Numerical simulation of hole drilling method to determine residual stress

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***Abstract* — The present study deals with the finite element modelling and simulation of the through-hole drilling method for the residual stress analysis in isotropic materials and laminated composites. Through a theoretical study how the relaxed strains around a hole are connected to the residual stresses are explained. Using finite element simulation a methodology for hole-drilling method under in-plane loads is proposed. The results obtained from the numerical method are compared with experimental results. An acceptable agreement between the results shows the reliability of the numerical method presented in this study.**

***Keywords*— hole drilling method; laminated composites; strain gage;**

I. Introduction

The hole-drilling method is one of the most used semi destructive techniques for measuring residual stress in metallic components. This method was originally proposed by Mather in 1937. Now this method is commonly used in laminated composites also. The relaxed strain at each stage of drilling can easily be determined by numerically simulating hole-drilling process. So the finite element modelling and simulation are now more important. Residual stress can be defined as the stress that remains within a material after manufacture or material processing in the absence of external force. They can also be produced by service loading. Residual stresses may also be defined as locked-in stresses without application of any exterior forces. Residual stresses are inherently present in virtually all composite materials and influence the properties of the composite structures significantly. So it is most important that the residual stresses are taken into account in both design and analytic modelling of composite structures. In order to understand the effects and nature of residual stresses the factors responsible for the residual stress build-up need to be understood.

II. Hole-drilling method

One of the most useful and widely used methods of residual stress measurement is the central hole- drilling method. This method is a well- established popular technique for measuring residual stresses in isotropic materials. It is easy to use, reliable in operation, and involves only limited damage to the specimen (ASTM E 837-01). The most common use of this method involves the application of a special three-element strain- gage rosette onto the surface of the component at the measurement location. A small shallow hole, usually with a depth equal to the diameter and about 0.8 mm to 3.2 mm in diameter, is made in the specimen through the centre of the rosette. The production of the hole in the material causes a redistribution of strains to occur near the hole, which can be detected and measured by the strain gages. These strain measurements can be then related to the original residual stresses at the hole location. The response of the strain gages is sensitive to the radius of the hole (r_a) and the radius of the rosette (r_m).

Drilling a circular through-hole in a plate causes residual stress relaxation around the hole. The relaxed residual stresses are given by the difference between the residual stress distribution in the drilled plate and the residual stress distribution before drilling the hole. Similarly, in the usual assumption of elastic relaxation, the relaxed strains (ε_r) are given by the difference between the strains (ε_d) of the plate after drilling and the strains (ε_{nd}) of the plate before drilling. By applying the superposition principle, the relaxed strains (ε_r) coincide with the strains obtained by applying to the hole edge a stress distribution opposite to the actual residual stress distribution. The standard method for hole drilling method is referred in [22].

A. *Isotropic materials*

For isotropic materials, the released strains measured by each strain gage, located at the angle of θ with respect to the *x* -axis, are expressed by

$$\varepsilon_r = A(\sigma_x + \sigma_y) + B(\sigma_x - \sigma_y)\cos 2\theta + C\sigma_{xy}\sin 2\theta \quad \ldots\ldots\ldots\ldots\ldots(1)$$

Where A, B and C are constant values called calibration constants and. σ_x , σ_y and σ_{xy} are the residual stresses trapped in the sample .θ is the angle of each arbitrary point with respect to the *x* –axis. If the rosette is clockwise and the strain gages are located at 0, 135 and 270 degrees, then we get

$$\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\end{bmatrix} = \begin{bmatrix}A+B & 0 & A-B\\ A & -C & A\\ A-B & 0 & A+B\end{bmatrix}\begin{bmatrix}\sigma_x\\ \sigma_{xy}\\ \sigma_y\end{bmatrix} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

By measuring the strains ε_1, ε_2 and ε_3 and using Eq.(2), the residual stresses are calculated. The responses of the strain gages are sensitive to the radius of the hole (r_a) and the radius of the rosette (r_m). The depth of the hole is about $0.8r_a$, or slightly more. For a material if the thickness is less than $2.4r_a$, a through thickness hole must be applied. The ideal ratio of radius (r_a/r_m) for hole drilling method lies between 0.3 and 0.5.The calibration constants A, B, and C are dependent on the material properties, geometry of the rosette and the depth of the hole. The calibration constants are determined either by experimental or numerical methods. In isotropic materials C = 2B and, for a counter clockwise rosette, −C in equation (2) is changed to C [19].

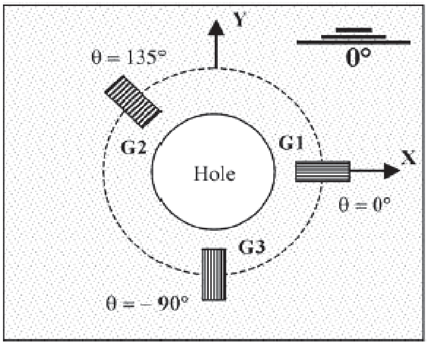


Fig.1. Strain gage location with respect to hole

B. Homogenous orthotropic materials

In orthotropic materials the residual stresses and the released strains are correlated by nine calibration factors. In order to relate the released strains to the stresses the following Eq is used [19].

$$\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\end{bmatrix} = \frac{1}{\sqrt{E_X}\sqrt{E_Y}}\begin{bmatrix}C_{11} & C_{12} & C_{13}\\ C_{21} & C_{22} & C_{23}\\ C_{31} & C_{32} & C_{33}\end{bmatrix}\begin{bmatrix}\sigma_{11}\\ \sigma_{12}\\ \sigma_{22}\end{bmatrix} \quad \ldots\ldots\ldots\ldots..(3)$$

in which the compliances terms C_{ij} are independent of the trigonometric constants A, Band C. The term $\frac{1}{\sqrt{E_X}\sqrt{E_Y}}$ is used in Eq(3) to make the compliance terms C_{ij} non- dimensional. If x and y are the principal elastic directions of the orthotropic material, then the terms C_{12} and C_{32} are zero. The elastic coefficients in the above Eq. are dependent on the orthotropic material properties of the sample, depth of the hole and the geometry of the strain gage. The holes depth effect for an orthotropic material is dependent on the ratio of the out- of-plane shear modulus to the in- plane longitudinal stiffness of the material.

C. Laminated composites

Due to the material non-homogeneity, the above formulation cannot be applied to a generic orthotropic laminate (cross-ply, angle-ply, etc.). For such laminates the material elastic properties change abruptly from one ply to another and, consequently, the residual stress state is always not uniform with depth. In order to overcome such a limitation, in this section an alternative formulation that permits to extend the method to the stresses (not equilibrated) in a generic orthotropic laminate due to in-plane initial loads, has been implemented. In this case the residual stresses are not uniform through the laminate thickness, the residual strains are uniform and simple relationships between surface relaxed strain and residual stresses can be detected by using the Classical Laminate Theory. The residual stresses in the laminates are expressed in L-T coordinate system.

If θ is 90, 225,360

for unidirectional laminates

$$\begin{bmatrix}\sigma_L\\ \sigma_T\\ \sigma_{LT}\end{bmatrix} = E_L\ [\hat{C}]^{-1}\begin{bmatrix}\varepsilon_3\\ \varepsilon_2\\ \varepsilon_1\end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

For Cross ply and angle ply laminates

$$\begin{bmatrix}\sigma_L\\ \sigma_T\\ \sigma_{LT}\end{bmatrix} = [\tilde{E}]_k\ [\bar{E}]^{-1}\ [\hat{C}]^{-1}\begin{bmatrix}\varepsilon_3\\ \varepsilon_2\\ \varepsilon_1\end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

If θ is 0,135,270

The equation changes to

$$\begin{bmatrix}\sigma_L\\ \sigma_T\\ \sigma_{LT}\end{bmatrix} = E_L\ [C]^{-1}\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots..\ldots.(6)$$

$$\begin{bmatrix}\sigma_L\\ \sigma_T\\ \sigma_{LT}\end{bmatrix} = [\tilde{E}]_k\ [\bar{E}]^{-1}\ [C]^{-1}\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots(7)$$

E_L represents Young’s Modulus in longitudinal direction in L-T coordinate system, that coordinate system represents the global longitudinal and transverse axis of the laminate.

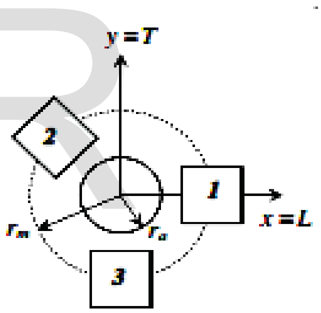


Fig.2. Strain gage location based on L-T axis

TABLE I. EQUIVALENT MATERIAL PROPERTIES [18]

	E_1 (MPa)	E_2 (MPa)	G (MPa)	U	$\bar{E}$ (MPa)	$\bar{G}$ (MPa)
$(0)_8$	14753	3022	1284	0.35	4.8	0.42
[(0/90)2]s	15420	15420	2065	0.02	1	0.13
[0/±45/90]s	10053	10053	3607	0.4	1	0.36

The table I. represents the equivalent material properties for three different GFRP laminates. P. Pagliaro and B. Zuccarello determine residual stress of these laminates by using hole drilling experimental tests. The laminate thickness of unidirectional laminates, cross ply laminates, angle ply laminates are taken as 4.8mm, 2.9mm, 3mm and corresponding in plane loads are 13.1kN, 8.6kN and 5.2kN respectively.

III. FINITE ELEMENT METHOD

There are various methods for simulating residual stress in materials. Among them birth and death technique in Ansys and model change operation in Abaqus are most popular. Both these techniques can be used to deactivate or reactivate selected elements in the model. Instead of killing elements they multiply stiffness by a severe reduction factor, so material continuity is achieved.

After applying the initial stress as the residual stress to the model, in order to simulate the hole- drilling process, the elements under the area of the hole must be removed. This is achieved by the element elimination effect, in this work which is done with the help of model change operation in Abaqus CAE. While using this technique the elements in the hole region are deactivated or multiplying their stiffness by a severe reduction factor.

In order to simulate hole drilling in isotropic materials a steel specimen of dimension 150mm x 150mm x 1mm is selected. Using partition tool a rosette region of radius 2.56mm and a hole region of radius 0.7695mm is created. For laminated composites a rectangular laminate of length 270mm and width 75 mm is used for the same test, but the laminate thickness is varied for different laminates. Corresponding rosette radius and hole radius are 5.15mm and 2.5mm respectively. The laminates used in this study are an uni-directional laminate $(0)_{8}$, a cross ply laminate $[(0/90)_{2}]_{s}$ and a quasi isotropic laminate$(0/\pm 45/90)_{s}$. The numerical procedures followed are same as that of the steel specimen.

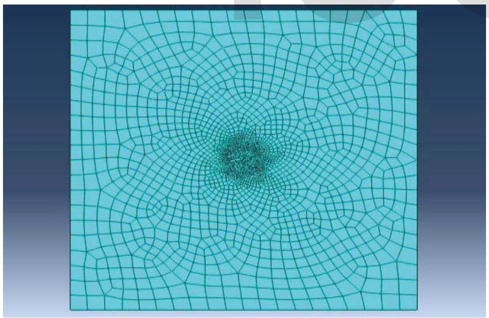


Fig.3. meshed model (steel).

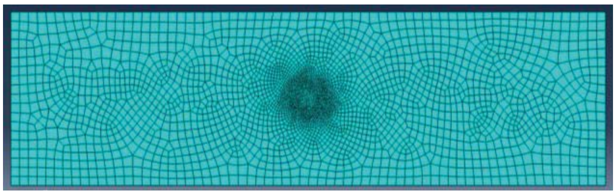


Fig.4. meshed model (laminated composite).

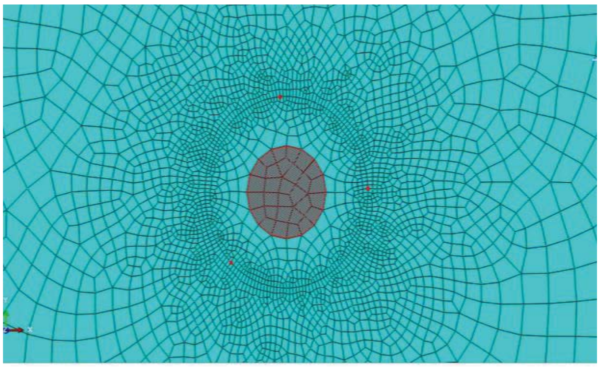


Fig.5. Zoomed view near hole region.

IV. RESULT AND DISCUSSION

A. Isotropic materials

The load applied for simulating residual stress in steel specimen is taken as 20MPa.After applying this initial load, the difference in strains is measured after and before drilling at three strain-gage locations. The following table shows the comparison of value obtained from experimental method and FEM.

TABLE II. COMPARISON OF RELAXED STRAIN-EXPERIMENTAL VALUE V/S FEM VALUE.

strain	Experimental value (μm/m) [19]	FEM value (μm/m)	Error
ε_1	19.69	20.32	3.1%

The experimental value obtained from [19] match with numerical value. The error is only 3.1%.

B. Laminated composites

For unidirectional laminates, cross ply laminates and angle ply laminates, the load applied to simulate residual stress are taken as 13.1kN, 8.6kN and 5.2kN respectively

1) Unidirectional laminate - $(0)_8$

A laminate of eight layered 0 plies is selected for hole-drilling simulation. After applying an initial load, difference in strains after and before drilling are measured at three strain gage locations. The rosette strains obtained from numerical simulations are compared with the experimental strain values [18].

International Journal of Scientific & Engineering Research, Volume 5, Issue 7, July-2014
ISSN 2229-5518

TABLE III. COMPARISON OF RELAXED STRAIN- EXPERIMENTAL VALUES V/S FEM VALUE

Relaxed strain	Experimental values[18] µm/m	FEM value µm/m
ε_3	-1590	-1700
ε_2	-1262	-1250
ε_1	1093	1131

From these relaxed strain values corresponding residual stresses are obtained from Eq (5).

Experimental values [18]

$$\begin{bmatrix} \sigma_L \\ \sigma_T \\ \sigma_{LT} \end{bmatrix} = \begin{bmatrix} 35.3 \\ -0.5 \\ 3.86 \end{bmatrix} \text{MPa}$$

FEM values

$$\begin{bmatrix} \sigma_L \\ \sigma_T \\ \sigma_{LT} \end{bmatrix} = \begin{bmatrix} 37.92 \\ -0.19 \\ 0 \end{bmatrix} \text{MPa}$$

Results show that numerical simulation gives comparable results with experimental values.

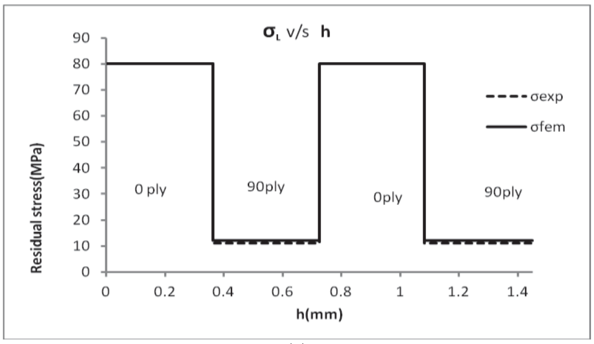
2) Cross ply laminate - $[(0/90)_2]_s$

In case of cross ply laminates eight layers of 0 and 90 plies are arranged in a symmetry layup. After applying a load of 8.6kN relaxed strains are measured. The relaxed strain values obtained from experimental and FEM are given below.

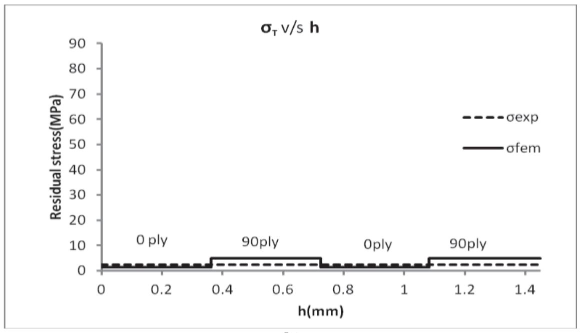
TABLE IV. COMPARISON OF RELAXED STRAIN- EXPERIMENTAL VALUES V/S FEM VALUE

Relaxed strain	Experimental values[18] µm/m	FEM value µm/m
ε_3	-1742	-1760
ε_2	-1456	-1672
ε_1	574	612

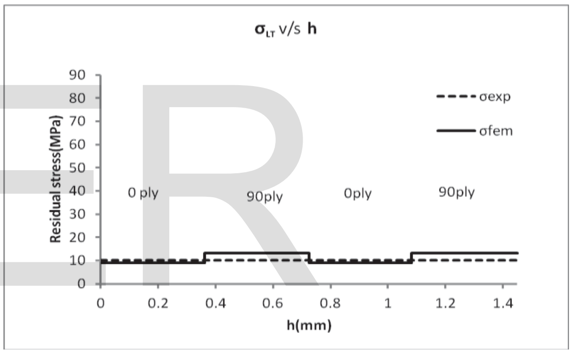
While substituting relaxed strain in Eq (5) the in plane residual stress field is obtained. The following graphs show the comparison of experimental values and the numerical values of residual stresses against the laminate thickness.



(a)



(b)



(c)

Fig.6. (a),(b),(c)-Variation of residual stresses with respect to laminate thickness(in cross ply laminates)

The comparison between the finite element method and experimental values from [18] shows that the magnitudes of residual stresses are very near to each other and the percentage of error is very small. The small differences between these magnitudes confirm the accuracy of the proposed model.

3) Angle ply laminates - $[0/\pm45/90]_s$

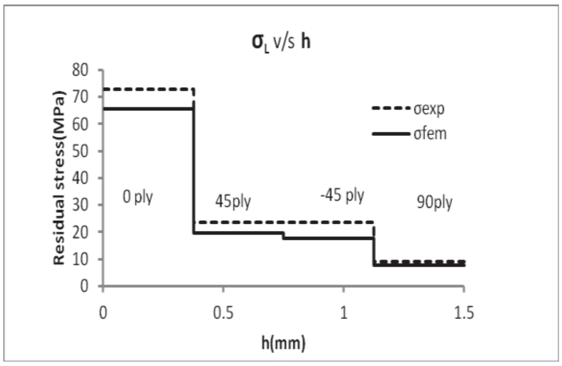
A quasi isotropic laminate of $[0/\pm45/90]_s$ layup is used for analyzing residual stress in angle ply laminated composite. After applying 5.2kN the relaxed strain are measured at three strain gage locations. The relaxed strains obtained from numerical simulations are compared with experimental strain values of [18].

International Journal of Scientific & Engineering Research, Volume 5, Issue 7, July-2014
ISSN 2229-5518

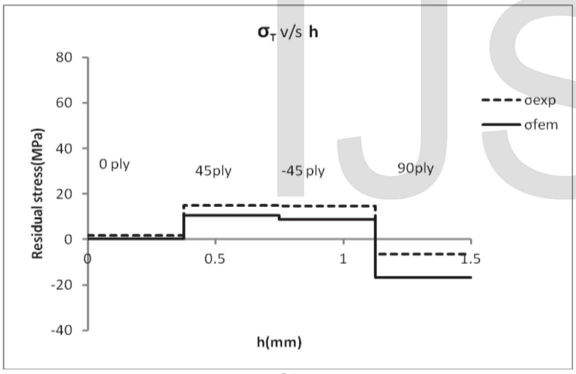
TABLE V. COMPARISON OF RELAXED STRAIN-EXPERIMENTAL VALUES V/S FEM VALUE

Relaxed strain	Experimental values[18] µm/m	FEM value µm/m
ε_3	-1365	-1294
ε_2	-456	-400
ε_1	457	612

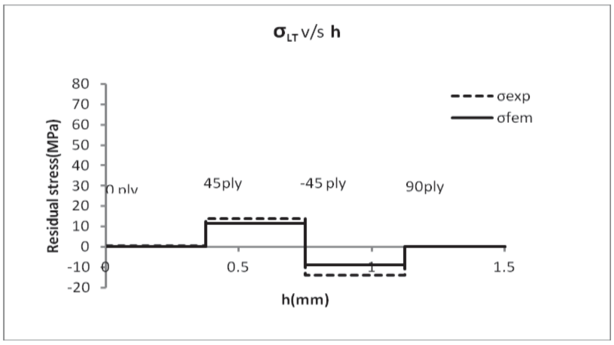
In order to compare the residual stress induced in each ply for FEM and experimental method, normal components and shear component residual stresses are plotted against laminate thickness.



(a)



(b)



(c)

Fig.7.(a),(b),(c)-Variation of residual stress with laminate thickness(in quasi isotropic laminates)

The residual stresses on each ply are evaluated from relaxed strains using finite element method. It gives a good agreement with experimental values.

A good conformance is found to exist between the experimental and numerical results for all samples. So this method provides a good methodology for simulating hole drilling method in isotropic materials and laminated composites, which gives accurate and reliable results.

V. CONCLUSION

Hole drilling method is one of the reliable methods for residual stress in isotropic materials as well as laminated composites. A numerical simulation of hole drilling method is attempted for studying the stress relaxation during hole drilling process. The numerical value of residual stress showed good agreement with experimental values. While simulating hole-drilling method a clear picture of residual stress field in laminates is obtained. In hole-drilling simulation we directly measure the relaxed strains only. For the residual stress analysis of orthotropic laminates caused by in-plane initial loads, residual stresses are not uniform throughout the laminate thickness. But the residual strains are uniform and make a simple relationship between surface relaxed strain and residual stresses, which can be detected by using the Classical Laminate Theory.

Appendix

$$[C] = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix}$$

$$[\hat{C}] = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & -C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix}$$

[C] and $[\hat{C}]$ represents the influence coefficient matrix for 0,135,270 & 90,225,360 rosette sequence.

Values of influence coefficient from reference [18];

For $(0)_8$

$$[\hat{C}] = \begin{bmatrix} -0.66 & 0.26 & 0 \\ -0.31 & -0.81 & -2.14 \\ 0.43 & -1.94 & 0 \end{bmatrix}$$

For $[(0/90)_2]$s

$$[\hat{C}] = \begin{bmatrix} -0.574 & 0.163 & 0 \\ -0.287 & -0.287 & -1.041 \\ 0.163 & -0.574 & 0 \end{bmatrix}$$

For $[0/\underline{+}45/90]$s

$$[\hat{C}] = \begin{bmatrix} -0.468 & 0.176 & 0 \\ -0.152 & -0.152 & -0.669 \\ 0.176 & -0.468 & 0 \end{bmatrix}$$

$$[\tilde{E}]_k = [T\alpha_k][E^*]_k\,[\check{T}\alpha_k]^{-1}$$

$$[T\alpha_k] = \begin{bmatrix} \cos^2\alpha_k & \sin^2\alpha_k & 2\cos\alpha_k\sin\alpha_k \\ \sin^2\alpha_k & \cos^2\alpha_k & -2\cos\alpha_k\sin\alpha_k \\ \cos\alpha_k\sin\alpha_k & \cos\alpha_k\sin\alpha_k & \cos^2\alpha_k - \sin^2\alpha_k \end{bmatrix}$$

$$[\check{T}\alpha_k] = \begin{bmatrix} \cos^2\alpha_k & \sin^2\alpha_k & 2\cos\alpha_k\sin\alpha_k \\ \sin^2\alpha_k & \cos^2\alpha_k & -2\cos\alpha_k\sin\alpha_k \\ 2\cos\alpha_k\sin\alpha_k & 2\cos\alpha_k\sin\alpha_k & 2(\cos^2\alpha_k - \sin^2\alpha_k) \end{bmatrix}$$

$$[E^*]_k = \begin{bmatrix} E_1/(1-\upsilon_{12}\upsilon_{21}) & \upsilon_{12}E_2/(1-\upsilon_{12}\upsilon_{21}) & 0 \\ \upsilon_{12}E_2/(1-\upsilon_{12}\upsilon_{21}) & E_2/(1-\upsilon_{12}\upsilon_{21}) & 0 \\ 0 & 0 & 2G_{12} \end{bmatrix}$$

Where $[\tilde{E}]_k$ represents the effective stiffness matrix for general orthotropic laminate and $[T\alpha_k]$ represents the transformation matrix.

$$[\bar{E}] = \begin{bmatrix} \frac{\bar{E}}{(\bar{E}-\bar{\upsilon}^2)} & \frac{\bar{\upsilon}}{(\bar{E}-\bar{\upsilon}^2)} & 0 \\ \frac{\bar{\upsilon}}{(\bar{E}-\bar{\upsilon}^2)} & \frac{1}{(\bar{E}-\bar{\upsilon}^2)} & 0 \\ 0 & 0 & \frac{\bar{G}}{\bar{E}} \end{bmatrix}$$

$$\bar{E} = \frac{E_L}{E_T} \quad \bar{G} = \frac{G_{LT}}{E_T} \quad \bar{\upsilon} = \nu_{LT}$$

Where E, G, ν are engineering constants and α_k represents the orientation of k^{th} ply with respect to L-T coordinate system.

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