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Finite element modeling and updating of the composite plate structure

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Abstract. Composite plate structure is broadly used in engineering structures for automotive and aerospace applications. Furthermore, the problem in vibrational is one of the industries main challenges. Composite materials are frequently used in industry for weight and cost reduction to enhance mechanical properties in structural components. This research aims to execute a composite plate structure model updating procedure. Through finite element analysis (FEA) and experimental modal analysis (EMA), modal parameters such as natural frequencies, mode shapes, and damping ratios are collected. Composite plate structure is set to be free-free boundary condition and node equivalence is done in the surface plate area. Correlation is executed between these two data sets. The discrepancies in natural frequencies between FEA and EMA were reduced with the selected parameters identified to perform structure updating model using sensitivity analysis.

1. Introduction

Natural fiber composites have been one of the major research topics in recent decades for a number of reasons, including their potential to improve sustainability at a lower cost to replace synthetic fiber reinforced plastics [1]. Several literature studies have been conducted to report natural plant-based cellulose fibers such as ramie, jute, flax, sisal, henequen, and pineapple as reinforcement of composites due to low cost, low density, high specific strength, and modulus, as well as good insulation and acoustic properties [2-7]. Natural fiber-reinforced bio-composites was a good alternative to conventional materials for applications in aerospace, underwater, and transport [8]. Composite materials, therefore, came into play, which serves as a confining material for all applications requiring weightless and high resistance applications in structural and non-structural fields. Combining two or more constituents that should have different chemical or physical properties forms the composite material. One constituent is referred to as reinforced material or fiber, and the other is referred to as the matrix embedding fiber. This newly formed material has different characteristics and is known as a composite material. These individual components remain separate and within the finished structure can be in a different orientation with each other [9]. Composites have good vibrational properties, especially when added with a natural fiber like reinforcements. India has significant natural fiber availability like a fiber, jute fiber, coir fiber, sisal, pineapple fiber, banana fiber, and ramie fiber [10].

Based on previous literature studies, composite materials have some unique properties at the microscopic level, such as homogeneous and heterogeneous, it has high strength, rigidity, toughness and results in weight and cost reduction [10]. Fiber's function is to enhance composite properties while the matrix of composites used to support and protect the fibers. It can be increased to enhance the mechanical strength of these composites by improving molecular bonding in the matrix by adding materials such as acrylic resin, etc. that have good molecular structured material properties [9].

The method of finite element (FE) is one of the practical methods of engineering analytical modeling. The construction of large and sophisticated analytical models has been made possible by modern computers capable of processing large matrix problems at high speed. Studies have found that the finite element analysis is broadly used to model structural dynamics to simulate the behavior of real systems because accurate results are considered to be reliable. According to Zienkiewics et al, FE was the most suitable tool in structural engineering for numerical modeling due to the ability to handle complex geometry structures, large complex assemblies of structural components and the ability to perform many different types of analysis [11]. In 2007, Zivanovic, S. et al. [12] pointed that the simulation of near-resonant dynamics is very sensitive to even small variations in modal parameters (natural frequencies, damping ratio, and mode shape) when performing design response calculations. Structural analysts are constantly challenged to produce better designs to meet the authorities ' requirements for safety, economic and environmental regulations. A current study attempts to cover a wide variety of modal analysis that focuses on determining the dynamic behavior of a test structure using experimental approaches via experimental modal analysis (EMA) and a numerical prediction technique using finite element analysis (FEA).

Updating the finite element model is an updating technique that provides more accurate data-related results than the other initial models [13]. The main purpose of model updating is to reduce the discrepancies for both numerical and experimental results by updating selected parameters from resonance frequencies and mode shapes [14-15]. The updating technique has two methods that are sensitivity method and the direct method. The most important task in model updating is selecting the updating parameter. If numerical predictions are insensitive to a parameter chosen, then updating will lead to a change in the uncertain value parameter. The difference between results and predictions was reconciled with changes to other (more sensitive) parameters that may require fewer updates. This is due to selecting only sensitive parameters to minimize percentage error discrepancies. Before the updating process, a sensitivity analysis had to be performed to identify which parameters were the most influential to choose from. As mentioned by [16], the selected parameters should be justified by an engineering understanding of the structure and the number of parameters should be kept to a minimum in order to avoid problems with un-conditioning. A few published papers managed to reduce the discrepancies between predicted results of FEA and measured data from EMA using FE model updating with MSC Nastran optimization algorithm, SOL200 [17-21].

The aim of this study is to examine the dynamic properties of the composite plate structure to be performed in numerical and experimental analysis for the determination of modal properties. Sensitivity method is one of the techniques of updating that focuses on model updating problem approach. Fabrication is carried out using the hand lay-up method and compression molding technique at a pressure of 100 – 110 bar and temperature of 140 – 150^{o}C.

2. Experimental set-up

2.1 Materials

Ramie woven fibers are used as reinforcement material and this composite uses epoxy resin as a polymer matrix material.

Figure 1. Ramie woven fiber

2.2 Hardener

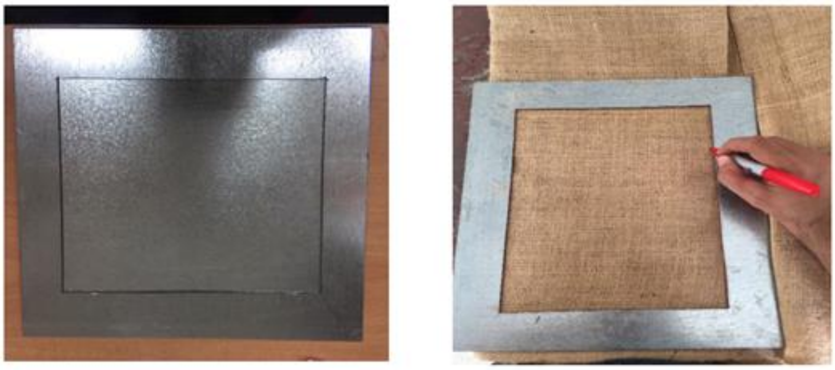
The curing action of Epoxy is performed by mixing a substance or mixture called a hardener. It is added in an epoxy ratio of 1:2.

2.3 Fabrication of material

Fabrication of the composite ramie-enhanced polymer matrix is prepared and cured at room temperature [22 – 23, 28]. Resin and Hardener needed quantities were mixed in a beaker. The mixture of the Ramie Epoxy was stirring by using the chopstick for a few minutes until the mixture is fully penetrated. The mixture needs to be stirred in slow and constant speed to avoid the increasing number of air bubbles. As the speed increase, the reaction of the resin and hardener will increase, then it will produce more air bubbles. The reason for minimizing the mixture's air bubbles is to reduce the number of voids on the composite plate surface.

2.4 Mold preparation

The mold is made of 350 x 250 mm aluminum for the base of the mold and 263 x 193 mm for the composite plate mold frame. The aluminum plate for the frame structure was marked with the marker pen and cut using the hand grinder. Figure 2 (a-b).



(a) (b)

Figure 2. (a) Aluminum Mold; (b) Marking Process on Ramie Woven Fibre

2.5 Curing of castings

Curing takes place at room temperature for approximately 24 hours at 25 degrees Celsius. Once the healing has been completed, the mold has been opened and the specimen carefully removed. The polystyrene barriers were created to block the excessive epoxy from the composite plate to prevent damaged the surface of the machine (Figure 3).

Figure 3. Compression Machine

3. Experimental modal analysis

Recent developments in the field of capabilities in data acquisition and processing have led to significant advances in experimental modal analysis or modal testing. Modal testing defines a study of a mechanical structure's dynamic characteristics to extract modal parameters (mode shape, damping ratio, and natural frequency The instrumentation and setup used in modal testing to influence the experimental result [24-27]; therefore, modal testing should be performed in free-free boundary condition in order to obtain the accurate result. A certain input (hammer, shaker) will excite the structure and the sensing mechanism will be used to measure the input force to produce a frequency response (FRF's) set. EMA plays an important role in structure design and analysis and validates the results of simulation models before they can be used for further detailed analysis. To achieve an adequate spatial resolution of global structural mode shapes, the composite plate structure was divided into 24 grid points. In order to avoid nodal points, the location and measuring points were carefully selected. Figure 4 shows the placement of grid points on the structure of the composite plate.

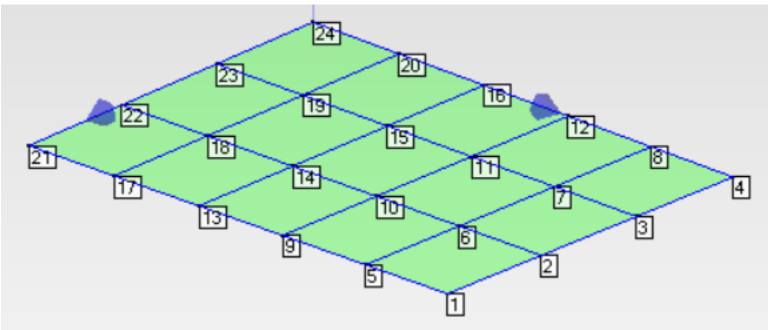


Figure 4. Composite plate structure with labeled grid points

In this study, the excitation method used impacts hammer with rowing accelerometer. Then, the impact hammer is attached to exciting the structure with a force transducer on its head. While a uni-axial accelerometer attached to the structure detected the response and the data analyzer was used to convert the signal response to the frequency domain in the time domain. The DAQ (Data Acquisition System) records the dynamic force signal and transfers the data to the computer to obtain FRF's by comparing the excitation of force and the acceleration of response signals. Figure 5 shows an experimental configuration for measuring systems.

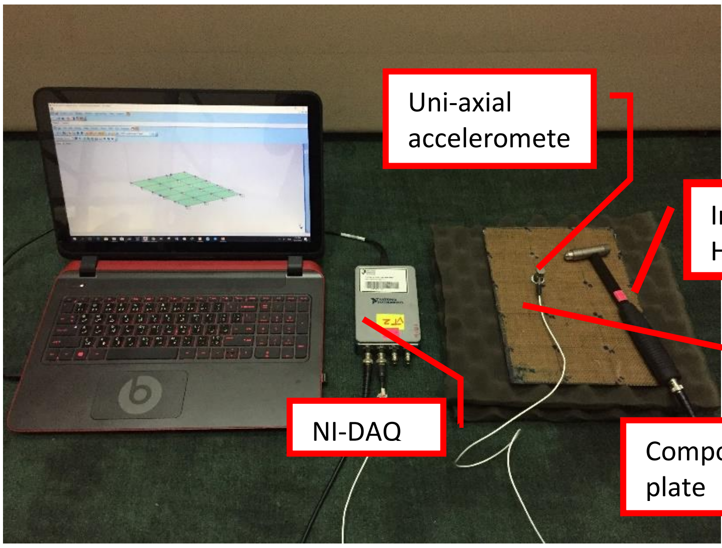


Figure 5. Experimental modal analysis setup.

Natural frequencies and mode shapes have been extracted from ME'scopeVES software using a curve fitting method and are summarized in Table 1.

Table 1: Resuts of experimental natural frequencies

Mode	Natural Frequency (Hz)
1	114
2	158
3	272

4. Finite element analysis

In this study, using MSC Nastran/Patran Software, FEA was performed. Modeling of finite elements took place in the free-free boundary condition. The interface FEA model consisting of 60 nodes and 40 shell elements (CQUAD4). Furthermore, the model properties are shown in Table 2. Node equivalence was performed in the model's entire area to represent the surface rigidity in the structure. In order to achieve better results, a higher percentage of mesh size is set, but a supercomputer is required to carry out the analysis [16]. For this study, 20-30 mode shapes were analyzed and the test specimen was not subject to any loading or boundary condition. By supporting the structure with a soft material such as a sponge, the free-free boundary condition was simulated. The simulation was performed part by part to compare it later with the experimental analysis.

Modal properties calculation in MSC.Natran/Patran was performed using SOL 103, the solution for normal mode analysis [26]. The mode shapes and natural frequencies of the structure can be calculated using normal mode analysis. The equation of motion in normal modes analysis is indicated as Eq. (1).

$$\boldsymbol{M}u + \boldsymbol{K}u = 0 \tag{1}$$

where K and M are respectively rigidity and mass matrices. MSC Nastran/Patran calculates these system matrices automatically based on the FEA model's geometry and properties. From Eq. 1, it can be reduced by assuming a harmonic solution to an eigenvalue problem which is indicated as Eq. (2).

$$[\boldsymbol{K} - \lambda_i \boldsymbol{M}]\{\emptyset_i\} = 0 \tag{2}$$

Where {ϕ}is the eigenvector (mode shape) equivalent to the eigenvalue λ (natural frequency). Generally, each eigenvalue is proportional to a natural frequency and corresponds to eigenvector. The eigenvalues are correlated to the natural frequencies as Eq. (3).

$$\boldsymbol{f} = \frac{\sqrt{\lambda_i}}{2\pi} \tag{3}$$

Table 2. Material properties of the plate structure

Properties		Nominal value
Material properties (Composite)	Young's Modulus, E	7.3 GPa
	Poisson ratio	0.3
	Density	1243 kg/m^3
Shell properties	Thickness	0.004 m

5. Correlation between EMA and FEA

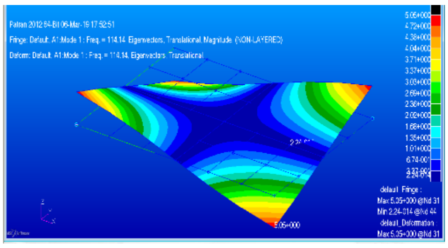
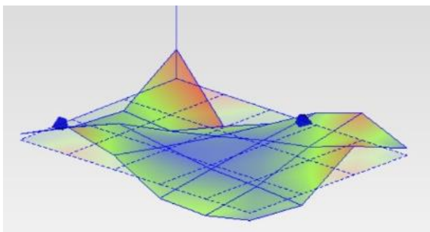
The objective of the FEA-EMA correlation is to clarify the results obtained from this research, where discrepancies will be compared between both results and the percentage error will be captured. Table 3 indicates the natural frequencies attained from the finite element model and the structure experimental modal testing and the percentage of error in the various cases. Mode 1 had the lowest error percentage while Mode 2 had the highest error percentage. Table 4 illustrates the mode shape between FEA and EMA.

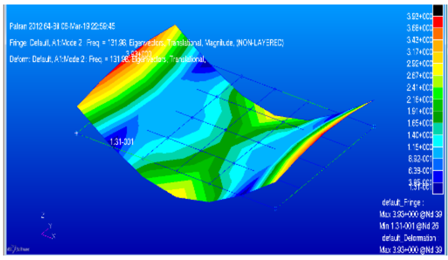
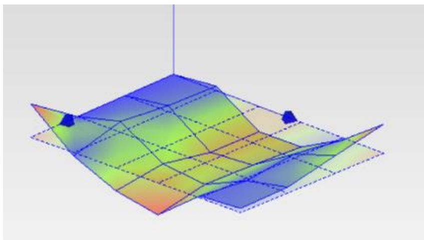
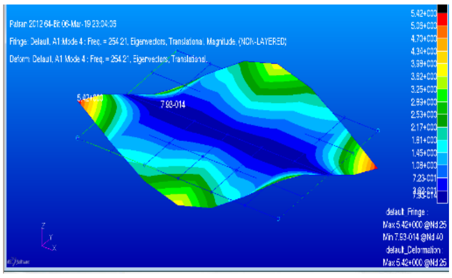
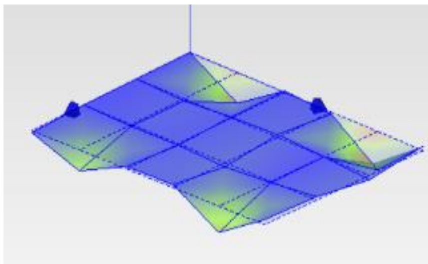
Table 3. Correlation between natural frequency, FEA, and EMA

Mode	FEA	EMA	Error (%)
1	114.14	114	0.12
2	131.98	158	16.47
3	254.21	272	6.54

This study indicates that the inclusion of residual stresses for both numerical and experimental results occurs when the plate tends to increase the natural frequency, as these stresses are primarily tensile in nature, thus increasing the lateral stiffness of the plate, resulting in an increase in natural frequency. This is due to residual stress is small as these stresses act on small areas relative to the plate area.

Table 4. Correlation between mode shape, FEA and EMA

Mode	Mode Shape	
	FEA	EMA
1		

2		
3		

6. FE model updating

In finite element analysis, model updating is a process modifying selective parameters to decrease the discrepancies of the results for both experimental and numerical. The correlation objective is to minimize the error percentage between FEA and EMA. This can be accomplished by model updating. The iterative methods using modal data has been used in this study with the adoption of SOL200 optimization algorithm supported by MSC Nastran.

It is very important to perform model updating with a selection of sensitive parameters to minimize the discrepancies. In this study, which resulted in three parameters were picked, namely Modulus Young, plate density and thickness. Table 5 represents the results of the plate structure before updating, comparison of natural frequencies in FEA between before and after updating. Significant errors were observed in Mode 2 when the model updated reduced the error rate from 16.47% to 10.13%. Mode 1 shows an increasing percentage of error, but other modes show the percentage of error significantly reduced.

Table 5. Comparison values of natural frequencies for initial and updated results.

Mode	EMA natural frequency (Hz)	Initial FEA natural frequency (Hz)	Initial percentage of error (%)	Updated numerical natural frequency (Hz)	Percentage of error after Model Updating (%)
1	114	114.14	0.12	123	7.89
2	158	131.98	16.47	142	10.13
3	272	254.21	6.54	274	0.74
		Total Error	**4.63**	Total Error	**3.75**

Three parameters were identified to reduce natural frequency discrepancies between EMA and FEA through model updating. Table 6 indicates the update parameter deviation and explains that Young's Modulus, density, and thickness play a major role in reducing discrepancies. The thickness of the plate shows a higher sensitivity value when analyzing using sensitivity analysis.

This study indicated that the error percentage of mode 1 after updating was increased due to numerical analysis. This is because in this studies it using homogenous surface in FEA for the composite plate. In this case, approached of modeling plate perhaps not appropriate for composite because it has other methods such as solid surface. Besides that, it also can try and error for materials properties in FEA using composite structure based on a layer by layer for each fiber and matrix. As overall, the total percentage of error has decreased which is it achieve the main objective in updating the error from the initial result. In the other hand, the results also effect from updating method because it used the same weighted for each parameter. In future research, it can improve using different approaching of updating method.

Table 6. Changes in updating parameters from the initial values.

Parameter	A Initial Value	B Updated Value	Deviation (%) $= \left\lvert \frac{B-A}{A} \right\rvert \times 100$
Young's Modulus (GPa)	7.3	7.49	2.54
Thickness	.004	.0042	4.76
Density	1246	1208.62	3.09

7. Conclusion

This paper presented results that reduced the discrepancies on the composite plate between EMA and FEA. The equivalence of nodes is performed at the surface area in FEA with the free-free boundary condition applied to the composite plate. The findings of this study indicate that by selecting appropriate fabrication techniques, the bonding between fibers and matrix can be improved. In this study, three parameters were selected to update parameters. In an earlier phase, parameters were assumed when performing FEA, resulting in natural frequency discrepancies, this gap is narrowed down with the updating procedure. By applying the model updating technique using optimization of sensitivity analysis, the discrepancies between EMA and FEA have been reduced. This research has raised many questions that need to be investigated further. Further work needs to be done by focusing on updating the composite plate's different material properties and thickness, defining the element can likely reduce the discrepancies between EMA and FEA.

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