $D_{13}$ |
| $M_y$ | $B_{12}$ | $B_{22}$ | $B_{23}$ | $D_{12}$ | $D_{22}$ | $D_{23}$ |
| $M_{xy}$ | $B_{13}$ | $B_{23}$ | $B_{33}$ | $D_{13}$ | $D_{23}$ | $D_{33}$ |

(6)

$N_x$, $N_y$ and $N_{xy}$: Force intensities
$M_x$, $M_y$ and $M_{xy}$: Moment intensities
$\varepsilon_x^o$, $\varepsilon_y^o$ and $\gamma_{xy}^o$: Midplane strains
$k_x$, $k_y$ and $k_{xy}$: Midplane curvatures

The $A_{ij}$ terms are the extensional stiffness terms relating the membrane (in-plane) force intensities to the laminate midplane membrane strains. The $B_{ij}$ terms are the coupling stiffness terms relating the membrane force intensities to the out-of-plane curvature deformation. The $B_{ij}$ terms also relate the moment intensities to the laminate midplane membrane strains. The $D_{ij}$ terms are the bending stiffness terms which relate the moment intensities to the bending curvatures.

4. The laminate stiffness terms $A_{ij}$, $B_{ij}$ and $D_{ij}$ are inverted to obtain the corresponding compliance terms $a_{ij}$, $b_{ij}$ and $d_{ij}$. For symmetric laminates, as is the case being considered in this work, all $B_{ij}$ terms are zero. Thus, Equation (6) becomes:

| | $N_x$ | $N_y$ | $N_{xy}$ |
|---|---|---|---|
| $\varepsilon_x^o$ | $a_{11}$ | $a_{12}$ | $a_{13}$ |
| $\varepsilon_y^o$ | $a_{12}$ | $a_{22}$ | $a_{23}$ |
| $\gamma_{xy}^o$ | $a_{13}$ | $a_{23}$ | $a_{33}$ |

(7)

| | $M_x$ | $M_y$ | $M_{xy}$ |
|---|---|---|---|
| $k_x$ | $d_{11}$ | $d_{12}$ | $d_{13}$ |
| $k_y$ | $d_{12}$ | $d_{22}$ | $d_{23}$ |
| $k_{xy}$ | $d_{13}$ | $d_{23}$ | $d_{33}$ |

(8)

**Analysis of thin-walled composite open sections**

A thin-walled composite open section is made from an assembly of flat layered laminated composite. A section is defined as thin-walled if its thickness is small compared to the cross-sectional dimension; the ratio of the thickness to the cross-sectional dimension being at least one tenth.

**Assumptions and axes system**

Orthotropic materials have material properties that change with direction of a point. The material axes, which denoted by 1 and 2 axes is a set of mutually perpendicular directions parallel and perpendicular to the fiber directions. It is also known as the symmetry axes or principal axes. Direction 1 is the direction of the long fiber (longitudinal direction) and direction 2 is the direction of the matrix (transverse direction). The reference axis is a set of mutually perpendicular directions parallel and perpendicular to a reference direction. The reference direction is usually coincident with the loading direction. It is denoted by x, y, z axes system. The software developed in this work uses x-direction as the length of the beam, y-direction as width of beam's cross section and z-direction as the height of the cross section.

**Centroid and stiffness of cross section**

If each element is made of different ply orientation, the material properties will be different for each section. That means, the Young's modulus of upper flange, lower flange and web will be different. Thus, in order to analyze the stress of a composite laminate due to various loading condition such as tensile load and bending, location of centroid ($z_c$), the equivalent tensile stiffness (EA) and equivalent bending stiffness ($EI_{yy}$ and $EI_{zz}$) must be obtained. Equations (9) through (12) are obtained from [3].

$$z_c = \frac{1}{EA}\left[\frac{b_{fu}}{(a11_{fu})} bw + \frac{b_w}{(a11_w)} z_w\right] \tag{9}$$

$$EI_{yy} = \frac{b_{fu}}{(a11_{fu})}(bw - z_c)^2 + \frac{b_{fl}}{(a11_{fl})} z_c^2 + \frac{b_{fu}}{(d11_{fu})} + \frac{b_{fl}}{(d11_{fl})} + \frac{1}{(a11_w)}\left(\frac{b_{w1}^3 + b_{w2}^3}{3}\right) \tag{10}$$

$$EI_{zz} = \frac{b_w}{(d11_w)} + \frac{b_{fl}^3}{12(a11_{fl})} + \frac{b_{fu}^3}{12(a11_{fu})} \tag{11}$$

$$EA = \frac{b_{fu}}{(a11_{fu})} + \frac{b_{fl}}{(a11_{fl})} + \frac{b_w}{(a11_w)} \tag{12}$$

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where $b_{fu}$ is the width of top flange, $b_w$ is the width of web and $z_w$ is the distance from bottom flange to the center of web. To calculate stiffness for T-section, width of lower flange, $b_{fl}$ is removed from the equation.

**Bending**

If bending moment is applied about y- axis, the beam will bend about y-axis on its flanges. The curvature of the mid-plane of the web remains flat. Thus, only flanges will have moment per unit length, $M_y$. The resultant of applied bending moment about y-axis, $m_y$ is the summation of axial forces acting on the flanges and web and moment per unit length acting on the flanges.

$$m_y = (b_f N_x z_f + b_f M_y)_{fu} + (b_f N_x z_f + b_f M_y)_{fl} + \int_{bw} N_x z_w dz \quad (13)$$

Once the axial force intensity $N_x$ and moment per unit length $M_y$ are known, these valus can be substituted into Eq. 7 and 8. Similarly for a bending moment about z-axis, the curvature of the mid-plane of the web remains flat. The resultant of moment about z-axis is as follow:

$$m_z = (b_f N_x y_f + b_f M_y)_{fu} + \int_{bw} N_x y_w dz + \int_{bw} M_x dz \quad (14)$$

**Axial force**

Under the application of axial load, the beam remains straight. The axial strains are the same across the cross section and the curvature is zero. Thus, only axial force intensity, $N_x$ on each wall segment is required to determine in order to calculate the stresses.

**ANSYS SIMULATION**

The I-, C-, and T- cross section beams are modeled using ANSYS V14 by using Shell 181 layered element. Meshing is done by setting the size of width lines to 0.01, meanwhile the length lines are set to 500 number of division. The spacing ratio is set to a negative value so that the density of the element will be increased at the edges. Prior to application of load, the model is bonded to each other using the Contact Wizard. Three lines at one edge of the beam is constraint by setting the degree of freedom to zero.

The tensile and bending stiffness are measured using formula obtained in [4]:

$$EA = \frac{NL}{2U_{x\,(at\ x=\frac{L}{2})}} \quad (15)$$

**RESULTS AND DISCUSSIONS**

The programming for the stress analysis components discussed in the previous section was carried out in MATLAB R2013b. Three different standard thin-walled cross sections C, I, and T-sections have been considered in the analysis.

**Coding for stress analysis of thin-walled open sections**

User will be asked to enter material properties, cross-sectional of the beam, number of layers and their orientation. The software will compute the laminate stiffness properties based on the user input data.

Later, the user will be asked to select cross sectional of the beam and desired loads which are either axial load, moment $M_y$ and/or $M_z$. The outputs are the direct or normal stress, transverse stress and shear stress in each ply.

**Validation of the results**

The individual components of the software are checked to ensure its validity and accuracy by comparing the results with ANSYS V14 (Mechanical APDL).

**Material properties**

The material of composite laminate beams used in this work is carbon /epoxy prepreg [5]. The elastic properties of the plies are: $E_1$ = 140 kN/mm$^2$, $E_2 = E_3$=10 kN/mm$^2$, $G_{12} = G_{13}$ =5 kN/mm$^2$, $G_{23}$ =3.85 kN/mm$^2$, $\nu_{12}$= $\nu_{13}$= $\nu_{23}$= 0.3. The plies are each 0.005mm thick.

**Configuration of composite laminate beams**

For I-beam, the bottom and top flange configurations are $(\pm45/0_2/90)_s$ and $(\pm45/0/90)_s$, respectively meanwhile the web configuration is $(\pm45)_s$. For C-beam, the bottom and top flange configurations are $(0/\pm45/90)_s$, meanwhile the web configuration is $(\pm45)_s$. The configuration for T-beam is similar to the C-beam except that no bottom flange is required.

**Table-1.** Geometrical dimension of beams.

| Section | $b_{fu}$(mm) | $b_{fl}$(mm) | $b_w$(mm) |
|---|---|---|---|
| I | 0.5 | 0.75 | 0.5 |
| C | 1 | 1 | 2 |
| T | 1 | - | 0.5 |

**Equivalent axial stiffness of composite laminates**

**Table-2.** I-beam tensile and bending stiffness.

| | **Software** (N) | **ANSYS**(N) | **% Difference** |
|---|---|---|---|
| EA | 3.93($10^3$) | 3.94($10^3$) | 0.25 |
| $EI_{yy}$ | 198.48 | 198.81 | 0.16 |

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**Table-3.** C-beam tensile and bending stiffness.

| | **Software** (N) | **ANSYS** (N) | **% Difference** |
|---|---|---|---|
| EA | $5.0350(10^3)$ | 5076.49 | 1.71 |
| $EI_{yy}$ | $4.7377(10^3)$ | 4670.309 | 1.42 |

**Table-4.** T-beam tensile and bending stiffness.

| | **Software** (N) | **ANSYS** (N) | **% Difference** |
|---|---|---|---|
| EA | $2.3401(10^3)$ | $2.35(10^3)$ | 0.388 |
| $EI_{yy}$ | 16.1267 | 17.59751 | 9.12 |

**Beam under axial load**

The C-beam is subjected to 30kN. Pressures are applied to each flange and web lines so that it equivalent to the desired load.

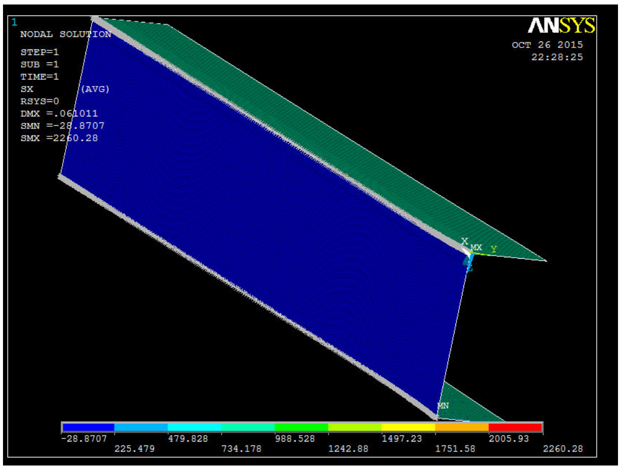


**Figure-2.** SX contour plot of C-beam subjected to axial load.

**Table-5**. Stresses due to axial load on C-beam of web.

| **PLY** | **WEB** | **SX** | **SZ** | **SXZ** |
|---|---|---|---|---|
| 1 (45°) | ANSYS | 106.36 | 1.2168 | 44.826 |
| | Software | 105.70 | 0.0 | 44.04 |
| | %Diff | -0.62 | 100.00 | -1.78 |
| 2 (-45°) | ANSYS | 106.18 | 0.97797 | -44.649 |
| | Software | 105.70 | 0.0 | -44.04 |
| | %Diff | -0.45 | 100.00 | -1.38 |
| 3 (-45°) | ANSYS | 106 | 0.74817 | -44.481 |
| | Software | 105.70 | 0.0 | -44.04 |
| | %Diff | -0.28 | 100.00 | -1.00 |
| 4 (45°) | ANSYS | 105.81 | 0.50027 | 44.294 |
| | Software | 105.70 | 0.0 | 44.04 |
| | %Diff | -0.10 | 100.00 | -0.57 |

**Table-6.** Stresses due to axial load on C-beam of top flange.

| **PLY** | | **SX** | **SY** | **SXY** |
|---|---|---|---|---|
| 1 (0°) | ANSYS | 833.96 | -0.66158 | 0.0 |
| | Software | 833.95 | -0.68 | 0.0 |
| | %Diff | -0.001 | 2.18 | 0.0 |
| 2 (45°) | ANSYS | 200.07 | 121.95 | 134.15 |
| | Software | 200.14 | 122.01 | 134.23 |
| | %Diff | 0.035 | 0.049 | 0.059 |
| 3 (-45°) | ANSYS | 200.13 | 121.99 | -134.22 |
| | Software | 200.14 | 122.01 | -134.23 |
| | %Diff | 0.005 | 0.017 | 0.007 |
| 4 (90°) | ANSYS | 54.362 | -243.52 | 0.0 |
| | Software | 54.37 | -243.34 | 0.0 |
| | %Diff | 0.011 | -0.072 | 0.0 |
| 5 (90°) | ANSYS | 54.358 | -243.65 | 0.0 |
| | Software | 54.37 | -243.34 | 0.0 |
| | %Diff | 0.018 | -0.126 | 0.0 |
| 6 (-45°) | ANSYS | 199.79 | 121.63 | -133.87 |
| | Software | 200.14 | 122.01 | -134.23 |
| | %Diff | 0.17 | 0.31 | 0.27 |
| 7 (45°) | ANSYS | 200.28 | 122.12 | 134.41 |
| | Software | 200.14 | 122.01 | 134.23 |
| | %Diff | -0.07 | -0.09 | -0.13 |
| 8 (0°) | ANSYS | 833.85 | -0.72761 | 0.0 |
| | Software | 833.95 | -0.68 | 0.0 |
| | %Diff | 0.012 | -7.58 | 0.0 |

The results given by the software for axial of all composite sections agree very well with the results from ANSYS simulation.

**Bending of composite sections**

The following shows the results of T-section beam under bending moment $M_y$=0.5 kNmm about y-axis at the centroid. Figure 3 shows that T-beam is subjected to $M_y$. Figure-4 shows that I-beam is subjected to bending moments $M_y$=$M_z$=0.5 kNmm about y and z-axes.

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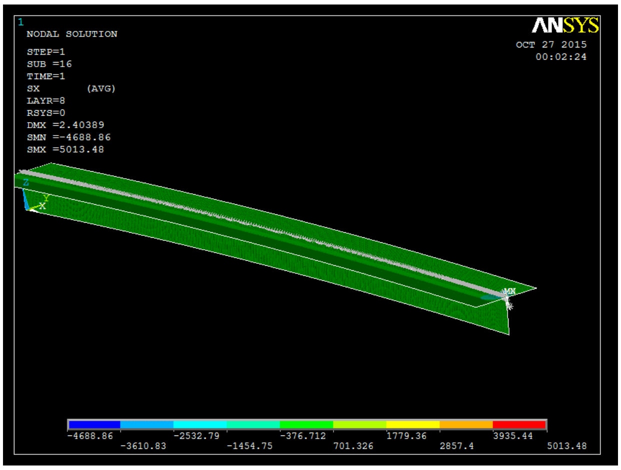


**Figure-3.** SX contour plot of T-section beam subjected to bending $M_y$.

**Table-7.** Stresses due to bending about y-axis on T-beam of top flange.

| PLY | | SX | SY | SXY |
|---|---|---|---|---|
| 1 (0°) | ANSYS | 19.625 | 1.3358 | 0.38938 |
| | Software | 19.58 | 1.33 | 0.39 |
| | %Diff | -0.21 | -0.20 | -0.19 |
| 2 (45°) | ANSYS | 15.212 | 12.028 | 11.816 |
| | Software | 15.18 | 12.00 | 11.79 |
| | %Diff | -0.21 | -0.20 | -0.20 |
| 3 (-45°) | ANSYS | 16.966 | 11.057 | -11.443 |
| | Software | 16.93 | 11.03 | -11.42 |
| | %Diff | -0.21 | -0.20 | -0.20 |
| 4 (90°) | ANSYS | 6.008 | -26.891 | 0.0 |
| | Software | 6.00 | -26.84 | 0.0 |
| | %Diff | -0.20 | -0.20 | 0.0 |
| 5 (90°) | ANSYS | 7.4579 | -40.292 | -0.12979 |
| | Software | 7.44 | -40.21 | -0.13 |
| | %Diff | -0.20 | -0.20 | -0.18 |
| 6 (-45°) | ANSYS | 32.418 | 18.334 | -21.613 |
| | Software | 32.35 | 18.30 | -21.57 |
| | %Diff | -0.20 | -0.20 | -0.20 |
| 7 (45°) | ANSYS | 32.474 | 15.665 | 19.359 |
| | Software | 32.41 | 15.63 | 19.32 |
| | %Diff | -0.20 | -0.21 | -0.20 |
| 8 (0°) | ANSYS | 188.87 | -1.9554 | -0.51917 |
| | Software | 188.48 | -1.95 | -0.52 |
| | %Diff | -0.21 | -0.20 | -0.19 |

**Table-8.** Stresses due to bending about y-axis on T-beam of web at z=0.25.

| PLY | WEB | SX | SZ | SXZ |
|---|---|---|---|---|
| 1 (45°) | ANSYS | -142.4 | 0 | -59.333 |
| | Software | -141.60 | 0 | -58.9984 |
| | %Diff | -0.57 | 0 | -0.57 |
| 2 (-45°) | ANSYS | -142.4 | 0 | 59.333 |
| | Software | -141.60 | 0 | 58.9984 |
| | %Diff | -0.57 | 0 | -0.57 |
| 3 (-45°) | ANSYS | -142.4 | 0 | 59.333 |
| | Software | -141.60 | 0 | 58.9984 |
| | %Diff | -0.57 | 0 | -0.57 |
| 4 (45°) | ANSYS | -142.4 | 0 | -59.333 |
| | Software | -141.60 | 0 | -58.9984 |
| | %Diff | -0.57 | 0 | -0.57 |

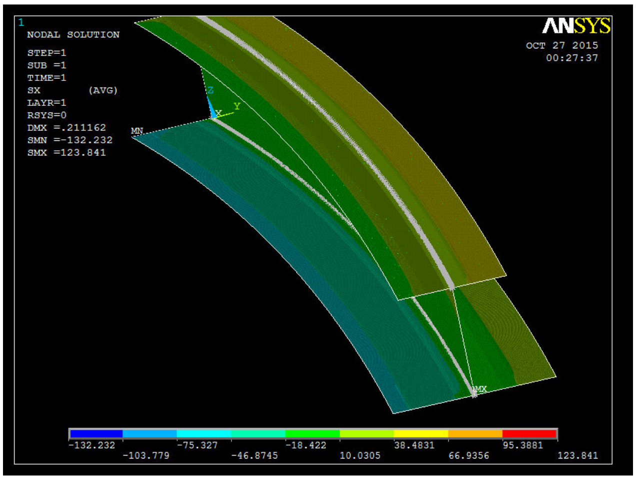


**Figure-4.** SX contour plot of I-beam under moment about y- and z-axes.

**Table-9.** Stresses due to bending about y- and z-axes on I-beam of bottom flange (at y=-0.375).

| PLY | | SX | SY | SXY |
|---|---|---|---|---|
| 1 (45°) | ANSYS | -55.505 | -33.343 | -36.993 |
| | Software | -56.132 | -33.722 | -37.412 |
| | %Diff | 1.116 | 1.123 | 1.119 |
| 2 (-45°) | ANSYS | -55.432 | -33.484 | 37.069 |
| | Software | -56.058 | -33.864 | 37.488 |
| | %Diff | 1.116 | 1.122 | 1.117 |
| 3 (0°) | ANSYS | -230.950 | 0.282 | 0.008 |
| | Software | -233.553 | 0.284 | 0.008 |
| | %Diff | 1.115 | 0.909 | 0.618 |
| 4 (0°) | ANSYS | -229.210 | 0.229 | 0.004 |
| | Software | -231.805 | 0.232 | 0.004 |
| | %Diff | 1.119 | 0.993 | 0.694 |
| 5 (90°) | ANSYS | -14.832 | 66.270 | 0.000 |
| | Software | -15.000 | 67.024 | 0.000 |
| | %Diff | 1.122 | 1.125 | 0.000 |
| 6 (90°) | ANSYS | -14.733 | 65.045 | -0.004 |
| | Software | -14.901 | 65.792 | -0.004 |
| | %Diff | 1.126 | 1.136 | 0.387 |
| 7 (0°) | ANSYS | -223.990 | 0.072 | -0.008 |
| | Software | -226.563 | 0.074 | -0.008 |
| | %Diff | 1.136 | 1.959 | 0.465 |
| 8 (0°) | ANSYS | -222.250 | 0.020 | -0.011 |
| | Software | -224.815 | 0.021 | -0.011 |
| | %Diff | 1.141 | 5.508 | 0.492 |
| 9 (-45°) | ANSYS | -53.526 | -33.083 | 36.060 |
| | Software | -54.142 | -33.461 | 36.474 |
| | %Diff | 1.137 | 1.128 | 1.134 |
| 10 (45°) | ANSYS | -53.502 | -33.274 | -36.191 |
| | Software | -54.118 | -33.653 | -36.605 |
| | %Diff | 1.138 | 1.125 | 1.132 |

**Table-10.** Stresses due to bending about y- and z-axes on I-beam of web at z=0.

| PLY | WEB | SX | SZ | SXZ |
|---|---|---|---|---|
| 1 (45°) | ANSYS | -6.137 | 0.00 | -2.597 |
| | Software | -6.351 | 0.00 | -2.646 |
| | %Diff | 3.377 | 0.00 | 1.875 |
| 2 (-45°) | ANSYS | -6.393 | 0.00 | 2.664 |
| | Software | -6.651 | 0.00 | 2.771 |
| | %Diff | 3.885 | 0.00 | 3.885 |
| 3 (-45°) | ANSYS | -6.859 | 0.00 | 2.963 |
| | Software | -6.951 | 0.00 | 2.896 |
| | %Diff | 1.330 | 0.00 | -2.303 |
| 4 (45°) | ANSYS | -6.905 | 0.00 | -2.798 |
| | Software | -7.251 | 0.00 | -3.021 |
| | %Diff | 4.775 | 0.00 | 7.405 |

The results given by the software for bending of composite T-section beam about y-axis agree very well with the results from ANSYS simulation. The I-beam under bending moment $M_y$ and $M_z$ also gives excellent result compare to ANSYS.

## CONCLUSIONS

A software to perform stress analysis of thin-walled open sections made of composite materials has been developed using MATLAB. The results obtained from the software were found to be in excellent agreement with ANSYS. Shear load and torsional analysis will be added to the software in order to improve its capability in computing stress analysis of thin wall beams. Thus, the software is expected to be useful as guidance and educational tool for students and lecturers.

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