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OMA of model steel structure retrofitted with CFRP using earthquake simulator

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Abstract. Nowadays, there are a great number of various structures that have been retrofitted by using different FRP Composites. Due to this, more researches need to be conducted to know more the characteristics of these structures, not only that but also a comparison among them before and after the retrofitting is needed. In this research, a model steel structure is tested using a bench-scale earthquake simulator on the shake table, using recorded micro tremor data, in order to get the dynamic behaviors. Beams of the model steel structure are then retrofitted by using CFRP composite, and then tested on the Quanser shake table by using the recorded micro tremor data. At this stage, it is needed to evaluate the dynamic behaviors of the retrofitted model steel structure. Various types of methods of OMA, such as EFDD, SSI, etc. are used to take action in the ambient responses. Having a purpose to learn more about the effects of FRP composite, experimental model analysis of both types (retrofitted and no-retrofitted models) is conducted to evaluate their dynamic behaviors. There is a provision of ambient excitation to the shake table by using recorded micro tremor ambient vibration data on ground level. Furthermore, the Enhanced Frequency Domain decomposition is used through output-only modal identification. At the end of this study, moderate correlation is obtained between mode shapes, periods and damping ratios. The aim of this research is to show and determine the effects of CFRP Composite implementation on structural responses of the model steel structure, in terms of changing its dynamical behaviors. The frequencies for model steel structure and the retrofitted model steel structure are shown to be 34.43% in average difference. Finally, it is shown that, in order to evaluate the period and rigidity of retrofitted structures, OMA might be used.

Keywords: experimental modal analysis; CFRP; modal parameter; EFDD; shake table

1. Introduction

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.

Recently, application of fiber reinforced plastic composite system by gluing them to external part of the reinforced concrete structures is gradually becoming popular for the aim of repairing and strengthening Kakaletsis (2016), (Liang *et al.* 2016, Smyrou *et al.* 2015). Fibers to be used, as they have required characteristics include: glass, aramid and carbon. The production of these fibers is done in two ways: either as plates (covered by thin fibers) or as tissues (knitted in one and two directions). The behavior of the system that is covered with external FRP composite is related to the type of the element covered. Generally FRPs have been separated into three categories: bending strengthening, shear strengthening and envelope scripts.

In order to strengthen reinforced concrete structures, the prevention of severe bending and shearing is realized by covering beams by FRP composite. The aim of this covering is to increase the resistance and ductility of the system under lateral seismic loads.

The analytical and experimental results in Li and Sung (2003) of tests on benchmark and a damaged circular bridge column are presented. The benchmark column is a 40% scale reinforced concrete circular bridge column damaged as a result of shear failure during a cyclic-loading test. The benchmark column was then repaired by epoxy and non-shrinkage mortar and rehabilitated by carbon fiber reinforced plastic (CFRP) after the cyclic-loading test. The analytical lateral force-displacement relationship of the bridge columns can accurately predict the experimental result, especially in the nonlinear regions. In their study, for circular reinforced concrete bridge column, the result has been reached so that for a true repair; a change of the shear-failure mode of bridge column to the bending-failure

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refraction occurs, in other words this increases the seismic performance. Nonlinear finite element evaluation for the behavior of steel and FRP contained concrete columns were formulated and implemented. It is shown that numerical results agree well with the experimental results (Montoya *et al.* 2004). The performance of reinforced concrete column which was covered with carbon FRP was determined under uniaxial compression load Cole (2001). When Strengthened with CF-130 carbon fiber laminates, five circular columns and three rectangular columns were tested in pure compression. The experimental result shows that ±45 degrees CFRP laminate can effectively be used to provide columns ductility performance. When the main goal is to enhance the load capacity, a unidirectional FRP laminate might be more effective according to Paretti and Nanni (2002). In Parvin and Wang research (2002), they investigated the effect of strain gradient and FRP thickness on square concrete columns reinforced with FRP wraps. In their work, it was shown that the chosen eccentricity values were small enough to produce any longitudinal tension in the wrap. Nine square concrete columns were tested under eccentric load and two different levels of eccentricity. Experimental results were validated by non-linear finite element analysis elsewhere. As it is noticed, in the last decade, for these projects' aim of CFRP composite material usage for seismic repair-strengthening has become widespread. In addition, for repairing and strengthening columns, there is a still a lack in the sufficient researches; and thus it becomes inappropriate for comparisons and safe applications. Until today there hasn't been any widespread handbook, it needs to be prepared by coordinate effort of both applicator and researcher engineer organizations (Büyüköztürk *et al.* 2000, Sika, 1997).

The aim of this study is to evaluate the performance of reinforced concrete column, which has rectangular cross-section, under axial static compression load by using analytical, numerical and experimental evaluations and also to increase the source of statistics with a comparison target on this field. It has been shown that beams of existing structures suffer too much during seismic loading.

The behavior of the reinforced concrete beam with "T" cross section that was strengthened with carbon fiber reinforced plastic composite (CFRP) has been evaluated analytically and experimentally, it has been observed that tension increased approximately 40% according to (Namboorimadathil *et al.* 2002) study, at the negative moment region. The distance from support to CFRP origin and effect of cross-section beam and its behavior have been studied in (Ahmed *et al.* 2001) study, when it was strengthened with CFRP composite at the tensile region of reinforced concrete beam**.** Computation formula has been composed related to experimental results, to guess the design load that is equal to the limit position of beam. In this examination original shear stress and slight effect have been taken into consideration. The behavior of partial bridge that was strengthened with CFRP composite has been examined in (Ramos *et al.* 2004) study. On partial scaled and full-scaled specimen, partial beams experiments were conducted. Bond scaled experiment has been shown as alternative for characterizing repair and strengthening the partial structures with CFRP composite. Experimental results of repair-strengthening with CFRP composite have been presented in (Klaiber *et al.* 2003) study, for the example of pre-stressed three reinforced concrete girder bridge that suffered damage. Before and after repair, experimental results have shown that usage of CFRP is productive. It has been observed that usage of CFRP decreased the girder bending displacement more than 20%. As already known, forced (shaker, impact, pull back or quick release tests) and ambient vibration techniques are available for vibration testing of large structures. Force vibration methods are tougher and generally not cheap compared to ambient vibration tests. So the later (ambient vibration testing, also called Operational Modal Analysis) is the most economical non-destructive testing method to acquire vibration data from large civil engineering structures for Output-Only Model Identification. General characteristics of structural response (appropriate frequency, displacement, velocity, and acceleration rungs), suggested measuring quantity (such as velocity or acceleration); depend on the type of vibrations (Traffic, Acoustic, Machinery inside, Earthquakes, Wind…) that are given in Vibration of Buildings (1990).

These structure response characteristics give a general idea of the preferred quantity to be measured. A few studies on the analysis of ambient vibration measurements of buildings from 1982 until 1996 were discussed in Ventura and Schuster (1996). Last ten years Output-Only Model Identification studies of buildings are given in appropriate references as structural vibration solutions. For the modal updating of the structure it is necessary to estimate sensitivity of reaction of examined system to the change of parameters of a building. The work of Kasimzade (2006) on system identification is about the process of developing or improving a mathematical representation of a physical system. The experimental data are investigated in HO and Kalman (1966), Kalman (1960), Ibrahim and Miculcik (1977), Ibrahim (1977), Bendat (1998), Ljung (1999), Juang (1994), Van Overschee and De Moor (1996), and system identification applications in civil engineering structures are presented in works of Trifunac (1972), Turker (2014), (Altunisik *et al.* 2010), (Brincker *et al.* 2000), Roeck (2003), Peeters (2000), (Cunha *et al.* 2005), Wenzel and Pichler (2005), Kasimzade and Tuhta (2007a, b), (2009), (Ni *et al.* 2015), Lam and Yang (2015), Papadimitriou and Papadioti (2013), Au and Zhang (2016), Zhang and Au (2016), (Zhang *et al.* 2016), (Ni *et al.* 2017). Extracting system physical parameters from identified state space representation was investigated in the following references: Alvin and Park (1994), Balmes (1997), (Juang *et al.* 1988), Juang and Pappa (1985), (Lus *et al.* 2003), (Phan *et al.* 2003), Sestieri and Ibrahim (1994), (Tseng *et al.* 1994). The solution for algebraic Riccati equation matrix and orthogonality projection, which is more intensively and inevitably used in system identification, was deeply investigated in works of Aliev (1998). In engineering structures there are three types of identification that are used: modal parameter identification; structural-modal parameter identification and control-model identification methods. In the frequency domain the identification is based on the singular value decomposition of the spectral density matrix and it is denoted as Frequency Domain Decomposition (FDD) and its further development Enhanced Frequency Domain Decomposition (EFDD). In the time domain there are three different implementations of the Stochastic Subspace Identification (SSI) technique: Unweighted Principal Component (UPC); Principal component (PC); Canonical Variety Analysis (CVA) which were used for the modal updating of the structure Friswell and Mottershead (1995), Marwala (2010). It is required to estimate the sensitivity of reaction of examined system to change of random or fuzzy parameters of a structure. Investigated measurement noise perturbation influences to the identified system modal and physical parameters, estimated measurement noise border, for which identified system parameters are acceptable for validation of finite element model of examined System identification is realized by observer Kalman filter (Juang *et al.* 1993) and Subspace Overschee with De Moor (1996) algorithms. For some specialties, the observer gain coincides with the Kalman gain. Stochastic state-space model of the structure is simulated by Monte-Carlo method. The Quanser Shake Table is a bench-scale earthquake simulator ideal for teaching structural dynamics, control topics related to earthquake, aerospace and mechanical engineering and it is widely used in applications. In this study investigated is the possibility of using the recorded micro tremor data on ground level as ambient vibration input excitation data for investigation, and the application of Operational Modal Analysis (OMA) on the bench-scale earthquake simulator (The Quanser Shake Table) for model steel structures.

For this purpose, experimental modal analysis of a model steel structure for dynamic characteristics was evaluated. Then, retrofitted model steel structure for dynamic characteristics was also evaluated. Ambient excitation was provided by shake table from the recorded micro tremor ambient vibration data on ground level. The Enhanced Frequency Domain Decomposition is used for the output-only modal identification.

2. Modal parameter extractions

As it is already known, the ambient modal identification (FDD) 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 to determine 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 (Brincker *et al.* 2000). The Enhanced Frequency Domain Decomposition technique is an extension to Frequency Domain Decomposition (FDD) technique. This technique is a simple technique that is extremely basic for 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 and the mode shapes, including the damping ratios (Jacobsen *et al.* 2006). In EFDD technique, the single degree of freedom (SDOF) Power Spectral Density (PSD) function, identified as 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 Peeters (2000).

In this research, modal parameter identification is implemented by the Enhanced Frequency Domain Decomposition. The relationship between the input ($x(t)$) and responses ($y(t)$) in the EFDD technique can be written as

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

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

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

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

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

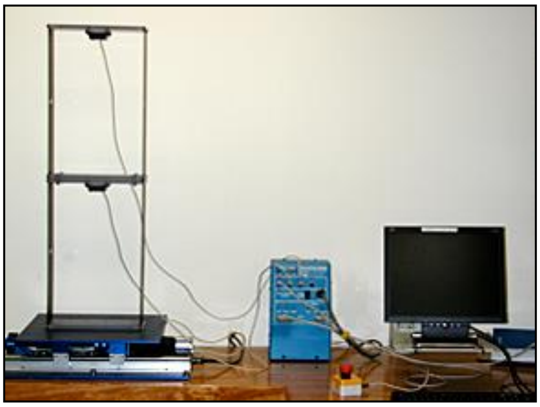
Where s the singular values, superscript is H denotes complex conjugate and transpose. Multiplying the two partial fraction factors and making use of the Heaviside partial fraction theorem, after some mathematical manipulations, the output PSD can be reduced to a pole/residue form as fallows

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

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;

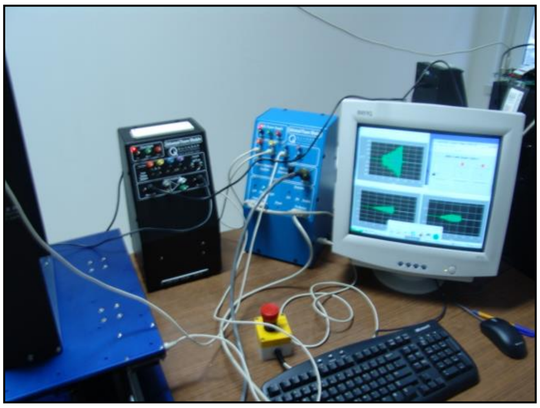
$$G_{yy}(j\omega_i)=U_i S_i U_i^{\overline{H}} \quad (5)$$

Where the matrix $U_i=[u_{i1},u_{i2},\ldots,u_{im}]$ is a unitary matrix holding the singular vectors u_{ij} and s_{ij} G 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 then be obtained.



(a)

(b)



(c)

Fig. 1(a), (b), (c) Illustration of model steel structure and shake table

3. Description of model steel structure

The Quanser shake table II is a uniaxial bench-scale shake table. This unit can be controlled by appropriate software illustrated in Figs. 1(a), (b), (c). It is effective for various types of experiments in civil engineering structures and models. The specifications for the Shake table are shown below Quanser (2008).

Model steel structure is 1.03 m height. Thickness of elements is 0.001588 m. The structure dimensions are shown in Fig. 2.

4. Experimental modal analysis of model steel structure

The ambient excitation is provided by using recorded micro tremor data on ground level. Three accelerometers (with both *x* and *y* directional measures) are used to measure ambient vibrations, one of them is allocated as reference sensor, which is always located in the first

Table 1Shake Table Specifications

Dimensions (H×L×W)	(61×46×13) cm
Total mass	27.2 kg
Payload area (L×W)	(46×46) cm
Maximum payload at 2.5 g	7.5 kg
Maximum travel	± 7.6 cm
Operational bandwidth	10 Hz
Maximum velocity	66.5 cm/s
Maximum acceleration	2.5 g
Lead screw pitch	1.27 cm/rev
Servomotor power	400 W
Amplifier maximum continuous current	12.5 A
Motor maximum torque	7.82 N.m
Lead screw encoder resolution	8192 counts/rev
Effective stage position resolution	1.55 μm/count
Accelerometer range	± 49 m/s²
Accelerometer sensitivity	1.0 g/V

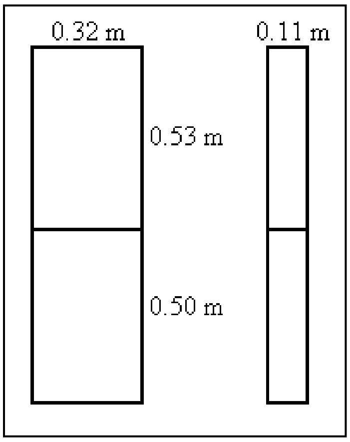
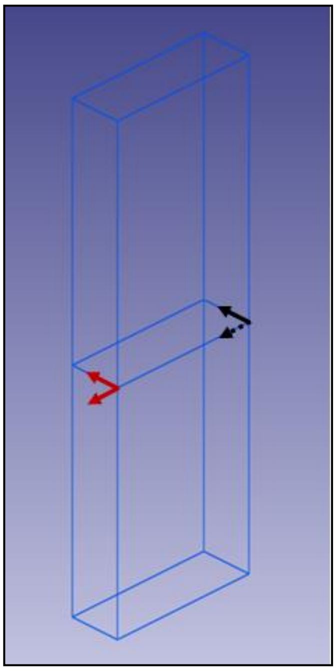
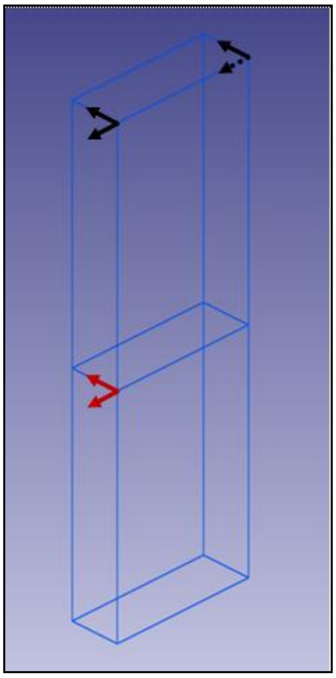


Fig. 2 Illustration of the model steel structure's dimensions

floor (shown by the red arrows in Fig. 3(a), (b)). Two accelerometers are used as roving sensors (shown by the black arrows in Fig. 3(a), (b)). The response was measured in two data sets (Fig. 3(a), (b)). For two data sets, 3 and 5 degree of freedom records are used respectively (Fig. 3(a), (b)). Every data set (Fig. 3(a), (b)) is measured within 100 minutes. The selected measurement points and directions are shown in Fig. 3(a), (b). The ambient excitation is provided by using recorded micro tremor data on ground level (Fig. 4(a), (b)).



(a) First setup



(b) Second setup

Fig. 3 Accelerometers location of experimental model in the 3D view

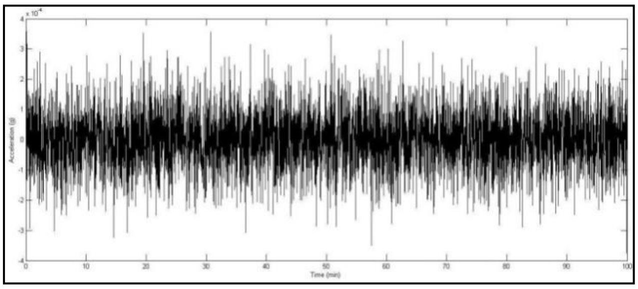


Fig. 4(a) Ambient vibrations recorded by the seismometer

Fig. 4 (b)Ambient excitation data from the recorded micro tremor data on ground level used in the shake table

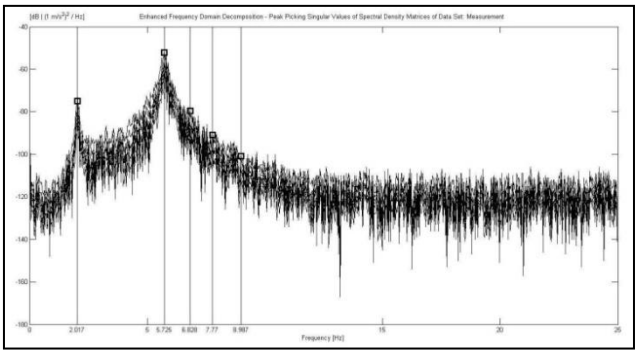
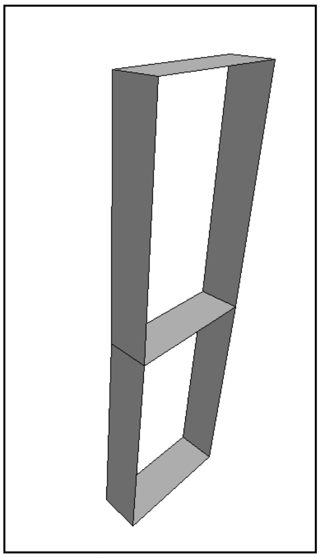


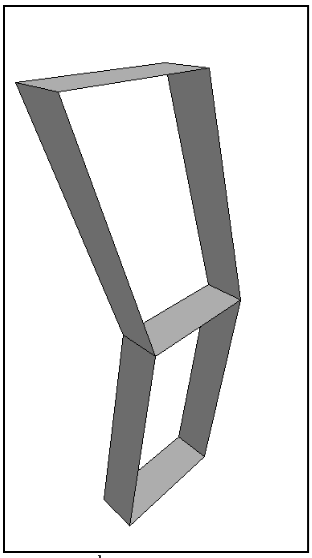
Fig. 5 Singular values of spectral density matrices (model steel structure)

The data acquisition computer provides the ambient vibration records. During measurements, the data files from the previous setup are transferred to the computer for data analysis by using a software package. However, in case there is a display of unexpected signal drifts or unwanted noise or corrupted for some unknown reasons, the data set must be discarded and measurements be repeated.

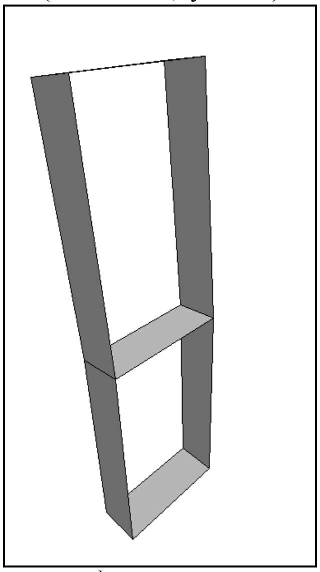
Before measurements the cable used to connect the sensors to the data acquisition equipment must be laid out. Following each measurement, the roving sensors are systematically located from floor to floor until the test is completed (Fig. 3(a), (b)). The equipment used for the measurement includes three Quanser accelerometers (with both x and y directional measurements) and güralp systems seismometer and matlab data acquisition toolbox (wincon). For modal parameter estimation from the ambient vibration data, the operational modal analysis (OMA) software ARTeMIS Extractor (1999) is used.



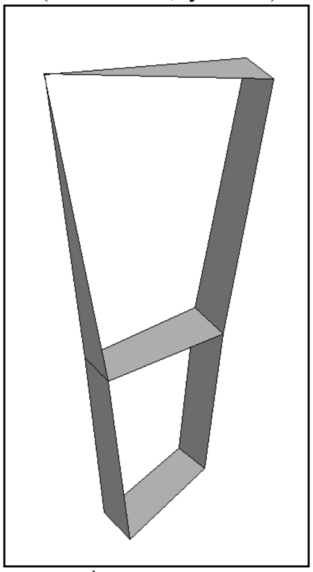
1^{st} Mode Shape
(f=2.017 Hz, ξ=0.672)



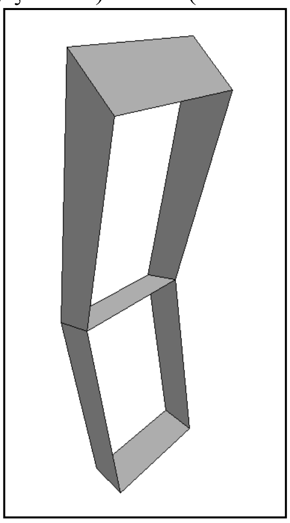
2^{nd} Mode Shape
(f=5.725 Hz, ξ=1.822)



3^{rd} Mode Shape
(f=6.828 Hz, ξ=1.035)



4^{th} Mode Shape
(f=7.770 Hz, ξ=0.551)



5^{th} Mode Shape (f=8.987 Hz, ξ=0.670)

Fig. 6 Experimentally identified mode shapes of model steel structure

Table 2 Experimental modal analysis result at the model steel structure

Mode number	1	2	3	4	5
Frequency (Hz)	2.017	5.725	6.828	7.770	8.987
Modal damping ratio (ξ) (%)	0.672	1.822	1.035	0.551	0.670

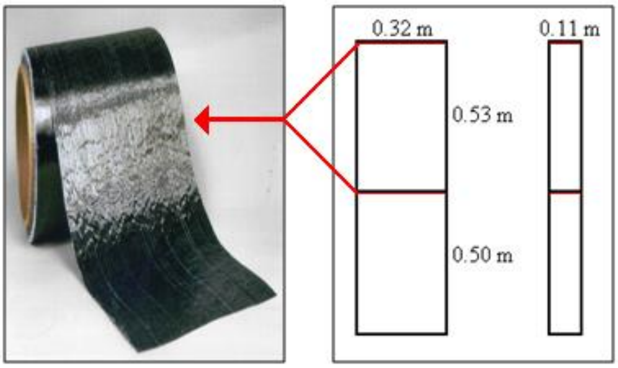


Fig. 7 CFRP composite and using details

The Eigen frequencies are found as the peaks of non-parametric spectrum estimates when the simple peak-picking method (PPM) is used. This frequency selection procedure becomes a subjective task in case of noisy test data, weakly excited modes and relatively close Eigen frequencies. Also for damping ratio estimation, the related half-power bandwidth method is not favorable. This why the most popular and useful algorithm to use is Frequency domain one, because of its convenience and operating speed.

Singular values of spectral density matrices, attained from vibration data using PP (Peak Picking) technique are shown in Fig. 5. Natural frequencies acquired from all measurement setup are given in Table 2. The first five mode shapes extracted from experimental modal analyses are given in Fig. 6. When all measurements are examined, it can be seen that a best accordance is found between experimental mode shapes. In addition, when both setup sets are experimentally identified modal parameters are checked with each other, it can be seen that there is a best agreement between the mode shapes in the experimental modal analyses.

5. Experimental modal analysis of retrofitted model steel structure

In the case of retrofitted beams, the following are studies made on it to check and examine the efficiency of using unidirectional CFRP composite: beams of the model steel structure are retrofitted with one layer CFRP composite. The Unidirectional CFRP composite and its components YKS Fiber is product of YKS Corporation (Fig. 7). The properties of the dry carbon fiber composite are: E=1.350E11 N/m^2, Poisson ratio μ=0.3, mass per unit volume ρ=15696 N/m^3, thickness=0.000152 m.

The steps to pass through during retrofitting are shown

Table 3 Experimental modal analysis result at the retrofitted model steel structure

Mode number	1	2	3	4	5
Frequency (Hz)	2.759	6.515	8.986	11.149	14.905
Modal damping ratio (ξ) (%)	1.001	1.111	0.726	4.628	2.306

Table 4 Comparison of existing and retrofitted modal analysis results

Mode number	1	2	3	4	5
Frequency (Hz)-E	2.075	5.890	7.025	7.994	9.246
Frequency (Hz)-R	2.759	6.515	8.986	11.149	14.905
Difference (%)	32.963	10.611	27.914	39.467	61.204

E: Existing model
R: Retrofitted model

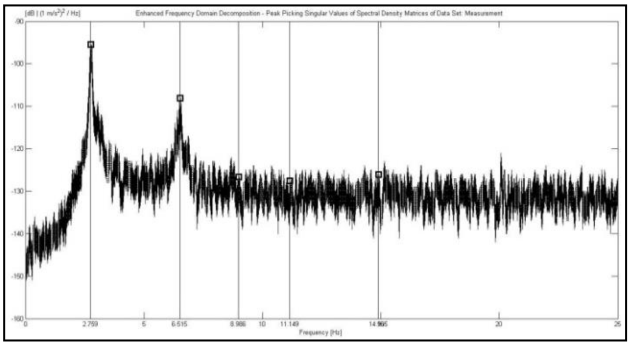


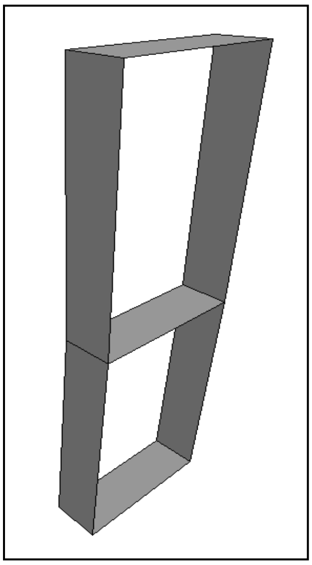
Fig. 8 Singular values of spectral density matrices (retrofitted model steel structure)

below in details: a thin layer two sided tape is applied (Fig. 7) to the beams, approximately 1hour of curing in order to prepare a surface for application of CFRP composite. Next step, bottom surface of beams is covered with CFRP composites. After these setups, ambient vibration tests are followed by curing to obtain experimental dynamic characteristics similar to previously used properties in order to obtain comparative measurements. SVSDM are shown in Fig. 8. Table 3 shows the identified natural frequencies and modal damping ratios.

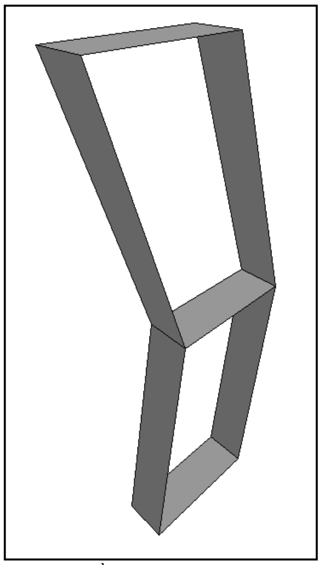
It is clear that using CFRP composites seems to be very effective for strengthening steel members along with increasing stiffness; this research aims to determine how CFRP composite implementation affects structural response of model steel structure by changing of dynamic characteristics.

6. Conclusions

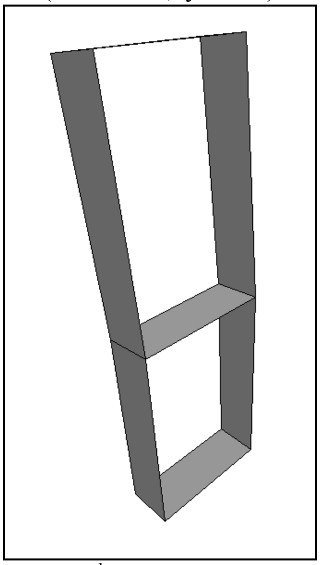
In this research, the conducted were both experimental modal analysis of existing model steel structure and CFRP composite retrofitted model steel structure. Comparing the result of study, the followings are noticed:



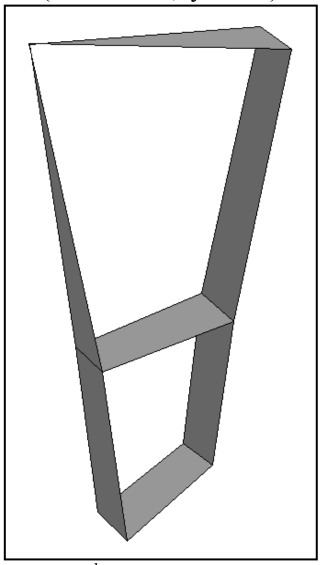
1st Mode Shape (f=2.759Hz, ξ=1.001)



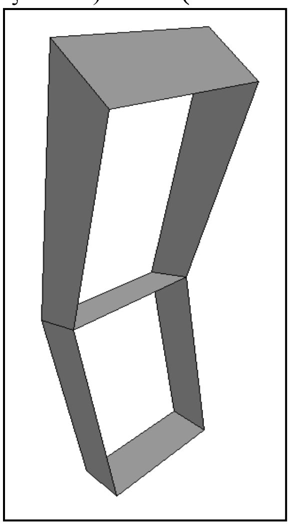
2nd Mode Shape (f=6.515 Hz, ξ=1.111)



3rd Mode Shape (f=8.986Hz, ξ=0.726)



4th Mode Shape (f=11.149 Hz, ξ=4.628)



5th Mode Shape (f=14.905 Hz, ξ=2.306)

Fig. 9 Experimentally identified mode shapes of retrofitted model steel structure

• From the ambient vibration test, the first five natural frequencies attained experimentally, range between 2 and 10 Hz.

• The modal frequency difference lies in the interval of 32.963%-61.204% for Existing and retrofitted case and it provides the increase of frame structure stiffness about 34.43%; for the retrofitted model, using CFRP applied to beams only.

• The investigated results ensure and confirm the possibility of using the recorded micro tremor data on ground level as ambient vibration input excitation data for investigation and application of Operational Modal Analysis (OMA) on the bench-scale earthquake simulator (The Quanser Shake Table) for retrofitted structures and shed light on the development of related research.

• The conclusion of the experiment strongly suggests that the retrofitting should be very efficient to increase stiffness and natural frequencies.

• In this study, it is shown that OMA may be used to evaluate the period and rigidity of the retrofitted structures.

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