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OMA OF RC INDUSTRIAL BUILDING RETROFITTED WITH CFRP USING SSI

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Abstract — *Today, there are a great number of various structures that have been retrofitted by using different FRP composites. For this reason, more research is needed to learn more about the properties of such structures, as well as a comparison before and after retrofitting. In this study, one story reinforced concrete (waffle slab) building is tested using ambient vibrations, in order to get the dynamic behaviors. Slabs of this building are then retrofitted by using CFRP composite, and then tested with ambient vibrations. At this stage it is necessary to evaluate the dynamic behavior of the existing and retrofitted state of the building. 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, operational modal analysis of both types (retrofitted and no-retrofitted buildings) is conducted to evaluate their dynamic behaviors. Furthermore, the Stochastic Subspace Identification is used through output-only modal identification. At the end of this study, reasonable correlation is obtained between mode shapes, frequencies and damping ratios. The goal of this research is to show and determine the effects of CFRP composite implementation on structural responses of this building, in terms of changing its dynamical behaviors. There is an average difference of 18.844% between the frequencies of existing and retrofitted buildings. Finally, it is shown that, in order to evaluate the frequencies and rigidity of retrofitted structures, OMA might be used.*

Keywords*- operational modal analysis; CFRP; RC building; modal parameter; SSI*

I. INTRODUCTION

Most of the structures found in earthquake hazardous areas are subject to various destructive effects caused by seismic loads. When an earthquake occurs, the structural elements (especially the columns) of the structures are damaged.
On the other hand, especially considering the performance of structures in seismic load effect, it is very important to strengthen the columns without changing the mass of the building. It is clear that this technique needs to investigate the relationship between repair and retrofitting operations and column capacity. More work should be done to clarify the performance of structures under seismic loads. 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, basalt 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 or two directions at different angles). The behavior of the system that is covered with external FRP composite is related to the type of the element covered (Dong et al. 2002). Usually 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. Increasing the resistance and ductility of the system under lateral seismic loads the main goal of this covering.
Li and Sung in (2003) they had presented lot of analytical and experimental tests on benchmark and on reinforced concrete damaged circular bridge column. In the benchmark column is a 40% scale reinforced concrete circular bridge column damaged because of shear failure during a cyclic-loading test. Then the column repaired by epoxy and non-shrinkage mortar and rehabilitated by (CFRP) carbon fiber reinforced plastic after the cyclic-loading test.
Experimental result could be predicted accurately by the analytical lateral force-displacement relationship of the bridge columns, 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 refraction occurs, in other words this increases the seismic performance the analytical and experimental by (Montoya et al. 2004) are fitted with the numerical results of nonlinear finite element evaluation for the behavior of steel and FRP contained concrete columns which formulated and implemented. 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, the experimental result for five circular columns and three rectangular columns were tested in pure compression shows that ±45 degrees CFRP laminate can effectively be used to provide columns ductility performance. When the main goal is to boost the load capacity, a unidirectional FRP laminate might be more effective according to Paretti and Nanni (2002). According to Parvin and Wang study (2002), they talk over the effect of strain gradient and FRP thickness on square concrete columns reinforced with FRP wraps. The results for nine square concrete columns were tested under eccentric load and two different levels of eccentricity. it was shown that the chosen eccentricity values were small enough to produce any

longitudinal tension in the wrap. 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. Reinforced concrete rectangular cross-section column was used to evaluate their performance 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. analytical and experimental results by testing “T” cross section reinforced concrete beam, the beams strengthen with carbon fiber reinforced plastic composite (CFRP), the results show that tension increased at the negative moment region approximately 40% according to (Namboorimadathil et al. 2002) study. 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 performance of partial bridge strengthened by CFRP composite has been tested 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. For pre-stressed three reinforced concrete girder bridge that suffered damage which repair-strengthening with CFRP composite. Experimental results before and after repairing was presented by (Klaiber et al.2003) study, the results shown that using of CFRP is productive. The girder bending displacements have been decreased more than 20% when CFRP was used. When Strengthened with CF-130 carbon fiber laminates, fifteen rectangular beams were tested in pure compression. The experimental result shows that CFRP laminate can effectively be used to provide beams ductility performance. The effect of FRP wrapping number to the maximum axial capacity has been evaluated Kasimzade and Tuhta (2012).

As already known, forced (impact, shaker, pull back or quick release tests) and ambient vibration techniques are available for vibration testing of large structures. Forced 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, displacement or acceleration); depend on the type of vibrations (Traffic load, Acoustic, Machinery inside, Earthquake waves, Wind excitation…) that are given in Vibration of Buildings (1990).

These structure response characteristics give a general idea of the preferred quantity to be measured. Several 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. In this study operational modal analysis of a RC building for dynamic characteristics was evaluated. Then, retrofitted RC building for dynamic characteristics was also evaluated. Ambient vibration was provided by traffic load on ground level. The Stochastic Subspace Identification is used for the output-only modal identification.

II. MODAL PARAMETER EXTRACTIONS

The Stochastic Subspace Identification Technique (SSI) is a time-domain method that works directly with raw time data without the need to convert them to correlations or spectra. The stochastic subspace identification algorithm defines state space matrices based on measurements using robust digital techniques. When the mathematical definition of construction (state-space model) is found, modal parameters are simple to determine. The theoreticaly distances is given in Overschee and De Moor (1996), like Peeters (2000). The model of the vibrational structures can be described by a series of linear, constant-coefficient and second-order differential equations, Peeters (2000):

$$m\ddot{u}(t)+c\dot{u}(t)+k\,u(t)=F(t)=d\,f(t) \tag{1}$$

Where m, c, k are the mass, damping and stiffness matrices, $F(t)$ is the stimulation force, and $u(t)$ is the displacement vector at continuous time t . d is an input influence matrix, characterizing the locations and type of known inputs $f(t)$ .The state-space model is derived from the control theory, but it also appears in mechanical-civil engineering to calculate the modal parameters of a dynamic structure with a general viscous damping model, Ewins (1984). The motion equation (1) is transformed into space-space, which is the first of the first-order equations, that is, the system is regarded as a continuous-time state-space model.

$$\dot{z}(t)=A_c\,z(t)+B_c\,f(t) \tag{2}$$

$$A_c=\begin{bmatrix} 0 & I \\ -m^{-1}k & -m^{-1}c \end{bmatrix}$$

$$B_c=\begin{bmatrix} 0 \\ m^{-1}d \end{bmatrix} \tag{3}$$

$$z(t)=\begin{bmatrix} u(t) \\ \dot{u}(t) \end{bmatrix}$$

Where A_c is the state matrix, B_c is the input matrix and $z(t)$ is the state vector. The number of elements of the state space vector is the number of arguments needed to describe the state of the system. Assuming that the measurements are evaluated only at one sensor position and that these sensors are speedometers, speed or displacement transducers (accelerometers), the observation equation is

$$y(t)=C_a\,\ddot{u}(t)+C_v\,\dot{u}(t)+C_d\,u(t) \tag{4}$$

Where $y(t)$ are the outputs, and C_a, C_v, C_d are the output matrices for acceleration, velocity, displacement. With this definitions

$$C=[C_d-C_a\,m^{-1}k \quad C_v-C_a\,m^{-1}c] \tag{5}$$
$$D=C_a\,m^{-1}d$$

Equation (4) can be transformed into:

$$y(t)=C\,z(t)+D\,u(t) \tag{6}$$

Where C is the output matrix and D is the direct transmission matrix. Equations (2) and (6) form a continuous-time deterministic state-space model. Continuous time means that the expressions can be evaluated at each time instant $t\in\mathbb{R}$ and deterministic means that the input-output quantities $u(t), y(t)$ can be measured exactly. Of course, this is not realistic: measurements are available at discrete time instants $k\Delta t$, $k\in\mathbb{N}$ with Δt, sample time and noise always influence the data. After the example, the state-space model looks like this:

$$z_{k+1}=Az_k+Bu_k \tag{7}$$
$$y_k=C\,z_k+Du_k$$

Where $z_k=z(k\Delta t)$ is the discrete-time state vector, is the process noise due to disturbance and modeling imperfections; v_k is the measurement noise due to sensors' inaccuracies; It includes stochastic noise and we obtain the following discrete-time combined deterministic-stochastic state-space model:

$$z_{k+1}=Az_k+Bu_k+w_k \tag{8}$$

$$y_k = C z_k + D u_k + v_k$$

w_k, v_k vectors are non-measurable, but they assume that there is zero average and white noise. If this white noise hypothesis is violated, in other words if the input contains also some dominant frequency components in addition to white noise, These frequency components are indistinguishable from the system's own frequencies and appear as eigenvalues of the system matrix A.

$$E\left[\begin{pmatrix} w_p \\ v_p \end{pmatrix} \begin{pmatrix} w_q^T & v_q^T \end{pmatrix}\right] = \begin{pmatrix} Q & S \\ S^T & R \end{pmatrix} \delta_{pq} \tag{9}$$

Where E is the expected value operator and δ_{pq} is the Kronecker delta. Vibration information available in structural health monitoring (SHM) is often the reaction of a structure induced by operational inputs, some of which are unmeasured inputs. Due to the lack of input information it is not possible to distinguish deterministic input u_k from the noise terms w_k, v_k in Bendat and Piersol (1984). If the deterministic input term u_k is modeled by the noise terms w_k, v_k the discrete-time purely stochastic state-space model of a vibration structure is obtained:

$$\begin{aligned} z_{k+1} &= A z_k + w_k \\ y_k &= C z_k + v_k \end{aligned} \tag{10}$$

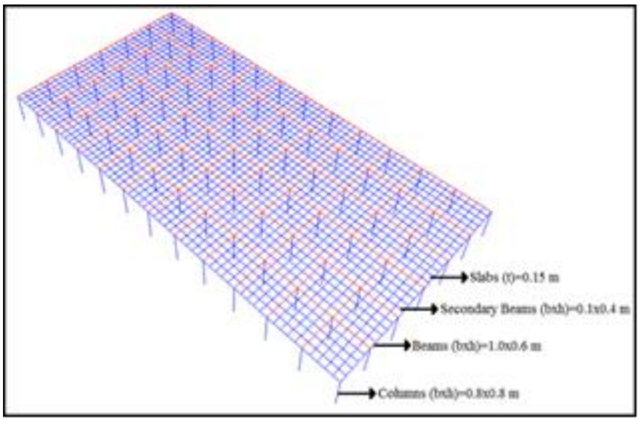
Equation (10) Operational vibration measurements provide the basis for defining the time-consuming system. The stochastic subspace method defines state space matrices based solely on output measurements and robust digital techniques.

III. DESCRIPTION OF BUILDING

The building is 8.5 m in height from the ground level. Story height is 8 m appropriately. All slabs are two way waffle slabs. Total area of slabs are 108 m x 54 m = 5832 m2 in area. Construction of the building began in the fall of 2003 and was completed (retrofitted) during the winter of 2005. Picture and a typical floor plan of the building are shown in (Fig.1 a, b).

(a)

(b)



(c)

Fig 1a, b ,c . Pictures and dimensions of the industrial building

Story dimensions of Industrial building are six bay (x direction) and twelve bay (y direction). Both bay are 9 m. Concrete C16 and steel S220 are respectively used. The building was designed accordance with Turkish reinforced concrete design standard TS-500 and design loads for buildings TS-498.

IV. OPERATIONAL MODAL ANALYSIS OF BUILDING

The ambient vibration is provided by traffic load on ground level ten 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 floor (shown by the black arrows in Fig. 2). The response was measured in two data sets (Fig. 2). Every data set was measured within 100 minutes. The selected measurement points and directions are shown in Fig. 2. The ambient vibration is provided by traffic load on ground level (Fig. 3).

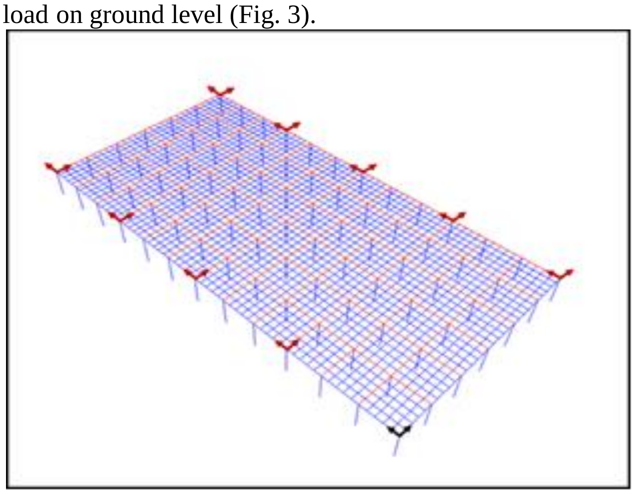


Fig 2. Accelerometers location of building in the 3D view

Fig 3. Ambient vibration record from the traffic load with seismometer on ground level

The sensors mounted using anchor bolts. The bolts could remain in place until all of the tests were completed.

Acceleration measurements were obtained using force balanced accelerometers (Full scale range: $\pm$ 2g; DC to 100 Hz bandwidth; digital sensor control; output voltage range 0 $\pm$ 5V). Lengths of cable 100 m were available to connect sensors to the signal conditioner. The maximum possible cable length for the sensors with an allowed power voltage drop of 1 volt in the wire are 450 m. Cable configuration are three twisted pairs.

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. The equipment used for the measurement includes geosig accelerometers (with both x and y directional measurements), güralp systems seismometer and geosig data acquisition software (geodas). For modal parameter estimation from the ambient vibration data, the operational modal analysis (OMA) software ARTeMIS Extractor (1999) is used.

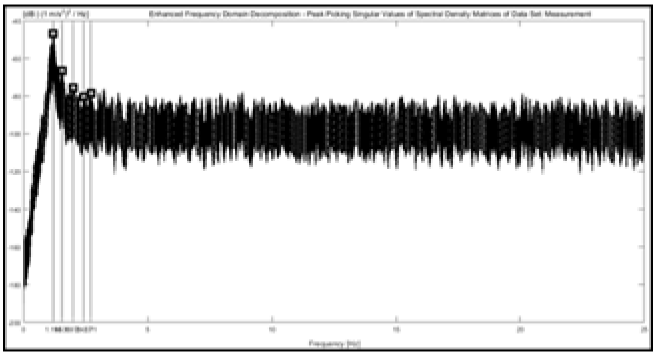
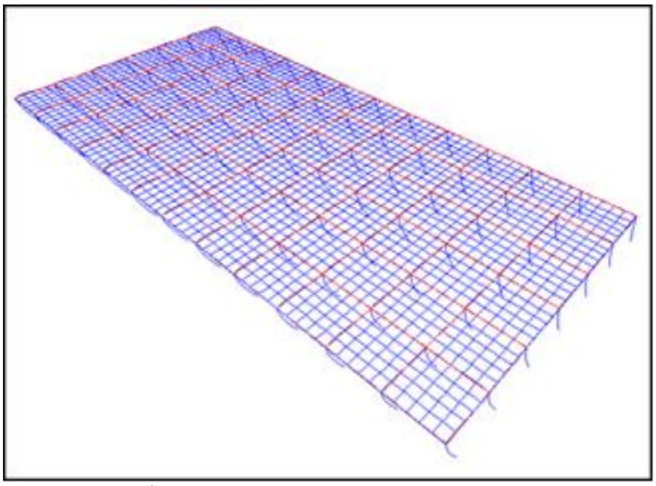


Fig 4. Singular values of spectral density matrices (existing building)

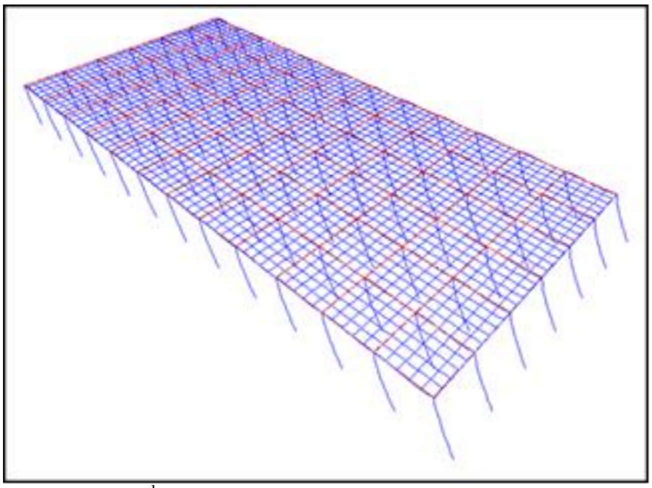
The Eigen frequencies are found as the peaks of non-parametric spectrum estimates when the simple peak-picking method (PPM) is used. This frequency selection procedure becomes a subjective task in case of noisy test data, weakly excited modes and relatively close Eigen frequencies. Also for damping ratio 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. 4. Experimentally identified frequencies acquired from all measurement setup are given in Table 1. The first five mode shapes extracted from operational modal analyses are given in Fig. 5. 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 operational modal analyses (existing and retrofitted building).

Table 1. Operational modal analysis result at the building

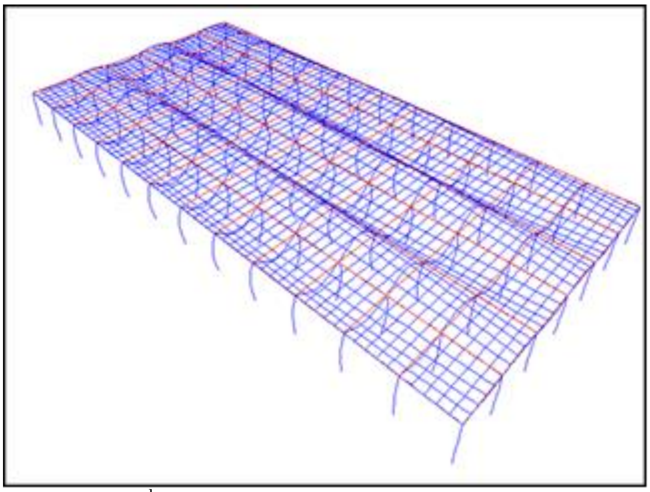
Mode number	**1**	**2**	**3**	**4**	**5**
Frequency (Hz)	1.196	1.538	1.978	2.417	2.710
Modal damping ratio (ξ) (%)	2.30	1.80	1.40	1.14	1.02



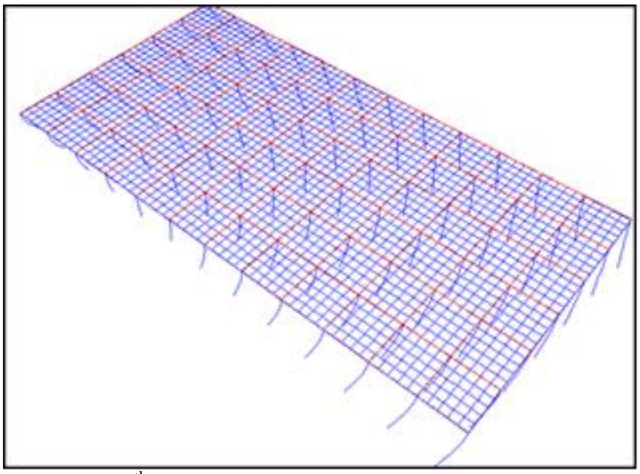
1st Mode Shape (f=1.196 Hz, ξ=2.30)



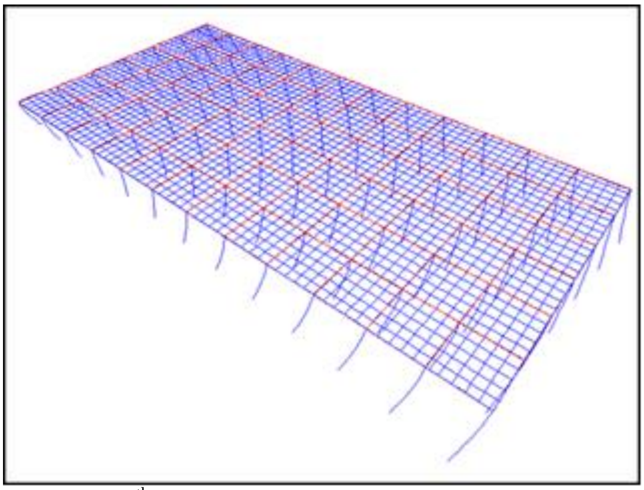
2nd Mode Shape (f=1.538 Hz, ξ=1.80)



3rd Mode Shape (f=1.978 Hz, ξ=1.40)



4th Mode Shape (f=2.417 Hz, ξ=1.14)

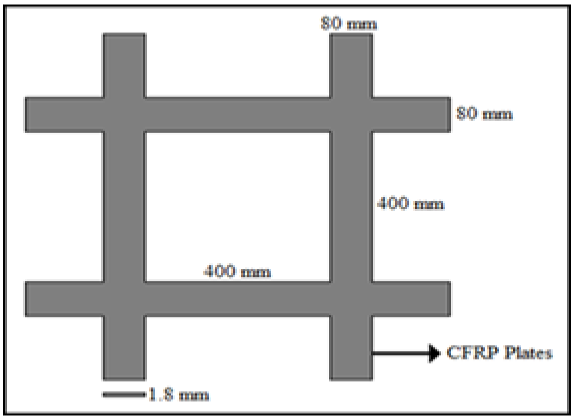


5th Mode Shape (f=2.710 Hz, ξ=1.02)

Fig 5. Experimentally identified mode shapes of existing building

V. OPERATIONAL MODAL ANALYSIS OF RETROFITTED BUILDING

In this part of the study, all slabs of the structure are retrofitted with single layer CFRP plates as shown in figure 6a. The CFRP composite and its components YKS Fiber is product of YKS Corporation (Fig. 6 a, b). 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.



(a)

(b)

Fig 6. a, b CFRP composite plates and used details

The steps to pass through during retrofitting are shown below in details: thin layer epoxy putty is applied (Fig. 6) to the slabs, approximately 2 hours of curing in order to prepare a surface for application of CFRP composite. In Next step, top surface of slabs is covered with CFRP composite plates. 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. 7. Table 2 shows the experimentally identified 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 existing building by changing of dynamic characteristics (Fig. 8).

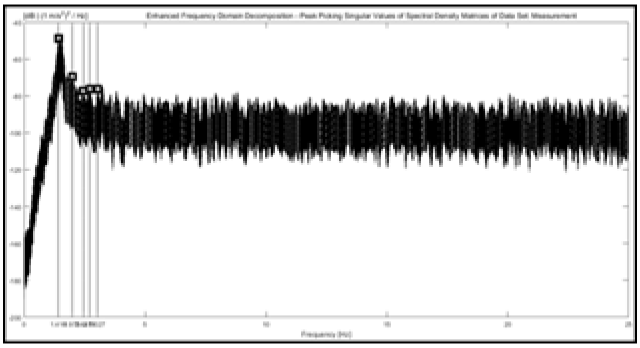
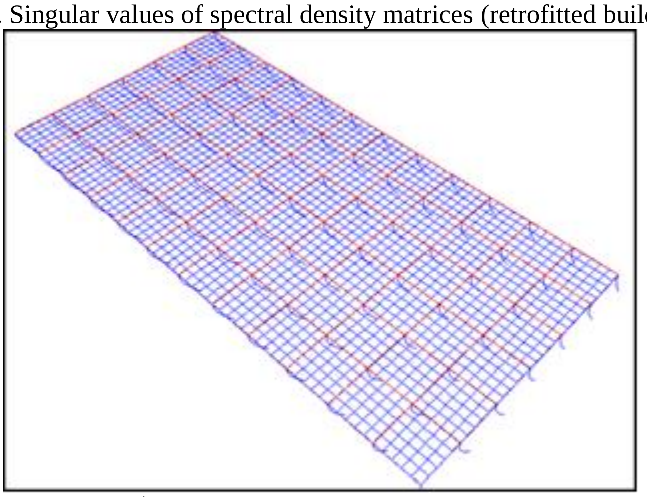
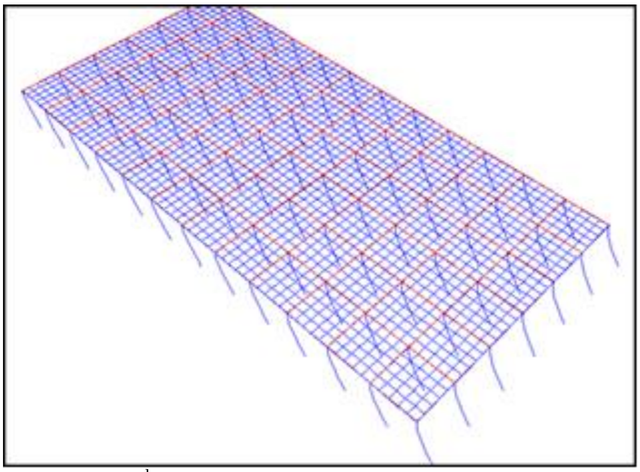


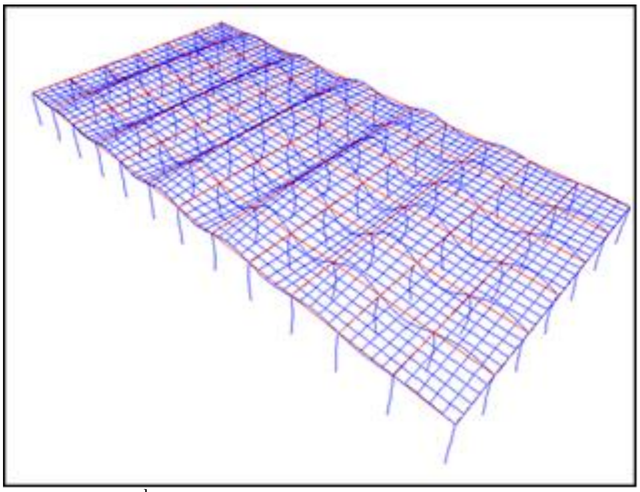
Fig 7. Singular values of spectral density matrices (retrofitted building)



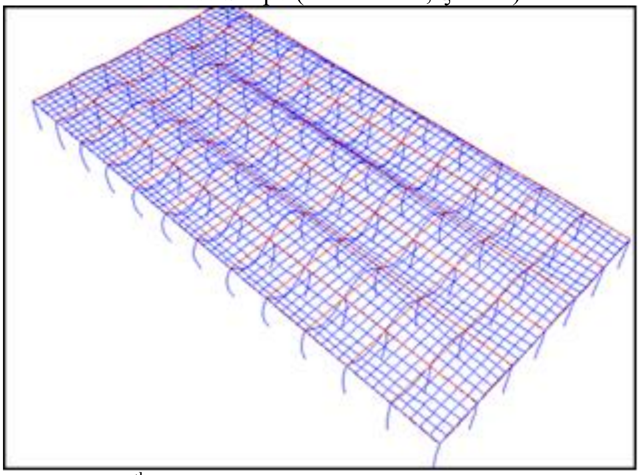
1st Mode Shape (f=1.416 Hz, ξ=1.95)



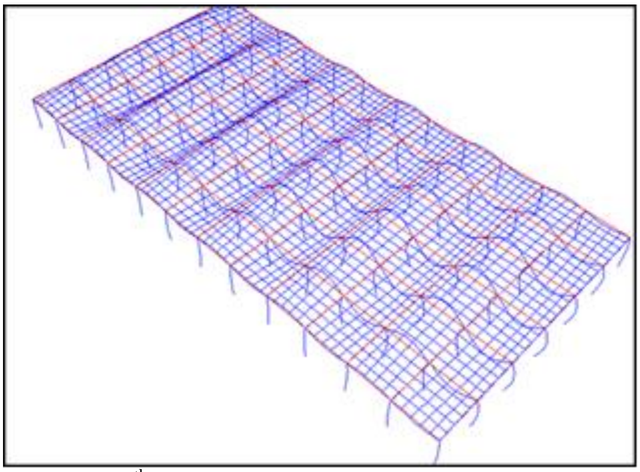
2nd Mode Shape (f=1.978 Hz, ξ=1.40)



3rd Mode Shape (f=2.441 Hz, ξ=1.13)



4th Mode Shape (f=2.710 Hz, ξ=1.02)



5th Mode Shape (f=3.027 Hz, ξ=0.91)

Fig 8. Experimentally identified mode shapes of retrofitted building

Table 2. Operational modal analysis result at the retrofitted building

Mode number	**1**	**2**	**3**	**4**	**5**
Frequency (Hz)	1.416	1.978	2.441	2.710	3.027
Modal damping ratio (ξ) (%)	1.95	1.40	1.13	1.02	0.91

Table 3. Comparison of existing and retrofitted modal analysis results

Mode number	**1**	**2**	**3**	**4**	**5**
Frequency (Hz)-E	1.196	1.538	1.978	2.417	2.710
Frequency (Hz)-R	1.416	1.978	2.441	2.710	3.027
Difference (%)	18.394	28.600	23.407	12.122	11.697

E: Existing building
R: Retrofitted building

VI. CONCLUSIONS

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

- From the ambient vibration test, the first five natural frequencies attained experimentally, range between 1.196 and 3.027 Hz.
- The modal frequency difference lies in the interval of 11.697%-28.600% for Existing and retrofitted case and it provides increase of structure stiffness about 18.844%; for the retrofitted building, using CFRP applied to slabs only.
- Best agreement between the mode shapes in the operational modal analyses (existing and retrofitted building).
- The investigated results ensure and confirm the possibility of using traffic load on ground level as ambient vibration input excitation data for investigation and application of Operational Modal Analysis (OMA) for retrofitted structures.
- 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 frequencies and rigidity of the retrofitted structures.

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