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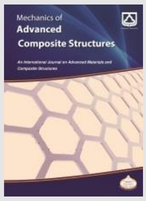

Damage Detection in Concrete Filled Tube Columns Based on Experimental Modal Data and Wavelet Technique

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KEYWORDS

CFST column
Damage identification
Modal data
Wavelet transform

ABSTRACT

Damage detection in Concrete-Filled Tubes (CFSTs) and the study of their application in special structures such as high-rise buildings, towers and bridges are important issues. CFST columns are widely studied by researchers and engineers due to the simultaneous utilization of both their steel and concrete properties. Hence, any damage to this structural element may result in extremely severe and irreversible injury. In this study, we researched the factors that may be involved in such damage. In addition, identification of a particular type of damage that may be due to the buckling of steel tube plates was performed in this study as well. Since, the buckled part in the column is eliminated from the system or decreases its bearing capacity significantly, in this study, in order to simulate the damage, a part of the CFST column steel wall was cut off and eliminated. And, since buckling is more likely to occur in the middle of the column, damage has been located in the middle of the column. After preparing the specimen and performing the tests, the modal data was extracted and was entered in the MATLAB software to be analyzed with the aid of the wavelet transform tool. The results showed that the frequency was reduced and the mode shape of the specimens did not match entirely before and after the damage with the Modal Assurance Criteria (MAC), which indicated damage in a specimen. To identify the location of the damage, the mode shape obtained from the experimental modal was given to the wavelet transform as the input signal and Daubechies (Db) wavelet was applied to correctly identify the location of the damage.

1. Introduction

CFST columns are widely used in the building industry, especially in areas with very high seismicity line, due to their high load bearing capacity under gravity and lateral loads, as well as demonstrating the beneficial and mechanical properties of both steel and concrete materials simultaneously. In addition, by occupying only small sections for placing building columns, they have a role in increasing the useable interior space of the building. Considering the position and importance of these columns, and the likelihood of their damage under any circumstances, it is important to identify failure, since such damage may be worsened causing significant financial and human disasters created due to the effect of load and time.

One of the drawbacks of using CFST columns is the transfer of force from beam to column. To provide rigidity for the panel zone, researchers have proposed a variety of methods to overcome this problem, for example, the use of trapezoidal external stiffener and reinforcement grids in the panel zone [1-4]. Rezaeifar et al. found particular damages in these columns in their research and proposed a way to identify possible damage in CFST columns. For that purpose, engineers could eliminate them or reinforce the structures. Therefore, in this section, studies on reinforced concrete and steel concrete columns and on concrete steel tubes are discussed first.

Moreover, lead zirconate titanate (PZT), as a type of piezoceramic material, has the advantage of superior linearity, fast response, low cost, and significant sensing and actuating capacities, and has hence been widely used to generated and detect stress waves for the purpose of structural damage detection and health monitoring. Howev-

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er, PZT is extremely fragile, and must therefore be properly protected before deployment it civil structures [5-9].

However, how could such damages be identified in concrete columns based on damage detection techniques? For this purpose, four conditions, including: intact concrete, concrete cracking, initial and final yield of steel were investigated and simulated under the influence of cyclic loads. Consequently, results showed that the damage detected corresponded to the damage observed in the beam [10]. Additionally, the structural damage of a declining reinforced concrete bridge in a period characterized by an earthquake have also been analyzed. For example, in a case study carried out on three concrete bridges in Taiwan, the probability of damage occurrence was investigated in different periods and the deterioration of bridge foundations by chloride were studied. As a result, the study assisted engineers to better understand the seismic performance of bridges and their usability in servicing safety and has provided engineers with an appropriate scientific bank to repair and retrofit these bridges [11]. Moreover, damage detection for a reinforced concrete column after a semi-static loading using modal test data with the aid of the Eigen-System Realization Algorithm (ESRA) method, indicated that damage to the composite beam was correctly identified [12]. Evaluation of the damage to concrete columns reinforced with steel jackets conducted theoretically and experimentally under cyclic loads showed that the site of damage was well-identified by the algorithm and vibration experimentally. Finally, a technique was introduced for reducing modelling errors [13].

Additionally, the probabilistic Bayesian method was proposed to monitor the damage in civilian structures. In this method, experimentally data derived from concrete column vibration was used to predict the location of plastic joints. It should be noted that a gradual increase in load simulated the gradual deterioration of the column. The proposed method was able to determine the damage range using an analytical model and modal parameters derived from the vibration test. In addition, the proposed method for the new test data also had a systematic update function [14]. Innovative piezoelectric materials based on intelligent materials were used under the reverse cycle loading protocol to monitor the health of the base. Experimental results indicated that damage was transmitted to the weakened energy region. In addition, the wavelet-transform-based damage index and time-history sensor of failure index matrix were expanded based on the definition of a transmission wave. The results showed that the piezoelectric location, affected the amplitude of the response, but it did not work in the process of energy transfer dissipation. In addition, smart aggregate had the potential to be used to monitor the integrity of large-scale concrete structures [15].

On the other hand, a sensitivity test was developed based on the finite element model update to identify structural parameters and identify damage for structural monitoring of steel structures based on environmental vibration measurements. In this study, the stiffness of the beam-to-column connection and the modulus of elasticity of the structure were updated in the next step. Moreover, the finite element method was used to identify the damages of braces with different damage parameters. Comparing the experimental results and the updated finite element model showed that, the updated version of the finite element model was a suitable tool for identifying structural parameters and identifying damage to steel frame structures [16]. A hybrid method based on artificial neural networks and a genetic model was used for damage identification in a scaled three-story spatial steel structure. Progressive damage was simulated by cutting one of the columns above the first floor and then two error functions that measured the difference between the experimental and analytical results of the finite element model. The steel frame was used with a genetic algorithm to detect damage. The results of the algorithm were compared with experimental results which indicated that the capability of this method in detecting damage were significant [17].

A Multi-mode Multi-directional Damage Index (MMDI) method was proposed to take advantage of the recognition of the multi-directional effects of damages in order to reduce damage detection errors. The novelty of the method resides in the use of specifically developed modal combination factors for the identification of the vibration modes more relevant to the damage detection and for the assessment of the directionality of the damage effects. The detection capability of the MMDI method was experimentally investigated on a bridge consisting of a two-column moment resisting frame. Individual and combined damages were simulated into the columns and beams of the tested material, by removal of steel parts [13]. In this paper, we developed a two-stage method with the ability to quantify structural damages by using the quasi-static moving load induced displacement response. As the displacement response of beam structure caused by quasi-static moving load is in close proximity to displacement influence line (DIL), this paper investigates the correspondence between damage parameters and several DIL related features systematically. Numerical and experimental examples were carried out to demonstrate the effectiveness of the proposed method [19].

In this section, previous studies conducted to identify the damage to CFSTs are presented. The identification of steel tube separation from a central concrete core in a rectangular CFST column has been evaluated based on the energy spectrum of wavelet transform with piezo-ceramics [20-22], the separation of the confined core from the steel tube reduced the bearing capacity and structural ductility. In a study conducted by Xu B. et al., with the fitting of piezo-electrics in predetermined locations of the external surfaces as sensors, a new method was proposed for monitoring the status of the internal surface. In this study, wavelet energy spectrum analysis was also carried out and a Weight-Change-Based Damage (WPES) indicator defined for the detection of artificial detachment areas. Their results showed that the proposed indices were sensitive to detachment defects and fully assessed the interior surface of a CFST column. In addition, the results showed that no unobstructed detachment defects could be identified in the monitoring of the condition of the CFST column in high-rise structures. Tort, C. et al. have evaluated damage in rectangular concrete-filled columns and members of the beam column of experimental data from various researchers around the world and for the first time created a database of experimental data. According to the experimental data, various types of damage were defined and for each damage mode, the performance of the specimens was quantitatively recorded using the functions of ductility and damage and finally, a hybrid design method for damage functions were presented in the framework of Performance-Based Design (PBD) principles [23].

Furthermore, multi-physical numerical simulation on the wave propagation and embedded PZT sensor response of rectangular CFST members with numerical concrete core considering the randomness in circular aggregate distribution, and coupled with surface mounted PZT actuator and embedded PZT sensor was carried out. The results showed that the effect of the interface debondings on the embedded PZT measurement was dominant when compared to the meso-scale structures of the concrete core. This study verified the feasibility of the PZT based debonding detection for rectangular CFST members and even the meso-scale structure of the concrete core was taken into consideration [24]. Also, to investigate the seismic behavior of spatial composite frames that were constructed by connecting steel beams to L-shaped concrete-filled steel tubular (CFST) columns, a Finite Element Analysis (FEA) model using commercial finite element software ABAQUS was proposed. This was done, to simulate the behavior of the composite spatial frames under a static axial load on columns and a fully-reversed lateral cyclic load applied to frames. The test results showed that the proposed FEA model in this study could evaluate the behavior of the composite spatial frames accurately [25].

Furthermore, the importance of structural health monitoring (SHM) in the design, construction, maintenance and post-extreme event repair of civil engineering structures has been recognized in the past decade. Vibration-based SHM methods have the potential to detect damages in structures globally [26-30]. This study was also conducted, because of the paucity of experimental studies on damage detection of CFST columns and specifically global buckling damage. Since buckling in steel plates due to its low thickness is inevitable compared to its high bearing capacity, and due to the importance of CFST columns in this study, the identification of this damage was investigated. After the specimen was manufactured and tests were conducted, the modal data (frequency, mode shape and damping) were extracted. Then, with the help of the MAC criteria and frequency comparison, the form of damage was investigated and the continuous wavelet transform used to determine the damage. The simulated damage was well-defined by the wavelet and under the coding program in MATLAB.

2. Experimental Program

2.1. Specimens

Two specimens of CFST columns with similar characteristics were used to perform the test, with an intentional damage created in the wall of one of the specimens. The column section of the specimens was 120*120mm from the steel plate with a thickness of 3mm and a length of 800mm, which was filled with fine aggregate concrete. In order to simulate damage a gap with the size of 114*45mm with similar thickness of the plate was created in the middle of one of the columns, which indicated the buckling in the column plate. The specimen specifications are presented in Table 1 and Fig.1.

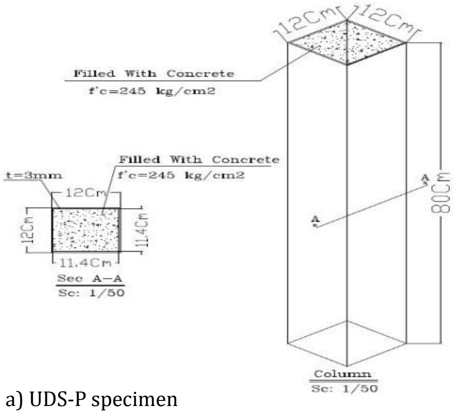
It is worth noting that the damage created by the high precision before filling the column and the site of damage was completely filled in order to prevent the release of the concrete. After the concrete reached the strength required, the filler material was removed from the site of damage.

2.2. Materials of Test

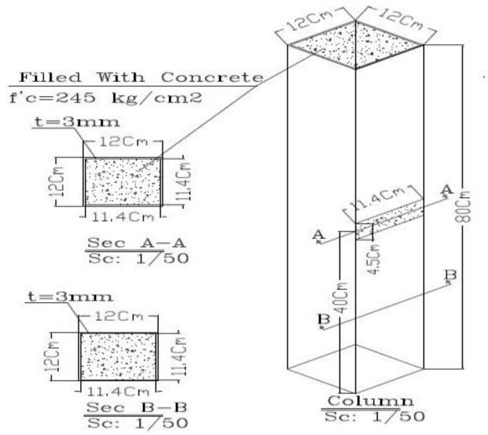
The steel tube was made of St37 steel with, the precise specification of the specimens obtained from the tensile test on standard specimens (Fig.2). After preparing the appropriate mixing plan, the concrete specifications were obtained by compressive testing on the cube specimens (Fig.3).

Table 1. Introduction of specimens(mm)

Specimen	Damage Dimension	Damage Type	Damage Location
UDS-P	-	Healthy	-
DGB-P	114x45	Buckling of Column Plate	Middle of the Column



a) UDS-P specimen



b) DGB-P specimen

Fig. 1. Details of test specimens

In this study, four specimens of concrete and steel plate were prepared and tested. The average (four specimens of each material) mechanical properties of the materials are listed in Table 2.

The final specimen properties are presented in Table 2 after performing the relevant tests. Since the purpose of the study was to compare the results before and after the injury, the mechanical properties of the materials had no effect on the results. Therefore, they were excluded to provide standard deviation.

2.3. Test setup and instrumentation

Since the existence of any supporting conditions can cause high rigidity in the structure, great force may be needed to stimulate it for modal analysis. As a result, this force may cause unforeseen damage and even collapse of the structure causing error in the results that are analyzed on this basis. So, in the present study free-free supporting conditions were used. In order to achieve this goal, the steel column was suspended by a high elastic cache with the accelerometer being connected at one point of the column (Fig. 4). The accelerometer sensor connection was located between the middle and the edges of the beam so that, it did not separate with the impact, and secondly, it was at zero point of the moment to have the least error. In the next step, the impact (Impact hammer) was applied to the test points (the nodes of the meshes) and for each impact, the frequency response function was extracted.

Finally, using the sum of the resulting frequency functions, the form of the first to third modes of the frequency response functions were obtained. The type of impact signal was selected so that non-linear effects of the specimen were averaged and the best linear model was presented. Choosing the best type of impact depended on the geometry and structure of the piece. Finding the best method did not follow the general rule but was rather achieved by trial and error. The tools for testing are presented in Table 3.

3. Experimental results

3.1. General observations

After the specimens were manufactured and the structure was installed in the setup and the sensor was installed, the specimens were subjected to the impact hammer. Fig.5 shows how the specimens were tested. Afterwards, the frequency, mode shape and damping patterns of the specimens were extracted as modal data.

Table 2. Specimens Propertises (mm)

Matelials	f_y MPa	f_u MPa	f'_c MPa	E x10^5 MPa	v	Specific Gravity (kN/m^3)
Steel	242.8	378.2	-	2	0.29	78.50
Srandard Deviation	6.75	6.42	-	-	-	-
Concrete	-	-	26.06	0.79	0.20	24.15
Srandard Deviation	-	-	1.35	-	-	-

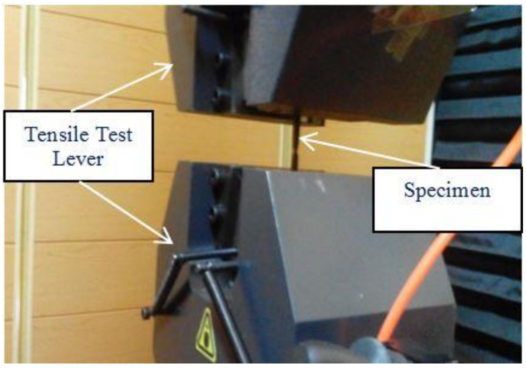


Fig.2. Machine and specimen of tensile test of steel plate

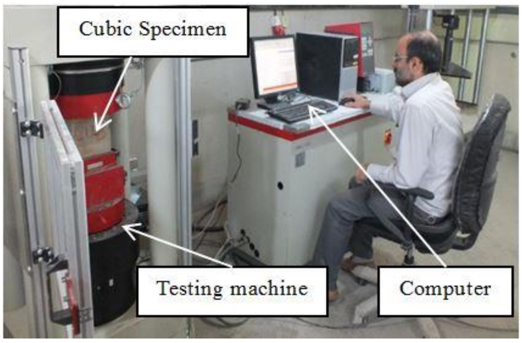


Fig. 3. Machine and specimen of Compressive test of concrete

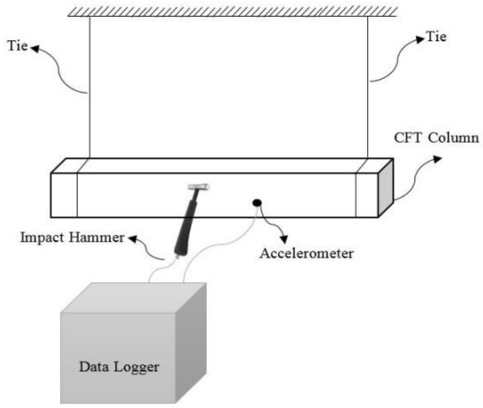
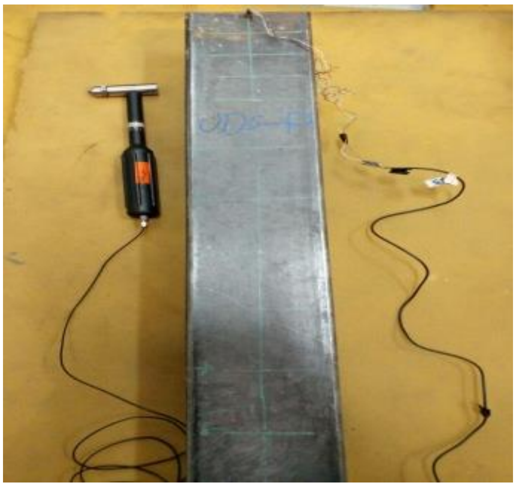


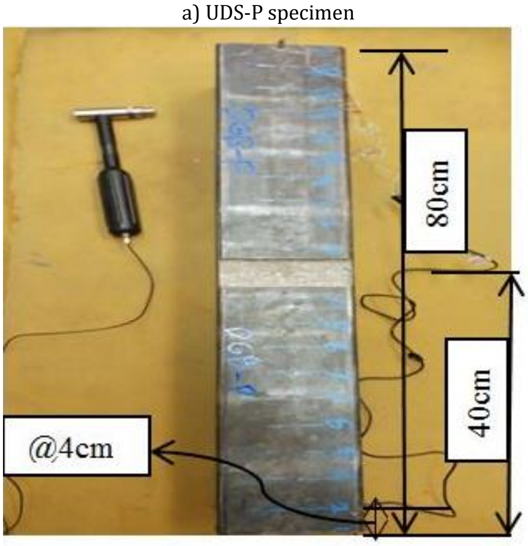
Fig. 4. Test Setup with impact hammer(Free-Free condition)

Table 3. Introduction of specimens(mm)

No.	Equipment	Model	Manufacturer
1	Portable Pulse 4/2 I/O Module	3560C	B&K
2	Impulse Hammer	AU02	AP Tech
3	Accelerometer	4397	B&K
4	Charge Convertor	2646	B&K
5	Force Transducer	9301B	Kistler
6	Power Amplifier	BAA120	Tira



a) UDS-P specimen



b) DGB-P specimen

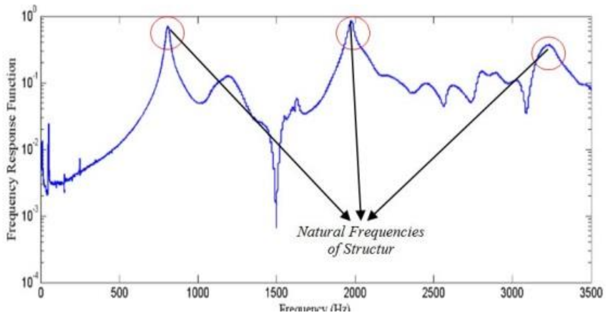
Fig. 5. How to test the specimens for damage detection

The specimen frequency in all modes was reduced compared to the healthy state, which indicated the change in the mechanical characteristics and, consequently, the change in the dynamic behavior of the structure. In the monitoring of the health of the structures, frequency variation could be considered as an example of damage in the specimen.

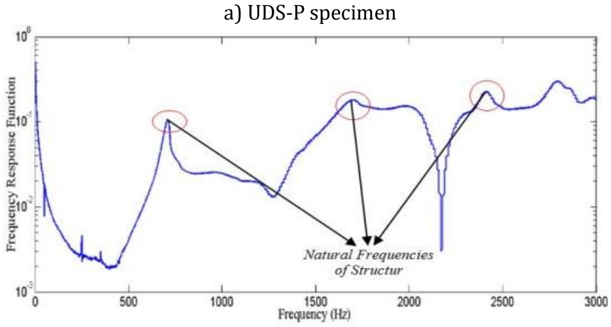
On the other hand, the damping coefficient in the DGB-P specimen was increased in proportion to the healthy specimen (UDS-P). This was due to the hardening of the damaged specimen. By observing the shape of the specimen mode, it was concluded that the amplitude of the mode in the damaged specimen was higher than the normal specimen and the structure had a softer characteristic.

To determine the frequencies of each curve mode, FRF of the specimens were extracted (Fig.6). In a Frequency Response Function measurement, the resonances peaks indicated the presence of the natural frequencies of the structure under test which could be observed [30].

On the other hand, the COHERENCE curve was plotted to monitor the accuracy of the tests. If the points in the COHERENCE curve were closer to one, it was an indication of the high accuracy of the experiments (Fig. 7). It could also be concluded that the point-to-point slope of the mode shape in the specimen after damage was lower, which in general indicated a reduction in the stiffness of the structure.



a) UDS-P specimen



b) DDB-P specimen

Fig. 6. Phase-Amplitude curve of the specimens

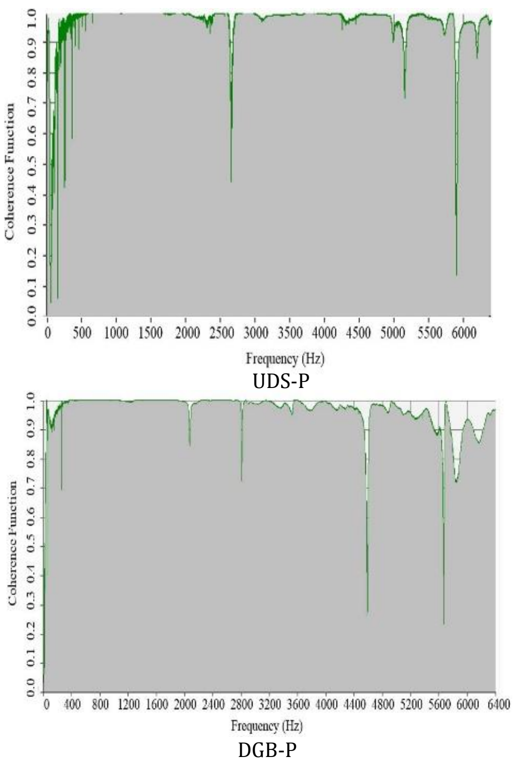


Fig. 7. COHERENCE curve of the specimens

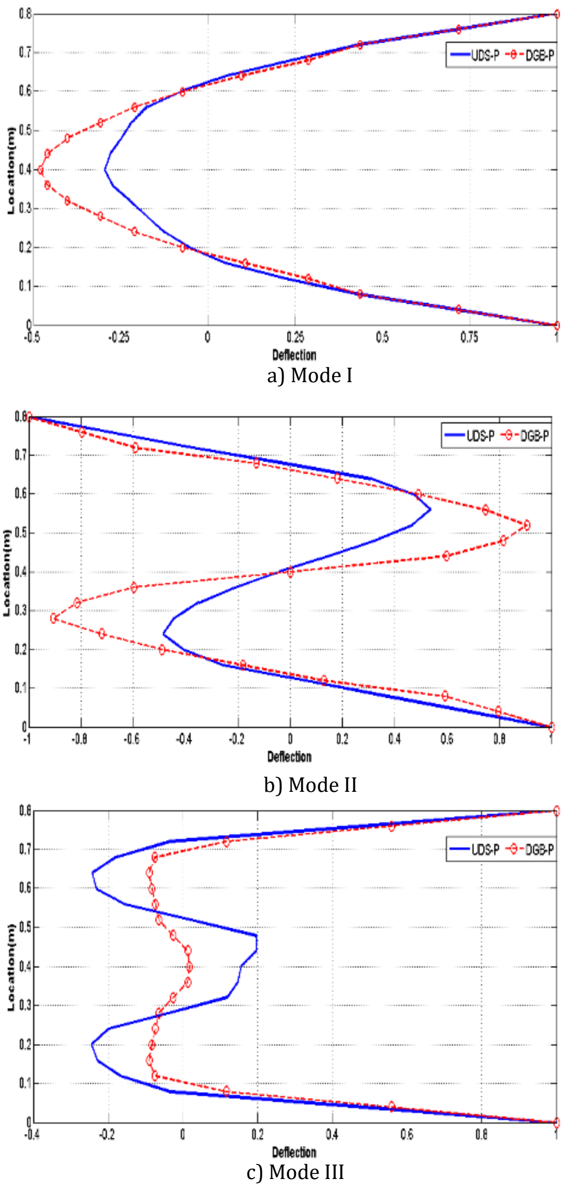


Fig. 8. Comparison of the mode shape of the specimens

3.2. Results and Interpretation

3.2.1 The mode shape of the specimens

One of the methods for detecting damage of structures is their mode shape. Mode shape is one of the modal data that, can be used to detect the damage by comparing the healthy and damaged states and even in specific conditions, detecting it even through extreme damage.

In the study, the damage to the DGB-P specimen caused the displacement of mode shape points compared to the state of health (UDS-P). The reason for these displacements was the softened behavior of the specimen away from a healthy state. This displacement was higher in the middle of the column than in other parts, as seen in the first mode, about 60%. In the second mode, about 70% of displacement occurred on both peaks. However, in the third mode, the midpoint distance of the two sides (normalized to 1) decreased due to the damage.

In general, damage to the specimen reduced the slope of each side of each arc of the mode shape, which indicated a decrease in the stiffness of the specimen. From the results, it could be seen that damage had occurred in the specimen (Fig. 8).

3.2.2 Comparison of Frequency and Damping

Another modal data is natural frequency, which is very important in determining the damage. The analysis results are presented in Table 4.

Moreover, one of the ways to detect damage to the specimen was to reduce the natural frequency. According to Table 4, the frequency was reduced in all modes due to a further reduction in the stiffness of the structure relative to its mass reduction due to damage. Reduction in the frequency was higher in higher modes, indicating the higher sensitivity of the higher modes to change. But reaching the higher modes required incurring more energy and sometimes it was not possible to reach it due to the possibility of damage to the structure under the influence of a great force.

Damping was also one of the modal test outputs. In general, structure damage reduced the power dissipation potential of the system because the damage reduced the stiffness and consequently reduced the damping of the structure.

3.2.3 MAC criteria

One of the valid criteria for examining the damage in structures is the Modal Assurance Criteria (MAC). MAC equation is[31]:

$$MAC(j,k) = (\sum_{i=1}^{n} \emptyset_{Aj}^{i} \times \emptyset_{Bk}^{i})^2 / (\sum_{i=1}^{n} (\emptyset_{Aj}^{i})^2 \times \sum_{i=1}^{n} (\emptyset_{Bk}^{i})^2 \quad (1)$$

with j=1,...,m_A *and* $k = 1, \ldots, m_B$

Where(Eq.(1)): $\emptyset_{Aj}^{i}$ and $\emptyset_{Bk}^{i}$ are two series of mode shape expressed in matrix from (eigenmode matrices), $n \times m_A$ and $n \times m_B$ class respectively, with m_A and m_B equal to the number of investigated modes and n equal to the number of considered coordinates(that is the number of measurement points); $\emptyset_{Aj}^{i}$ is the *i*-th coordinate of the *j*-th column of $\emptyset_{Aj}^{i}$ (that is the *j*-th vibrational mode), while $\emptyset_{Bk}^{i}$ is *i*-th coordinate of the kth column of $\emptyset_{Bk}^{i}$ (that is the kth mode o vibration).

Another criterion for examining the existence of damage in specimens is the Modal Assurance Criterion (MAC). This criterion is in fact the dot product of the eigenvectors. The value of 1 denotes the perfect compliance and zero denotes the verticality of the eigenvectors. By comparing the eigenvectors of the two mode shapes, one can find the extent point of their overlap. In this study, healthy and damaged modes were compared, and as this value was close to 1, it represented high compliance of the modes and their lesser damage.

Table 4. Frequency and damping absolute values and their difference percentage compared to the Healthy specimen

DGBP	UDSP	Specimens	
703.79	808.40	Freq(Hz.)	Mode1
-12.94	Base	Difference(%)	
1.810	1.380	Damping	
31.16	Base	Difference(%)	
1706.50	1971.50	Freq(Hz.)	Mode2
-13.47	Base	Difference(%)	
0.333	1.140	Damping	
-70.79	Base	Difference(%)	
2408.50	3218.90	Freq(Hz.)	Mode3
-25.19	Base	Difference(%)	
0.425	2.09	Damping	
-79.66	Base	Difference(%)	

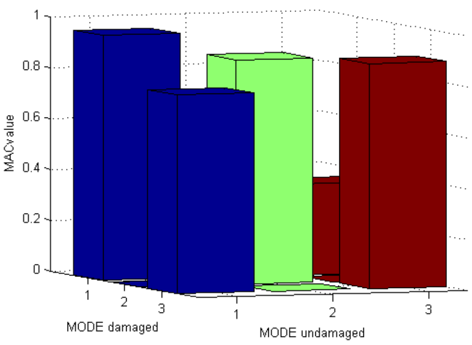


Fig. 9. MAC diagram of the DGB-P specimen relative to the UDS-P

According to Fig.9, in all modes, the MAC value was less than one, indicating that the damage occurred in the structure. On the other hand, in the higher modes, the compliance decreased so damage detection was easier. In general, in all of the modes, since the number was less than one, it indicated the damage to the structure.

3.2.4 Identification of damage by wavelet transform

A wavelet transform is a mathematical tool that converts the original signal (mode shape) into a signal with the main signal characteristics and, more briefly, in the time domain. Its major uses are; finding discontinuous signal points, eliminating disturbances (disturbing waves) from the signal compression signal and identifying the system were studied. In the following, the definition of continuous wavelet transform used in this study are discussed.

3.2.4.1 One-dimensional Continuous Wavelet Transform

Continuous wavelet transform was presented as an alternative method to the time-short Fourier transform and its goal was to overcome problems related to the resolution in the time-short Fourier transform. In the wavelet analysis, similar to the time-short Fourier transform, the signal was multiplied by a function (wavelet) which in fact had the same function as the window function. Similarly, wavelet transforms were also applied separately on different timepieces of the signal. However, there were essentially two major differences with the time-short Fourier transform, which were:

- In the wavelet transform, the Fourier transform was not applied on the windowed signal and so the singular peak points corresponding to a sinusoid, or, in other words, negative frequencies were not computed.
- In the wavelet transform, the window width changed along with the change of the frequency components, which was by far the most important feature of wavelet transform. Accordingly, the continuous wavelet transform was defined as follows (Eq.2) [31]:

$$CWT_x^{\varphi}(\tau,s)\varphi_x^{\varphi}(\tau,s)=1\sqrt{s}\int_{-\infty}^{+\infty} x(t)\varphi^*((t\tau)s)dt \quad (2)$$

Where, the parameters τ, s were the translation and scaling parameters, respectively. The concept of translation was exactly the same as the concept of time transfer in the time-short Fourier transform, which indicated the amount of window displacement and clearly included time information of transform. Unlike short-time wavelet transform, there was no frequency parameter included directly in the wavelet transform. Instead, there was a scale parameter that was inversely related to the frequency, in other words *S=1/f*. In Eq. (2), φ is the window function called the "mother wavelet". The term "wavelet" means a small wave. The reason for the use of the term "small" was the limited and short window function. The reason for using the word "wave" was also due to the oscillatory nature of this function. The word "mother" was also used for the purpose because all translated and scaled versions were all derived from the initial function, which was called the mother wavelet. In scientific terms, mother wavelet is a prototype function for producing other windows. As previously stated, there was a scale parameter in the wavelet transform instead of frequency. As the meaning of this parameter states, there is a kind of concept within its scale. In the wavelet transform, the large scales are correspondent to a general view, free from the details of the signal (corresponding to the low frequencies), but the small scales are correspondent to the view of the signal details and so they will correspond with the high frequencies. Moreover, scaling, as a mathematical operator, expands or shrinks the signal. Thus, in the high scales where the signal is expanded, the details will be dealt with and on the low scales where the signal shrinks, the general effects will be discussed. It should be noted that the scale variable in the definition of the wavelet transform appears in the denominator.

So, it expands for signal values of s<1 and compresses for a signal of s>1. In this research, the Db wavelet identified the site of damage with the least possible error. Figs. 10a to 10c show the location of damage in specimens by wavelet transform.

Wavelet transform at discontinuous points created a jumble-mode shape through which the damage could be detected. As shown in Fig.10, in the middle of the column, a jumper was created through the wavelet whose jumper length was equal to the length of the damage along the column (4.5Cm). In order to better understand the damage level, the damaged area has been highlighted with red color. The results indicated that wavelet transform was able to identify the area of damage with high accuracy (without error).

4. Conclusions

Due to the importance of CFSTs in the building industry and in general high-rise buildings, the identification of damage in this structural element is also very important. In the discussion of structural health monitoring, the first step was to identify the existence of damage. In this study, it was done with the frequency method (frequency comparison), mode shape and MAC parameter and the results indicated changes in all of the specimen modes compared to the healthy state and confirmed the existence of damage in the structure.

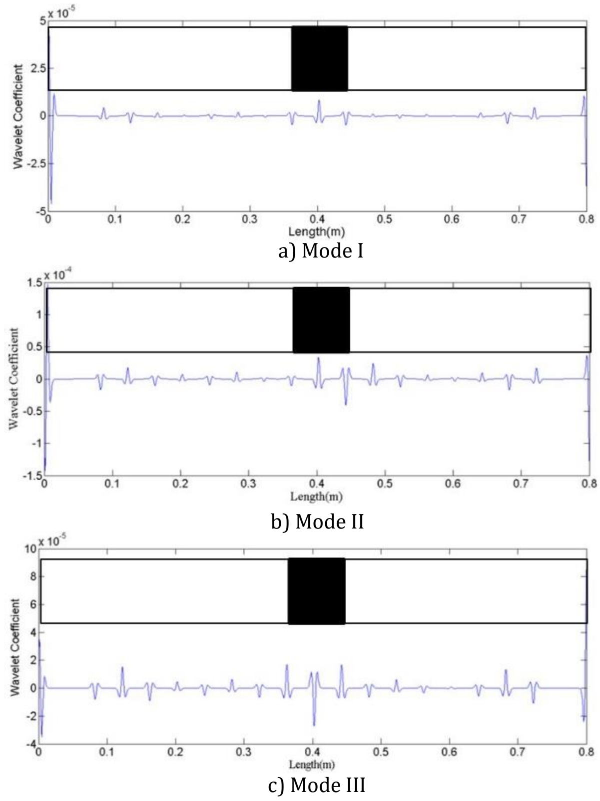


Fig. 10. Wavelet transform of DGBP specimen

The second step was to identify the location of the damage. To achieve the research objectives, the wavelet transform method was used. One of the advantages of this method was that without the knowledge of the modal data of healthy structure, the damage and its location could be detected. Furthermore, the results indicated that the specified damage range was identified with a very high accuracy and this method was capable of identifying the presence and location of damage. In addition, the results indicated the existence of damage Although small, it changed the parameters of MAC, COMAC and frequency.

Other advantages of this monitoring method over other methods (For example, the methods outlined in references 10, 15, 19, 21, 22 and24) were:

- Speed and convenience of testing.
- Lower cost due to project being performed on site and no need for sophisticated machines.
- Being applicable to any type of structural element.
- Having acceptable accuracy in terms of cost and equipment.
- Being applicable to old monuments and old structures.

References

[1] Rezaifar O, Yoonesi A, Yousefi SH, M. Gholhaki M. Analytical study of concrete filled effect to the seismic behavior of

restrained beam-column steel joints. *Sci. Iran* 2016; 23(2): 475–485.

[2] Rezaifar O, Yoonesi A. Finite element study the seismic behavior of connection to replace the continuity plates in (NFT/CFST) steel columns. *Steel Compos. Struct.* 2016; 21(1): 73–91.

[3] Rezaifar O, Nazari M. Experimental Study the Seismic Behavior of Types of Continuity Plates in Beam-to-HSS Column Connections. *MSc. Thesis, Semnan univers., Semnan, Iran* 2016.

[4] Rezaifar O, Monavari M. Experimental Study the Seismic Behavior of Types of Continuity Plates in Beam-to-CFST Column Connections. *MSc. Thesis, Semnan univers., Semnan, Iran* 2016.

[5] Luo, M., Li, W., Hei, C. and Song, G. Concrete infill monitoring in concrete-filled FRP tubes using a PZT-based ultrasonic time-of-flight method. *Sensors* 2016; 16, 2083.

[6] Luo, M., Li, W., Wang, B., Fu, Q. and Song, G. Measurement of the Length of Installed Rock Bolt Based on Stress Wave Reflection by Using a Giant Magnetostrictive (GMS) Actuator and a PZT Sensor. *Sensors* 2017, 17, 444.

[7] Hou, S., Zhang, H.B., Ou, J.P. A PZT-based smart aggregate for compressive seismic stress monitoring. *Smart Mater. Struct.* 2012, 21, 105035.

[8] Siu, S., Ji, Q., Wu, W., Song, G. and Ding, Z. Stress wave communication in concrete: I. Characterization of a smart aggregate based concrete channel. *Smart Mater. Struct.* 2014; 23, 125030.

[9] Siu, S., Qing, J., Wang, K., Song, G. and Ding, Z. Stress wave communication in concrete: II. Evaluation of low voltage concrete stress wave communications utilizing spectrally efficient modulation schemes with PZT transducers. *Smart Mater. Struct*. 2014; 23, 125031.

[10] Xu B, Gong X. Damage Detection of Reinforced Concrete Columns Based on Vibration Tests. *In Earth and Space 2010@ sEngineering, Science, Construc., and Operat.s. in Chall. Envir.* 2010 2321-2329.

[11] Chiu C. K, Lyu Y. C, Jean W. Y. Probability-based damage assessment for reinforced concrete bridge columns considering the corrosive and seismic hazards in Taiwan. *Natur. hazards 2014*; 71(3): 2146-2160.

[12] Yuen M M. A numerical study of the eigenparameters of a damaged cantilever. J*ournal of sound and vib.* 1985; 103(3): 301-310.

[13] Feng M. Q, Bahng E. Y. Damage assessment of jacketed RC columns using vibration tests. *Jour. of Struct. Eng.* 1999; 125(3): 265-271.

[14] Sohn H, Law K. H. Bayesian probabilistic damage detection of a reinforced-concrete bridge column. *Earth. Eng. and struct. dynamic.* 2000; *29*(8): 1131-1152.

[15] Moslehy Y, Gu H., Belarbi A., Mo Y. L., Song G. Smart aggregate based damage detection of circular RC columns under cyclic combined loading. *Smart Mat. and Struct.* 2010; 19: 065021.

[16] Wu, J. R, Li Q S. Structural parameter identification and damage detection for a steel structure using a two-stage finite element model updating method. *Jour. of Const. Steel Res.* 2006; 62(3): 231-234.

[17] Betti M, Facchini L, Biagini P. Damage detection on a three-storey steel frame using artificial neural networks and genetic algorithms. *Mec.* 2015; 50(3): 875-886.

[18] Bonessio N, Benzoni G, Lomiento G. A multi-mode approach for multi-directional damage detection in frame structures. *Eng. Struct.* 2017; 147: 505-516.

[19] Xu B, Li B, Song G, Active debonding detection for large rectangular CFSTs based on wavelet packet energy spectrum with piezo-ceramics. *Jour. of Struct. Eng.* 2012; 139(9): 1435-1443.

[20] He W Y, Ren W X, Zhu S. Damage detection of beam structures using quasi-static moving load induced displacement response. *Eng. Struct.* 2017; 145: 70-82.

[21] Xu B, Zhang T, Song G, Gu H. Active interface debonding detection of a concrete-filled steel tube with piezoelectric technologies using wavelet packet analysis. *Mech. Sys. and Signal Proces.* 2013; 36(1): 7-17.

[22] XU B, SHU Z, DYKE S. Embedded Interface Debonding Detection for an Irregular Complex Multi-chamber Steel Reinforced Concrete Column with PZT Impedance. *Struct. Health Monitor.* 2015.

[23] Tort C, Hajjar J F. Damage assessment of rectangular concrete-filled steel tubes for performance-based design. *Earth. Spectra* 2004; 20(4): 1317-1348.

[24] Xu, B., Chen, H., Mo, Y.L. and Zhou, T., Dominance of debonding defect of CFST on PZT sensor response considering the meso-scale structure of concrete with multi-scale simulation. Mechanical Systems and Signal Processing 2018; 107: 515-528.

[25] Zhang J, Li Y, Zheng Y, Wang Z. Seismic Damage Investigation of Spatial Frames with Steel Beams Connected to L-Shaped Concrete-Filled Steel Tubular (CFST) Columns. *Applied Sci.* 2018; 8(10): 1713.

[26] Doebling, S. W., Farrar, C. R., Prime, M. B., and Shevitz, D. W. A review of damage

identification methods that examine changes in dynamic properties. *Shock and Vib. Dig.* 1998; 30(2):91-105.

[27] Sohn, H., Farrar, C. R., Hemez, F. M., Shunk, D. D., Stinemates, D. W., Nadler, B. R. and Czarnecki, J. J. *A rev. of struct. health monitor. liter.* 2003; 1996–2001. Los Alamos National Laboratory, USA.

[28] Carden, E. P., Fanning, P., Vibration based condition monitoring: a review. *Struct. health monitor.* 2004; 3(4), 355-377.

[29] Humar, J., Bagchi, A., and Xu, H., Performance of vibration-based techniques for the identification of structural damage. *Struct. Health Monitor.* 2006; 5(3): 215-241.

[30] Heylen, W. Modal Analysis Theory and Testing; Katholieke Universiteit Leuven. *Leuven*, Belgium 2007.

[31] Pandey A K, Biswas M, Samman M M. Damage detection from changes in curvature mode shapes. *Jour. of Sound and Vib.* 1991; 145(2): 321-332.