# ANALYTICAL AND EXPERIMENTAL MODAL ANALYSIS OF GFRP BENCHMARK STRUCTURE USING SHAKE TABLE

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## ABSTRACT

In this study was investigated of possibility using the recorded micro tremor data on ground level as ambient vibration input excitation data for determination and application Operational Modal Analysis (OMA) for GFRP benchmark structure. As known OMA methods (such as FDD, EFDD, SSI-UPC/SSI-PC/SSI-CVA and so on) are supposed to deal with the ambient responses. For this purpose, analytical and experimental modal analysis of GFRP benchmark structure for modal properties was evaluated. 3D Finite element model of the building was evaluated SAP2000 for the GFRP benchmark structure based on the design drawing. Ambient excitation was provided from the recorded micro tremor ambient vibration data on ground level. Enhanced Frequency Domain Decomposition (EFDD) is used for the output only modal identification. From this study, very best correlation is found between mode shapes and frequencies. Natural frequencies and analytical frequencies in average (only) %1.24 are differences.

**Keywords:** Experimental modal analysis, EFDD, GFRP, Shake table

## INTRODUCTION

In recent years, in the world and our country, the determination of the effect of vibrations on structures and structural behaviour has become very important. Our country has many important structures in terms of its historical background and geographical location. In addition, the earthquakes that have frequently occurred in recent years in our country have increased the researches and studies on the experimental determination of the behaviour of structures under vibration. Many buildings built in the past are known to suffer many damages due to faults in the design and manufacturing stages, as well as natural disasters and overload effects. Especially when our country is on an active earthquake zone, we have over 80 million inhabitants, considering our geographical position; Damage assessment and assessment are clearly visible in terms of our country. Structures are under constant vibration. Many factors such as wind, earthquake, wave, explosion, and vehicle load etc. cause vibration. These vibrations sometimes cause cracks and sometimes serious damage.

Thus, the determination of the behaviour of structures under vibrations directly affects the life of that structure. The behaviour of the structure under the vibrations affecting it can only be determined by experimental studies. At the design of the structures, firstly analytical models are formed to represent the structures and static and dynamic analyses are carried out for different loading situations on these models. But in most cases the analytical model created does not fully represent the actual behaviour of the building. The comparison of dynamic parameters is used as a practical solution in determining and eliminating differences in building behaviour. Most of structures located in regions prone to earthquake hazards suffer from various types of destruction caused by seismic loads. Under such earthquake occurring, the parts (especially the columns) of building structures suffer damage. Looking on the other side, especially considering the performance of such buildings under seismic occurrence, there is a great need to strengthen the column seven without changing their building masses; this clearly shows that there is a need to investigate the connection between technical repairing or strengthening procedures and the column capacity. In this understanding, more researches are being conducted to get required performance of structures under seismic loading, by means of looking at different point of view and directions. Framing, in civil engineering, is the fitting together of pieces to give a structure support and shape. Framing materials are usually wood, engineered wood, structural steel or FRP (Fiber Reinforced Plastic). Glass reinforced plastics (GRP), sometimes; they are called glass reinforced polyester, glass fiber, glass fiber reinforced plastic (GFRP), fiber reinforced plastic (FRP) or fiber reinforced polymer (FRP) [1-3]. First developed in the 1930s, it emerged as a composite, laminate material made of glass fibers used to reinforce a plastic, typically a polyester resin. Glass fibers can be used as "random" short cut yarns formed into a mat, or can be gathered together into "rovings" (bundle of ropes) or woven into a fabric. GFRP can be mass-produced or made by hand, and after curing it forms a complex matrix of plastic and glass fibers. The composite properties of high strength glass fiber and high strength plastic make GFRP strong, lightweight, and weather and corrosion resistant. It can also be manufactured as a flame retardant. Fiber reinforced polymers (FRP) have high potential for use as structural elements in the field of civil engineering due to their high strength, lightness and improved durability. In the literature review, the following studies have been made on (FRP) and this study has also been used at a high level in these publications [4-11]. In particular, the pultruded glass fiber reinforced polymer (GFRP) elements used in this study offer such advantages at relatively low cost. However, the widespread use of GFRP elements has not yet reached high use due to the sensitivity to brittle fracture, high deformability and instability phenomena, which are different from conventional materials, and the lack of specific and widely accepted design guidelines. On the other hand, GFRP is widely used in civil engineering structures. GFRP elements (profiles, plates, etc.) are frequently used in structures where corrosion effects, environmental factors (temperature change, humidity, etc.) and structure weight are important. Academic studies on civil engineering structures that are entirely composed of GFRP elements are very limited [12]. Some researchers have done similar studies under different environmental conditions. There are few studies in the literature for the operational modal analysis of GFRP frame structures. Studies on operational and experimental modal analysis began on the basis of system identification. There are many studies on system identification [13-19]. Nowadays, researchers use genetic algorithm [20], artificial neural networks [21-24], fuzzy logic [25-26], etc. they moved the works in different directions. In the studies, the use of traditional tools and equipment has been replaced by more advanced technological materials. Wireless accelerometers, self-powered sensors, etc. are some of them. Many new technologies have been developed for the continuous monitoring of the dynamic parameters of the GFRP frame structures. With these technologies, it has become possible to produce safer structures and to constantly control the structure. In order to reach the dynamic parameters correctly, it is necessary to define the parameters of the structure correctly. In most studies, it was observed that the finite element model of the GFRP frame structures and the dynamic parameters obtained from the operational modal analysis were different. The differences between the finite element model and the operational modal analysis are at an acceptable level of 2-5%. In situations where there is more difference, it is frequently encountered that there are errors in the finite element model or measurement. Errors in the finite element model are often due to incorrect material properties, dimensional measurement errors, etc. It arises. Errors in measurement are deficiencies in fixing the accelerometers, environmental effects, etc. can be listed as. In this study, special attention was paid not to make mistakes in the finite element model and operational modal analysis measurement mentioned above, which was positively reflected in the results [27].

In general, operational modal analysis is used to determine the damage levels of the existing structures, to check the validity of the assumptions made while constructing the finite element model, to update the initial numerical model of the existing structures according to the experimental data, to determine the dynamic characteristics of the structures by the experimental modal analysis method when the numerical model of the existing structures cannot be formed and to follow the structural health is widely used in the process [28-36]. For this purpose, analytical and experimental modal analysis of GFRP benchmark structure for dynamic characteristics was evaluated. 3D Finite element model of the building was evaluated for GFRP benchmark structure based on the design drawing. Ambient excitation was provided from the recorded micro tremor ambient vibration data on ground level. Enhanced Frequency Domain Decomposition is used for the output only modal identification.

## Modal parameter extractions (EFDD)

The (FDD) ambient modal identification is an extension of the Basic Frequency Domain (BFD) technique or called the Peak-Picking technique. This method uses the fact that modes can be estimated from the spectral densities calculated, in the case of a white noise input, and a lightly damped structure. It is a non-parametric technique that determines the modal parameters directly from signal processing. The FDD technique estimates the modes using a Singular Value Decomposition (SVD) of each of the measurement data sets. This decomposition corresponds to a Single Degree of Freedom (SDOF) identification of the measured system for each singular value [37]

The Enhanced Frequency Domain Decomposition technique is an extension to Frequency Domain Decomposition (FDD) technique. This t technique is a simple technique that is extremely basic to use. In this technique, modes are easily picked locating the peaks in Singular Value Decomposition (SVD) plots calculated from the spectral density spectra of the responses. FDD technique is based on using a single frequency line from the Fast Fourier Transform analysis (FFT), the accuracy of the estimated natural frequency based on the FFT resolution and no modal damping is calculated. On the other hand, EFDD technique gives an advanced estimation of both the natural frequencies, the mode shapes and includes the damping ratios [38]. In EFDD technique, the single degree of freedom (SDOF) Power Spectral Density (PSD) function, identified about a peak of resonance, is taken back to the time domain using the Inverse Discrete Fourier Transform (IDFT). The natural frequency is acquired by defining the number of zero crossing as a function of time, and the damping by the logarithmic decrement of the correspondent single degree of freedom (SDOF) normalized auto correlation function [39].

In this study modal parameter identification was implemented by the Enhanced Frequency Domain Decomposition. The relationship between the input and responses in the EFDD technique can be written as, in this method, unknown input is represented with x(t) and measured output is represented with y(t)

$$\left[G_{yy}(j\omega)\right]=[H(j\omega)]^{*}[G_{xx}(j\omega)][H(j\omega)]^{T} \qquad (1)$$

Where $G_{xx}(j\omega)$ is the r x r Power Spectral Density (PSD) matrix of the input. $G_{yy}(j\omega)$ is the m x m Power Spectral Density (PSD) matrix of the output, $H(j\omega)$ is the m x r Frequency Response Function (FRF) matrix, and * and superscript T denote complex conjugate and transpose, respectively. The FRF can be reduced to a pole/residue form as follows:

$$[H(\omega)]=\frac{[Y(\omega)]}{[X(\omega)]}=\sum_{k=1}^{m}\frac{[R_k]}{j\omega-\lambda_k}+\frac{[R_k]^{*}}{j\omega-\lambda_k^{*}} \qquad (2)$$

Where n is the number of modes $\lambda_k$ is the pole and, $R_k$ is the residue. Then Eq. (1) becomes as:

$$G_{yy}(j\omega)=\sum_{k=1}^{n}\sum_{s=1}^{n}\left[\frac{[R_k]}{j\omega-\lambda_k}+\frac{[R_k]^{*}}{j\omega-\lambda_k^{*}}\right] G_{xx}(j\omega)\left[\frac{[R_s]}{j\omega-\lambda_s}+\frac{[R_s]^{*}}{j\omega-\lambda_s^{*}}\right]^{\bar{H}} \qquad (3)$$

Where s the singular values, superscript is H denotes complex conjugate and transpose. Multiplying the two partial fraction factors and making use of the Heaviside partial fraction theorem, after some mathematical manipulations, the output PSD can be reduced to a pole/residue form as fallows;

$$\left[G_{yy}(j\omega)\right]=\sum_{k=1}^{n}\frac{[A_k]}{j\omega-\lambda_k}+\frac{[A_k]^{*}}{j\omega-\lambda_k^{*}}+\frac{[B_k]}{-j\omega-\lambda_k}+\frac{[B_k]^{*}}{-j\omega-\lambda_k^{*}} \qquad (4)$$

Where $A_k$ is the k th residue matrix of the output PSD. In the EFDD identification, the first step is to estimate the PSD matrix. The estimation of the output PSD known at discrete frequencies is then decomposed by taking the SVD (singular value decomposition) of the matrix;

$$G_{yy}(j\omega_i)=U_i S_i U_i^{\bar{H}} \qquad (5)$$

Where the matrix $U_i=[u_{i1},u_{i2},\dots,u_{im}]$ is a unitary matrix holding the singular vectors $u_{ij}$ and $s_{ij}$ is a diagonal matrix holding the scalar singular values. The first singular vector $u_{ij}$ is an estimation of the mode shape. PSD function is identified around the peak by comparing the mode shape estimation $u_{ij}$ with the singular vectors for the frequency lines around the peak. From the piece of the SDOF density function obtained around the peak of the PSD, the natural frequency and the damping can be obtained.

## Description of GFRP benchmark structure and Shake Table

GFRP benchmark structure is 1.0 m height. Elements are 5.0 mm thickness. Dimension of element is shown in Figure 1.

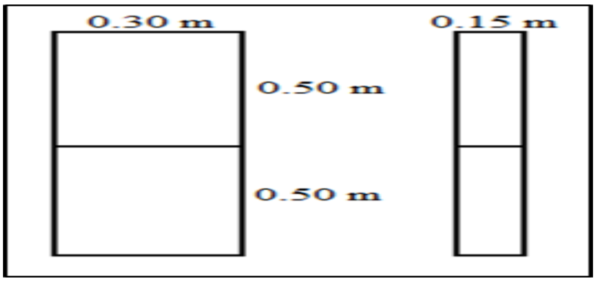

Figure 1: Illustration of GFRP benchmark structure (front and side view)

The Quanser shake table II is a uniaxial bench-scale shake table. This unit can be controlled by appropriate software was illustrated. It is effective for a wide variety of experiments for civil engineering structures and models. Shake table specifications are in table 1.

Table 1. Shake Table Specifications

| Parameter | Units | Value |
|---|---|---|
| Table dimensions | cm | 46x46 |
| Weight | kg | 27 |
| Motor maximum torque | N.m | 1.65 |
| Maximum force | N | 700 |
| Maximum payload at peak acceleration | kg | 15 |
| Operational bandwidth | Hz | 20 |
| Stroke length | cm | +/- 7.5 |
| Peak velocity | cm/sec | 83.4 |
| Peak acceleration | g | 2.5 |
| Ball screw efficiency | % | 90 |

## Analytical modal analysis of GFRP benchmark structure

A finite element model was generated in SAP2000 (1997). GFRP benchmark structure was modelled as 3D shell element (in Figure 2). Structure modelled as an absolutely rigidity shell (thin shell). The selected structure is modelled as a space frame structure with 3D element. GFRP benchmark structure was modelled as 3D shell element which has degrees of freedom. At the base of the structure in the model, the ends of every element were fixed against translation and rotation for the 6 degree of freedom (DOF) then creating finite element model of the structure in SAP2000. The following assumptions were considered. GFRP benchmark structure is modelled using an equivalent thickness and shell elements with isotropic property. All supports are modelled as fully fixed. The members of GFRP benchmark structure are modelled as rigidly connected together at the intersection points. In modelling of GFRP benchmark structure the modulus of elasticity E=4E10 N/m$^2$, Poisson ratio $\mu$=0.25, mass per unit volume $\rho$=18639 N/m$^3$.

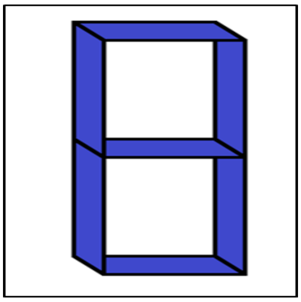

Figure 2: Finite element model of GFRP benchmark structure

Natural frequencies and vibration modes are concerned a significant impact on the dynamic performance of structures is an important dynamic property. A total of five natural frequencies of the structure are attained which range between 3 and 16 Hz. The first five vibration mode of the structure is shown in Figure 3. Analytical modal analysis results at the finite element model are shown in Table 2.

Table 2. Analytical modal analysis result at the first at the Finite Element (FE) model

| Mode number | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Frequency (Hz) | 3.22 | 6.30 | 9.28 | 12.08 | 15.16 |

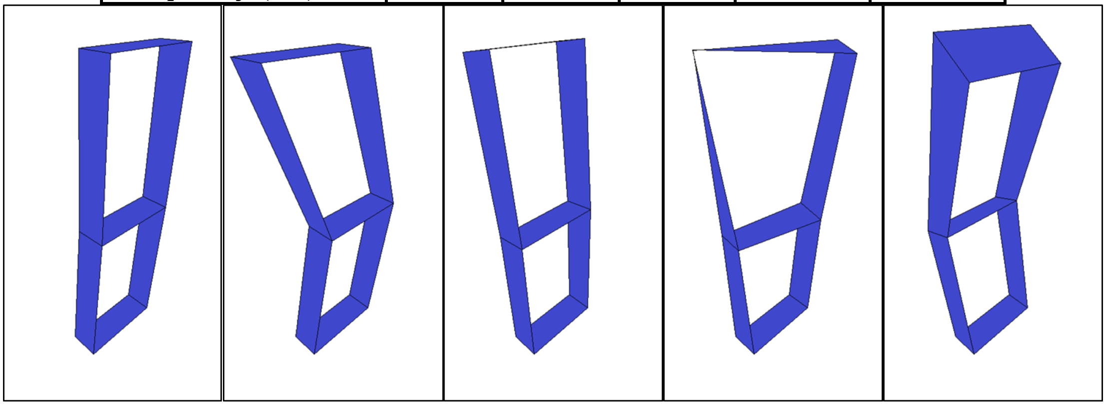

Figure 3: Analytically identified respectively mode shapes of GFRP benchmark structure

**Experimental modal analysis of GFRP benchmark structure**

Ambient excitation was provided by the recorded micro tremor data on ground level. Three accelerometers (with both x and y directional measures) were used for the ambient vibration measurements one of which were allocated as reference sensor always located in the wall (they are shown in Figure 4). Two accelerometers were used as roving sensors (they are shown in Figure 4). The response was measured in two data sets (Figure 4). For two data sets were used 3 and 5 degree of freedom records respectively (Figure 4). Every data set was measured 100 min. The selected measurement points and directions are shown in Figure 4. Ambient excitation data from the recorded micro tremor data on ground level given in figure 5.

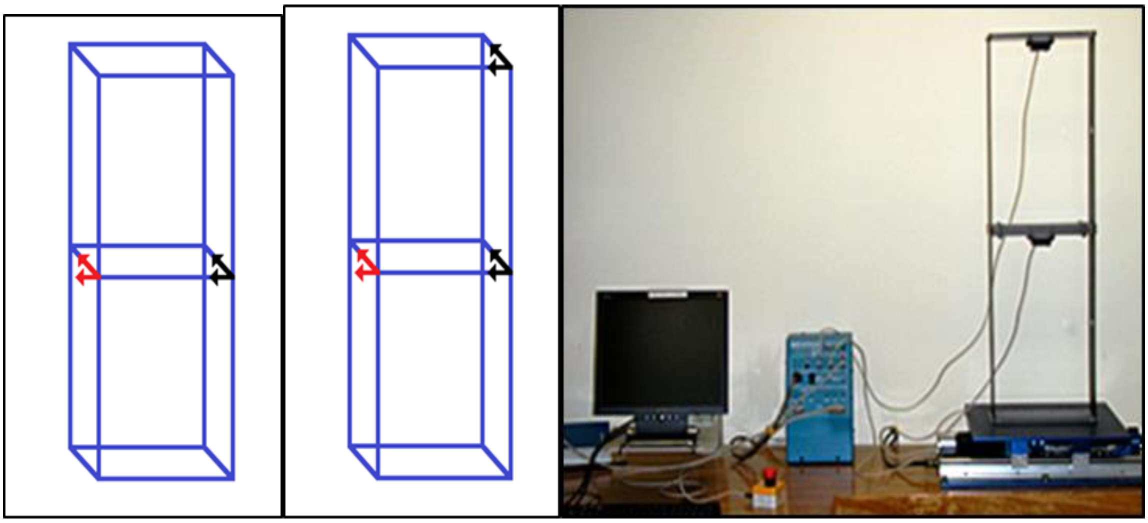

Figure 4: First setup, Second setup and Measurement view

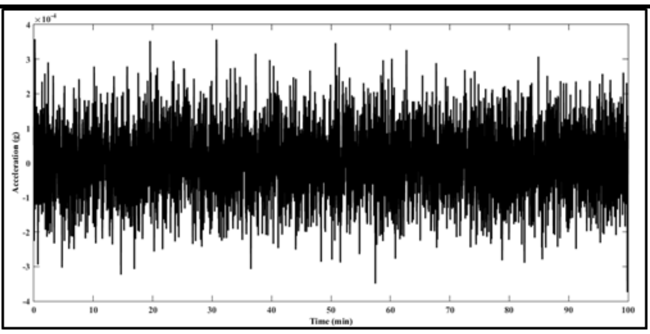

Figure 5: Ambient excitation data from the recorded micro tremor data on ground level

The data acquisition computer was dedicated to acquiring the ambient vibration records. In between measurements, the data files from the previous setup were transferred to the data analysis computer using a software package. This arrangement allowed data to be collected on the computer while the second, and faster, computer could be used to process the data in site. This approach maintained a good quality control that allowed preliminary analyses of the collected data. If the data showed unexpected signal drifts or unwanted noise or for some unknown reasons, was corrupted, the data set was discarded and the measurements were repeated.

The simple peak-picking method (PPM) finds the eigenfrequencies as the peaks of nonparametric spectrum estimates. This frequency selection procedure becomes a subjective task in case of noisy test data, weakly excited modes and relatively close eigenfrequencies. Also, for damping ratio estimation the related half-power bandwidth method is not reliable at all. Frequency domain algorithms have been the most popular, mainly due to their convenience and operating speed. For modal parameter estimation from the ambient vibration data, the operational modal analysis (OMA) software Artemis extractor (1999) is used. Singular values of spectral density matrices, attained from vibration data using PP (Peak Picking) technique are shown in Figure 6. Natural frequencies acquired from the all measurement setup are given in Table 3.

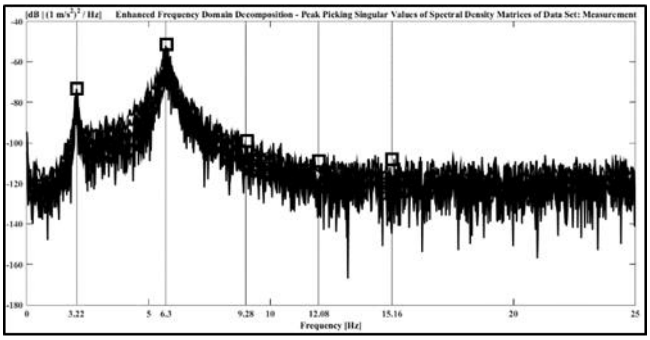

Figure 6: Singular values of spectral density matrices

Table 3. Experimental modal analysis result at the GFRP benchmark structure

| Mode number | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Frequency (Hz) | 3.18 | 6.23 | 9.12 | 11.98 | 14.95 |
| Modal damping ratio (ξ) | 0.87 | 0.79 | 0.61 | 0.59 | 0.68 |

The first five mode shapes extracted from experimental modal analyses are given in Figure 7.

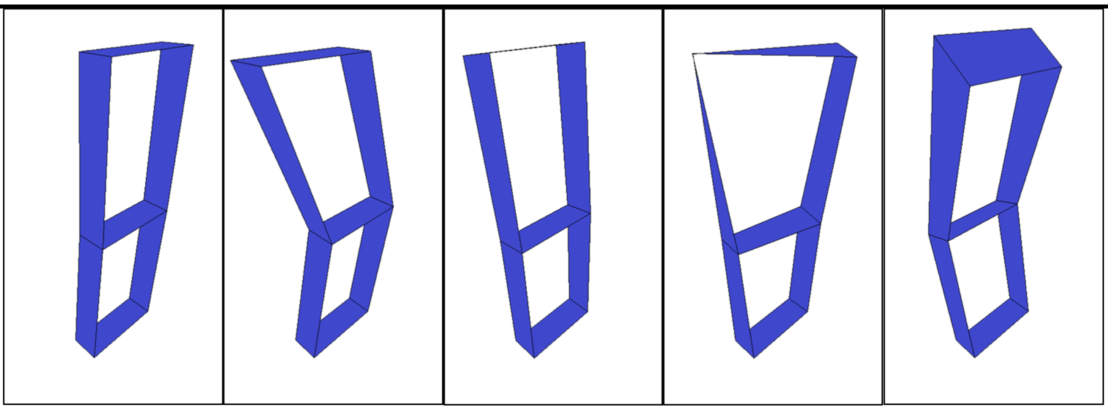

Figure 7: Experimentally identified respectively mode shapes of GFRP benchmark structure

When all measurements are examined, it can be seen that there is best accordance is found between experimental mode shapes. When the analytically and experimentally identified modal parameters are checked with each other, it can be seen that there is a best agreement between the mode shapes in experimental and analytical modal analyses (Table 4).

Table 4. Comparison of analytical and experimental modal analysis results

| Mode number | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Analytical frequency (Hz) | 3.22 | 6.30 | 9.28 | 12.08 | 15.16 |
| Experimental frequency (Hz) | 3.18 | 6.23 | 9.12 | 11.98 | 14.95 |
| Difference (%) | 1.24 | 1.11 | 1.72 | 0.82 | 1.38 |

## CONCLUSIONS

In this paper, analytical and experimental modal analysis of GFRP benchmark structure was presented. Comparing the result of study, the following observation can be made:

From the finite element model of GFRP benchmark structure a total of five natural frequencies were attained analytically. 3D finite element model of GFRP benchmark structure is constructed with SAP2000 software and dynamic characteristics are determined analytically. The ambient vibration tests are conducted under provided from ambient vibration data on ground level. Modal parameter identification was implemented by the Enhanced Frequency Domain Decomposition (EFDD) technique. Comparing the result of analytically and experimentally modal analysis, the following observations can be made:

From the finite element model of GFRP benchmark structure, the first five mode shapes are attained analytically that range between 3.22 and 15.16 Hz.

From the ambient vibration test, the first five natural frequencies are attained experimentally, which range between 3.18 and 14.95 Hz.

When comparing the analytical and experimental results, it is clearly seen that there is very best agreement between mode shapes and frequencies.

Analytical and experimental modal frequencies differences between 0.82%-1.72%.

Presented investigation results are shown and confirm of possibility using the recorded micro tremor data on ground level as ambient vibration input excitation data for investigation and application experimental modal analysis for GFRP benchmark structure.

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