Experimental Study on Behavior of Bench-Scale Steel Structure Retrofitted with CFRP Composites under Ambient Vibration

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Abstract—Usage of FRP composites for the retrofitting purpose of the structures against the harmful effect of dynamic loads is gaining popularity, it is used in a wide variety of disciplines including civil engineering. Thus, there is a great need to study the behavior of FRP composites for strengthening purposes of structures using empirical methods. In this study, a bench-scale steel structure model was strengthened with CFRP composite and tested using operational modal analysis. To conduct operational modal analysis a bench-scale earthquake simulator and ambient vibration emulator were used. Same steel structure model was tested without strengthening procedure. Obtained dynamic responses (maximum-minimum displacements and accelerations before and after application of CFRP) of steel structure model have compared to each other. This study shows that floor displacements of the model have been decreased along the height of the structure up to 41.43%. Therefore, the results of the experiment confirm the effectiveness CFRP composites for the strengthening of steel structures.

Index terms—Operational Modal Analysis, Ambient Vibration, CFRP, Shake Table, Bench-Scale Steel Structure.

I. INTRODUCTION

Buildings located in seismically active regions are under high risk of severe damages caused by harmful earthquake loads. Under the effect of such ground motions members of the structures (particularly the columns) are highly vulnerable. Considering the performance of such buildings under seismic occurrence, there is a great need to strengthen the columns even without changing their building masses. It can be achieved using FRP composites through certain strengthening procedure of members such as columns, beams, and slabs. These composites are much lighter than other construction materials such as concrete or steel alongside having high strength and durability. This material is produced either as plates (covered with a thin layer of fiber) or as tissues. The structural response of a system covered with fiber reinforced polymer composite is related to the covered element. Basically, FRPs are categorized as shear strengthening, envelope scripts and bending strengthening. Usage of FRP composites for strengthening reinforced concrete structures showed that it could prevent the structure from severe bending and shearing. Also, it can improve the resistance and ductility of the structure against lateral loads.

Plenty of research has been conducted in relation to the behavior of structural element retrofitted using FRP composites and its comparison with the non-retrofitted model. Composite material such as high-performance fiber reinforced (AFRP, BFRP, HMCF, etc.) and carbon fiber are used in different industries for the past three decades. These materials could be used for civil engineering purposes such as the strengthening of steel structures which became popular.

Generally, this material is glued to the external part of the RC structures [1–4]. Experimental and analytical failure testing of the RC circular bridge column is presented in [5]. The damage in the circular RC column (%40 scale) occurred as shear failure under cyclic loading. After the test, the damaged column was repaired using mortar (non-shrinkage) and epoxy and retrofitted by CFRP. Experimental result of the test was assessed based on the lateral force-displacement relationship of the columns of the concerned bridge. Based on their study, circular reinforced concrete bridge column has been reached for a true repair; a change of the shear-failure mode of bridge column to the bending-failure refraction occurred. In other words, it would increase the seismic performance of the structure.

The analytical studies [6] on the response of reinforced concrete columns bounded with FRP and steel shows good potential to improve the strength of the columns. The performance of the reinforced concrete column which was covered with carbon FRP was examined under uniaxial compression load strengthened with CF-130 carbon fiber laminates [7]. According to test results, ±45 degrees CFRP laminate is capable of enhancing the ductility performance of columns. On the other hand, if the main purpose is to boost the load-bearing capacity of the columns, a unilateral FRP laminate would be more efficient [8].

“Effect of strain gradient and FRP thickness on square concrete columns reinforced with FRP wraps” has been studied in [9]. In this study, 9 concrete columns were examined under eccentric loads (two distinct eccentricities were used). The results of this study indicate that the applied eccentricity values were capable of producing longitudinal tension within the wrap. It has been shown that beams of existing structures suffer too much during seismic loading. Analytical and experimental results of testing “T” cross-section reinforced concrete beam strengthened with carbon fiber reinforced plastic composite (CFRP) show that tension is increased at the negative moment region approximately 40% [10]. A number of reinforced concrete beams were
examined after strengthening with CFRP laminates to understand the effect of external reinforcement and area of cross-section on the response of strengthened beams. Obtained results were then compared to experimental results, and computed design limit state to get the design load which is equivalent to limit position of the concerned beam [11]. A bridge fortified using carbon-fiber-reinforced polymer has been examined in a research article [12]. Where, full-scaled specimen, partial scaled and sectional beam experiments show carbon-fiber reinforced polymer composites could be used as a good strengthening and repairing material for damaged RC bridge girders and similar structures. The ductility performance, stiffness, and strengthening capabilities of CFRP for repairing of masonry and bridge structures have been studied in reference [12-14]. In this research firstly experimental modal analysis of a steel structure model (Fig. 1) was conducted, then the slabs of the steel structure model were strengthened with FRP composite and the same analysis process repeated. Lastly, the result of both analyses has compared to each other. In order to conduct the dynamic operational modal analysis (OMA); Quanser Shak-Table II seismic simulator was used. The input excitation was applied as ambient vibration based on recorded micro-tremor data on the ground level. The Quanser Shak-Table II is an earthquake simulation device which is an effective tool for structural dynamic, seismic simulation, etc. experiments and it's widely implemented in various similar experiments.

II. METHODOLOGY OF OPERATIONAL MODAL ANALYSIS

Ambient Modal Definition (FDD) is an extended form of Basic Frequency-Domain (BFD) method and often referred to as Peak Collecting technique as well. It is a nonparametric method which is useful to calculate the white noise ratio of the nodes and to determine model parameters directly via signal processing. Modes of the concerned structure could be estimated via the FDD method using Singular Value Decomposition of every measure data sets. Mentioned decomposition correlates to system identification of a 1-DOF system calculated based on every sole parameter [15]. Enhanced Frequency Domain Decomposition (EFDD) method is an improved version of FDD which is very easy to use. In this method, the modes of the system are determined by peak picking technique in Singular Value Decomposition plots, these plots are measured based on the spectral density of the system's response. The FDD method relies on a frequency line of Fastest Fourier Transform (FFT) analysis, the precision of predicted natural frequency depends on the quality of FFT. However, it is feasible to obtain an advanced measurement of natural frequency, mode shapes and the ratio of damping using the EFDD method [16]. According to the EFDD method, 1-DOF Power Spectral Density (PSD) is recognized as the resonance apex. Natural frequencies can be achieved by specifying the value of zero crossing-function of time and respective damping of related SDOF normalized autocorrelation function [17].

In this research, it is aimed to implement the modal parameter identification using advanced frequency domain-decomposition method. The relation of inputs (x(t)) and response (y(t)) in EFDD method could be written as equation (1).

\[
[G_{yy}(j\omega)] = [H(j\omega)]*[G_{ss}(j\omega)]*H^T(j\omega)
\] (1)

In equation (1) \(G_{ss}(j\omega)\) represents the \(r \times r\) (PSD) matrix of the inputs, \(G_{yy}(j\omega)\) indicates the \(m \times m\) (PSD) matrix of the outputs. \(H(j\omega)\) is the \(m \times r\) response function of frequency matrix, * is complex-conjugate and T is transpose. The FRF could be presented as brief residual form as equation (2):

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

Here, \(\lambda_k^s\) represents pole, \(n\) number of modes and \(R_k^s\) represents the residue. Thus, the equation (1) can be written as:

\[
G_{yy}(j\omega) = \sum_{k=1}^{n} \sum_{j=1}^{n} \left[ \frac{[R_k^j]}{j\omega - \lambda_k^j} + \frac{[R_k^r]}{j\omega - \lambda_k^r} \right]
\] (3)

Where * and \(H\) represents complex-conjugate and respective response and on the other hand \(s\) denotes for singular values. By multiplication of partial fraction factor using heavy-side partial fraction theory and conducting some mathematical operations, the PSD output can be presented as equation (4).

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

In equation (4), \(A_k\) refers to \(k\) \% residue matrix of the PSD output. In the first phase of EFDD identification, the PSD matrix is estimated. Then the obtained PSD output (estimated at discrete frequencies) will be decomposed using Singular Value Decomposition (SVD) of the matrix.

\[
G_{yy}(j\omega) = U_S U_\Omega^T
\] (5)

In equation (5) the matrix \(U_i = [u_{i1}, u_{i2}, u_{i3}, \ldots, u_{im}]\) refers to a unitary matrix possessing \(u_{ij}\) and \(S_{ij}\) singular vectors, \(G\) refers to a diagonal matrix containing single numeric values. The singular vector \(u_{ij}\) is an estimated form of shapes of the modes. The PSD function identification will be done by comparison of \(u_{ij}\) and singular vectors for frequency-lines near the apex. Then, the natural frequency of the system can be acquired using the segment of single degree of freedom density function near the apex of the PSD.

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III. DESCRIPTION OF STEEL STRUCTURE AND SHAKE TABLE

In this study, a two-story steel structure model has been used to conduct the experiment. This structure model is installed on a bench scale shake table (Quanser II) to perform a dynamic test, shake table device is controlled using specific software synchronized with installed accelerometers in the stories of the structure. Overall view of the shake table is provided in Fig. 1(a) and the properties of the shake table are given in Table I [18]. The dimension of bench-scale steel model is presented in Fig. 1(b).

| TABLE I: THE PROPERTIES OF THE SHAKE TABLE AND STEEL STRUCTURE MODEL |
|-----------------------------------------------|-----------------------------------------------|
| Shake table characteristics (a)            | Steel structure model specifications (b) |
| Dimension (W x L x H)                      | Elasticity modulus 2.000E11 N/m²            |
| Mass                                        | Poisson ratio (µ) 0.3                       |
| Pay-load area (WxL) (0.46x0.46)m            | Mass per unit (ρ) 78500 N/m²               |
| Maximum pay-load at 2.5 g 7.5kg             | Thickness of elements 0.001588 m            |
| Maximum travel ± 0.076m                     | Storey height 0.53m                        |
| Operational bandwidth 10 Hz                 | Length 0.32m                               |
| Maximum velocity 0.665 m/s                  | Width 0.11m                                |
| Maximum acceleration 2.5 g                  | Total height 1.06m                         |
| Lead screw pitch 0.127 cm/rev               | Number of accelerometers 2                 |
| Servomotor power 400W                      |                                             |
| Amplifier maximum continuous current 12.5A |                                             |
| Motor maximum torque 7.82N.m                |                                             |
| Lead screw encoder resolution 8192counts/rev|                                             |
| Effective stage position resolution 1.55μm/count|                             |
| Accelerometer range ± 49 m/s²              |                                             |
| Accelerometer sensitivity 1.0g/V            |                                             |

IV. SHAKE TABLE TEST OF THE STEEL STRUCTURE MODEL

Dynamic time history analysis of steel structure model was performed using acceleration values of ambient vibration (Fig. 2) with and without FRP composite strengthening. The time history record length is 100 seconds.

The excitation is provided by using ambient vibration on a shake table. Two accelerometers (A and B) are used to measure vibrations, one of them allocated on the first floor, and another on the second floor (shown in red in Fig. 3).

The absolute displacements and accelerations of steel structure model without FRP composite strengthening are obtained from accelerometers (A and B) presented in Table II and Fig. 4-7.

Fig. 2. Ambient vibration record based on micro tremor data on the ground level

Fig. 3. The location of accelerometers in 3D view
TABLE II: DISPLACEMENTS AND ACCELERATIONS OF EXISTING MODEL STEEL STRUCTURE

<table>
<thead>
<tr>
<th>Joint</th>
<th>Acceleration (m/s²)</th>
<th>Displacement (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.09360</td>
<td>0.0003490</td>
</tr>
<tr>
<td>B</td>
<td>0.12510</td>
<td>0.0006343</td>
</tr>
</tbody>
</table>

Fig. 4. Node (A) displacement response

Fig. 5. Node (B) acceleration response

Fig. 6. Node (B) displacement response

Fig. 7. Node (B) acceleration response

V. SHAKE TABLE TEST OF RETROFITTED STEEL STRUCTURE MODE

In the case of retrofitted beams, the following studies are made on it to check and examine the efficiency of using unidirectional CFRP composite: the beams of the steel structure model are retrofitted with one layer CFRP composite. The Unidirectional CFRP composite and its components YKS Fibre is a product of YKS Corporation (Fig. 8a). Specifications of steel structure model have been provided in Table III.

TABLE III: MATERIAL PROPERTIES OF STEEL STRUCTURE MODEL AND CFRP COMPOSITE

<table>
<thead>
<tr>
<th></th>
<th>Steel structure</th>
<th>CFRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elasticity modulus [N/m²]</td>
<td>2.000E11</td>
<td>1.350E11</td>
</tr>
<tr>
<td>Poisson ratio (μ)</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Mass per unite [N/m³]</td>
<td>78500</td>
<td>15696</td>
</tr>
<tr>
<td>Thickness of elements [m]</td>
<td>0.001588</td>
<td>0.000152</td>
</tr>
</tbody>
</table>

The steps to pass through during retrofitting are shown below in details: a thin layer two-sided tape is applied (Fig. 8) to the beams, approximately 1 hour of curing in order to prepare a surface for the application of CFRP composite. Next step, the bottom surface of beams is covered with CFRP composites.

After these setups, dynamic tests are followed to obtain absolute displacements and accelerations similar to previously used properties in order to obtain comparative measurements as shown in Table IV and Fig. 9-12.

TABLE IV: DISPLACEMENTS AND ACCELERATIONS OF EXISTING MODEL STEEL STRUCTURE

<table>
<thead>
<tr>
<th>Joint</th>
<th>Acceleration (m/s²)</th>
<th>Displacement (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.09186</td>
<td>0.0002343</td>
</tr>
<tr>
<td>B</td>
<td>0.12810</td>
<td>0.0003715</td>
</tr>
</tbody>
</table>

(a) (b)

Fig. 8. CFRP composite (a) and its usage in the bench-scale steel structure (b)
The presented result indicates that usage of FRP material in steel structure model decreases the absolute displacement values along the columns of the structure. According to the experimental results, the maximum absolute displacement of structure reduced from 0.0006343 m to 0.0003715 m after FRP application. Maximum absolute displacements were reduced 41.43% approximately without adding tangible mass to the main structure. Fig. 4 – 7 and Fig. 9– 12 clearly shows that FRP composites are could be very effective in similar applications. It is clear that using CFRP composites seems to be very effective for strengthening steel members alongside with increasing stiffness; this research aims to determine how CFRP composite implementation affects the structural response of steel structure model by changing of dynamic characteristics.

VI. CONCLUSION AND DISCUSSIONS

This research was an experimental dynamic analysis of a steel structure retrofitted and non-retrofitted model with CFRP composites. Dynamic analysis of the steel structure model was conducted on a shake table using ambient vibration. As a conclusion of the study, the followings aspects are noticed:

- Shake table test shows that floor displacements range between 0.0002343 and 0.0006343 m.
- There is a considerable reduction in the absolute displacement response of the retrofitted model compared to a non-retrofitted model which lies between the interval of 32.86% - 41.43%. It improves the stiffness of the frame structure about 37.14 %.
- Obtained results ensure and confirm the efficient usage of micro-tremor data as ambient vibration input excitation for conducting dynamic analysis using bench scale earthquake simulator (Quanser Shake Table II).
- The conclusion of the experiment strongly suggests that the retrofitting could be very efficient to increase stiffness and decrease floor displacement of similar structures.
- This study indicates that the shake table test may be used to evaluate the displacement and acceleration of structures retrofitted by CFRP.

REFERENCES


