Delamination detection in composite laminates

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Delamination is the separation of layers which are bonded together in composite laminate. In the case of bending loads delamination usually leads to significant loss of bending stiffness and strength. Therefore it is important to detect the presents of delamination at an early stage. The delamination causes reduction of stiffness and thereby the modal frequencies also change

In order to find the damage location and size of delamination present in the composite materials, we have to determine changes in modal frequencies of the delaminated structure as a function of the damage parameters such as delamination location, size, interface at which it is present. In this work modal analysis is used to determine the delamination in the composite specimen. This is done by modelling a four layered composite material in the lamination codes of 0/90/90/0 and 0/45/-45/90 in ANSYS. A parametric study is conducted by varying delamination location, width and length. From this study it is observed that modal frequencies have more significant variation in the mid plane. So the further study is limited on the mid plane only. The change in frequency of intact and control model shows that the natural frequency is affected by the different parameters of delamination. From the results, a reverse design process is implemented for finding the delamination location and area at a particular natural frequency.

Keywords—delamination, natural frequency, mode shape, bending stiffness.

I. INTRODUCTION

A multi directional laminate can be a combination of number of lamina with different fibre orientation. The multi directional laminate can be represented by a laminate code, which is represented by the individual fibre direction of each lamina. Some of examples of laminate codes are $[0/90/90/0]_s$, $[0/45/-45/90]_s$ etc.

In modern world, the applications of composite materials mainly in the area where strength to weight ratio plays an important role. The most common types of damages in the composite materials are delamination between the layers, damages like fiber breakage, matrix crack and fiber-matrix debonding when subjected to service conditions. If the damages presence in the inner interfaces, it cannot be identified by visual inspection. There are lots of non - destructive tests like coin tap test to identify the presence of damages in a structure member .But it is not practical in the case of aerospace application .In the case of air crafts, the defects which could not be identified by visual inspection are identifies at the C-checks only, at this time damage will be in a critical stage. So it is important to detect the damages at an early stage. One of the most important damages in composite laminates is delamination, which leads to significant loss of strength and stiffness of the structure. Laminate composite beams have extensive use in aircraft, spacecraft and space structures because of less strength to weight ratio and stiffness to weight ratio. As the applications are very huge and expensive, they require non-destructive testing or predictive testing. In effort to this Ramkumar et all [3] first proposed the vibration analysis model of composite beams. The model was based on four Timoshenko beams.

II. VIBRATION,MODAL ANALYSIS.

A. Theory of free vibration of cantilever beams

For a cantilever beam subjected to free vibration, and the system is considered as continuous system in which the beam mass is considered as distributed along with the stiffness of the beam, the equation of motion can be written as:-

$$\frac{d^2}{dx^2}\{EI(x)\frac{d^2Y(x)}{dx^2}\} = \omega_n{}^2 m(x)Y(x) \qquad (1)$$

Where,

E is the modulus of elasticity of beam material,
I is the moment of inertia of the beam cross-section,
Y(*x*) is displacement in *y* direction at distance *x* from fixed end,
ω_n is the circular natural frequency,
m is the mass per unit length,
ρ is the material density

B. Classical Lamination Theory (CLT)

Classical lamination theory (CLT) as presented here is applicable to orthotropic continuous fiber laminated composites only. The approach used in formulating CLT is similar to that used in developing load-stress relationships in elementary strength of materials courses. An initial displacement field consistent with applied loads is assumed.

Through the strain-displacement fields and an appropriate constitutive relationship, a state of stress is defined. By satisfying the conditions of static equilibrium, a load-strain relation is defined, and subsequently a state of stress is defined for each lamina.

1) Basic Assumptions for CLT

i. Each layer of the laminate is quasi-homogeneous and orthotropic.
ii. The laminate is thin compared to the lateral dimensions and is loaded in its plane.
iii. State of stress is plane stress.
iv. All displacements are small compared to the laminate thickness.
v. Displacements are continuous throughout the laminate.
vi. Straight lines normal to the middle surface remain straight and normal to that surface after deformation.
 • In-plane displacements vary linearly through the thickness.
 •Transverse shear strains (γ_{xz} & γ_{yz}) are negligible.
vii. Transverse normal strain ε_z is negligible compared to the in-plane strains ε_x and ε_y
viii. Strain-displacement and stress-strain relations are linear.

2) Classical Lamination Theory from Classical Plate Theory:

The classical lamination theory is almost identical to the classical plate theory; the only difference is in the material properties (stress-strain relations). The classical plate theory usually assumes that the material is isotropic, while a fiber reinforced composite laminate with multiple layers (plies) may have more complicated stress-strain relations.

The four cornerstones of the lamination theory are the kinematic, constitutive, force resultant, and equilibrium equations. The outcome of each of these segments is summarized as follows: Theoretical evaluations

Theoretical evaluation of the effective properties of the facings was done using composite laminate theory (CLT). CLT consists of a collection of mechanics of materials type of stress and deformations hypotheses. By use of this theory, one can consistently proceed directly from the basic building block, the lamina, to the end result, a structural laminate.

$$\begin{bmatrix} N_X \\ N_Y \\ N_{XY} \\ M_X \\ M_Y \\ M_{XY} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_X \\ \varepsilon_Y \\ \gamma_{XY} \\ K_X \\ K_Y \\ K_{XY} \end{bmatrix} \quad 2)$$

$$A_{ij} = \sum_{k=1}^{n} (Q_{ij})k(h_k - h_{k-1}) \quad 3)$$

$$B_{ij} = \sum_{k=1}^{n} (Q_{ij})k(h_{k^2} - h_{k^2-1}) \quad 4)$$

$$D_{ij} = \frac{1}{3}\sum_{k=1}^{n} (Q_{ij})k(h_{k^3} - h_{k^3-1}) \quad 5)$$

where i = 1,2,6 and j = 1,2,6

N_x , N_y are the normal force per unit length and N_{xy} is the shear force per unit length whereas M_x , M_y are the bending moment per unit length and M_{xy} is the twisting moment per unit length.The [A], [B], [D] matrices [2] are extensional coupling and bending stiffness matrices. [Q_{ij}] is the reduced transformed matrix, h represents the laminate thickness. The extensional stiffness matrix [A] relates the resultant in-plane forces to the in-plane strains. Bending stiffness matrix [D] relates the resultant bending moments to the mid plane curvatures. The coupling stiffness matrix [B] couples the force and moment terms to the mid plane curvatures and mid plane strains.

3) Effective properties of laminate using composite laminate theory

The effective properties of laminates using composite lamination theory for a lamination code of [(0º/±45º/90] are presented at table 1

III. FINITE ELEMENT ANALYSIS

A. *Modal analysis in Ansys*

Modal Analysis is a tool used to determine vibration characteristics or natural frequencies of a mechanical structure. It can also be used for dynamic analysis, harmonic response, and transient dynamic analysis. Modal analysis in ANSYS® is linear analysis. In this research natural frequencies and mode shapes are concentrated upon.[6]

A Cantilever beam of the dimensions Length 250mm Width of 50 mm of composite material was considered for the numerical analysis. The beam was modelled with eight nodded shell elements so as to introduce the delamination. The delamination length is taken as 10mm and 30mm.

B. *SOLSH 190 Element Description*

SOLSH 190 is used for simulating shell structures with a wide range of thickness (from thin to moderately thick). The element possesses the continuum solid element topology and features eight-node connectivity with three degrees of freedom at each node: translations in the nodal x, y, and z directions. Thus, connecting SOLSH190 with other continuum elements requires no extra efforts. The element SOLSH 190 can be used for layered applications such as modeling laminated shells or sandwich construction. The layered section definition is given by section commands. Accuracy in modeling composite shells is governed by the first-order shear-deformation

C. Model geometry

The model geometry of the composite laminate is shown in the fig1

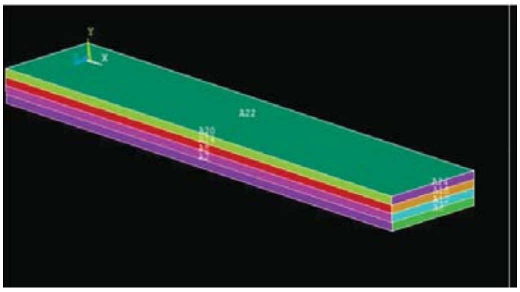

Fig.1 Model geometry

Length of specimen 250mm
width 50mm
Height 5mm
Number of layers 4.
Material properties and specification of specimen used is shown in table 1.

D. Mesh generation

Number of divisions on the length is 50 and number of divisions on the width is 10

E. Visualize/Review the results

Results from a modal analysis are written to a structural result file called, Job name. RST.
Results could include: Natural frequencies, expanded mode shapes. The results can be reviewed in the general postprocessor.

F. Apply loads and obtain the solution

There are several mode-extraction methods that can be selected in ANSYS®. These include: Block Lanczos, Supernode, PCG Lanczos, reduced, unsymmetrical, damped, and QR damped. Damping in the structure can be accomplished by the damped and QR damped methods. Block Lanczos is used to obtain the solution and boundary condition used is as cantilever beam.

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TABLE I.

Specimen dimensions and material properties	
Length of beam	250(mm)
width	50(mm)
Number of layers	4
Density	1901(Kg/m3)
E_{11}	135.5(GPa)
E_{22}	9(GPa)
E_{33}	9(GPa)
Poisson's ratio	0.24
Shear modulus G_{12}	5.2(GPa)
Shear modulus ,G_{13}	3.08(GPa)

H. Requirement specifications

This step is done in pre-processing in ANSYS. In this work the composite beam element model used was solishell 190 and it has specification at the pre-processing stage. The parameters indicated below in the table are entered in to the analysis. The Layer orientation selected for this study are 0/90/90/0 and 0/45/-45/90. Each lamina is modelled as per the laminate code. Total four layers having thickness is equal to 5 mm.

TABLE II.

MODES	MODE FREQUENCIES IN Hz				
	1	***2***	***3***	***4***	***5***
	57.505	251.42	358.26	889.37	994.19

Fig 2 Delamination positions

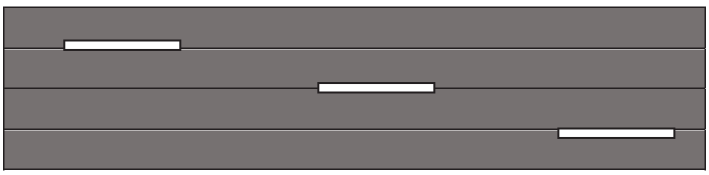

TABLE III

	Mode frequencies in Hz for delamination length of 30mm								
	INTERFACE 1			***INTERFACE 2***			***INTERFACE 3***		
Delamination starting location	***0.04L***	***0.48L***	***0.88L***	***0.04L***	***0.48L***	***0.88L***	***0.04L***	***0.48L***	***0.88L***
MODE 1	57.491	57.496	57.405	56.929	57.134	57.478	56.945	57.146	57.479
MODE 2	275.80	276.53	275.52	257.09	274.20	278.40	263.88	277.55	278.93
MODE 3	357.58	357.59	278.28	320.67	358.02	353.35	321.90	358.01	353.54
MODE 4	689.22	689.91	631.52	690.56	690.69	690.70	689.26	690.17	690.67
MODE 5	882.87	881.59	690.68	804.78	867.14	833.02	815.98	878.14	835.65
MODE 6	986.10	989.63	911.44	811.80	874.31	909.71	825.92	879.00	914.49
MODE 7	1378.8	1406.4	1014.5	1469.1	1547.4	954.51	1495.4	1579.3	986.23
MODE 8	1558.4	1553.8	1616.2	1598.5	1808.8	1455.9	1603.0	1812.6	1204.9
MODE 9	1728.8	1797.7	1819.4	2351.5	2411.9	1479.9	2374.8	2455.9	1594.0
MODE 10	1946.5	2007.5	2116.2	2743.6	2582.8	1585.8	2749.3	2593.8	1619.6

The comparison of mode frequencies at different interfaces for the stacking sequence of 0/90/90/0 for delamination length of 10 mm from the fixed position are presented in the table III and for the delamination length of 30 mm from the fixed position are presented in the table IV. It is observed from the table III and table IV is that the presence of delamination at the mid interface having more frequency reduction than other two interfaces.

Visualize/Review the results in ANSYS

The Ansys results from a modal analysis were read from the general postprocessor. The results include natural frequencies, mode shapes etc.

Ansys modal analysis on the mid interface.

Modal analysis was carried out in delamination induced model, delamination area varied from 2.4% to 12% of the mid interface area. The length of delamination selected as 30mm and delamination width varied as 10, 20, 30, 40, 50mm (up to the through width if the specimen. First position of delamination length starting from the 0.04Lmm. Second position of delamination length starting from starting from the 0.48L, third position of delamination length starting from starting from the 0.88 L from the fixed end.

TABLE IV

	FOR DELAMINATION LENGTH 10mm								
	INTERFACE 1			***INTERFACE 2***			***INTERFACE 3***		
Delamination starting Location	***0.04L***	***0.48L***	***0.88L***	***0.04L***	***0.48L***	***0.88L***	***0.04L***	***0.48L***	***0.88L***
MODE1	57.502	57.503	57.504	57.425	57.450	57.504	57.427	57.452	57.504
MODE2	280.56	280.29	281.33	275.52	279.75	280.75	276.73	280.50	280.92
MODE3	358.18	358.23	358.24	352.57	358.20	358.16	352.78	358.20	358.17
MODE4	690.44	690.57	690.70	690.66	690.70	690.70	690.44	390.60	690.70
MODE5	896.62	897.48	897.35	873.86	895.68	884.41	878.51	897.01	888.46
MODE6	993.58	993.83	993.86	953.82	974.04	992.21	955.30	974.78	992.33
MODE7	1662.3	1660.6	1660.3	1597.5	1636.3	1619.9	1607.6	1644.5	1633.7
MODE8	1921.5	1920.9	1922.5	1792.0	1922.9	1910.9	1796.3	1922.9	1911.7
MODE9	2638.5	2637.5	2633.0	2496.2	2633.8	2562.9	2512.5	2637.4	2587.8
MODE10	2911.3	2916.2	2915	2870.1	2915.9	2916.2	2877.1	2916.2	2916.1

TABLE V

DELAMINATION AREA		Delamination location from the fixed end			un damaged	f-f1	f-f2	f-f3
		0.04L	**0.48L**	**0.88L**		**0.04L**	**0.48L**	**0.88L**
20% of full width delamination	MODE1	44.043	44.082	44.133	44.135	0.092	0.053	0.002
	MODE2	267.9	269.6	269.94	270.1	2.2	0.5	0.16
	MODE3	392.96	400.55	408.53	408.88	15.92	8.33	0.35
	MODE4	625.78	631	631.68	631.72	5.94	0.72	0.04
	MODE5	743	742.69	751.06	752.7	9.7	10.01	1.64
40% of full width delamination	MODE 1	44.011	44.045	44.131	44.135	0.124	0.09	0.004
	MODE 2	264.95	269.47	269.65	270.1	5.15	0.63	0.45
	MODE 3	386.03	396.34	408.12	408.88	22.85	12.54	0.76
	MODE 4	625.1	630.37	631.62	631.72	6.62	1.35	0.1
	MODE 5	727.88	733.67	747.47	752.7	24.82	19.03	5.23
60% of full width delamination	MODE1	43.923	44.019	44.128	44.135	0.212	0.116	0.007
	MODE2	261.26	269.41	269.27	270.1	8.84	0.69	0.83
	MODE3	383.16	394.42	407.54	408.88	25.72	14.46	1.34
	MODE4	621.82	629.39	631.56	631.72	9.9	2.33	0.16
	MODE5	709.31	726.52	742.02	752.7	43.39	26.18	10.68
80% of full width delamination	MODE1	43.739	43.999	44.125	44.135	0.396	0.136	0.01
	MODE2	257.38	269.37	268.81	270.1	12.72	0.73	1.29
	MODE3	381.49	393.69	406.93	408.88	27.39	15.19	1.95
	MODE4	615.47	628.36	631.52	631.72	16.25	3.36	0.2
	MODE5	690.75	720.56	734.29	752.7	61.95	32.14	18.41
100% of full width delamination	MODE1	43.305	43.935	44.115	44.135	0.83	0.2	0.02
	MODE2	252.72	268.87	266.78	270.1	17.38	1.23	3.32
	MODE3	347.59	381.26	405.04	408.88	61.29	27.62	3.84
	MODE4	604.98	626.15	631.34	631.72	26.74	5.57	0.38
	MODE5	657.33	704.54	657.57	752.7	95.37	48.16	95.19

IV. RESULTS AND DISCUSSIONS

The variation in natural frequencies with the delamination length, width and delamination position at the all interfaces carried out. It is found that for the most cases mode frequency reduction is comparatively more at the mid interface with respect to the presence of delamination.

It is observed that the first mode frequency reduction is more if the delamination appears very near to the fixed end, frequency reduction in lesser if the presents of delamination is near to the far end.

The delamination in the composite beam has an effect on the stiffness of the beam; this will affect the natural frequency of the composite beam. So, with the increasing of the delamination length, the stiffness of beam will decrease and this will cause a decreasing in the natural frequency of the composite beam.

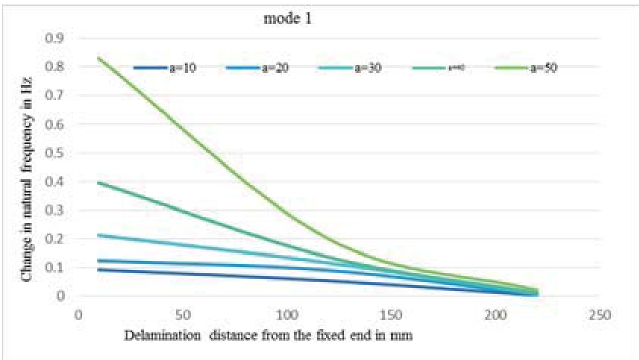

Fig. 3: First mode frequency vs delamination distance from the fixed end

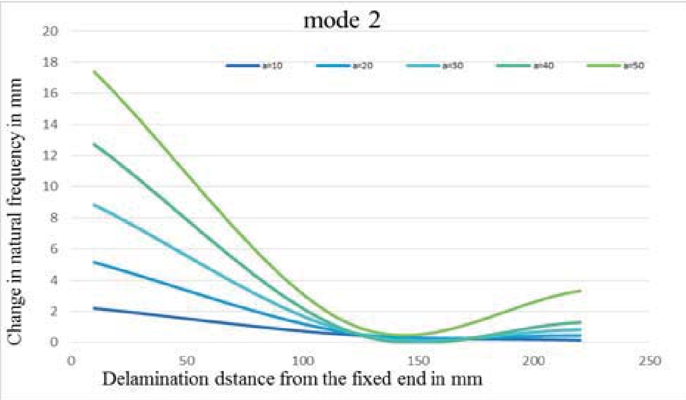

Fig 4 2nd frequency vs delamination distance from the fixed end

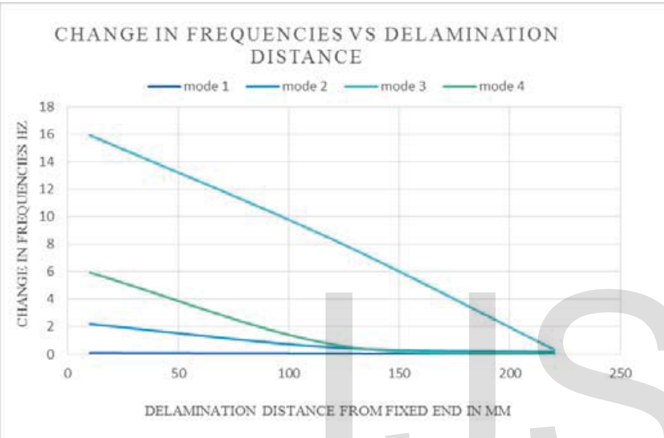

Fig 5 Fundamental mode frequencies vs delamination distance

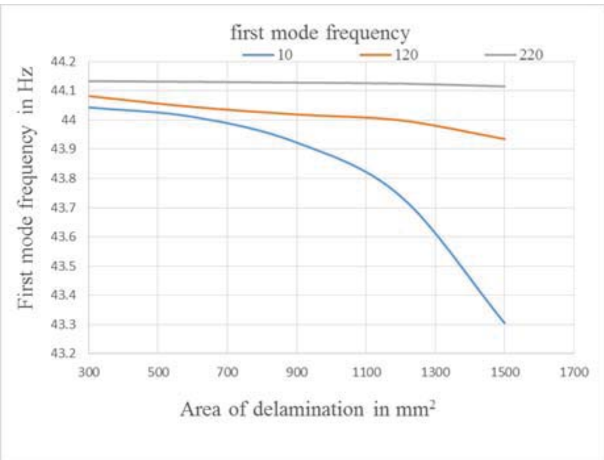

Fig 6 Area of delamination vs natural frequency

Thus from the above result we could conclude that the presence of delamination in composite structures will affect its life. [17] So by using suitable frequency measurement techniques we could detect the presence of delamination in structures at the early stages and necessary remedial action could be implemented.

From the graphs it is observed that if the delamination starting position is near to the fixed end then the reduction in the natural frequencies is more and it reduces towards middle [18] portion and then slightly increases when the delamination starting position approaches the far end of the cantilever beam.The variation of mode frequencies with the different position of delamination area of 20 % of through width delamination are presented in the graph shown in figure.

V. CONCLUSION

The following conclusions can be made from the present study of the composite four layer beam by ANSYS. The finite element modal analysis were performed and studied the variation in natural frequencies. The variation study conducted by varying the different parameters like delamination area, delamination starting position from the fixed end. The study were conducted at the three interfaces. It is observed that the changes in variables have a significant influence on the reduction of mode frequencies.
It is found that the reduction in natural frequencies is more on the interface between 45and -45 layers when the delamination occurs there. The rate of decrease in the natural frequencies of the delaminated composite beam increases as the delamination starting position approaches towards the fixed end.
The reduction in the frequency increases with the increase in the delamination area. From the database we can identify the location and area of delamination from a particular mode frequency.

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