Damage Detection in Concret Filled Tube Column Based on Experimentally Modal Data and Wavelet Technique

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ABSTRACT

Damage detection in Concrete-Filled Tubes (CFST) and its application in special structures such as high rise buildings, towers and bridges is important. CFST columns are widely considered by researchers and engineers due to the simultaneous utilization of steel and concrete properties. Hence, any damage to this structural element may result in more serious and irreparable damages. Accordingly, identification of a particular type of damage that may be due to the buckling of a steel tube plate has been performed in this study. Since the buckled part in the column goes out of the system or its bearing capacity significantly decreases, in order to simulate the damage in this study, a part of the CFST column steel wall was cut off and since it’s more likely to occur in the middle of the column, damage has been located in the middle of the column. After making the specimen and performing the test, the modal data has been extracted and has been called in MATLAB software and analyzed with the aid of the wavelet transform tool. The results show that the frequency is reduced and the mode shape of the specimens does not match completely before and after the damage (Modal Assurance Criteria(MAC)), which indicates the damage in the specimen. To identify the location of the damage, the mode shape obtained from the modal experimentally has been given to the wavelet transform as the input signal and Daubechies (Db) wavelet has been applied that correctly identifies the location of the damage.

Keyword: CFST Column, Damage Identification, Modal Data, Wavelet Transform

1. Introduction

CFST columns due to the high load bearing capacity under gravity and lateral loads, as well as benefiting the mechanical properties of both steel and concrete materials simultaneously and the creation of small sections for building columns and increasing the useful interior space of the building are widely used in the building industry, especially the areas with the very high seismicity line. Considering the position and importance of these columns, and because if under any circumstances this structural element could be damaged, damage may be worsened and harmful financial and human failures may be created due to the effect of load and time, it is important to identify failure.

One of the drawbacks of 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 that, an example of this is 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 the process of research which in the present study they decided to find a way to identify possible damages...
in the CFST columns. For that engineers can eliminate them and reinforce the structures. In this section, studies on reinforced concrete and steel concrete columns and then on concrete steel tubes are discussed first.

Lead zirconate titanate, as a type of piezoceramic material, has the advantages of good linearity, fast response, low cost, and sensing and actuating capacities, and has been widely used to generate and detect stress waves for the purpose of structural damage detection and health monitoring. However, PZT is extremely fragile, and therefore it must be properly protected before deployment in civil structures [5-9].

By whom, could identify the damage in the concrete column based on damage detection techniques. For this purpose, four healthy conditions, concrete cracking, initial and final yield of steel have been investigated and simulated under the influence of cyclic load and the results have shown that the damage detected corresponds to the damage observed in the beam [10]. It has been analyzed the structural damage of a declining reinforced concrete bridge in a period characterized by an earthquake. In their research, a case study has been carried out on three concrete bridges in Taiwan and the probability of damage occurrence has been investigated in different periods and the deterioration of bridge foundations by chloride has been studied that, this review will help engineers to better understand the seismic performance of bridges and their usability in servicing safety and has provided the engineer with an appropriate scientific bank to repair and retrofit these bridges [11]. Damage detection for a reinforced concrete column after a semi-static loading using modal test data using the Eigen-System Realization Algorithm (ESRA) method indicates that damage to the composite beam is correctly identified [12]. Evaluation of the damage to concrete columns reinforced with steel jackets conducted theoretically and experimentally under cyclic load shows that the site of damage is well-identified by algorithm and vibration experimentally and finally, a technique has been introduced for reducing modeling errors [13].

The probabilistic Bayesian method has been proposed to monitor the damage in civilian structures. In this method, experimentally data derived from concrete column vibration has been used to predict the location of plastic joints. It should be noted that gradual increase in load simulates the gradual deterioration of the column. The proposed method is 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 has a systematic update function [14]. Innovative piezoelectric materials based on intelligent materials are used under the reverse cycle loading protocol to monitor the bases’ health. Experimentally results indicate that damage is transmitted to the weakened energy region. In addition, the wavelet-transform-based damage index and time-history sensor of failure index matrix have been expanded based on the definition of a transmission wave. The results show that the piezoelectric location affects the amplitude of the response but it does not work in the process of transfer energy dissipation. In addition, smart aggregate has the potential to be used to monitor the health of large scale concrete structures [15].

A sensitivity test has been developed based on the finite element model update to identify structural parameters and identify damage for health 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 have been updated and in the next step, 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 shows that, the updated version of the finite element model is 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 has been used for damage identification in a scaled three-story spatial steel structure. Progressive damage is simulated by cutting one of the columns above the first floor and then two error functions that measure the difference between the experimental and analytical results of the finite element model and the steel frame have been used and the genetic algorithm has been used to detect damage that, the results of the algorithm have been compared with experimental results which indicates the capability of this method in detecting damage [17].

A Multi-mode Multi-directional Damage Index (MMDI) method is proposed to benefit from 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 is experimentally investigated on a bridge tested consisting of a two-column moment resisting frame. Individual and combined damages are simulated into columns and beams of the tested through steel parts remov-
al [13]. In this paper 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 are carried out to demonstrate the effectiveness of the proposed method [19].

In this section, studies conducted to identify the damage to CFSTs have been 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 reduces 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 have been proposed as a new method for monitoring the status of internal surface. In this study, wavelet energy spectrum analysis was also carried out and a Weight-Change-Based Damage (WPES) indicator has been defined for the detection of artificial detachment areas. These results show that the proposed indexes are sensitive to detachment defect and fully assess the interior surface of a CFST column. In addition, the results show that no unobstructed detachment defects can be identified in the monitoring of the health 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 experimentally data from various researchers around the world and for the first time created a database of experimentally data. According to experimentally data, various types of damage have been defined and for each damage mode, the performance of the specimens is quantitatively recorded using the functions of ductility and damage and finally, a hybrid design method for damage functions has been presented in the framework of Performance-Based Design (PBD) principles [23].

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 is carried out. The results show that the effect of the interface debondings on the embedded PZT measurement is dominant when compared to the meso-scale structures of concrete core. This study verified the feasibility of the PZT based debonding detection for rectangular CFST members even the meso-scale structure of concrete core is considered [24]. 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 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 in this paper. The test results showed that the proposed FEA model in this paper could evaluate the behavior of the composite spatial frames accurately [25].

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 in a global sense [26-30].

Due to the few experimentally studies on damage detection of CFST columns and specifically global buckling damage, this study was conducted.

Since the 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 has been investigated. After the specimen is made and test have been conducted, the modal data (frequency, mode shape and damping) have been extracted. Then, with the help of the MAC criteria and frequency comparison, the form of damage has been investigated. Then, using the first time created a database of experimentally data. According to experimentally data, various types of damage have been defined and for each damage mode, the performance of the specimens is quantitatively recorded using the functions of ductility and damage and finally, a hybrid design method for damage functions has been presented in the framework of Performance-Based Design (PBD) principles [23].

2. Experimental Program

2.1. Specimens

Two specimens of CFST columns with similar characteristics were used to perform the test, that an intentional damage has been created in the wall of one of the specimens. The column section of the specimens is 120*120mm from the steel plate with a thickness of 3mm and a length of 800mm, which is filled with fine aggregate concrete. In order to simulate damage a gap with the size of 114*45mm with similar thickness of the plate has created in the middle of one of the column, which indicates the buckling in the column plate. The specimen specification has 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 is completely filled in order to prevent the release of the concrete. After the concrete has reached the strength required, the filler material removed from the site of damage.

Table 1: Introduction of specimens (mm)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Damage Type</th>
<th>Dimension</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>UDS-P</td>
<td>Healthy</td>
<td>114x45</td>
<td>Middle of the Column</td>
</tr>
<tr>
<td>DGB-P</td>
<td>Buckling of Column Plate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.2.2 Materials of Test

The steel tube is made of St37 steel that the precise specification of the steel obtained from the tensile test on standard specimens of can have been extracted (Fig.2). After preparing the appropriate mixing plan, the concrete specifications have been obtained by compressive testing on the cube specimens (Fig.3).

Since the purpose of the study is to compare the properties before and after the injury, the mechanical properties of the materials have no effect on the results. Therefore it is excluded to provide standard deviation.

Table 2: Specimens Properties (mm)

<table>
<thead>
<tr>
<th>Material</th>
<th>f_y (MPa)</th>
<th>f_u (MPa)</th>
<th>f'_c (MPa)</th>
<th>E (GPa)</th>
<th>v</th>
<th>Specific Gravity (kN/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>242.8</td>
<td>378.2</td>
<td>-</td>
<td>2062.0</td>
<td>0.79</td>
<td>78.50</td>
</tr>
<tr>
<td>Concrete</td>
<td>-</td>
<td>-</td>
<td>26.06</td>
<td>0.79</td>
<td>0.20</td>
<td>24.15</td>
</tr>
</tbody>
</table>

Fig. 3. Machine and specimen of compressive test of concrete plate prepared and tested after the specimen properties of the materials obtained in Table 2.
Since the existence of any supporting conditions causes high rigidity in the structure, and in order to stimulate it for modal analysis, great force is needed and this force may cause unforeseen damage and even collapse of the structure and error in the results will be analyzed on this basis, the present study has used free-free supporting conditions and to achieve this goal, the steel column is suspended by a high elastic cache and the accelerometer has been connected at one point of the column (Fig. 4). The accelerometer sensor connection is located between the middle and the edges of the beam therefore first, it does not separate while the impact, and secondly, it is at zero point of the moment to have the least error. In the next step, the impact (Impact hammer) is applied to the test points (the nodes of the meshes) and for each impact, the frequency response function has been extracted, finally, using the sum of the resulting frequency functions, the form of the first to third modes of the frequency response functions has been obtained. The type of impact signal is selected so that non-linear effects of the specimen are averaged and the best linear model are presented. Choosing the best type of impact depends on the geometry and structure of the piece. Finding the best method does not follow the general rule and is achieved by trial and error.

![Test Setup with impact hammer](image)

**Table 3. Introduction of specimens(mm)**

<table>
<thead>
<tr>
<th>No.</th>
<th>Equipment</th>
<th>Model</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Portable Pulse 4/2 I/O Module</td>
<td>3560C</td>
<td>B&amp;K</td>
</tr>
<tr>
<td>2</td>
<td>Impulse Hammer</td>
<td>AU02</td>
<td>AP Tech</td>
</tr>
<tr>
<td>3</td>
<td>Accelerometer</td>
<td>4397</td>
<td>B&amp;K</td>
</tr>
<tr>
<td>4</td>
<td>Charge Converter</td>
<td>2646</td>
<td>B&amp;K</td>
</tr>
<tr>
<td>5</td>
<td>Force Transducer</td>
<td>9301B</td>
<td>Kistler</td>
</tr>
<tr>
<td>6</td>
<td>Power Amplifier</td>
<td>BAA120</td>
<td>Tira</td>
</tr>
</tbody>
</table>

3. **Experimental results**

3.1. **General observations**

After the specimens are made and the structure is installed in the setup and the sensor is installed, the specimens are subjected to the impact hammer, which shows how the specimens are tested in Fig.5 then, the frequency, mode shape and damping patterns of the specimens have been extracted as modal data.

The specimen frequency in all modes reduced compared to the healthy state, which indicates 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 can be considered as an example of damage in the specimen.

![Fig. 5. How to test of specimens for damage detection](image)

On the other hand, the damping coefficient in the DGB-P specimen has been increased in proportion to the healthy specimen (UDS-P). This is due to the hardening of the damaged specimen. By observing the shape of the specimen mode, it is concluded that the amplitude of the mode in the damaged specimen is higher than the normal specimen and the structure has a softer behavior. It can also be concluded...
that the point-to-point slope of the mode shape in the specimen after damage is lower, which in general indicates a reduction in the stiffness of the structure. To determine the frequencies of each curve mode, FRF of the specimens have been extracted (Fig.6). In a Frequency Response Function measurement the resonances peaks indicate the presence of the natural frequencies of the structure under test can be observed[30].

On the other hand, COHERENCE curve has been plotted to monitor the accuracy of the tests. As the points in the COHERENCE curve are closer to one, it indicates the high accuracy of the experiments (Fig.7).

![Fig. 6. Phase-Amplitude curve of the specimens](image)

![Fig. 7. COHERENCE curve of the specimens](image)

### 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, the damage can be detected by comparing the healthy and damaged states and even in specific conditions, damage can be detected through extreme damage. The damage to the DGB-P specimen causes the displacement of mode shape points compared to the state of health (UDS-P). The reason for these displacements is the softened behavior of the specimen towards a healthy state. This displacement is higher in the middle of the column than in other parts, as in the first mode, about 60%, and in the second mode, about 70% of displacement occurs on both peaks. But in the third mode, the midpoint distance of the two sides (normalized to 1) decreases due to the damage. In general, damage to the specimen has reduced the slope of each side of each arc of the mode shape, which indicates a decrease in the stiffness of the specimen. From the results, it can be seen that damage has 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 have been presented in Table 4.

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

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Frequency (Hz.)</th>
<th>Damping (%)</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>DGBP</td>
<td>703.79</td>
<td>12.94</td>
<td>Mode 1</td>
</tr>
<tr>
<td>UDSP</td>
<td>808.40</td>
<td>1.810</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.380</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1706.50</td>
<td>Mode 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.347</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.333</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.140</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>70.79</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2408.50</td>
<td>Mode 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25.19</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.425</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.09</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>-79.66</td>
<td></td>
</tr>
</tbody>
</table>

One of the ways to detect damage to the specimen is to reduce the natural frequency. According to Table 4, the frequency is reduced in all modes that is due to a further reduction in the stiffness of the structure relative to its mass reduction due to damage. Reduction in the frequency is higher in higher indicating the higher sensitivity of the higher modes to change but reaching the higher modes requires spending more and sometimes it is not possible to reach it due to the possibility of damage to the structure under the influence of great force.

Damping is also one of the modal test outputs. In general, structure damage reduces the power dissipation potential of the system because the damage reduces the stiffness and then reduces 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]:

$$MAC(j,k) = \frac{\sum_{i=1}^{n} \phi_{Aj}^i \times \phi_{Bk}^i}{\left(\sum_{i=1}^{n} \phi_{Aj}^i\right)^2 \times \left(\sum_{i=1}^{n} \phi_{Bk}^i\right)}$$

With $j=1,...,m_A$ and $k = 1, ..., m_B$ (1)

Where(Eq.1): $\Phi_A$ and $\Phi_B$ are two series of mode shape expressed in matrix from (eigenmode matrices), respectively of $n \times m_A$ and $n \times m_B$ class, 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); $\Phi_{Aj}^i$ is the ith coordinate of the jth column of $\Phi_A$ (that is the jth vibrational mode), while $\Phi_{Bk}^i$ is ith coordinate of the kth column of $\Phi_B$ (that is the kth mode of vibration).

Another criterion for examining the existence of damage in specimens is the Modal Assurance Criterion (MAC) criterion. 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 of their overlap. In this study, healthy and damaged modes have been compared, and as this value is close to 1, represents high compliance of the modes and their lesser damage. According to Fig.9, in all modes, the MAC value is less than one, indicating that the damage occurred in the structure. On the other hand, in the higher modes, the compliance decreases so that damage detection will be easier. In general, in all of the modes, since the number is less than one, it indicates 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 and its major uses are:
Finding discontinuous signal points, eliminating disturbances (disturbing waves) from the signal compression signal and identifying the system. In the following, the definition of continuous wavelet transform used in this study has been 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 is 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 is multiplied by a function (wavelet) which in fact has the same function as the window function. Similarly to before, wavelet transforms is also applied separately on different timepieces of the signal. But there are essentially two major differences with the time-short Fourier transform, which are:

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

\[
\text{CWT}_X(\tau, s) = \sqrt{s} \int_{-\infty}^{+\infty} x(t) \phi^*(t - \tau) \, dt
\]

Where, the parameters \( \tau, s \) are the translation and scaling parameters, respectively. The concept of translation is exactly the same as the concept of time transfer in the time-short Fourier transform, which indicates the amount of window displacement and clearly includes time information of transform. Unlike short-time wavelet transform, there is no frequency parameter in the wavelet transform directly. Instead, there is a scale parameter that is inversely related to the frequency, in other words \( S = 1/f \). In Eq.(2), \( \phi \) is the window function called the "mother wavelet". The term "wavelet" means a small wave. The reason for the use of the term small is the limited and short window function. The reason for using the word wave is also due to the oscillatory nature of this function. The word mother is also used for the purpose that, all translated and scaled versions are all derived from the initial function, which is called the mother wavelet. In scientific terms, mother wavelet is a prototype function for producing other windows. As previously stated, there is a scale parameter in the wavelet transform instead of frequency. As the meaning of this parameter comes, there is a kind of concept within its scale. In the wavelet transform, the large scales are corresponding to a general view, free from the details to the signal (corresponding to the low frequencies), and small scales, corresponding to the view of the signal details and so it will correspond with the high frequencies. 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 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 could well identify 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 creates a jumble-mode shape through which the damage can be detected. As shown in Fig.10, in the middle of the column, a jumper has been created through the wavelet whose jumper length is 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 indicate that wavelet transform has been 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 is to identify the existence of damage that, in this study, it has been done with the frequency method (frequency comparison), mode shape and MAC parameter and the results indicate changes in all of the specimen modes compared to the healthy state and confirm the existence of damage in the structure. The second step is to identify the location of the damage. To achieve the research objectives, the wavelet transform method has been used. One of the characteristics of this method is that without the knowledge of the modal data of healthy structure, the damage and its location can be detected. The results indicate that the specified damage range has been identified with a very high accuracy and this method is capable of identifying the presence and location of damage. In addition, the results indicate that existence of damage Although small, it changes the parameters of MAC, COMAC and frequency.

The advantages of this monitoring method than other methods (For example, the methods outlined in references 10, 15, 19, 21, 22 and 24) are:

1. Speed and convenience of testing.
2. Lower cost due to project on site and no need for sophisticated machines.
3. Applicable to any type of structural element.
4. Acceptable accuracy in terms of cost and equipment.
5. Applicable to monuments and old structures.
References


