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Research Paper

DELAMINATION IDENTIFICATION ON COMPOSITE MATERIAL BY FREE VIBRATION TEST

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The composite materials are well known by their excellent combination of high structural stiffness and low weight. Their inherent anisotropy allows the designer to tailor the material in order to achieve the desired performance requirements. However the delamination which is one of the serious defects often develops and propagates in composite structure. The presence of delamination warrants the design life of the structure and the safety. Hence the presence of such defect has to be detected in time to plan the remedial action well in advance. The present study involves extensive experimental works to investigate the free vibration of woven fiber Glass/ Epoxy composite laminate plates in simply supported boundary conditions based on the comparison between natural frequencies of the healthy and delaminated composite laminate plates. The square specimens of woven glass fiber and epoxy matrix composite were manufactured by the hand-layup technique with different areas of artificial delamination. Elastic parameters of the plate were also determined experimentally by tensile testing. The present free vibration experiments were used to validate the results obtained from the FEM numerical analysis. A three-dimensional finite element modelling was employed to simulate the dynamic response of composite laminated plates with and without delamination to extract their natural frequencies. The effect of increasing delamination area on natural frequencies was studied experimentally and numerically. The natural frequencies extracted from the current numerical simulations were compared with experimental results. Numerical results showed a good agreement with available experimental data.

Keywords: Laminated composite material, Finite element method, Free vibration test, Delamination

INTRODUCTION

Composite materials are composed of at least two elements working together to produce material properties that are different to the properties of those elements on their own. There are of constituent materials: matrix and

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reinforcement. The matrix material surrounds and supports the reinforcement materials by maintaining their relative positions. The reinforcements impart special physical (mechanical and electrical) properties to enhance the matrix properties. Composite materials are widely used because of their less weight to strength ratio. Now composites are also used in aerospace industry, many jets and airplanes are made of composite materials that are stronger and lighter than the materials they were made from (Jones, 1975; Tsai and Hahn, 1980; Agarwal and Broutman, 1990; and Schwartz, 1997). Woven fabrics provide excellent integrity and conformability for advanced structural composite applications. The reinforcement of composites with woven fiber materials lead to improved properties of composite structures in terms of acoustical, elastical and thermal properties. Glass fibers are the most commonly used ones in low to medium performance composites because of their high tensile strength and low cost. To better understand any structural vibration problem, the natural frequencies of a structure need to be identified. Today due to the advancement in computer aided data acquisition systems and instrumentation, experimental modal analysis has become an extremely important tool in the hands of an experimentalist. A number of researchers have been developed numerous solution methods to analysis the dynamic behaviour of laminated composite laminates. However experimental investigations on woven fabric composite laminated structures are still limited (Itishree and Shishir, 2012).

Several research studies have been carried for the composite structures with delamination. They are related to the modelling aspects of the composite structures with delamination (Della and Shu, 2007; Aniello, 2008; Alnefaie, 2009; and Kudela and Ostachowicz, 2009).

There are different studies using finite element method, Komur *et al.* (2009) presented a buckling analysis of woven glass polyester laminated composite plates with circular and elliptical hole. Alnefaie (2009) developed three dimensional finite element model of delaminated composite plate. Israr and Jyoti (2009) studied the dynamic behaviour of delaminated composite plate based on numerically simulated experiment. Various examples studied by Hua *et al.* (2002) in many previous researches to verify the justification, accuracy and efficiency of the finite element model with delamination. Zhang *et al.* (2010) used commercial finite element software ANSYS to build finite element models for both undamaged and delaminated carbon fiber reinforced composite beams and plates to study their vibration behaviour.

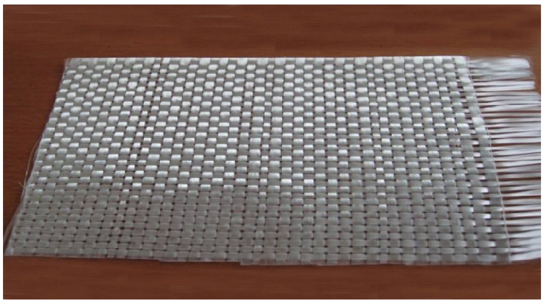
This work presents an experimental and numerical study of modal testing of woven fiber Glass/Epoxy laminated composite plates contain different areas of mid plane artificial delamination. A three-dimensional finite element modelling was employed to simulate the dynamic response of composite laminate plates with delamination to extract their natural frequencies. The effect of increasing delamination area on natural frequencies was studied experimentally and numerically. Numerical results show a good agreement with the available experimental data.

EXPERIMENTAL PROGRAMME

Production of the Laminates Specimens

E glass woven fiber was used as reinforcement in the form of bidirectional fabric as shown in Figure 1, and laminating epoxy resin as matrix for the composite material of the laminates specimens. The steps of manufacturing the composite laminate plates using the hand lay-up process were described below.

Figure 1: E-Glass Woven Roving Mat



Preparation of the Mould

The hand lay-up process is open molding technique, only one mould is used. The surface of the mould was thoroughly cleaned to be ready for the use, by removing any dust and dirt from it.

Application of the Release Wax Agent

After the mould surface has been cleaned, the release wax agent was applied by using smooth cloth as shown in Figure 2. The wax should be dry completely before the application of resin coat. It is very important stage otherwise the release will not be smooth.

Figure 2: Release Wax Agent

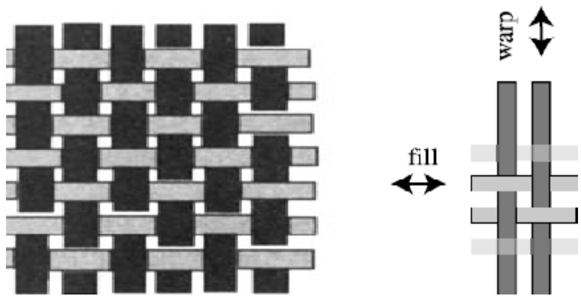
Preparation of the Matrix Material

The matrix material was prepared using laminating epoxy resin (Epolam, 2017) with hardener (Epolam, 2017). The mixing according to weight ratio 100:30. After adding both liquids in vessel, they should be mixing well before applying.

Preparation of the Reinforcement

E-glass woven roving of 200 g/m^2 (mass per unite area) was used as reinforcement. The fabrics were made of fibers oriented along two perpendicular directions (orthogonal-woven fabric): one is called the warp and the other is called the fill (or weft) direction. The fibers are woven together, which means the fill yarns pass over and under the warp yarns, following a fixed pattern. Figure 3 shows a plain weave where each fill goes over a warp yarn then under a warp yarn and so on. Present glass fiber mat woven, used for making the laminated plate, was cut in 8 plies of required size (200 $\times$ 200) mm^2.

Figure 3: Schematic Representation of Woven Fabric Architecture



Preparation of the Laminate Plate

The first layer of mat was laid and resin was spread uniformly over the mat by means of a brush. The second layer of mat was laid and resin was spread uniformly over the mat by means of a brush. After second layer, to enhance wetting and impregnation, a teethed steel roller was used to roll over the fabric before applying resin. This process was repeated till all the eight fabric layers were placed. Aluminum foils coated with special wax as artificial delaminations with different areas were shown in Figure 4, have been inserted in the mid plane of some plates. All the plates cured under room temperature. The plates were left for 72 hours before being transported and then cut to exact shape for testing.

Figure 4: Preparation of the Laminated Plates with Different Areas of Artificial Delamination

Preparation of the Test Specimens

After the cure process at room temperature, four test specimens were cut from the plate of 8 plies laminate. Cross ply 8-layered (0, 90) composite plates include E-glass fibres embedded in an epoxy matrix were used in present experimental work, with an overall laminate thickness of 2.5 mm and laminate density ρ = 1500 Kg/m^3. The dimensions of square specimens were (200 $\times$ 200) mm^2. Aluminum foils as the man-made square delaminations were manufactured with different areas (50 $\times$ 50, 100 $\times$ 100, 150 $\times$ 150) mm^2 inserted in the mid plane of some plates.

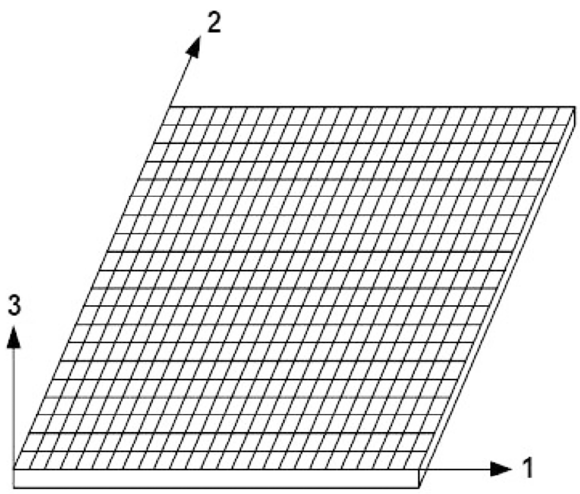
Tensile Test

The material constants E_{11}, E_{22} and ν_{12} of woven fiber Glass/Epoxy composite plate were determined experimentally by performing unidirectional tensile tests relevant to ASTM D3039 on specimens cut in longitudinal and transverse directions, and at 45° to the longitudinal direction. The shear modulus G_{12} was determined using the formula from Jones (1975). The measured experimental values of the elastic moduli (E_{11}, E_{22} , ν_{12} , G_{12}) were shown in Table 1.

Table 1: Experimental Measured Mechanical Properties of 8-Layerd Woven Fiber Glass/Epoxy Laminate

E_{11}	E_{22}	ν_{12}	G_{12}
19 GPa	19 GPa	0.256	2.8 GPa

Figure 5: Lamina Reference Axes



Test Procedure for Free Vibration Test

Vibration tests were conducted on plates with simply support boundary conditions around the four edges. Through vibration testing, it was determined FRFs (Frequency Response Functions) which relate the response given by the specimen when impacted by hammer, allowing for the determination of the natural frequencies, this was done by fixing the laminate specimen in special simply support locally manufactured apparatus as shown in Figure 6. The impact hammer was used to give the input load (pulse) to the specimen, then output was captured by the accelerometer and is amplified using a conditioning amplifier and then read using the high resolution signal analyzer, giving the FRF. For every specimen multiple measurements were conducted.

Figure 6: Vibration Test System

FINITE ELEMENT MODEL USING ANSYS

Finite element analysis for composite materials is much more complex as compared to isotropic materials, in terms of input and output informations. Special care needs to be taken for the orientation of plies and direction of their associated properties. In the present research, the commercial finite element software ANSYS was used to build finite element models for both healthy and delaminated cross ply 8-layered (0, 90) plates to study their vibration behaviour. The 3-D layered structural solid shell (SOLSH190) is 8 nodes element with three degrees of freedom per node was used; this element type can be used for simulating structure with wide range of thickness. The element allows 250 layers for modelling laminated composite. The layer information is input by using section commands rather than real constant.

RESULTS AND DISCUSSION

Generally, a plate with delamination will experience reduction in natural frequencies due to the loss of stiffness. The extent of stiffness loss depends on delamination characteristic.

Numerical Results

Numerical results were carried out to determine the capability of the present FEM to predict natural frequencies of healthy and delaminated cross ply (0, 90) laminate composite plates.

Verification

In order to analyze the vibration response to extract natural frequencies of healthy and delaminated composite plates, FEM was proposed in the present work. Previous published research was employed in this subsection to verify the justification, accuracy and efficiency of the present Finite Element Model. Clamped composite square laminates (0°/90°/45°/90°) with side length 250 mm, thickness 2.12 mm, and density ρ = 1446.20 kg/m^3, with a square delamination 125 $\times$ 125 mm^2 at middle plane of plate was investigated. The laminate elastic constants are E_{11} = 1.32 $\times$ 10^2 GPa; E_{22} = 5.35 GPa; G_{12} = 2.79 GPa; $\nu_{12} = \nu_{13}$ = 0.29; ν_{23} = 0.3. The numerical results of present FEM in Table 2 showed a good agreement with the previously published finite element results (Ju *et al.*, 1995).

Table 2: Comparison of Natural Frequencies of a Healthy and Delaminated Clamped Square Composite Laminate Plate (0°/90°/45°/90°)s

Mode	Condition	Present FEM	Ju et al. (1995)
First	Healthy	344.37	346.59
	Delaminated	322.53	334.67
Second	Healthy	658.60	651.51
	Delaminated	560.18	579.43

Modal Analysis

After validating the present finite element model with the existing literature, FEM can be used to study how midplane delamination with different areas effects natural frequencies and comparing the obtained numerical results with experimental measured results. The results from present FEM validated with the experiments conducted on cross eight plies (0/90) with simply supported boundary condition accomplished in our laboratory. Table 3 and Figure7 show the comparison of frequencies predicted for the first four modes by using the present finite element model (ANSYA 12.1) and those measured experimentally on the healthy and delaminated woven fiber Glass/Epoxy square plates. The natural frequencies with increase of delamination area for both experimental and numerical results were decreased. From Figure 7 it arises that the results obtained from numerical calculations were in good agreement with the experimental investigation. The maximum error between FEM and experimental test results were less than 5.41%. The present verified finite element model can be used for further analysis and the comparison shows that the introduced FEM is capable of providing accurate predictions for natural frequencies of healthy and delaminated laminate composite plates.

Table 3: Comparison Between Experimental Measured Natural Frequencies and Present Finite Element Results of Simply Supported Square Laminate Plates

Delamination area mm^2	First Mode		Second Mode		Third Mode		Fourth Mode	
	EX	FE	EX	FE	EX	FE	EX	FE
Healthy	172.2	179.40	459.5	466.95	466.3	466.95	686.4	697.47
50 $\times$ 50	170.3	178.82	420.8	413.85	432.5	424.57	637.3	648.62
100 $\times$ 100	169.2	174.86	314.5	326.02	337.4	329.47	549.2	547.26
150 $\times$ 150	159.4	156.30	258.8	267.13	271.2	267.31	293.3	277.43

Figure 7: Comparison of Present Finite Element Results with Experimental Measured Natural Frequencies

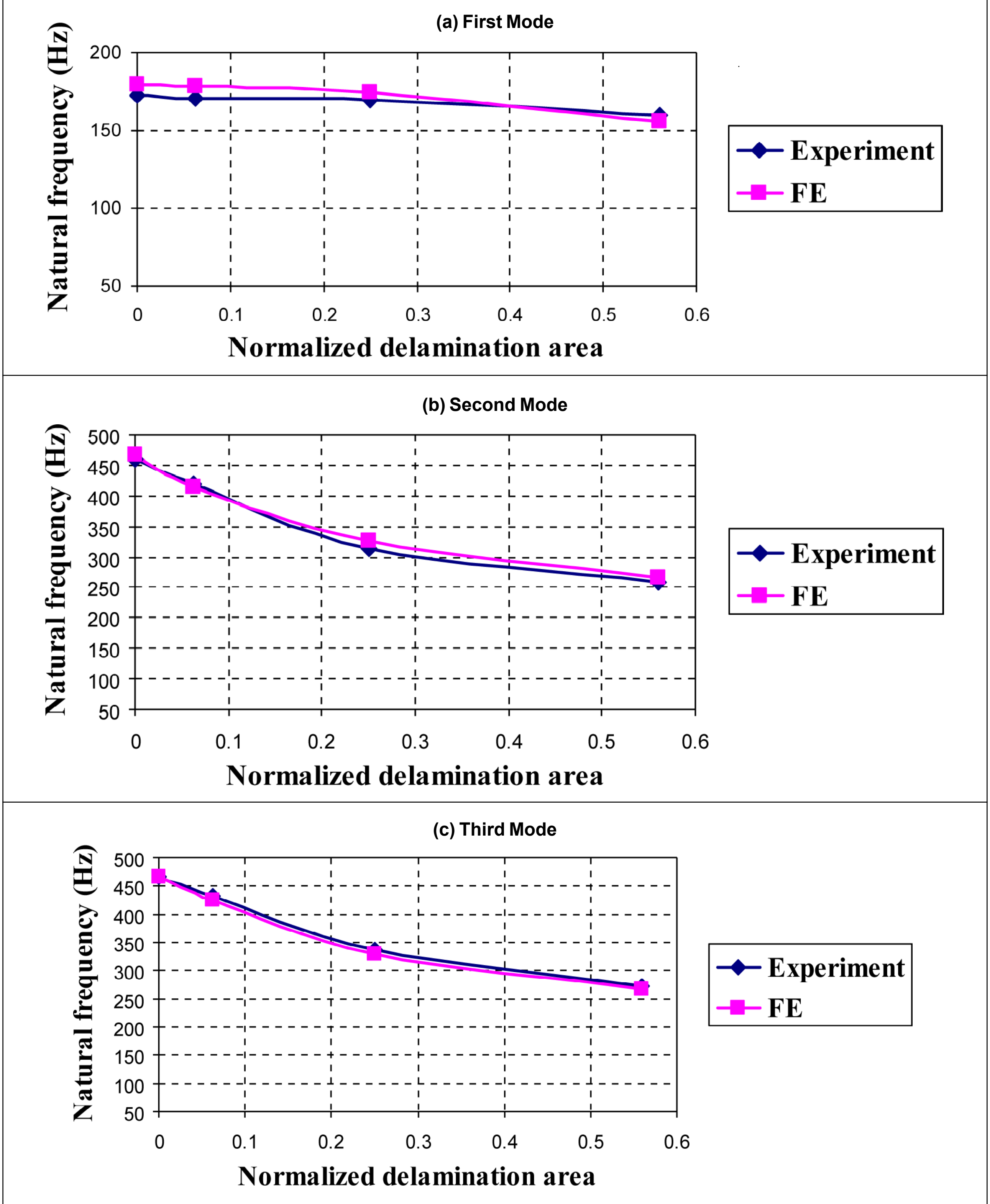
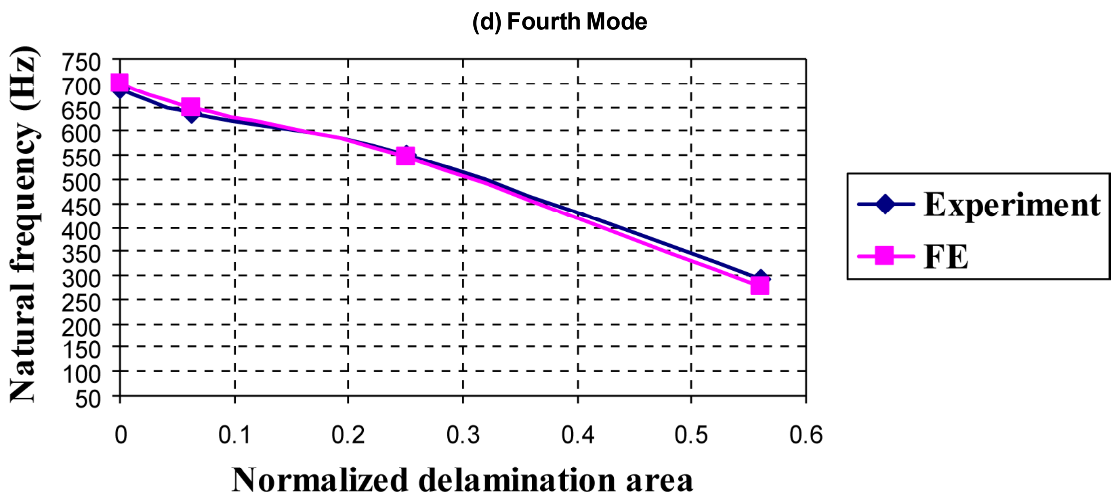


Figure 7 (Cont.)



CONCLUSION

In this study, the natural frequencies of the simply supported composite laminate plates with different areas of mid plane delamination were investigated numerically and experimentally. As a first step towards the goal of solving the problem of detecting delamination in composite laminate structures using natural frequency shifts, the application of finite element analysis using the commercial software ANSYS (version 12.1) for modelling the vibration behaviour of fibre reinforced composite laminates with embedded different delamination areas was investigated. This reliable finite element model successfully simulates eight cross plies (0/90) for healthy and delaminated plates. Based on the numerical and experimental results following conclusions can be drawn:

- Delamination in plates results in a decrease in the natural frequencies experimentally and numerically.
- The changes in natural frequencies are functions of the area of the delamination. When the area of delamination increases the reduction of natural frequencies also increases.
- Effect of delamination area is most dominant at moderate modes of vibration.
- Analytical methods to predict changes in the natural frequencies are of dubious worth in more complex structures and limited to a number of particular shapes of plates with particular boundary conditions, and the experimental methods used to obtain the natural frequencies are difficult to set up because we have to use a proper manufacturing boundary condition. So far, finite element method has been shown to be more realistic for application to engineering constructions. Laboratory experiments are often conducted to insure validity of numerical model.
- The accuracy of present finite element model in predicting the natural frequency was verified using an experimental work. The results obtained from numerical calculations were in excellent agreement

with the experimental investigation, where the maximum difference is 5.41%.

- Present finite element method introduced in the present work can be successfully applied further to analyze the natural frequencies of healthy and delaminated composite plates.
- The deviation of numeric results in relation to experimental ones, some possible measurements error can be pointed out such as: measurement noises, position of accelerometer, mass of accelerometer and non uniformity of specimens (bubble, voids, variation of thickness, bad surface finish).Such factors were not taken into account during numerical analysis, since the finite element model consider the model entirely perfect and homogeneous properties, what rarely occurs in practice. Also, the computational package ANSYS (version 12.1) does not allow for the consideration of the fibers interweaving present in the fabric used.
- It is advisable to design good experimental apparatus to simulate better boundary conditions effect.
- In finite element solution, the contact elements must be surly be used in delaminated region in order to obtain natural frequency in the delaminated plate.
- The numerical analysis using finite element package ANSYS to investigate the effect of delamination area on natural frequencies, was a successful tool for such applications.

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APPENDIX

Nomenclature	
E_{11}	Modulus of elasticity in fiber direction
E_{22}	Modulus of elasticity transverse to fiber direction
EX	Experiment
FE	Finite element
FEM	Finite element model
FRF	Frequency Response Function
G_{12}	In plane shear modulus of elasticity
ν_{12}	Major in plane Poisson's ratio
ρ	Laminate density