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Damage Detection of Ferrocement Tanks Using Experimental Modal Analysis and Finite Element Analysis

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Abstract

In the recent years, structural health monitoring for civil structures using experimental modal analysis has been developed. Experimental modal analysis is the process of determining the dynamic parameters (frequencies, damping factors, modal vectors and modal scaling) of a linear, time invariant system by way of an experimental approach. It began in 1940's in aircraft then it used in civil structures since the advent of the digital mini-computers and the digital Fast Fourier Transformation (FFT) spectrum analyzer in the early 1970's. In this paper, the damage in ferrocement tank is detected experimentally by changing in its dynamic parameters due to two damages that were manufactured in its wall. Also in the current paper, theoretical models using ANSYS finite element software were developed to find the modal parameters of the healthy and damage tank. The current results showed that the theoretical models give accurate results in comparing with the theoretical results. Also the experimental modal analysis is quick, easy and inexpensive method to detect the damage in the ferrocement tank.

Keywords: Ferrocment tank; Experimental modal analysis; Input-output response; Classic modal analysis; Impact testing; Frequency response function; Finite element analysis.

1. Introduction

There are several types of damage that may be occurred in the structure due to inherent weakness in the structural system, design, detailing, poor material or due to overloading on the structure such as earthquake, wind and snow load. These loads may be not considered in design of the structure. These damages may be matrix cracking, delamination or fiber breakage. These affect the structural performance of the components by reducing their stiffness and can lead to premature failure [(1)].

The traditional methods to detect the damage in the structure are conventional destructive tests and conventional non-destructive tests. The conventional non-destructive tests include penetrant, magnetic particle, eddy current, ultrasonic, and radiographic testing. These methods have several limitations when testing large structures. First, they have limited depth of penetration.

Second, the location of the damage must be known a priori or the whole structure needs to be tested. Lastly, there is no way to easily determine the health of the structure at the boundaries and joints [(2)].

Scott et al [(3)] concluded that in last few years the vibration-based damage identification has been rapidly expanded. This method depends on using changes in modal parameters (natural frequencies, mode shapes and modal damping) to detect damage. This method can avoid the conventional non-destructive limitations. The modal parameters are functions of the physical properties of the structure (mass, damping, and stiffness). Therefore, changes in the physical properties due to damage will cause detectable changes in the modal properties.

Farrar and James [(4)] explained the advanced of using mode shapes and their derivatives as a basic feature for damage detection than using natural frequencies. First, the mode shapes contain local information, which makes them more sensitive to local damages and enables them to be used directly in multiple damage localization. Second, the mode shapes are less sensitive to environmental effects such as temperature than natural frequencies.

Input-output modal analysis (classical, traditional or conventional model testing) is a method of the experimental modal analysis in which the structure is excited by artificial force. This exciting force (F_t) and obtained response of the structure (X_t) are measured. The response of the structure can be measured as displacement, velocity or acceleration. The structure is excited by either an impact hammer or a shaker (exciter). In the impact testing, the sensor that is used to measure the structural response is usually kept fixed at certain location then the impact hammer is moved around the structure. In the exciter testing, the shaker is fixed at certain location and the sensors are moved from one location to another one. The impact testing is quick, easy and inexpensive test to determine the structural dynamic parameters so that it is very suitable for field work. On the other hand the high exciting force from the impact hammer that is used for large structures may cause local damage. The measured date (the exciting force (F_t) and the response (X_t) are transferred from the time domain to frequency domain (F_w and X_w) using the FFT that is found in processing analyzer and computer software package. The output response (X_w) divided by the input force (F_w) is defined as Frequency Response Function (FRF). The FRF contains all necessary information to find the modal parameters [(5)].

Fan and Qiao [(6)] studied experimentally damage detection in FRP composite plate by the classic model testing. The plate is clamped at one end by a steel anchor beam. They used impact hummer to excite the plates and the frequencies are measured by accelerometer. Lestari and Qiao [(7)] estimated damage identification from comparison of dynamic responses of healthy and damaged FRP sandwich beams. Their study depended on using curvature mode shapes and using piezoelectric smart sensors in estimating the modal parameters.

Araujo dos Santos et al [(8)] studied the impact damage detection in carbon fiber reinforced epoxy rectangular plate using their vibration characteristics. They presented three methods for the damage localization using double pulse TV holography. Zhu et al [(9)] studied theoretically and experimentally damage detection method for shear buildings using the changing of the first mode shape slopes. The building model was subjected to a white noise random ground excitation generated. They compared the results of the experimental work and the theoretical model and they found that the numerical model gives accurate results.

Ferrocement is a type of reinforced concrete commonly composed of hydraulic cement mortar reinforced with closely spaced layers of continuous and relatively small size wire mesh. This material proved during last years that it is low cost, durable, weather-resistance, lightweight and particularly its versatility comparing to the reinforced concrete (Robles-Austriaco et al. [(10)] and Ali [(11)]). This material is also used in repairing the reinforcement element such as beams, slabs, walls or column (Fahmy et al**.** [(12)], Elavenil and Chandrasekar [(13)], Jumaat [(14)] and Mourad and shang [(15)]). Kaish et al [(16)] and Xiong [(17)] investigated the possibility of using ferrocement jacket in strengthening of square reinforced concrete short column.

Several researches studied the behavior of ferrocement elements (beam, slabs and column) under applied loads up to failure. Ibrahim [(18)] and Hago et al [(19)] studied experimentally the ultimate capacity of ferrocement slabs and simply supported slab panels; respectively. Their tested slabs reinforced with different types of reinforced wired mesh. Nassif and Najm [20] investigated an experimental and a theoretical model for ferrocement–concrete composite beams. Various types of reinforced concrete beam overlaid on a thin section of ferrocement were tested up to failure under two-point loading system. Their results showed that the proposed composite beam has good ductility, cracking strength and ultimate capacity more than reinforced concrete beam. Moita and Estevam [21] indicated that crack widths in ferrocement tanks with the same steel stress in reinforced concrete tank are smaller than in reinforced concrete.

In the current work, the damage identification procedure based on dynamic response for ferrocement tank is developed. Healthy ferrocement tank and damage tank was tested to determine their dynamic parameters using the classic modal analysis technique. The dynamic test on the two tanks was done using an impact hammer to excite the tank and accelerometers to measure their dynamic responses. Also in this paper, a theoretical model is developed using ANSYS program package [22] to evaluate the experimental work.

2. Experimental program.

2.1. Materials and mixing proportions.

Ordinary Portland cement provided from Suez Cement Factory and natural clean sand were used for producing the ferrocement mortar with ratio of 1:2 cement/sand ratio. Fresh drinking water was added by 0.35 water/cement ratio. The sieve analysis was done on the used sand and its results are presented in Table 1. Silica fume replacement of cement with 10% by weight with a powder form and a light-gray color and its chemical composition indicated in Table 2, Polypropylene fibers (see Figure 1) by 900 gm/m^3 of the mortar mix and super plasticizer EDECRETE DM2, complies with ASTM C494-86 with specific weight of 1.05 at 20 °c were added to increase the strength characteristics, cracking properties and the workability of the mortar mix.

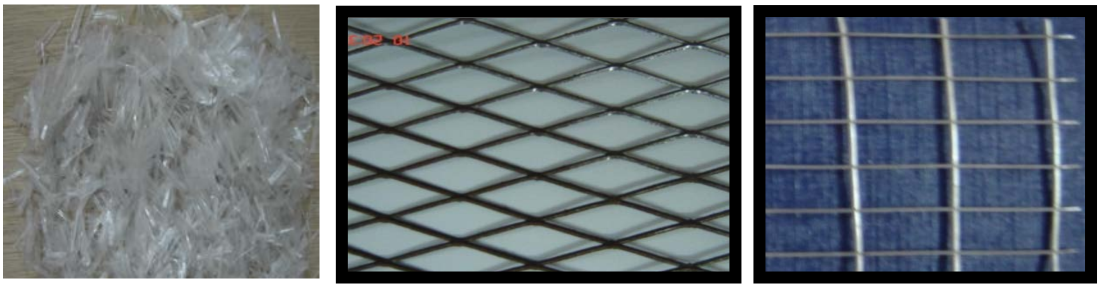
The mixes were cast in 100 x 100 mm cubes and tested under compression loadings after 28 days. From the test results, the compressive strength is considered as 45 MPa. Three 150 x 300 mm cylinders were cast and tested after 28 days to determine the splitting tensile stress of the selected mortar mix. The tensile splitting strength is considered as 3.9 MPa. Two types of steel wire meshes (welded and expanded wire mesh as shown in figure 1) were employed in the experimental work. The two types are locally produced and available in the Egyptian market on commercial scale. Three samples of each type of the meshes were tested using the Universal Testing Machine as shown in Figure 2. The specification and the mechanical properties and dimensions of the steel meshes are illustrated and shown in Table 3.

TAPLE 1: SIEVE ANALYSIS RESULTS FOR THE USED SAND

Sieve Size (mm)	4.75	2.83	1.4	0.7	0.35	0.15
% Passing by weight	100	95	79	68	17	2
Limits of (E.E.S.)	100	100-85	100-75	80-60	30-10	10-0

TAPLE 2: CHEMICAL COMPOSITION OF SILICA FUME

Chemical composition	Weight %
Si O2	92-94
Carbon	3-5
Fe2 O3	0.1-0.5
Ca O	0.1-0.15
AL2 O3	0.2-0.3
Mg O	0.1-0.2
Man O	0.008
K2 O	0.1
Na2 O	0.1



A-Polypropylene fiber B- Expanded steel mesh C- Welded steel mesh

Figure 1. Reinforcement Steel Meshes and Used Fibers.

TAPLE 3: DIMENSIONS AND MECHANICAL PROPERTIES OF USED STEEL MESHES

Mesh Type	Dimensions, Diamond size (mm)	Thickness and Diameter (mm)	F_u (MPa)	F_y (MPa)	Modulus of Elasticity (GPa)
Expanded metal mesh	19.7X43.7	1.5 X 2.1	350	250	120
Welded wire mesh	12x12	0.72	600	400	170

2.2. Test specimens

Two square ferrocement tanks were cast with internal dimensions of 800 mm x 800 mm x 400 mm depth and with wall and footing thickness of 40 mm and 70 mm; respectively as shown in Figure 3. The tank reinforced with one layer welded and another one expanded wire meshes and 5Ø6 mm/m were used as skeletal steel bars. Two artificial damages were manufactured in the tank wall as shown in Figure 4.

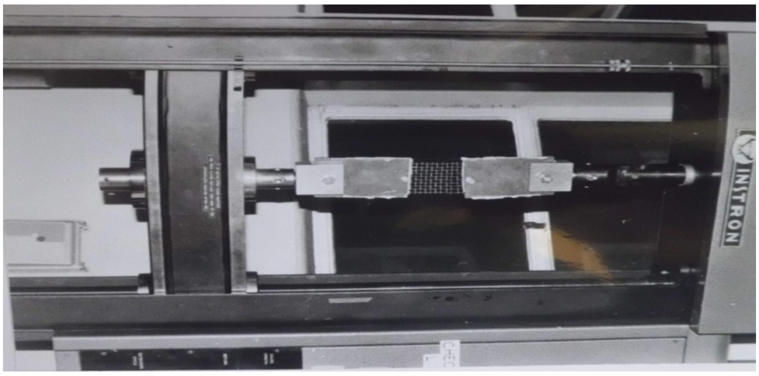


Figure. 2: Tensile Test of the Used Wire Meshes Using Instron Testing Machine.

Figure 3. Healthy Ferrocement Tank.

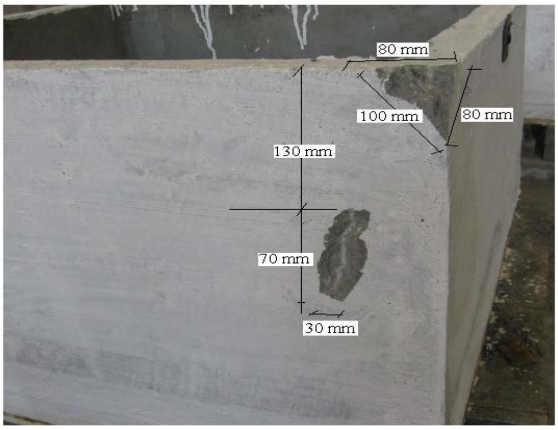


Figure 4. Damage Ferrocement Tank.

2.3. Test procedure and instrumentations

Impact hammer type 8206 was used to excite the tank and measure the impact forces as shown in Figure 5. The response of the structure was measured at four points at the top of the tank as shown in Figure 6 by accelerometer. By using multichannel FFT; the PULSE™ system (Type 8720/8721), the frequency response function (FRF) and mode shapes of the test structure can then be derived. FRF describes the relationship between input (impact forces) and output of the structure (the structure response).

Figure 5. Experimental Test for the Tested Tank.

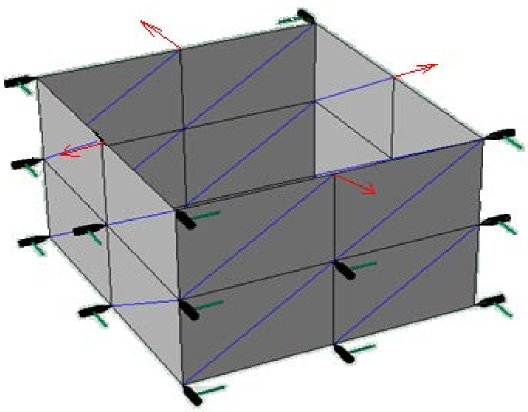


Figure 6. Positions of the Excitation Forces and Measured Response.

2.3. Experimental results

In this section, the results of the experimental program were presented. Figures 7 and 8 presented the frequency response function (FRF) for the healthy tank and damage tank; respectively. In these figures, the first four mode shapes were indicated from FRF. Figures 9 and 10 indicate mode shapes for the healthy tank and damage tank; respectively. From these figures and Table 4, it can be seen that the values of frequency for the two tanks are different hence the value of frequencies are decreased with damage. Also the mode shapes are different in position of the damages.

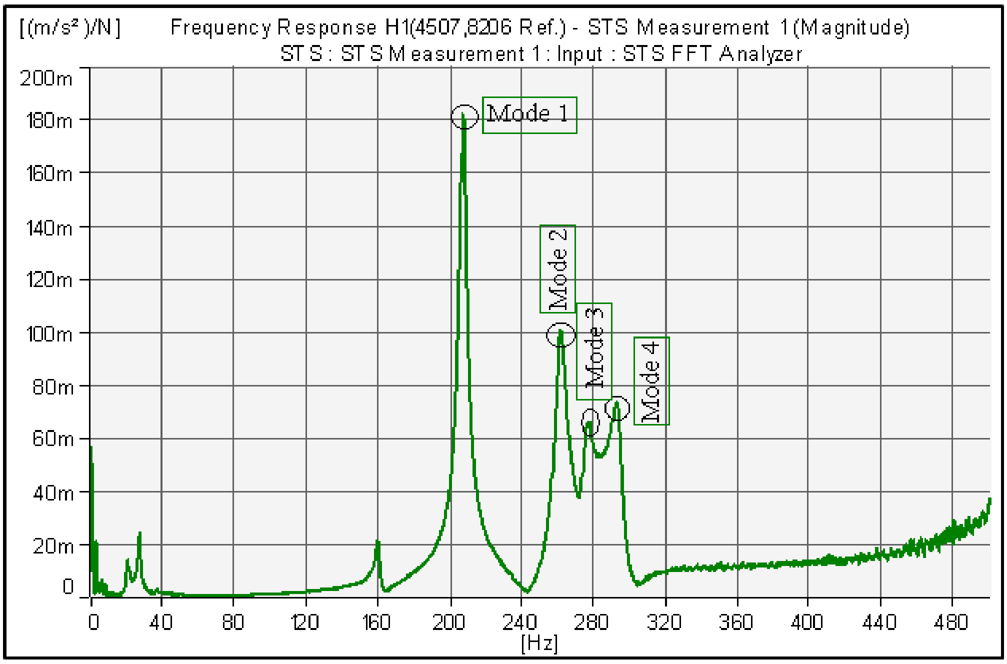


Figure 7. Frequency Response Function (FRF) for the Healthy Tank.

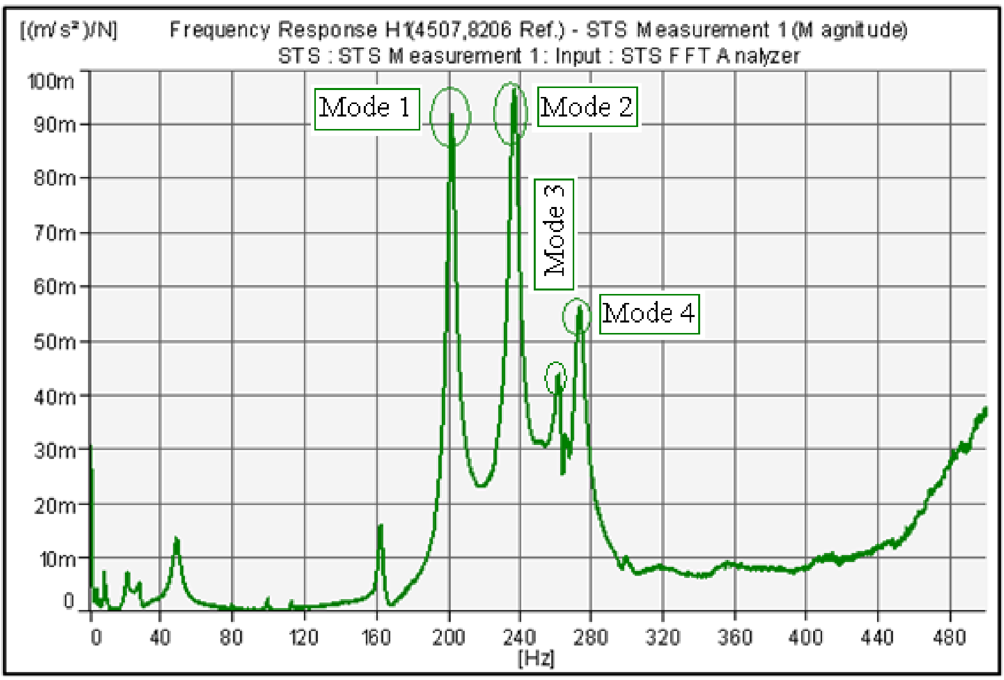
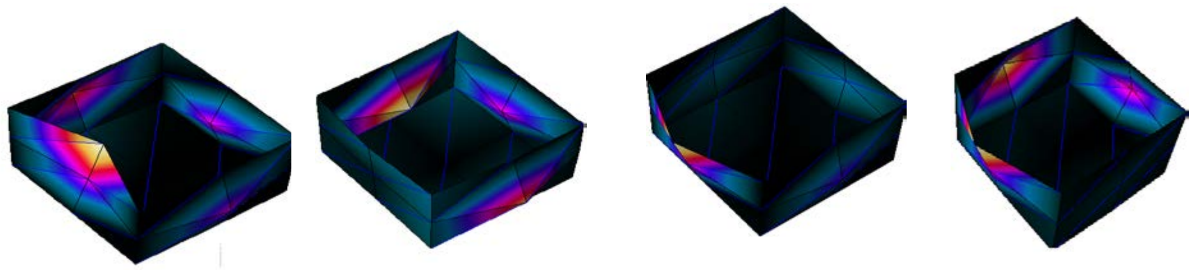
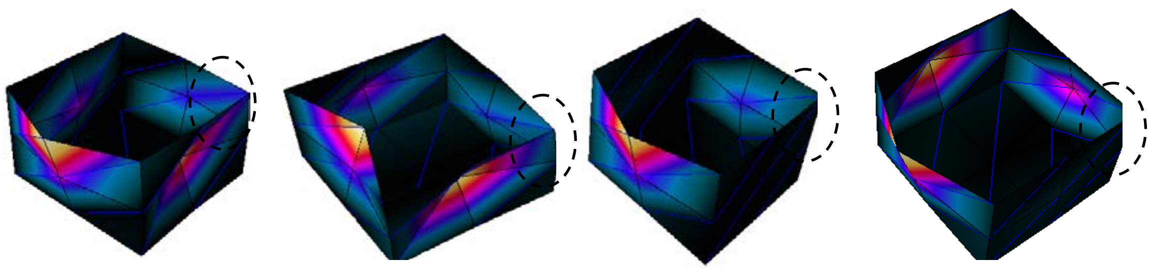


Figure 8. Frequency Response Function (FRF) for the Damage Tank.



Mode #1
206.49798 Hz

Figure 9. Various Experimental Mode Shapes for the Healthy Tank.



Mode #2
235.49163 Hz

Figure 10. Various Experimental Mode Shapes for the Damage Tank.

TAPLE 4: COMPARSION BETWEEN FREQUANCIES FOR HEALTHY AND DAMAGE TANK

Modal analysis	Frequency (Hz) for healthy tank	Frequency (Hz) damage tank
Mode #1	206.49798	201.33038
Mode # 2	259.18824	235.49163
Mode #3	271.47604	259.83486
Mode #4	293.49862	271.12395

3. Theoretical modal analysis

Several elements were used in the theoretical model. For the convenience of the reader a brief description of each element is introduced as follows. The well-known software ANSYS program is used in this research [22]. This program depended on the finite element analysis [23] and [24]. Solid65 was used for modeling mortar (Aboul-Anen [25], Hoque [26] and Singh [27]) of ferrocement. The element is defined by eight nodes. Each node has three degrees of freedom (translations in the nodal x, y, and z directions). Link8 element was used to represent the reinforcement. It has three degrees of freedom at each node (translations in the nodal x, y, and z directions).

3.2. Theoretical results

The modal analysis results from ANSYS program [22] are presented in this section. Mode shapes for the healthy tank and damage tank obtained from the developed models are presented in Figure 11 and 12; respectively. From the two figures, it can be found that the values of frequency and the mode shapes for the two tanks are different due to damage.

4. Comparison between the theoretical and the experimental results

Table 4 presents the relationship between the experimental frequencies and the frequencies obtained from the current theoretical model for the ferrocement tank without damage. Table 5 indicates the values of frequencies from the experimental modal analysis and the theoretical modal analysis. From the two tables, it can be concluded that the theoretical models give accurate results in comparison with the experimental results.

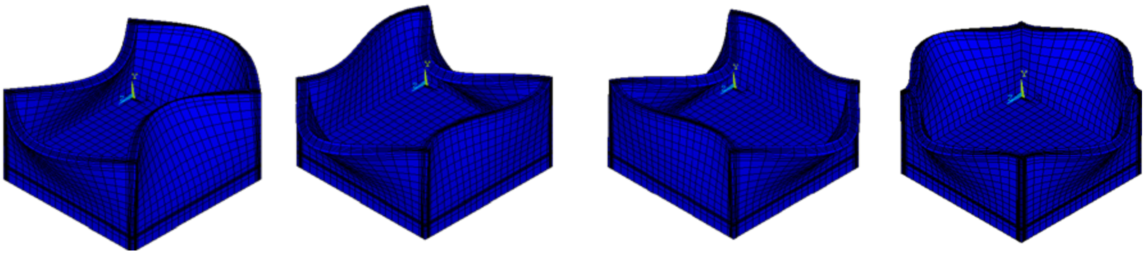


Figure 11. Various Theoretical Mode Shapes for the Healthy Tank.

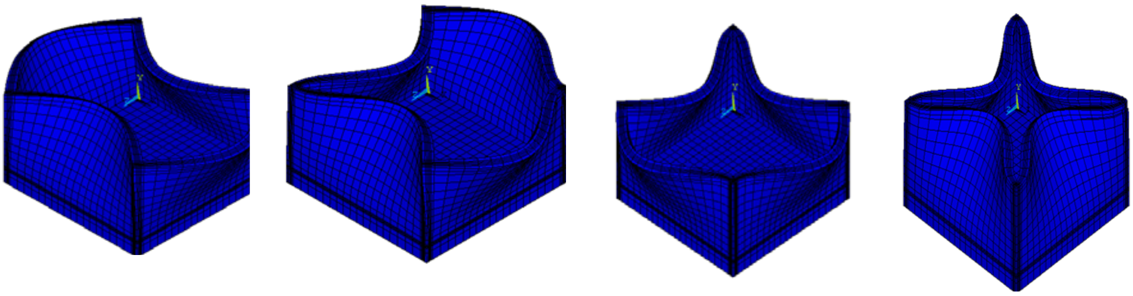


Figure 12. Various Theoretical Mode Shapes for the Damage Tank.

TAPLE 4: COMPARISON BETWEEN THE EXPERIMENTAL AND THEORETICAL FREQUANCIES OF THE HEALTHY TANK

Modal analysis	Frequencies (Hz)	
	Experimental Results	Theoretical Results
Mode #1	206.498	207.63
Mode #2	259.1882	261.51
Mode #3	271.476	275.68
Mode #4	293.4986	295.03

TAPLE 5: COMPARISON BETWEEN THE EXPERIMENTAL AND THE THEORETICAL FREQUANCIES OF THE DAMAGE TANK

Modal analysis	Frequencies (Hz)	
	Experimental Results	Theoretical Results
Mode #1	201.33038	203.29
Mode #2	235.49163	237.916
Mode #3	259.83486	261.262
Mode #4	271.12395	275.43

5. Conclusions.

This research was aimed to investigate the damage detection and structural health monitoring procedure based on mode shapes and frequency for ferrocement tank. The research was carried out into two phases. In the first phase, an experimental program was carried out on ferrocement tanks. Two tanks were cast and tested under dynamic load. The first tank is healthy tank. In the second tank, two damages were made. The experimental parameters (mode shapes and frequencies) of the two tanks were investigated using Pulse analyzer system. The second phase of the current research included theoretical models developed using ANSYS package. From the experimental results, it can be concluded that the values of frequencies of the damage tanks are decreased than the healthy tanks. Also the mode shapes of damaged tank are different in shape at the location of the two damages in comparing with the healthy tank. Furthermore it can be concluded that the FE models on the two tanks gave good results in comparison with experimental results obtaining from Pulse analyzer system. In general, it can be concluded that the classic modal analysis can be indicated the damage in the structures.

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