Update of Structural Parameters on the Bench-Scale Aluminum Bridge Model Using Ambient Vibration

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Abstract. **In this research was investigated of possibility using the recorded micro tremor data on ground level as ambient vibration input excitation data for investigation and application Operational Modal Analysis (OMA) for bench-scale aluminum bridges. As known OMA methods (such as EFDD) are supposed to deal with the ambient responses. For this purpose, analytical and experimental modal analysis of a bench-scale aluminum bridge for dynamic characteristics was evaluated. 3D Finite element model of the building was evaluated SAP2000 for the bench-scale aluminum bridge based on the design drawing. Ambient excitation was provided from the recorded micro tremor ambient vibration data on ground level. Enhanced Frequency Domain Decomposition is used for the output only modal identification. From this study, very best correlation is found between mode shapes and frequencies .Shown the eigensensitivity–based finite element model updating and given its application to bench-scale aluminum bridges. The fundamental periods and corresponding mode shapes for the bench-scale aluminum bridges were determined experimentally using ambient vibration measurements. The modal parameters obtained experimentally were used to calibrate a finite element model of the structure. Based on the eigen sensitivity-based FE model updating procedure a summary of the changes the FEM results to the EMA results is presented graphically and numerically in percent to the initial state of the structure. As seen from the modal updating result MAC values were generated between analytical and experimental mode shapes. Main difference between mode shapes of the FEM and EMA was explained. Modal updating from the MAC that the 90% approach in the mode shapes nearly reached 100% after the ±5% increase in mass density which is made from the material properties (ρ)**

Keywords: **System Identification, FEM, Model Updating, Ambient Vibration, Bridge, MAC, EFDD**

I. INTRODUCTION

Nowadays the determination of the effect of vibration on structures and structural behavior has become imperative all over the world and including in Turkey. Turkey possesses many important historical structures. In addition, frequent earthquakes that have occurred in recent years Turkey have necessitated the need for additional research and studies on the experimental determination of the behavior of structures under vibration. Numerous buildings built in the past are notoriously known to suffer from damages caused by flaws in the design and construction stages, natural disasters and also overloading. Turkey is a country of 80 million inhabitants and is located on an active earthquake zone; vibration-damage assessment and evaluation are of paramount importance. Structures are always under constant vibration. Many factors such as wind, earthquake, wave, explosion, and vehicle load etc. cause vibration. These vibrations occasionally cause cracks and sometimes serious damage. Thus, the performance of structures under vibrations directly affects the life of that structure. The performance of the structures under vibration can only be determined by experimental studies. At the design of the structure, firstly analytical models are formed to represent the structure, static and dynamic analysis is carried out for different loading combinations on these models. In most cases the analytical model created does not fully represent the actual behavior of the structure. The comparison of dynamic parameters is used as a practical solution in determining and eliminating differences in building behavior.

Calibration of the analytical model is made extremely effective by making changes on the analytical model such that the experimental results in this case the dynamic parameters obtained by the experimental modal analysis methods reflect the actual performance of the structure. Thus, analytical models that represent the actual performance of the structures can be attained. Experimental modal analysis methods are used to determine the dynamic parameters of structures. In this technique, the vibration signals from the accelerometers placed in the structure are collected with the help of the data acquisition units and the dynamic parameters are then obtained by means of software. Experimental modal analysis is in two parts, forced vibration test and ambient vibration test. In the forced vibration test method, the structure is vibrated with the aid of known and measurable stimuli, and the response of the structure is then measured. In the ambient vibration test method, which is referred to as the operational modal analysis method, it is assumed that the structure is vibrated by environmental stimuli and the response that the structure gives to these stimuliis measured. Different methods based on the frequency and time domain are used to measure and evaluate the reactions. The mathematical bases of the methods used are the same while the data processing, equations solving techniques and matrix arrays are different from each other. Depending on the input and output sizes of these systems, in order to obtain a behavioral model, it is necessary to determine and measure the magnitudes affecting the structures. Model identification, system-related, based on physical laws based on the preliminary information and the size of the system (introduction magnitude or input signal) from the system's response to these magnitudes (output magnitude or output signal) [4]

Ambient vibration testing (also known as Operational Modal Analysis) is the most economical non-destructive testing method used to obtain vibration data from large civil engineering structures for Output Model Definition only.

The structural response (general frequency, displacement, velocity, acceleration steps) depending on the type of vibration (Traffic, Acoustics, Indoor Machines, Earthquakes, Wind), the recommended measurement amount (such as speed or acceleration) are given in the Vibration.

These structures response characteristics give a general idea of the preferred quantity and its rungs to be measured. Some studies on the analysis of ambient vibration of buildings carried out from 1982 up until 2015 are discussed in [7]. In the last ten years Output-Only Model Identification studies of buildings are given in appropriate structural vibration solution references. Structure It is necessary to estimate sensitivity of reaction of examined system to the change of parameters of a building for modal updating of the structure. Kasimzade (2006) System identification is the process of developing or improving a mathematical representation of a physical system using experimental data this is investigated by [8],[13], [37], and system identification applications in civil engineering structures are presented in works by [34], [12], [25],[30],[29][7],[38], [19],[20],[21],[22],[23],[24].Extracting system physical parameters from identified state space representation was investigated by [2],[5]. The solution to a matrix algebraic Riccati equation and orthogonality projection which are intensively and inevitably used in system identification was investigated by[1].In engineering structures there are three types of identification methods used, modal parameter identification; structural-modal parameter identification and control-model identification. In the frequency domain the identification is based on the singular value decomposition of the spectral density matrix and it is denoted by Frequency Domain Decomposition (FDD) and it is further improved to Development Enhanced Frequency Domain Decomposition (EFDD). In the time domain there are three different applications of the Stochastic Subspace Identification (SSI) technique used for the modal updating of the structure: Unweighted Principal Component (UPC); Principal component (PC); Canonical Variety Analysis (CVA)[10]. It is necessary to estimate the sensitivity to reaction of the 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 examine system. System identification is realized by observer [18] and Subspace [37], algorithms. In special cases the observer gain may coincide with the Kalman gain. Stochastic state-space model of the structure is simulated by Monte-Carlo method.

The bench-scale aluminum bridge is ideal for teaching structural dynamics, system identification topics related to earthquake, aerospace and mechanical engineering and widely used in civil engineering applications. In this study the possibility of using the recorded micro tremor data on ground level as ambient vibration input excitation data in the application of Operational Modal Analysis (OMA) for bench-scale aluminum bridges is investigated.

Analytical and experimental modal analysis of dynamic characteristics of abench-scale aluminum bridge is evaluated. 3D Finite element model of the structure is evaluated for the bench-scale aluminum bridge based on the design drawing. Ground level ambient excitation was provided from the recorded micro tremor ambient vibration data. Enhanced Frequency Domain Decomposition is used for the output only modal identification.

II. MODAL PARAMETER EXTRACTION

The (FDD) ambient modal identification is an extension of the Basic Frequency Domain (BFD) technique also called the Peak-Picking technique. This method uses the fact that in the case of a white noise input, and a lightly damped structure modes can be estimated from the calculated spectral densities. It is a non-parametric technique that determines the modal parameters directly from signal processing. The FDD technique estimates the modes using a Singular Value Decomposition (SVD) of each of the measured data sets. This decomposition corresponds to a Single Degree of Freedom (SDOF) identification of the measured system for each singular value [8]

The Enhanced Frequency Domain Decomposition technique is an extension to Frequency Domain Decomposition (FDD) technique. This technique is a simple technique that is extremely rudimentary. In this technique, modes are simply picked by locating the peaks in Singular Value Decomposition (SVD) 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 is based on the FFT resolution and modal damping is not calculated. On the other hand, EFDD technique gives an advanced estimation of the natural frequencies, the mode shapes and includes the damping ratios [14] In EFDD technique, the single degree of freedom (SDOF) Power Spectral Density (PSD) function, which is identified by a peak of the 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 zeros crossing as a function of time, and the damping by the logarithmic decrement of the correspondent single degree of freedom (SDOF) of the normalized auto-correlation function

In this study modal parameter identification is implemented by the Enhanced Frequency Domain Decomposition.

III. DESCRIPTION OF BENCH-SCALE ALUMINUM BRIDGE

Bench-scale Aluminum Bridge is 1.27 m height. The shape of the bridge is trapezoid. The top and bottom width are 2.15 m-2.30 m respectively. The dimensions of the elements are shown in Fig. 1.

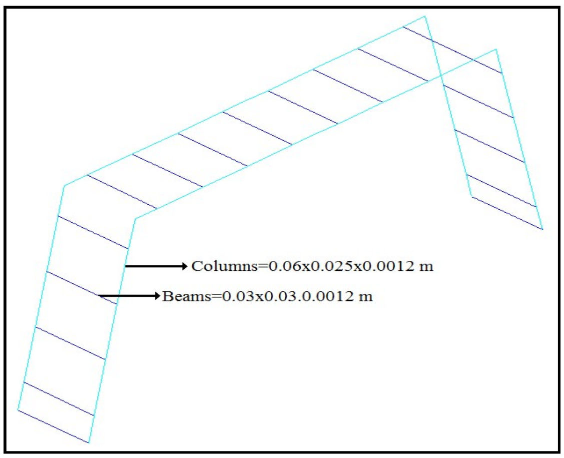


Fig. 1 Anillustration of bench-scale aluminum bridge

Fig. 2 Bench-Scale Aluminum Bridge

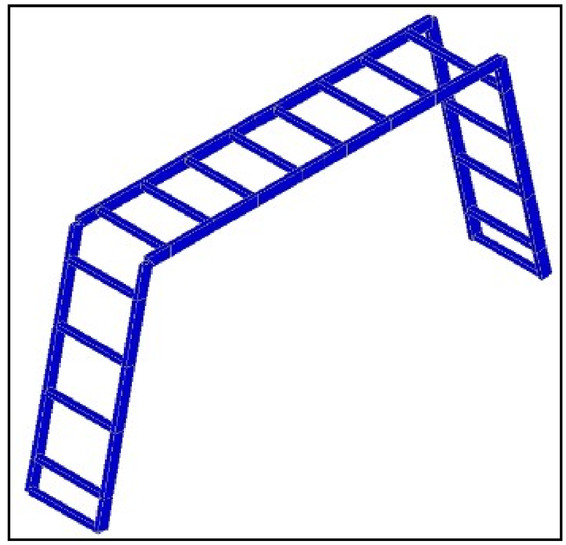
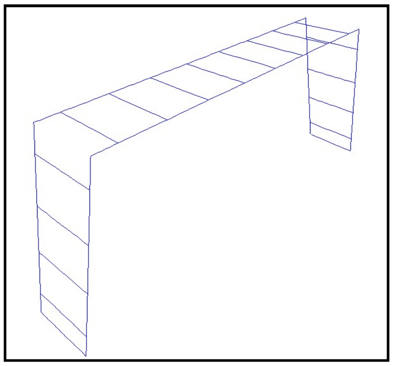


Fig. 3 Finite Element Model of a Bench-Scale Aluminum Bridge

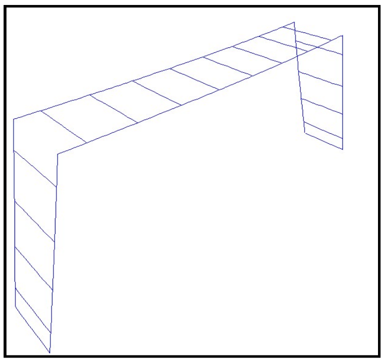
IV. ANALYTICAL MODAL ANALYSIS OF A BENCH-SCALE ALUMINUM BRIDGE

A finite element model was generated in [32]. Beams and columns were modeled as 3D beam-column elements (in Fig.3 shown by the black color). The slab is modeled as a rigid floor (rigid diaphragm). The selected structure is modeled as a space frame structure with 3D elements. Beams and columns were modeled as 3D beam-column elements which have degrees of freedom. A finite element model of the structure was created in SAP2000 the ends of every element were fixed at the base of the structure that is it is assumed that they is no translation andno rotation in the 6 degree of freedom (DOF)). The following assumptions were taken into account. Bench-scale aluminum bridge is modeled using equal thickness and shell elements have isotropic properties. All supports are modeled as fully fixed. The members of aluminum frame are modelled as is they are rigidly connected together at the intersection points. In modelling of beams and columns the following assumptions are made modulus of elasticity E=6.960E10 N/m^2, Poisson ratio μ=0.33, mass per unit volume ρ=26601 N/m^3

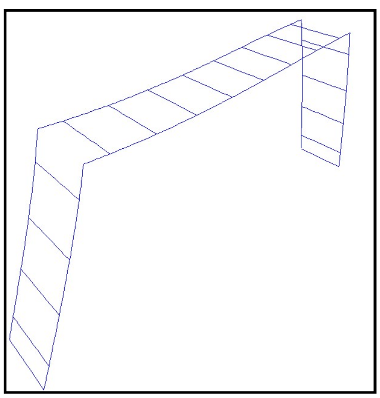
Natural frequencies and vibration modes are considered important dynamic properties and have significant impact on the dynamic performance of buildings. A total of five natural frequencies of the structure which range between 4 and 8 Hz were obtained. The first five vibration mode of the structure are shown in Figure 4. Analytical modal analysis results emanating from the finite element model are shown in Table 1.



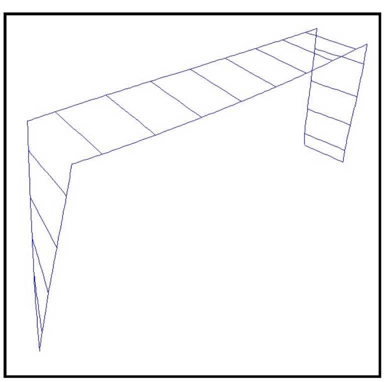
1st Mode Shape (f=4.880 Hz)



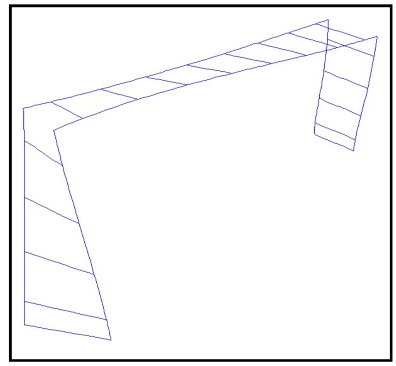
2nd Mode Shape (f=5.222 Hz)



3rd Mode Shape (f=5.740 Hz)



4th Mode Shape (f=6.502 Hz)



5th Mode Shape (f=7.084 Hz)

Fig.4 Mode Shapes Of Bench-Scale Aluminum Bridge Determined Analytically

V. EXPERIMENTAL MODAL ANALYSIS OF BENCH-SCALE ALUMINUM BRIDGE

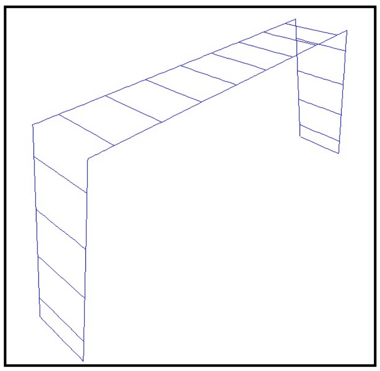
Ambient excitation was provided by the recorded micro tremor data on ground level. Three accelerometers (which can measure in both x and y directions) were used for the ambient vibration measurements Two accelerometers were used as roaming sensors Two data sets were used to measure the response .For the two data sets that were used 3 and 5 degrees of freedom were recorded respectively

The data acquisition computer was dedicated to acquiring the ambient vibration records. In between the measurements, the data files from the previous setup were transferred to the data analysis computer using a software package. This arrangement allowed data to be collected on the computer while the second, and faster, computer could be used to process the data on site. This approach maintained a good quality control that allowed preliminary analyses of the collected data. If the data showed unexpected signal drifts or unwanted noise or for some unknown reasons, was corrupted, the data set was discarded and the measurements were repeated.

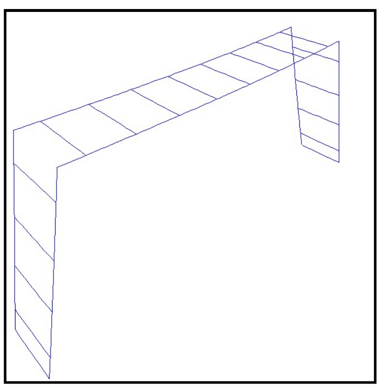
Before the measurements could begin, the cable used to connect the sensors to the data acquisition, equipment had to be laid out. Following each measurement, the roving sensors were systematically located from floor to floor until the test was completed. The equipment used for the measurement includes three sense box accelerometers (triaxial measures) and geosigseismometer, matlab data acquisition toolbox (wincon). For modal parameter estimation from the ambient vibration data, the operational modal analysis (OMA) software [3]was used.

The simple peak-picking method (PPM) finds the eigenfrequencies as the peaks of nonparametric spectrum estimates. This frequency selection procedure becomes a subjective task in the case of noisy test data, weakly excited modes and relatively close eigenfrequencies. For damping ratio estimation the related half-power bandwidth method is not reliable. Frequency domain algorithms have been the most popular, mainly due to their convenience and operating speed.

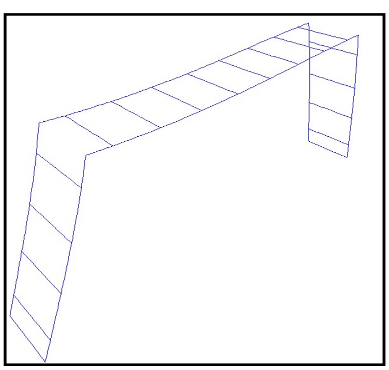
Singular values of spectral density matrices, attained from vibration data using PP (Peak Picking) technique Natural frequencies acquired from the all measurement setup are given in Table 2. The first five mode shapes extracted from experimental modal analyses are given in Fig 5. When all measurements are examined, it can be seen that the greatestharmony is found between experimental mode shapes. When the analytically and experimentally identified modal parameters are checked against each other, it can be seen that there is harmony between the mode shapes in experimental and analytical modal analyses



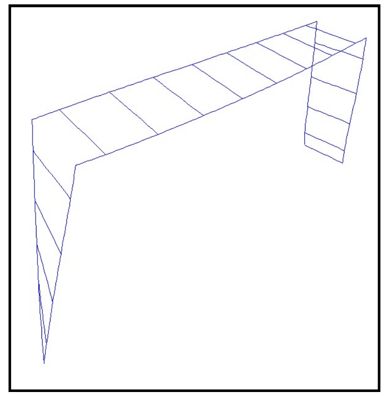
1st Mode Shape (f=4.761 Hz, ξ=0.743)



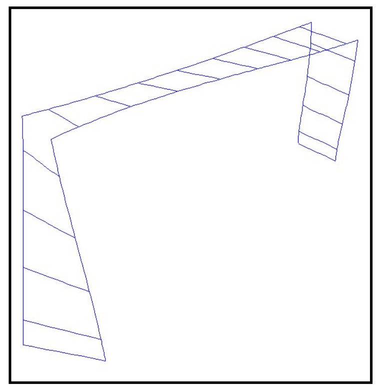
2nd Mode Shape (f=5.078 Hz, ξ=0.696)



3rd Mode Shape (f=5.591 Hz, ξ=0.632)



4th Mode Shape (f=6.323Hz, ξ=0.559)



5th Mode Shape (f=6.885 Hz, ξ=0.513)

Fig. 5ExperimentallyIdentified Mode Shapes Of Bench-Scale Aluminum Bridge

VI.FEM UPDATING STUDY

This study involved the comparison of the natural frequencies and mode shapes of the experimental model analysis and FE models until an acceptable correlation was achieved. Details of the FE model used for this study and the parameters selected for the model updating is given in the following sections.

6.1. Finite Element Model Calibration of the Structure

A finite element model was generated in SAP2000. Beams and columns were modeled as 3D beam-column elements. At the base of the structure in the model, the ends of every element were fixed against translation and rotation for the 6-DOF. In modeling of the aluminum space frame young's module E=69637.055 MPa, the material mass density ρ =26601N/m^3, the Poisson ratio μ=0.33. In total model consisted of 58 beam column elements and it contained 42 nodes. Dynamic analysis result of the finite element structure model is shown in Table 1.

Table 1. Analytical Modal Analysis Result From Finite Element Model

Mode number	1	2	3	4	5
Frequency (Hz)	4.880	5.222	5.740	6.502	7.084

Table 2. Operational Modal Analysis Result

Mode number	1	2	3	4	5
Frequency (Hz)	4.761	5.078	5.591	6.323	6.885

6.2. Selection of Parameters for Model Updating

When the table of comparison of the theoretical and experimental frequencies of the aluminum bridge is examined, it is seen that there are some differences between the natural frequencies obtained analytically and experimentally results. A sensitivity analysis of the dynamic response of the finite element model of the structure to a change in element properties was first conducted on a large number of parameters. A parameter refers to a selected property of a given element. Mass per unit volume (ρ) was chosen as parameter for sensitivity analysis. Table.3

Table 3.Material Updated Parameters

	Before Fem Updating	After Fem Updating
Material	Mass per unit volume ρ(N/m3)	Mass per unit volume ρ(N/m3)
Bridge	**26601**	**27931**

6.3.The Eigensensitivity-Based Finite Element Model Updating

In mention method, the relationship between the perturbation in the updating parameters $\delta\{P\}=\{P\}-\{P_{\text{cur}}\}$ and the difference $\delta\{D\}=\{D_{\text{mea}}\}-\{D_{\text{cal}}\}$ between the measured $\{D_{\text{mea}}\}$ and calculation results $\{D_{\text{cal}}\}$ from the finite element model can be represented by a sensitivity matrix $[S]$ as [5]:

$$\delta\{D\}=[S]\delta\{P\} \tag{1}$$

in which $\{P\}$ and $\{P_{\text{cur}}\}$ are updated and current vectors of the updating parameters, respectively; Elements of the sensitivity matrix are determined as:

$$S_{ij}=\frac{\partial\{D_i\}}{\partial\{P_j\}} \tag{2}$$

Where $\{D_i\}$ the *i*-th component of the modal is vector, and $\{P_j\}$ is the *j*-th component of the updating parameter vector. Through differentiating the eigen equation $[k]\{\phi\}=\lambda[m]\{\phi\}$ of a structural system with respect to updating parameters $\{P_j\}$, the derived formula for natural frequencies can be obtained as follows [8]:

$$\frac{\partial\lambda_k}{\partial P_i}=\{\phi_k\}^T\frac{\partial[k]}{\partial P_i}\{\phi_k\}-\lambda_k\{\phi_k\}^T\frac{\partial[m]}{\partial P_i}\{\phi_k\} \tag{3}$$

Where λ_k is the current *k*-th eigen value; $\frac{\partial\lambda_k}{\partial P_i}$ is the notation for the sensitivity of the *k*-th eigen values λ_k with respect to updating parameter P_i; $\{\phi_k\}$ is the current *k*-th mode shape which is normalized to the mass matrix $[m]$; $[k]$ is the current stiffness matrix. In ambient tests, higher natural frequencies are often obtained with less accuracy than the lower order ones. Therefore, a weighting matrix $[W_P]$, whose entries are often obtained from the reciprocals of the variance of the corresponding modal data, is introduced in the FE model updating algorithm. If only the weighting matrix of the updating parameters $[W_P]$ is considered, the best estimation for the updating parameters can be obtained through the weighted least squares method. In this way, the solution for simultaneous equation (1) can be obtained by considering a constrained optimization problem as follows:

Minimize $\delta\{P\}^T[W_P]\delta\{P\}$ subject to (4)

$$\delta\{D\}=[S]\delta\{P\}$$

Its corresponding solution is

$$\delta\{P\}=[W_P]^{-1}[S]^T\left([S][W_P][S]^T\right)^{-1}\delta\{D\} \tag{5}$$

If both the weighting matrices $[W_P]$, $[W_D]$ are included, the best estimation of the updating parameters can be obtained by the Bayesian estimation technique. The associated FE model updating procedure can be regarded as seeking the solution of the following constrained optimization problem:

Minimize

$$\left(\delta\{D\}-[S]\delta\{P\}\right)^T[W_D]\left(\delta\{D\}-[S]\delta\{P\}\right)+\delta\{P\}^T[W_P]\delta\{P\}$$

Subject to

$$\delta\{D\} = [S]\delta\{P\} \tag{6}$$

The corresponding solution can be obtained as [3]:

$$\delta\{P\} = [W_P]^{-1}[S]^T\left([W_D]^{-1} + [S][W_P]^{-1}[S]^T\right)^{-1}\delta\{D\} \tag{7}$$

In order to avoid the updated results being physically meaningless, the lower and upper limits for the updating parameters are necessarily set in the FE model updating procedure, these are listed in Table 2.

The convergence criteria were also set in each iteration loop as follows:

$$|f_k - f_{\bullet k}| \le \text{Specified limit of natural frequency difference} \tag{8}$$

$$\text{MAC}(d_k, d_{\bullet k})_{k=1,n} \ge \alpha \tag{9}$$

$$\{P_{lower}\} \le \{P_k\} \le \{P_{upper}\} \tag{10}$$

Where f_k, $f_{\bullet k}$ are the current analytical and corresponding experimental values of the natural frequency, respectively; $\{P_{lower}\}$, $\{P_{upper}\}$ are the lower and upper limits of the updating parameters, respectively; α is the lower limits of the MAC matrix; n is the compeered appropriate mode's number, another word it is the considered number of compeered degree of freedom of the structural system; $\text{MAC}(d_k, d_{\bullet k})_{k=1,n}$ is the modal assurance criterion indices for between the FE computational d_k and experimental $d_{\bullet k}$ mode shapes, which indicate how well the FE mode shapes fit to the corresponding measured ones and calculated as:

$$\text{MAC}(d_k, d_{\bullet k})_{k=1,n} = \frac{\left(\sum_{j=1}^{n} \phi_{jk}\phi_{\bullet jk}\right)^2}{\sum_{j=1}^{n}(\phi_{jk})^2 \sum_{j=1}^{n}(\phi_{\bullet jk})^2} \tag{11}$$

In which ϕ_{jk}, $\phi_{\bullet jk}$ are the j-th coordinates of the k-th analytical and measured mode shapes, respectively. Once all the conditions listed in equations (8-11) are satisfied, the iteration process ends, and the final FE model updated results are obtained.

VII. MODAL UPDATING RESULTS

In order to overcome these differences between natural frequencies and minimize them, the bridge's finite element model should be improved according to the experimental measurement results. It can be seen from the MAC graph (Fig.6-7) that the 90% approach in the mode shapes nearly reached 100% after the ±5% increase in mass density, which is made from the material properties. Table 3.

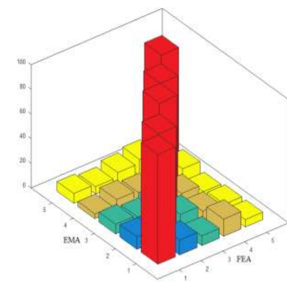


Figure 6. 3D view of the parameters-shape modes response.3D plots of MAC matrices to five mode shapes of structure before updating parameters.

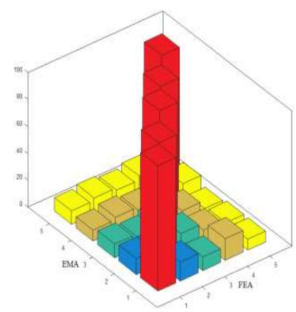


Figure 7. Comparison of 3D plots of MAC matrices to five mode shapes of structure after updating parameters

VIII. CONCLUSION

In this paper, analytical and experimental modal analysis of bench-scale Aluminum Bridge was presented. Comparing the result of study, the following observation can be made:

From the finite element model of bench-scale aluminum bridge a total of 5 natural frequencies were attained analytically, which range between 4 and 8 Hz. 3D finite element model of bench-scale Aluminum Bridge is constructed with SAP2000 software and dynamic characteristics are determined analytically. The ambient vibration tests are conducted under ambient vibration data on ground level. Modal parameter identification was implemented by the Enhanced Frequency Domain Decomposition (EFDD) technique. Comparing the result of analytically and experimentally modal analysis, the following observations can be made:

Shown the eigensensitivity–based finite element model updating and given its application to for bench-scale aluminum bridges. The fundamental periods and corresponding mode shapes for bench-scale aluminum bridges were determined experimentally using ambient vibration measurements. The modal parameters obtained experimentally were used to calibrate a finite element model of the building. MAC values were generated between analytical and experimental mode shapes. Main difference between mode shapes of the FEM and EMA was explained.

Based on the eigensensitivity-based FE model updating procedure a summery of the changes the FEM results to the EMA results is presented graphically and numerically in percent to the initial state of the structure. As seen from the modal updating from the MAC graph (Fig.6-7) that the 90% approach in the mode shapes nearly reached 100% after the ±5% increase in mass density, which is made from the material properties (ρ).As seen from the mac graphics, it was a complete overlap.

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