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Experimental Investigation on Dynamic Characteristics of Unidirectional and Woven Glass Fiber Laminated Composite Plates With and Without Cut-Outs

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Abstract
In this study, the vibration analysis of laminated composite plates have been fabricated and investigated experimentally. The unidirectional and woven glass laminated composite plates were tested to measure the vibration characteristics using LABVIEW, a virtual instrumentation technique. The obtained natural frequencies of the composite plates are verified with the values measured from the conventional deflection experiments. The woven glass laminated composite plates have higher natural frequency compared to unidirectional laminated composite plates irrespective of with and without cut-outs. However, the composite plates with cut-outs have higher natural frequency compared to plate without cut-outs, irrespective of materials considered. Further the changes in dynamic characteristics of the composite plates due to difference in fiber arrangements as well as due to the presence of cut-outs are observed.

Key words: Laminated composite plate, vibration, damping factor and load-displacement analysis.

Introduction
Laminated Composites are being used increasingly in variety of industrial applications such as aeronautical, aerospace, marine, automotive and civil construction due to their higher stiffness-to-weight and strength-to-weight ratios, higher resistance to fatigue, higher buckling resistance, design flexibility and low maintenance cost. Composites are the best replacements for metal parts on older planes. The use of fibrous composites offers improvements in helicopter rotors due to improved aerodynamic geometry, improved aerodynamic turning, good damage tolerance and potential low cost. At higher operating speeds the structures, machines and dynamic systems are affected due to vibrations and increased stresses. Hence the static and dynamic characterisation of laminated composite structures is required for true understanding.

Cut –outs commonly appeared in the structures due to the requirement of stability, low weight optimization and accessibility of other systems. In the operating condition, these structural elements may experience compressive loads and thus lead to buckling and post buckling. It was concluded that the determination of safe operating conditions and effective design of these structures depends on buckling and post buckling behaviour [1]. The effects of square cut-outs on the natural frequencies and mode shapes of cross-ply laminates made of S-glass-epoxy were investigate by Jeng et al., [2]. The natural frequencies and mode shapes of cantilever plates (with or without cut-out defects) were investigated both experimentally and numerically. A finite element code and shear deformation theory was used to analyze the problem numerically. They concluded that the mass removal and reduction of structural stiffness are the dominant factors to affect structural vibration frequencies. Gibson et al., investigated the model vibration response measurements for characterization of composite materials and structures by the use of impulsive excitation methods [3]. Modal vibration testing has the potential to provide the basis for rapid, inexpensive characterization of both elastic and viscoelastic properties of composites for design and manufacturing. The importance of material damping in the design process has increased in recent years as the control of noise and vibration in high precision, high performance structures and machines has become more of a concern. At the same time, polymer composites researchers have focused more attention on damping as a design variable and the experimental characterization of damping in composites and their constituents.

Kim et al., developed an efficient modal parameter estimation technique by developing a residual spectrum based structural system reconstruction and using the system matrix coordinate transformation to predict the natural frequency and damping ratios of composite laminated plates [4]. The modal parameters estimated from poles and residues of the system transfer functions expressed in modal coordinate basis, derived from the state space system matrices. However, for modal parameter estimation of multi-variable and higher order structural systems over broad frequency bands, this non iterative algorithm gives high accuracy in determining the natural frequencies and damping ratios. It is numerically well behaved unlike iterative frequency-response-function (FRF) curve fitting methods. The vibration analysis of fiber glass/epoxy/Nano clay Nano composites were investigated by Avila et al.,[5]. This modal analysis was performed using a grid of 35 response measurement points. The dispersion of Nano clays into fiber glass/epoxy laminates not only improves the damping coefficient but it also changes the shape modes and natural frequencies. This study concluded that high performance polymeric composites are a valuable alternative to conventional materials due to their high specific mechanical properties.

The large amplitude free vibration analysis of composite plates was investigated by Dash using finite element method [6]. The dynamic version of von Karman‘s field equation were used measure the large deformation effect on plate structures. The effects of variations in the Poisson‘s ratio, amplitude ratio, thickness parameter and aspect ratio on the non-linear frequency ratio has also included. It was concluded that the non-linear to linear frequency ratio varies directly with respect to the plate aspect ratios. Ullah et al., investigated the dynamics of the composite plate experimentally and compared by the finite element (FE) models using different element types in the ABAQUS FE code [7]. The study recommends that the FE model using the element type C3D8I could be suitable for modelling the thin composite structure with and without delamination for different dynamic analysis. From the above literature review, it can be seen that the properties of laminated composite plate have been analysed in various aspects. However the vibration analysis of various structures with and without cut-outs by considering the fiber angel orientations have not been explored experimentally. Maximum amplitude of the vibration must be in the limited region for the safety of the structure. Hence vibration analysis has become very important in designing a structure to know in advance its response and to take necessary steps to control the structural vibrations and its amplitudes.

In this present study, the vibration analysis of laminated composite plates with and without cut-outs are presented. The natural frequencies of laminated composite plate are investigated using virtual instrumentation LABVIEW technique. The values of natural frequency of the plates obtained are verified with the values obtained from the conventional deflection experiments. The young's modulus and damping factor also calculated in all the cases of laminated composite plates.

Experimental – Fabrication and Testing

Unidirectional glass fiber and woven glass fiber (Bi-directional) are used to manufacturing the laminated composite plate. Unidirectional fibers can be tailored more easily to match loads, also it provides better surface finish, less porous than fabric and higher allowable strength and stiffness. Woven glass fiber offers lower fabrication process, less material handling damage, easier forming on contours and corners, more resistant to surface breakout and delamination. Totally 8 specimens were fabricated using unidirectional (4 specimen) and woven glass fiber (4 specimen) with epoxy resin, each laminate (specimen) consists of four plies with fiber angle orientation of [$0^o/90^o/0^o/90^o$]. Each ply is typically a thin (approximately 0.5 mm) sheet of collimated fibers impregnated with epoxy. Each layer was a unique material and have a unique constant thickness. The orientation of each ply is fixed and the layup sequence is tailored to achieve the properties desired of the laminate. In order to achieve this process, the hand (wet) lay-up technique was used to fabricate the composite laminates. It consists of many steps, initially suitable mould was selected based on the requirement and the surface of Mould was cleaned with smooth finish and a good mould releasing agent (polyvinyl acetate) was applied evenly and properly over the mould surface. The required quantity of fabric glass plies was laid over the surface of the mould and the required quantity of epoxy resin mixed with hardener was applied over the fabric glass plies subsequently using painting brush by manual process. This process was repeated, till the required thickness is achieved. A vacuums bag was used to remove the excess resin from the laminated plate and it was cured in an autoclave with proper temperature.

The directional orientation of fibers influences the properties of the composite plates. For an example the unidirectional fiber orientation gives good tensile properties along the direction of the fibers as compared to lateral direction. In a similar fashion the woven fibers give additional strength along the lateral direction as compared to the unidirectional one. The further validation process for the experiments require specific properties of the plates on which experimentation is carried out. The experimentation is carried out by tenso-meter. The tensile testing was carried out by applying longitudinal or axial load at a specific extension rate to a standard tensile specimen with known dimensions (gauge length and cross sectional area perpendicular to the load direction) till failure. The applied tensile load and extension were recorded during the test for the calculation of stress and strain. The young's modulus of unidirectional and woven glass laminated composite plate was calculated through the plots shown in Fig. 1.

Young's modulus value of unidirectional laminated composite plate is 320.8654 Mpa

Young's modulus value of woven glass laminated composite plate is 365.4699Mpa.

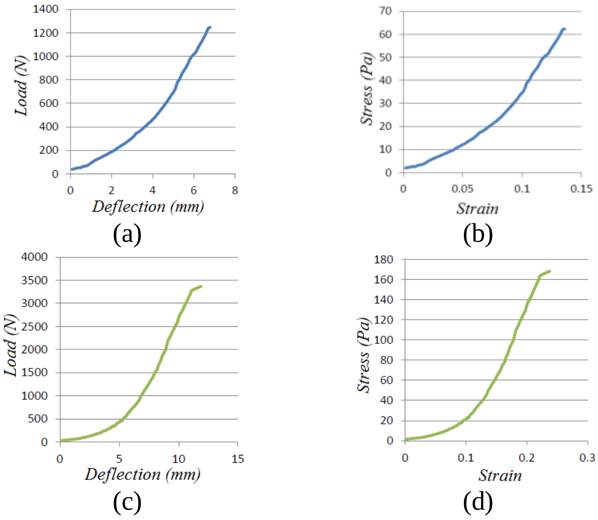


Fig. 1. (a). Uni-directional composite plate- Load Vs Deflection (b). Uni-directional composite plate- Stress Vs Strain (c). Woven composite plate -Load Vs Deflection (d). Woven composite plate- Stress Vs Strain.

Vibration analysis using LABVIEW

Vibration analysis of the laminated composite plates is carried by virtual instrumentation LABVIEW technique. Virtual Instrumentation is the use of customizable software and modular measurement hardware to create user-defined measurement systems, called virtual instruments. The concept of a synthetic instrument is a subset of the virtual instrument concept. A synthetic instrument is a kind of virtual instrument that is purely software defined. A synthetic instrument performs a specific synthesis, analysis, or measurement function on completely generic, measurement agnostic hardware. Vibration analysis requires a transducer, Data Acquisition System (DAQ), computer with LABVIEW software. Vibration analysis includes signal processing, Time domain analysis, Frequency domain analysis.

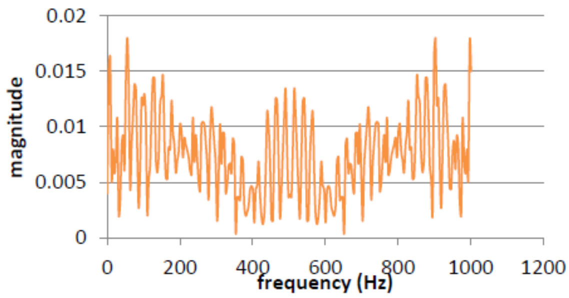
A piezo electric accelerometer of 5mV/g was used in this analysis. A piezo electric material generates EMF in the direction perpendicular to that of applied force. The accelerometer is interfaced to a DAQ (Data Acquisition device). NI USB-6061 is employed. Data acquisition (DAQ) is the process of measuring an electrical or physical phenomenon such as voltage, current, temperature, pressure, or sound with a computer. A DAQ system consists of sensors, DAQ measurement hardware, and a computer with programmable software LABVIEW. A transducer or a sensor converts the physical phenomenon such as light, heat, pressure into equivalent Voltage output. The DAQ device which has ports for input receiving and generating output signal. The signal obtained through input is in analog form and is sent to PC for signal processing through application software. The signal obtained from sensor is unprocessed and analog, which is difficult to analyze so it must be processed. LABVIEW has many signal filtering and signal processing techniques.

In order to analyze the frequencies and repeating functions in the raw signal it should be sampled and processed. For that it should be converted from time domain to frequency domain. The time domain methods try to analyze the amplitude and phase in formation of the vibration time signal to detect the vibrations caused in the composite plates. These methods include Signal Averaging Technique, Demodulation Methods, figures of Merit, Crest Factor, Energy Ratio and Side band Level Factor, etc. The frequency domain methods include Fast Fourier Transform (FFT), Hilbert Transform Method and Power Cepstrum Analysis etc. The most widely used frequency spectrum is found by applying a discrete FFT (Fast Fourier Transform) on the time averaged signals. FFT (Fast Fourier Transform) is the quick form of DFT (Differential Fourier Transform). Implementing DFT is a time consuming process. DFT: The algorithm used to transform samples of the data from the time domain into the frequency domain is the discrete Fourier transform. The DFT establishes the relationship between the samples of a signal in the time domain and their representation in the frequency domain. Natural frequency values are obtained from the frequency spectrum.

The laminated composite plates were clamped at the left edge using a steel fixture. A piezo electric accelerometer was installed at the free end of the plate to measure the acceleration due to excitation. In this research 4 types of square (200 x 200 x 2 mm) specimens and 4 types of rectangular (400 x 150 x 2 mm) specimens are considered with identical thickness as shown in Fig. 2 and Fig. 4 respectively, the corresponding frequency - magnitude plots for square and rectangular specimens are as shown in Fig. 3 and Fig. 5 respectively. In both square and rectangular composite plate the cut-outs are created at the centre of the plate with diameter of 32 mm. From Fig. 3 & 5 it could be observed that based on the fundamental natural frequency, the woven glass laminated composite plates have higher natural frequency compared to unidirectional laminated composite plates irrespective of with and without cut-outs. This can be attributed to the fact that the unidirectional fiber orientation gives good tensile properties along the direction of the fibers as compared to lateral direction. In a similar fashion the woven fibers give additional strength along the lateral direction as compared to the unidirectional one. At the same time, the natural frequencies are higher in the composite plate with cut-outs compared to without cut-outs irrespective of the materials considered, the removal of mass and reduction of structural stiffness are the dominant factors to affect structural vibration frequencies.

			
(a)	**(b)**	**(c)**	**(d)**

Fig. 2. Specimens (a).Uni-directional square laminated composite plate (b). Uni-directional square laminated composite plate with centre hole (c). Woven square laminated composite plate (d). Woven square laminated composite plate with centre hole.



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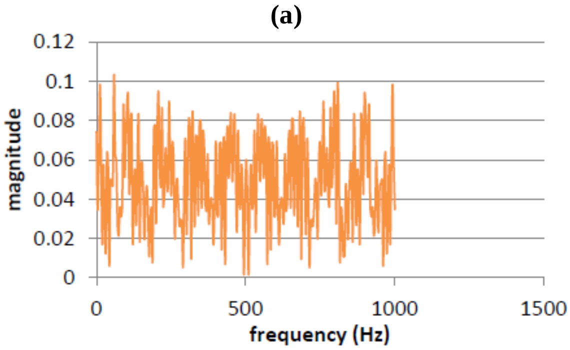

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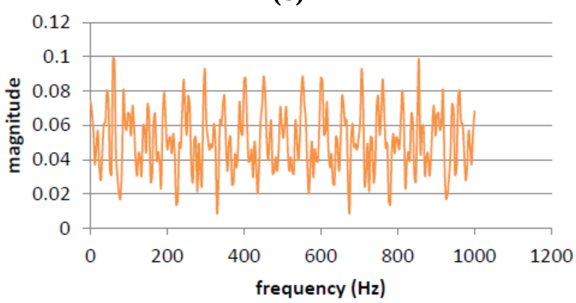

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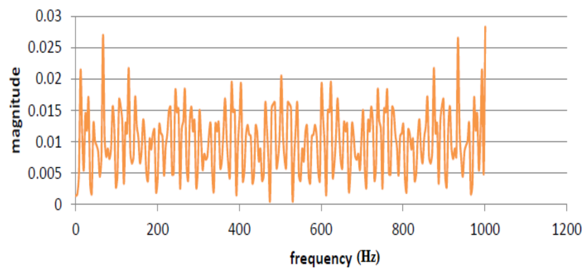
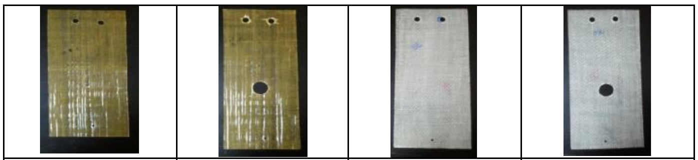


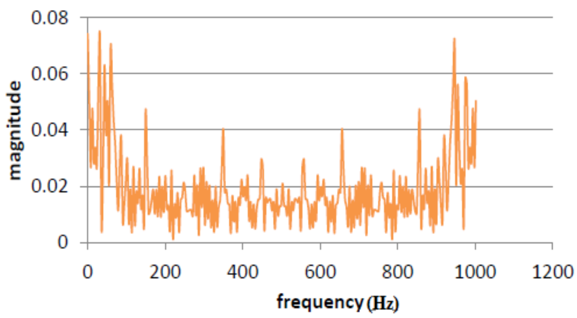
(d)

Fig. 3. Frequency-Magnitude plots (a).Uni-directional square laminated composite plate (b). Uni-directional square laminated composite plate with centre hole (c). Woven square laminated composite plate (d). Woven square laminated composite plate with centre hole.



(a)	**(b)**	**(c)**	**(d)**

Fig. 4. Specimens (a). Uni-directional rectangular laminated composite plate (b). Uni-directional rectangular laminated composite plate with centre hole (c). Woven rectangular laminated composite plate (d). Woven rectangular laminated composite plate with centre hole.



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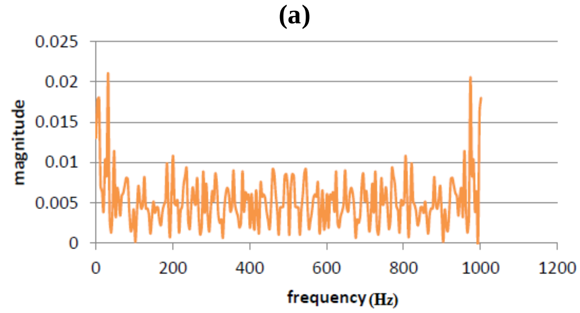

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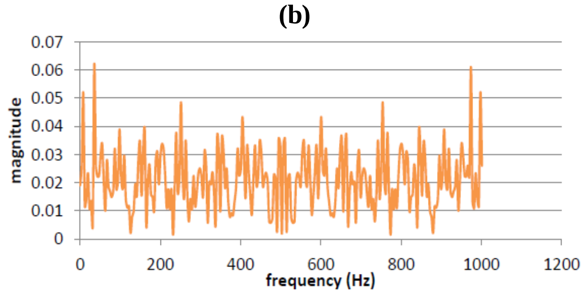

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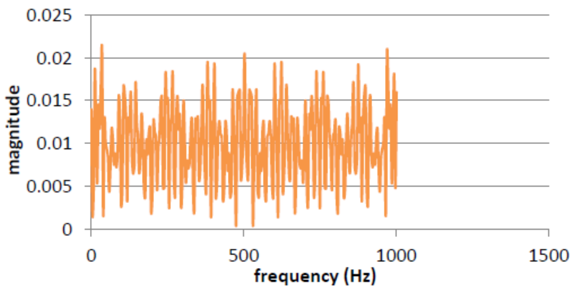

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Fig. 5. Frequency-Magnitude plots (a).Uni-directional rectangular laminated composite plate (b). Uni-directional rectangular laminated composite plate with centre hole (c). Woven rectangular laminated composite plate (d). Woven rectangular laminated composite plate with centre hole.

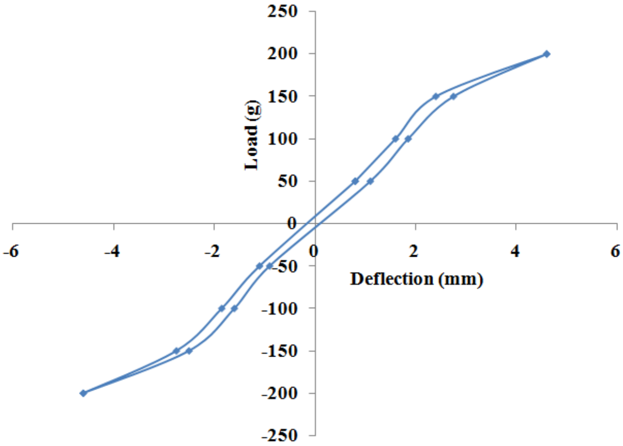
Vibration analysis by Hysteresis Damping Experiment

Hysteresis Damping Experiments were conducted to validate the natural frequencies of laminated composite plate obtained from LABVIEW technique. Hysteresis damping or structural damping is the damping caused by the friction between the internal planes that slip or slide as the material deforms. Hysteresis loop is formed by the load- displacement values by loading and unloading in forward and reverse directions. The deflectometer was arranged on the free end, for the deflections caused by various weights suspended from the plate through a hanger. The area enclosed by the hysteresis loop is the energy loss in one loading and one unloading in both directions. Energy loss is used for the calculation of stiffness value of the plate which is a measure of the resistance offered by an elastic body to deformation.

The stiffness factor and mass of the laminated composite plate provides a relation for the calculation of the natural frequency. Frequency value and hysteresis damping coefficient provides a relation for the calculation of equivalent damping coefficient and damping factor. Hysteresis damping experiment was carried out for 8 set of plates including rectangular, square plates with and without cut-outs and with unidirectional and woven fiber glass laminated composite plate. The equivalent damping coefficient and damping factors of all the specimens were calculated using fundamental relations through Fig. 6 and Fig. 7.

Table 1 shows the stiffness, loss factor, damping factor and natural frequencies of various specimens. From table1it could be understand that the natural frequencies are higher in woven composite plate compared to unidirectional composite plate. The plate with cut-outs has higher natural frequency compared to plate without cut-outs irrespective of materials considered. From table 2 it could be understand that the rectangular plates without cut-out having higher damping factor compared to plate with cut-out, however the square plates without cut-out having lesser damping factor compared to plate with cut-out. Also the damping capacity is higher in case of uni-directional plates whereas in case of natural frequency it is vice versa. The variation in natural frequencies and damping factor occurs due to removal of mass and reduction of stiffness of the laminated composite plate. Table

3 Shows the comparison on natural frequencies of cantilever laminated composite plates derived from the LABVIEW technique with the hysteresis damping experimental measured frequencies. A good agreement could be observed between the computed and measured frequencies, irrespective of materials considered.



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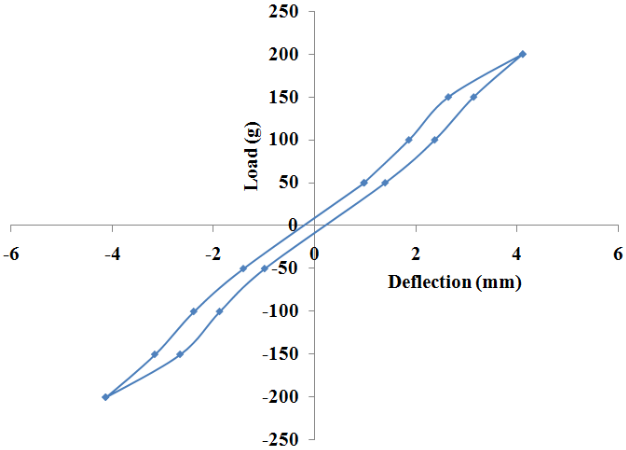

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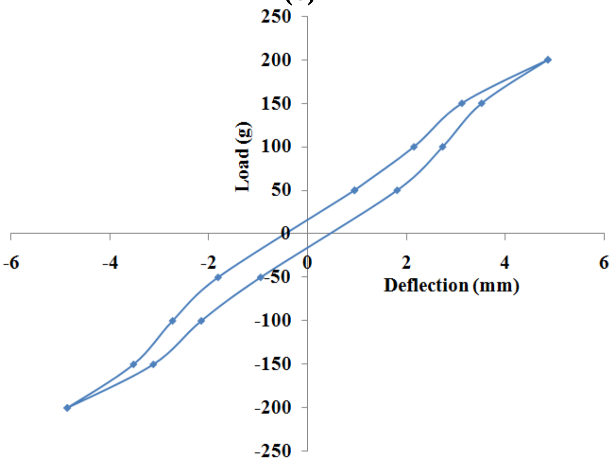

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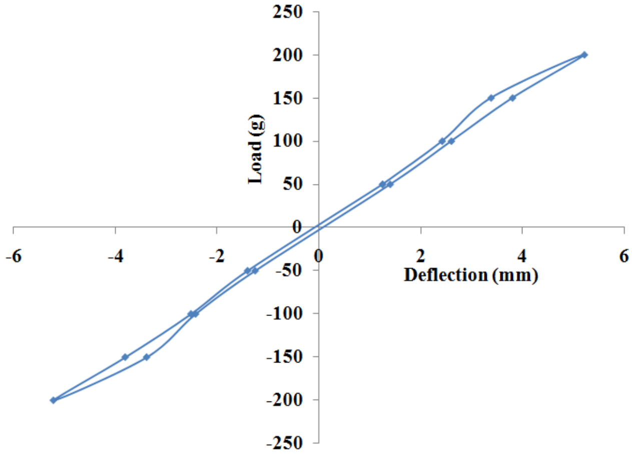
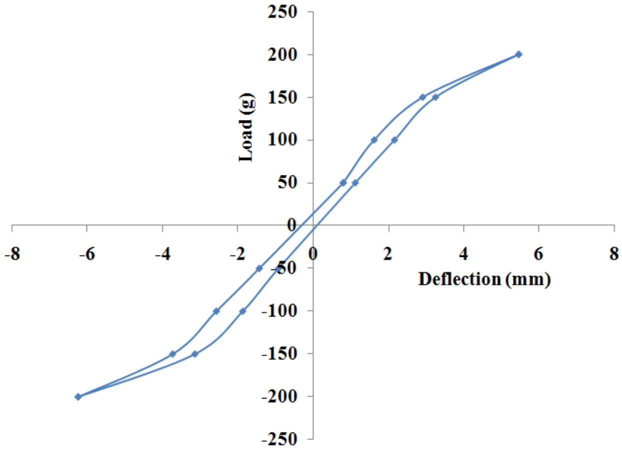


(d)

Fig. 6. Load Vs Deflection plots (a).Uni-directional square laminated composite plate (b). Uni-directional square laminated composite plate with centre hole (c). Woven square laminated composite plate (d). Woven square laminated composite plate with centre hole.



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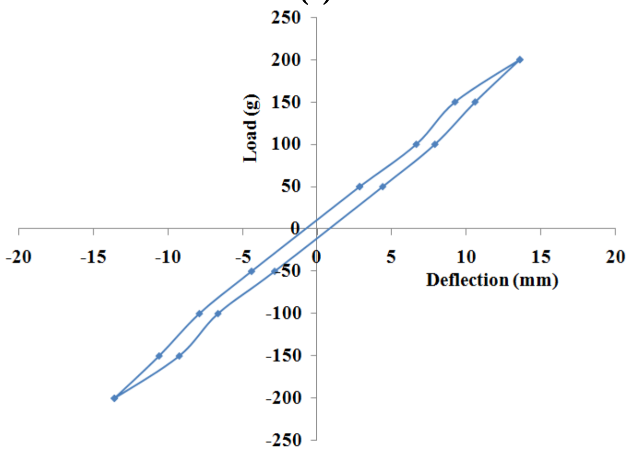

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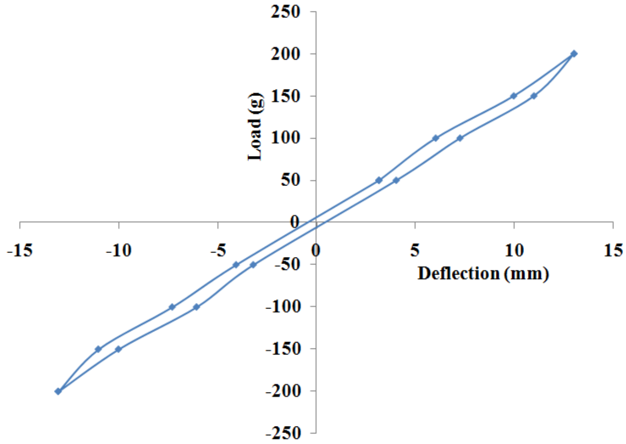

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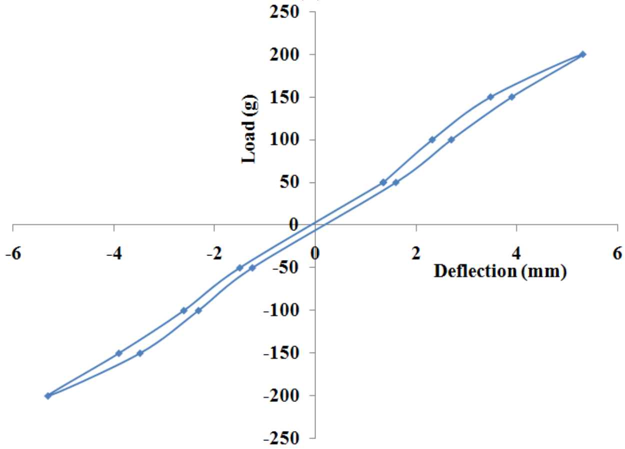

(d)

Fig. 7. Load Vs Deflection plots (a).Uni-directional rectangular laminated composite plate (b). Uni-directional rectangular composite plate with centre hole (c). Woven rectangular laminated composite plate (d). Woven rectangular composite plate with centre hole.

Table 1: Comparison on the deflection, stiffness, damping, loss factor and natural frequencies for the various specimens with and without cut-outs.

Uni-directional square laminated composite plate	Area (A) or energy (U) - N-m	0.004209
	Max deflection (δ) - m	0.0046
	Hysteresis damping (h) –N/m	63.34509
	Stiffness factor (k) – N/m	423.2804
	Loss factor (β)	0.149653
	Equivalent damping co-efficient (Ceq) - Kg/sec	1.172419
	Critical damping co-efficient (Cc) - Kg/sec	15.72283
	Damping factor (ξ)	0.0745
	Natural frequency – (Hz)	54.216
Uni-directional square laminated composite plate with centre hole	Area (A) or energy (U) - N-m	0.0045536
	Max deflection (δ) - m	0.0036
	Hysteresis damping (h) –N/m	111.465
	Stiffness factor (k) – N/m	536.9128
	Loss factor (β)	0.208409
	Equivalent damping co-efficient (Ceq) - Kg/sec	1.832524
	Critical damping co-efficient (Cc) - Kg/sec	17.58584
	Damping factor (ξ)	0.104205
	Natural frequency – (Hz)	61.064407
Woven square laminated composite plate	Area (A) or energy (U) - N-m	0.002346
	Max deflection (δ) - m	0.005
	Hysteresis damping (h) –N/m	63.69427
	Stiffness factor (k) – N/m	441.989
	Loss factor (β)	0.144108
	Equivalent damping co-efficient (Ceq) - Kg/sec	1.058217
	Critical damping co-efficient (Cc) - Kg/sec	14.68641
	Damping factor (ξ)	0.072054
	Natural frequency – (Hz)	60.1902
Woven square laminated composite plate with centre hole.	Area (A) or energy (U) - N-m	0.004185
	Max deflection (δ) - m	0.0043
	Hysteresis damping (h) –N/m	465.1163
	Stiffness factor (k) – N/m	72.0789
	Loss factor (β)	1.176896
	Equivalent damping co-efficient (Ceq) - Kg/sec	0.15497
	Critical damping co-efficient (Cc) - Kg/sec	15.18874
	Damping factor (ξ)	0.077485
	Natural frequency – (Hz)	61.2449

Table 2.Comparison on damping factors for unidirectional laminated composite plate to woven glass laminated composite plate.

Type of Plate	Plate Specimens	Equivalent Damping coefficient (Kg/sec)	Critical Damping coefficient (Kg/sec)	Damping Factor
Unidirectional laminated composite plate	Square Plate	1.72	15.722	0.074
	Square Plate with centre hole	1.833	17.585	0.104
	Rectangular Plate	0.62	7.67	0.081
	Rectangular Plate with centre hole	0.411	9.187	0.044
Woven Glass laminated Composite Plate	Square Plate	1.05	14.686	0.072
	Square Plate with centre hole	0.155	15.188	0.077
	Rectangular Plate	0.764	10.432	0.073
	Rectangular Plate with centre hole	0.195	9.257	0.021

Table 3: Comparison on natural frequencies of cantilever laminated composite plates derived from the LABVIEW with the experimental measured frequencies.

Type of Plate	Plate Specimens	Natural Frequency (Hz) by Lab view	Natural Frequency (Hz) by Hysteresis Damping Experiment
Unidirectional laminated composite plate	Square Plate	54.21	56.32
	Square Plate with centre hole	61.13	71.67
	Rectangular Plate	30.08	34.34
	Rectangular Plate with centre hole	35.28	38.56
Woven Glass laminated Composite Plate	Square Plate	60.19	66.24
	Square Plate with centre hole	61.24	70.56
	Rectangular Plate	33.12	37.97
	Rectangular Plate with centre hole	35.16	39.64

Conclusions

The dynamic characterizations of laminated composite plates have been fabricated and investigated experimentally. The unidirectional and woven glass laminated composite plates were tested and natural frequencies were calculated using LABVIEW technique. The obtained natural frequencies of the composite plates were compared with the values measured from the conventional deflection experiments. A good agreement was observed among the results evaluated using LABVIEW and the measured frequencies. The natural frequencies were higher in woven composite plate compared to unidirectional composite plate irrespective of size of specimen. The plate with cut-outs has higher natural frequency compared to plate without cut-outs, irrespective of materials considered. Further the rectangular plates without cut-out having higher damping factor compared to plate with cut-out, however the square plates without cut-out having lesser damping factor compared to plate with cut-out. The damping factor is found to be decreasing with increase in the length of the plate i.e. the square plates are found to have higher damping capacities as compared to rectangular plates. The damping capacity was higher in case of unidirectional plates whereas in case of natural frequency it is vice versa. The woven plates are stronger than the uni-directional plates i.e. woven plates have a higher value of young's modulus. Hence despite the fact that unidirectional plates having higher damping capacity, woven composites are more popularly employed owing to their higher strength.

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