Simulation Study of Stress and Deformation Behaviour of Debonded Laminated Structure

C K Hirwani[1], H Mittal[2] S K Panda[3] S S Mahapatra[4] S K Mandal[5] and A K De[6]

[1,2,3,4]Department of Mechanical Engineering, National Institute of Technology Rourkela Odisha, India.

[5,6]DRDO Integration Centre, Panagarh, West Bengal, India

Email[1]: chetanhirwani111@gmail.com

Abstract. The bending strength and deformation characteristics of the debonded laminated plate under the uniformly distributed loading (UDL) have been investigated in this research article. For the simulation study, an internally damaged laminated plate structure model has been developed in ANSYS based on the first-order shear deformable kinematic theory via ANSYS parametric design language (APDL) code. The internal debonding within the laminated structure is incorporated using two sub-laminate approach. Further, the convergence (different mesh densities), as well as the validity (comparing the responses with published results) of the present simulation model, have been performed by solving the deflection responses under the influence of transversely loaded layered structure. Also, to show the coherence of the simulation analysis the results are compared with the experimental bending results of the homemade Glass/Epoxy composite with artificial delamination. For the experimental analysis, Glass/Epoxy laminated composite seeded with delamination at the central mid-plane of the laminate is fabricated using an open mould hand lay-up composites fabrication technique. For the computational purpose, the necessary material properties of fabricated composite plate evaluated experimentally via uniaxial tensile test (Universal Testing Machine INSTRON-1195). Further, the bending (three-point bend test) test is conducted with the help of Universal Testing Machine INSTRON-5967. Finally, the effect different geometrical and material parameters (thickness ratio, modular ratio, constraint conditions) and magnitude of the loading on the static deflection and stress behaviour of the delaminated composite plate are investigated thoroughly by solving different kinds of numerical illustrations and discussed in detail.

1. Introduction

Since last few decades, the application of the layered composite material for the development of structure and the structural element has been increased in many industries such as aerospace, automobile, marine, aircraft and civil construction. The composite material is known for their specific strength and the stiffness and tailor-made property as per application. Instead of having all the all the favorable property the layered structure is always subjected to an unavoidable defect called delamination. The delamination is the detachment of the consecutive layer of the laminate. The presence of the debonding in the layered structure affect the structural performance largely. Therefore, it is important to study the effect of damage or delamination on the structural behavior of the layered structure. In this regard, many works have already been presented in the past. In order to have a progress, as well as a present status review of few important of them, are discussed further.

Alfano and Crisfield [1] presented an FE interface model of the delaminated composite using interface element and interface damage law. Zak et al. [2] model the delamination using the additional constraints condition at the delaminated front and consider the contact forces with the help of node to node contact. Parhi et al. [3] established the FE model to analyse the flexural characteristic of the first ply failure of the composites plates with multiple internal damages under low-velocity impact loading. Yam et al. [4] model the arbitrary delamination using FE approaches and obtained the structural behaviour. Bruno et al. [5] model the debonding using the concept of fracture and contact mechanics in addition with the FSDT kinematics to investigate the mixed-mode delamination behaviour. Cetkovic and Vuksanovic [6] investigated the bending, buckling and free vibration characteristics of a laminated composite plate using generalized laminated plate theory. The flexural response of the layered composites beam is analysed by Chen et al. [7] by developing a mathematical model based on modified couple stress theory based on FSDT. The crack closure integral technique along with finite element method (FEM) has been used by Sathish et al. [8] to investigate the debonding propagation within the woven fabric composite plate. Das et al. [9] investigated the stress and the energy release rate of the edge delaminated composites structure by developing a simulation model in ANSYS. Thai and Choi [10] investigated the bending and free vibration characteristic of a functionally graded plate using an FSDT kinematic based eloped mathematical model. Aslan and Daricik [11] examined the effect of multiple damages on the tensile, compressive, flexural and buckling characteristic of Glass/Epoxy layered composites structure. Transverse crack growth analysis of the edge delaminated composites plate and the shell is studied by Li [12] using the extended layer-wise method. Michalcova and Kadlec [13] studied the crack growth behaviour of the edge delaminated Carbon/Epoxy composite under various unlike environment condition, experimentally.

From the extensive literature review, it has been clear that work on modeling and analysis of delaminated layered composite structure has been reported by many authors in the past. Most of the work are related to the edge delamination compare to the internal debonding, but both have the equal importance. Therefore, **the aim of the present work is to develop a simulation model of the layered structure with internal debonding to analyse the bending and strength characteristics of the same**. In order to archive the objective a simulation model in ANSYS environment has been developed using APDL code. Further, the stability and the accuracy of the present model has been checked by computing the deflection responses for different mesh refinement and compare them with existing published literature. In addition, the present responses are compared with experimentally evaluated bending responses of Glass/Epoxy delaminated composite. Finally, the effect of design parameter on flexural behaviour of the delaminated composites plate have been reported and discussed in detail.

2. Theoretical Formulations

2.1. Mathematical model for without delamination

The mathematical model of the laminated composite plate as shown in figure 1 is developed in the present study. The geometrical parameters of the laminate are considered as length *a,* width *b* and thickness *h*. The laminate is composed of N number of orthotropic layers. The displacement field of the laminate is considered based on the FSDT and presents as:

$$\begin{aligned} u(x,y,z) &= u_0(x,y) + z\theta_x(x,y) \\ v(x,y,z) &= v_0(x,y) + z\theta_y(x,y) \\ w(x,y,z) &= w_0(x,y) + z\theta_z(x,y) \end{aligned} \tag{1}$$

where, *u*, *v* and *w* represents the displacements of any point along the *x*, *y* and *z* coordinate axes respectively. u_0, v_0 and w_0 are corresponding displacements of a point on the midplane. θ_x and θ_y are the rotations of normal to the mid-surface, i.e., *z*=0 about *y* and *x*-axes, respectively.

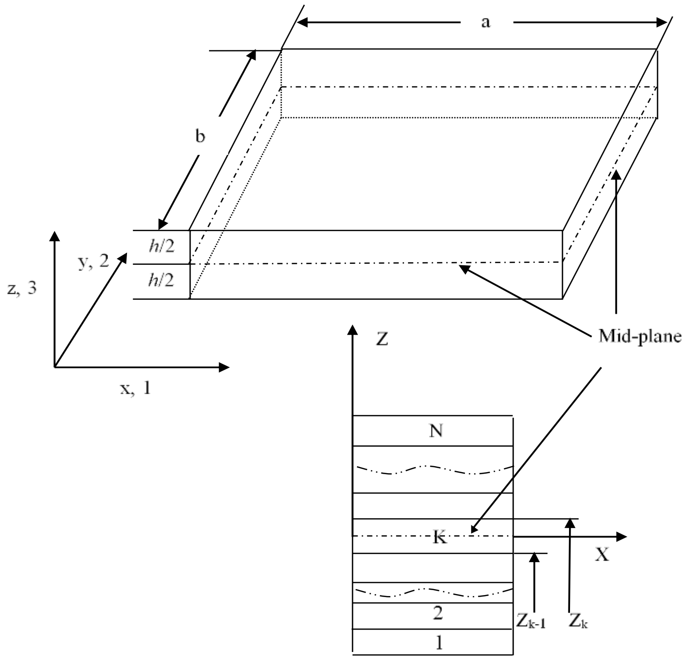


Figure 1. Geometry and stacking sequence of laminated composite plate.

2.2. Laminate constitutive relation

The laminate constitutive relation i.e. stress-strain relations for k^{th} lamina oriented at an arbitrary angle ϕ about any arbitrary axes is written as:

$$\{\sigma\} = \left[\overline{Q}_{ij}\right]\{\varepsilon\} \tag{2}$$

where, $\{\sigma\}$, $\left[\overline{Q}_{ij}\right]$ and $\{\varepsilon\}$ are the stress tensor, transformed reduced stiffness matrix and strain tensor, respectively.

2.3. Finite element formulation

The model is discretized using four-noded shell 181 elements, chosen from the ANSYS element library. The displacement vector 'δ' at any point within the mid-plane can be presented as:

$$\delta = \sum_{i=1}^{4} N_i(x, y)\delta_i \tag{3}$$

where, $\{\delta_i\} = \{u_{0_i}\ v_{0_i}\ w_{0_i}\ \theta_{x_i}\ \theta_{y_i}\ \theta_{zi}\}^T$ is the nodal displacement vector and N_i is the corresponding shape function for the 'i^{th}' node.

The strain vector can be expressed in the matrix form after introducing the FEM steps and conceded as:

$$\{\varepsilon\} = [H]\{\overline{\varepsilon}\} \tag{4}$$

where, $[H]$ is the thickness coordinate matrix and $\{\overline{\varepsilon}\}$ is the midplane strain vector which can be further expressed as:

$$\{\overline{\varepsilon}\} = [B_L]\{\delta\} \tag{5}$$

where, $[B_L]$ is a general strain displacement relation matrix.

The total strain energy of the laminate can be expressed as:

$$U = \frac{1}{2}\iint\left[\int_{-h/2}^{+h/2}\{\varepsilon\}^T\{\sigma\}\,dz\right]dxdy \tag{6}$$

The total work done due to the externally applied mechanical load (F) is expressed as:

$$W = \int_A \{\delta\}^T \{F\} dA \tag{7}$$

The stiffness matrix ([K]) and the mass matrix ([M]) can be written as:

$$[K] = \int_A (\sum_{k=1}^{n} \int_{z_{k-1}}^{z_k} [B_L]^T [D][B_L] dz) dA \tag{10}$$

The modeling of the delamination segment is as same as the modeling of the laminated segment. The modeling approach and the intermittent continuity condition can be seen in hirwani et al. [14]

2.4. Governing equations

The final form of governing equation for bending analysis of laminated plate is obtained using variational principle:

$$\partial \prod = \partial (U - W) = 0 \tag{11}$$

where, $\prod$ is the total potential energy.

Further, equation (11) is modified by substituting the equations (6) and (7) into equation (11) and expressed as:

$$[K]\{\delta\} = \{F\} \tag{12}$$

The equation (12) is solved by using the following sets of support conditions to avoid any rigid body motion as well as reduce the number of unknowns.

Simply supported

$$v_0 = w_0 = \theta_y = \theta_z = 0 \text{ at } x\text{=0 and } a;$$

$$u_0 = w_0 = \theta_x = \theta_z = 0 \text{ at } y\text{=0 and } b; \tag{13}$$

Clamped

$$u_0 = v_0 = w_0 = \theta_x = \theta_y = \theta_z = 0 \text{ at } x\text{=0 and } a; y\text{=0 and } b; \tag{14}$$

Free

$$u_0 \neq v_0 \neq w_0 \neq \theta_x \neq \theta_y \neq \theta_z \neq 0 \text{ at } x\text{=0 and } a; y\text{=0 and } b; \tag{15}$$

3. Result and discussion

The central deflection and the stress of the delaminated composite structure have been examined in the present investigation. For the computation purpose, a simulation model of the internally debonded plate structure in ANSYS environment using APDL code has been established. The model is discretised using four noded shell 181 elements chosen from the ANSYS element library. Further, the computed responses of the layered composite structure are compared with that of the numerical responses of the earlier published literature. In addition, the present responses are also compared with that of the experimentally computed central deflection responses of the Glass/Epoxy delaminated composite. Finally, the effect of various design parameter central deflection parameter and strength behaviour of delaminated composites plate has been examined via different numerical example and discussed in detail. **The procedure used to model the delaminated composite in ANSYS APDL has been discussed in the following line.**

- **First of all, the geometry of the plate is defined as length, *a*; width *b*; and thickness *h*.**
- **The orientation of each layer is provided and the material property is assigned to the corresponding layers.**
- **The delamination is model using two sub-laminate approach and the intermittent continuity condition has been given using the coincident node under coupling command.**
- **The model is discretised with the help of Shell 181 element, chosen from the ANSYS element library.**
- **Now the end/boundary condition, loading as well as analysis type has been provided.**
- **Finally, the bending as well as stress responses is computed via choosing suitable syntax from the post processing.**

3.1 Convergence and comparison study

In this section, the stability of the present model has been checked by computing the responses for different mesh division. In general, the structural domain is discretised via an equal number of elements in both the direction to maintain the symmetry of meshing. With increasing the number of the element, the responses changes and the computational cost increases simultaneously but after attaining certain mesh sizes the responses repeated and the percentage difference between the subsequent steps also decreases. In order to maintain the accuracy of the desired responses with minimum computational cost, the particular mesh sizes have selected. In this present example, the nondimensional central deflection of the square (a=b=0.2 m) simply supported three-layer cross-ply layered composites plate subjected to uniformly distributed load (q=100KN/m^2) have been examined for different mesh refinement. The responses are evaluated via present simulation model using the material properties from the material data-1 and presented in figure 2. The figure shows that the responses are converging well for various mesh refinement. Based on that the (13×13) mesh size is used for further investigation. The responses are nondimensionalized using the formulae: $\bar{w} = 100E_y h^3 w / qa^4$. Now, a square laminated composite plate with simply supported boundaries have been analysed for the bending responses, compared with Xiao et al. [15] and Reddy [16] and presented in Table 2. The material and the geometrical parameter are taken as same as the reference.

Table 1. Material properties used in present analysis

Material Properties	Material data-1	Material data-2	Material data-3 (Experimental)
E_x	250 GPa	172.5GPa	8.739 GPa
E_y	10 GPa	6.9GPa	7.926 GPa
E_z	10 GPa	6.9GPa	E_2
G_{xy}	5 GPa	3.45GPa	3.75 GPa
G_{yz}	2 GPa	1.38GPa	1.875 GPa
G_{xz}	5 GPa	3.45GPa	3.75 GPa
υ_{xy}	0.25	0.25	0.17
υ_{yz}	0.25	0.25	0.17
υ_{xz}	0.25	0.25	0.17

Table 2. Comparison study for square laminated composite plate

h/a	Present	Xiao et al.[15]	Reddy [16]
0.05	0.7951	0.8029	0.7694
0.1	1.138	1.1401	1.0250
0.2	2.312	2.2383	-

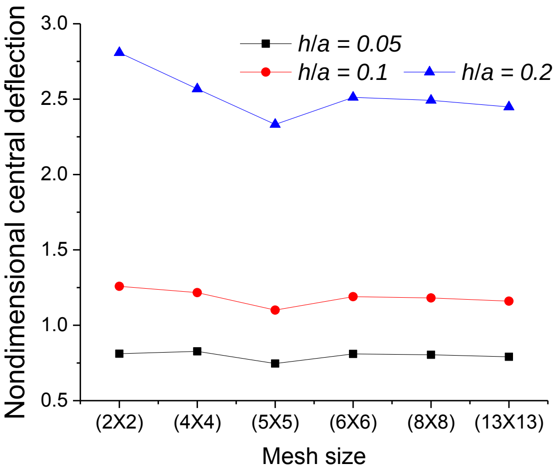


Figure 2. Convergence test central deflection for various mesh density

3.2 *Preparation of the woven Glass/Epoxy delaminated composite plate*

For the fabrication of the Glass/Epoxy laminated composites plate with debonding, a well-known composite fabrication technique hand layup is utilized. The steps used to fabricate the laminate are as follows:

- First of all, a square wooden mold is prepared with the help of flat plywood and wooden strip.
- The mylar sheet is placed at the bottom of the mold.
- Now, the mold release agent is applied to the Mylar sheet so that there will not be any difficulty at releasing the fabricated composite.
- The epoxy polymer (Lapox L-12) and the corresponding hardener (K-6) are mixed together in 10:1 proportion.
- The first thin layer of the mixture is applied to the mylar sheet.
- Further, the woven glass fiber sheet of the required dimension is placed in the mold.
- A small pressure is applied with the help of iron roller to ensure the proper binding of the mixture and the glass fiber.
- The above three steps are repeated till the plane of delamination reached.
- Now, the artificial delamination of the required size is created using the thin Teflon tape.
- Again the thin layer of mixture, another woven fabric and the small pressure are applied.
- The process is repeated until the required number of layers of the laminate is completed.
- The another mylar sheet, treated with mold release agent is placed at the top of the laminate.
- Now, the stacked laminate is pressed via hot-press for the proper stacking as well as pre-curing for half an hour at 60°C.
- After pre-curing the composite is kept at the environment condition for post curing for 72 hours.
- Finally, the mylar sheet is released and the laminate is kept at the air tied container.

In the present work, eight layers of Glass/Epoxy laminated composite with 6.25% of the total area of debonding, located at the center mid-plane of the laminate has been fabricated.

3.3 *Material property evaluation*

For evaluating the material property of the fabricated laminate, sample specimen for the tensile test has been prepared according to American Society for Testing and Materials (ASTM) standard ASTM D 3039/D3039M. The laminated composite is cut into three different directions along length, along with and 45° to the direction of the length to compute the young's modulus in x (E_x), young's modulus in y (E_y) and young's modulus in 45° to the length direction (E_{45}°), respectively. The tensile test is conducted in Universal Testing Machine (UTM) INSTRON-1195 at the parent Institute National Institute of Technology Rourkela, Rourkela, Odisha. The loading rate of the test is kept fix through the test as 1 mm/minute. Further, all the evaluated young's modulus is used are used to compute the shear modulus using the formulae as presented in equation (16). The poisons ratio of the GFRP is taken from the Crawley et al. [17] as 0.17. The experimentally evaluated material properties are shown in Table 1.

$$G_{xy} = \frac{1}{\frac{4}{E_{45^\circ}} - \frac{1}{E_x} - \frac{1}{E_y} - \frac{2\upsilon_{xy}}{E_x}} \tag{16}$$

3.4 Experimental bending test

The experimental three-point bending test has been conducted using UTM INSTRON-5967 at NITR Rourkela, Odisha. The loading rate for the experiment has been fixed as 2 mm/minute throughout the test. The sample specimen has been prepared according to the ASTM standard ASTM-D790. The size of the sample specimen is (48mm×16mm×3mm). Three sample of each type of the composite is tested and the average of them is taken as a final result. The experimentally evaluated material property is used to compute the bending responses using ANSYS and compared with those of the experimental responses and presented in Table 3.

Table 3. Comparison study central deflection of delaminated Glass/Epoxy composite

Delamination size (%)	Load (N)	Experiment (mm)	Current Simulation (mm)
6.25%	10	0.0840	0.0772
	20	0.1651	0.154
	30	0.2474	0.232
	40	0.3290	0.309

3.5 Numerical illustrations

The comparison study clearly indicates that the simulation model is capable enough to evaluate the bending response of the laminated and delaminated composite with adequate accuracy. Further, the applicability of the simulation model is expanded by solving the various illustration and highlighted the influence of the geometrical and material parameter. The examples are computed for the twenty-layer angle-ply laminate with 56% of debonding located at the center mid-plane of the laminate. The material data-2 is used for further study, else stated otherwise.

3.5.1 Influence of the modular ratios on bending behavior of the delaminated composite plate

In the present example, the influence of the modular ratios on bending behavior of the delaminated composite plate has been examined. For evaluating the responses, a square (a=b=0.5m) clamped twenty-layer angle-ply $(\pm 60^\circ)_{10}$ laminated composite (a/h=100) with 56.25% of centrally located debonding at the mid-plane of the laminate under UDL loading have been utilized. The responses are evaluated using simulation model and presented in figure 3. The figure clearly indicated that the central deflection parameter decreases with the increase of modular ratio. The depicted trend on the result is expected because with increasing the modular ratio the longitudinal modulus increase, which increase the global stiffness resulting in the deflection decreases.

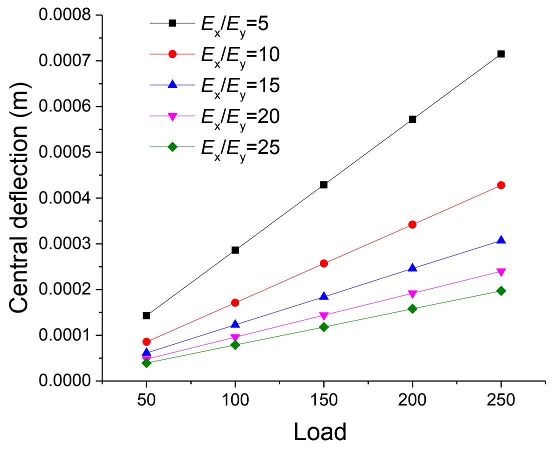


Figure 3. Effect of modular ratio on bending behavior of delaminated composite plate

3.5.2 Influence of the thickness ratios on bending behavior of the delaminated composite plate

The central displacement of square (a=b=0.5m) clamped twenty-layer $(\pm60°)_{10}$ 56% delaminated composite plate subjected to UDL loading have been computed for the different thickness ratio (a/h=10, 20, 50, 80,100) using the presently developed simulation model. The computed responses are shown in figure 4. From the figure it depicts that as the thickness ratio increases the central deflection responses increases irrespective of the magnitude of the loading. This is because of the decreasing thickness as well the global stiffness of the layered structure with increasing the thickness ratio.

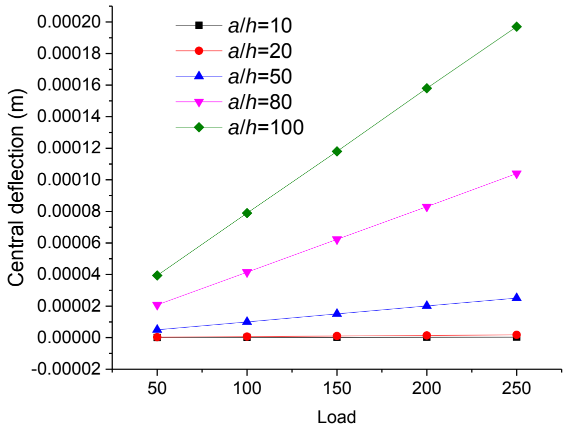


Figure 4. Effect of thickness ratio on bending behavior of delaminated composite plate

3.5.3 Influence of the boundary condition on bending behavior of the delaminated composite plate

In this illustration, bending behavior of the square (a=b=0.5m) angle-ply $(\pm60°)_{10}$ laminated composites plate with 56.25% of delaminated composite plate is examined for various boundary condition such as all side clamped (CCCC), three sides clamped and one side free (CCCF), two sides clamped and two sides free (CFCF). The responses ate evaluated via present simulation model and presented in figure 5. The figure indicated that the response follows the increasing trend with the CCCC, CCCF and CFCF independent of the magnitude of the loading. This is because the constraint degree of freedom decreases with CCCC, CCCF and CFCF.

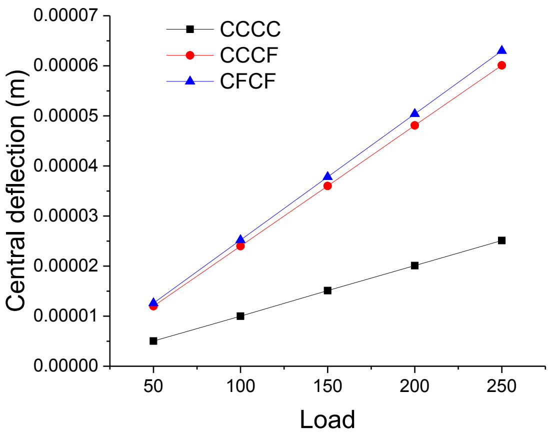


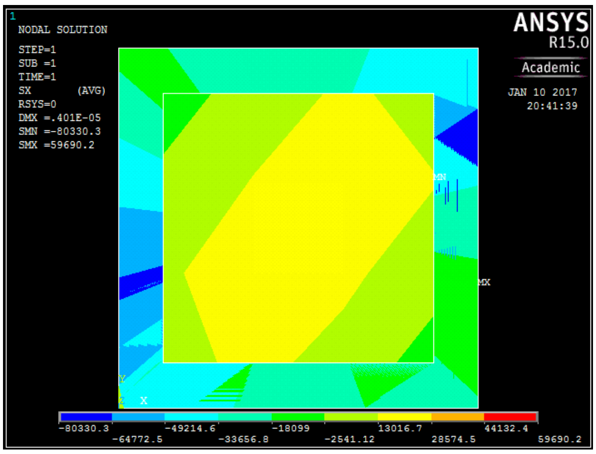
Figure 5. Effect of boundary condition on bending behavior of delaminated composite plate

3.5.4 In-plane normal and shear stress of the delaminated composite plate

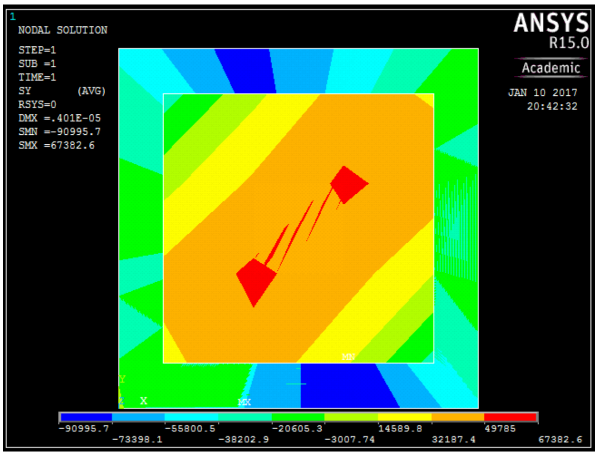
The in-plane normal as well as the shear stress of the square (a=b=0.5m) clamped angle-ply $(\pm 60°)_{10}$ 56% delaminated layered structure for two different thickness ratios (a/h=50 and a/h=100) have been evaluated in the present illustration. The stress responses are computed with the help of the current ANSYS simulation model and depicted in table 4. The table indicates that the stress value increases with increasing the magnitude of the load as well as the thickness ratio. The in-plane stress contour plot for the load magnitude 40 and thickness ratio 50 is presented in figure 6(a)-(c).

Table 4. In-plane normal as well as the shear stress

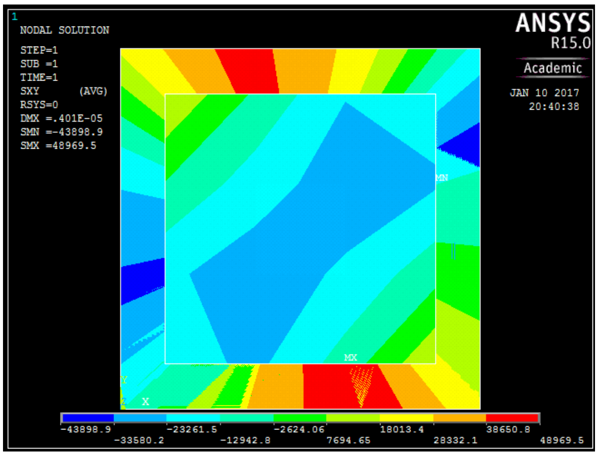
Load	a/h=50			a/h=100		
	σ_x (N/mm^2)	σ_y (N/mm^2)	τ_{xy} (N/mm^2)	σ_x (N/mm^2)	σ_y (N/mm^2)	τ_{xy} (N/mm^2)
40	59690.2	67382.6	48969.5	237768	270550	195806
80	119380	134765	97939	475536	541101	391612
120	179071	202148	146909	713304	811651	587417
160	238761	269530	195978	951071	1080000	783223
200	298451	336913	244848	1190000	1350000	979029



(a)



(b)



(*c*)

Figure 6. In-plane stress (*a*) Normal stress (σ_x); (*b*) Normal stress (σ_y); (*c*) Shear stress (τ_{xy})

4. Conclusion

The static and the strength behaviour of the delaminated composites plate has been analysed in the present work. A simulation model of the delaminated plate has been developed using the two sub-laminate method in commercial simulation software ANSYS with the help of ANSYS parametric design language (APDL) code. Now, the stability of the proposed model is checked by computing the responses for the different mesh refinement. The computed responses of the simulation model are compared with those of the numerically calculated responses of published literature. In addition, the simulation responses are also compared with that of the experimentally calculated responses. The woven glass fiber reinforced polymer (GFRP) composite is fabricated and the material property is evaluated using hand layup method and tensile testing, respectively. Finally, the influence of the design parameter is obtained and discussed in detail. Based on the outcome of the different illustration some important conclusions have been outlined and presented in the next lines.

- The validation study indicates that the model is capable enough to solve the bending problem of the damaged laminated composite.
- In addition, the validation with experimental study shows that the model is also stable with the experimental responses.
- The central displacement increases with the increasing the thickness ratio.
- Further, the deflection responses decrease with the increase in the modular ratio.
- The in-plane normal and the shear stress increase with the increase in the loading.

Acknowledgements

This work is under the project sanctioned by the Defence Research and Development organization (DRDO) through the grant DIC/MMG/LP/14-15/01/05 Dated: 15/09/2014. Authors are thankful to DRDO, Govt. of India for their consistent support.

References

[1] Alfano G and Crisfield M A 2001 Finite element interface models for the delamination analysis of laminated composites: mechanical and computational issues *International Journal for Numerical Methods in Engineering* **50** 1701-1736

[2] Zak A, Krawczuk M and Ostachowicz W 2001 Vibration of a laminated composite plate with closing delamination *Journal of Intelligent Material Systems and Structures* **12** 545-551

[3] Parhi PK, Bhattacharyya SK and Sinha PK 2001 Failure analysis of multiple delaminated composite plates due to bending and impact *Bulletin of Materials Science* **24** 143–149

[4] Yam LH, Wei Z, Cheng L and Wong WO 2004 Numerical analysis of multi-layer composite plates with internal delamination *Computers and Structures* **82** 627–637

[5] Bruno D, Greco F, and Lonetti P 2005 A 3D delamination modelling technique based on plate and interface theories for laminated structures *European Journal of Mechanics A/Solids* **24** 127–149
[6] Cetkovic M and Vuksanovic 2009 Bending, free vibrations and buckling of laminated composite and sandwich plates using a layerwise displacement model *Composite Structures* **88** 219-227
[7] Chen W, Li L and Xu M 2011 A modified couple stress model for bending analysis of composite laminated beams with first order shear deformation *Composite Structures* **93** 2723-2732
[8] Sathish S, Prasath J, Reddy KS and Naik NK 2012 Damage evolution in delaminated woven fabric E-glass/epoxy composite plates under transverse static patch loading *International Journal of Damage Mechanics* **22** 982–1005
[9] Das S, Choudhury P, Halder S and Sriram P 2013 Stress and free edge delamination analyses of delaminated composite structure using ANSYS *Procedia Engineering* **64** 1364-1373
[10] Thai H T and Choi D 2013 A simple first-order shear deformation theory for the bending and free vibration analysis of functionally graded plates *Composite Structures* **101** 332-340
[11] Aslan Z and Daricik F 2016 Effects of multiple delaminations on the compressive, tensile, flexural, and buckling behaviour of e-glass/epoxy composites *Composites Part-B* **100** 186-196
[12] Li D H 2016 Delamination and transverse crack growth prediction for laminated composite plates and shells *Computers and Structures* **177** 39-55
[13] Michalcova L and Kadlec M 2016 Carbon/epoxy composite delamination analysis by acoustic emission method under various environmental conditions *Engineering Failure Analysis* **69** 88-96
[14] Hirwani C K, Sahoo S S and Panda S K 2015 Effect of delamination on vibration behaviour of woven Glass/Epoxy composite plate-An experimental study, *IOP Conf. Series: Materials Science and Engineering* **115**
[15] Xiao J R, Gilhooley D F, Batra R C, Gillespie Jr. J W and McCarthy M A 2008 Analysis of thick composite laminates using a higher-order shear and normal deformable plate theory (HOSNDPT) and a meshless method *Composites Part-B* **39** 414-427
[16] Reddy J N Mechanics of laminated composite plates CRC press 1996
[17] Crawley E F 1979 The natural modes of Graphite/Epoxy cantilever plates and shells *Journal of Composite Materials* **13** 195-205