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Structural Model Calibration of Vierendeel Bridge Based on the Vibration Properties

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Abstract. In this study the Vierendeel bridge structural model is adopted as a complex structure case study scaled from a real structure located near Čačak city in Serbia. Experimental analysis is conducted under simulation of ambient vibration using shaker device for exciting the model. Frequency Domain Decomposition (FDD) technique is applied using ARTeMIS software extractor to extract the modal properties, natural frequencies and mode shapes. As a comparative study, Enhanced Frequency Domain Decomposition (EFDD) is used to verify the extracted results from FDD. A finite element model is created in ANSYS software to simulate the adopted model to estimate modal properties numerically. Calibration process is implemented to converge the numerically estimated with the experimentally extracted modal properties. Two procedures written in MATLAB environment, for calibration and damage identification, are proposed using heuristics optimization, Simulated Annealing (SA) and Tabu Search (TS). Both of proposed calibration procedures exhibit high accuracy and efficiency due to good convergence between experimentally extracted and numerically updated values of natural frequencies extracted based on ambient vibration measurements.

1. Introduction

The integrity of complex structures need special attention due to high cost of construction and maintenance. During service life, those structures are exposed to external ambient loads, like as traffic loads, wind loads...etc. as reported in Brincker et al. [1]. Vierendeel bridge is a one of complex structures which has two structural behaviours, flexural and truss actions. One of the integrity monitoring methods for structures is vibration-based damage detection technique. Ambient vibration identification is applied technique for extracting the dynamic properties of structure in civil engineering as presented in Brincker et al. [2] and ARTeMIS guide [3].

One of the advantages of ambient vibration analysis is application of an output-only modal identification, instead of excitation the structure artificially, dealing with the natural excitation as the source as mentioned in Brincker et al. [4], Wang [5] and Palacz and Krawczuk [6]. The other advantages of this kind of testing are: the testing is fast and cheap, equipment for excitation does not be required, the testing does not interfere with operation of structure and the real operating conditions could be presented. Many extractors of modal properties are used in literature, herein, Frequency Domain Decomposition (FDD) technique within ARTeMIS software extractor is adopted compared with the Enhanced Frequency Domain Decomposition (EFDD) technique as mentioned in ARTeMIS guide [3].

During the creating of numerical model based on certain experimental model, usually there are differences in modal properties between results of both models for the first analysis. This mismatch is treated by the concept of calibration process. FE tools are one of the famous tools that used for that purpose [7].

Modal identification process should be accurately accomplished, for both experimental and numerical models, in order to verify the stability of the extracted modes which are used later in structural purposes. The convergence of experimental and numerical estimated modes could be an indication for the stability of modes and the calibration process is the best way for achieving such convergence. For calibration process, updating of FE model parameters are required, such as natural frequencies or structural stiffness [8, 9].

Therefore, SA and TS heuristic optimization methods could be effective because of their ability to find global or near-global minimum and quick convergence performances, with their of objective function as mentioned in Michel et al. [10] and Kirkpatrick et al. [11].

In this study, proposed calibration procedures using SA and TS methods, depend on change in modal properties, are implemented for converging values of the natural frequencies that estimated experimentally and numerically.

2. Description of tested structure

The adopted Vierendeel bridge model is scaled of a real structure in site which is located near Čačak city in Republic of Serbia. The real structure is scaled with adequate changes to be suitable with the space of the laboratory of the Faculty of Civil Engineering in University of Belgrade. Figure (1) shows the scaled Vierendeel bridge model under its own mass during ambient vibration testing.

Figure 1. Tested Vierendeel bridge model structure in laboratory

The adopted model is a complex 3D-space, welded steel structure, has two structural actions, flexural and truss. The model consists of a grid floor and two fences with 11-column in each side. Total length of the model, Figure (2), is 6720 mm that consists of 10-bay at 672 mm c/c for each. The total width of the model is 800 mm c/c, containing 8-grid of 100 mm c/c. The grid floor is fabricated from two main longitudinal steel beams have rectangular hollow section of (30x50x2.8) mm located at the edges of the floor. For the main transverse beams, eleven beams have the same section of (30x50x2.8) mm are used by welding with the main two longitudinal beams to formulate the whole floor. Additional longitudinal beams act as stiffeners for the floor welded with the main transverse beams. The distribution of the stiffeners is equal over the total width of the model at 100 mm c/c. Each stiffener has a plate section of (45 x1.5) mm which is welded also with the top plate placed orthogonally. The plate of the deck is welded over the grid frame at 50 mm welding at 150 mm spacing, as shown in Figure (2).

The columns sections of the fences have (30x40x2.25) mm dimensions and the columns connect the two main longitudinal beams in the grid floor with main longitudinal upper beams. The main longitudinal upper beams have the same cross section as in the main longitudinal lower beams of grid floor. Each column is stiffened by two triangular steel parts have dimensions of (71x71x100x2.8) mm on the top and bottom, as shown in Figue (1). The supports are on the two edges of the model over four concrete blocks. Each two concrete blocks are glued together by two concrete struts to stiffen the supports from the side movement. One support is hinged in 3-direction, two supports are hinged in 2-direction and one support is roller, as shown in Figure (1).

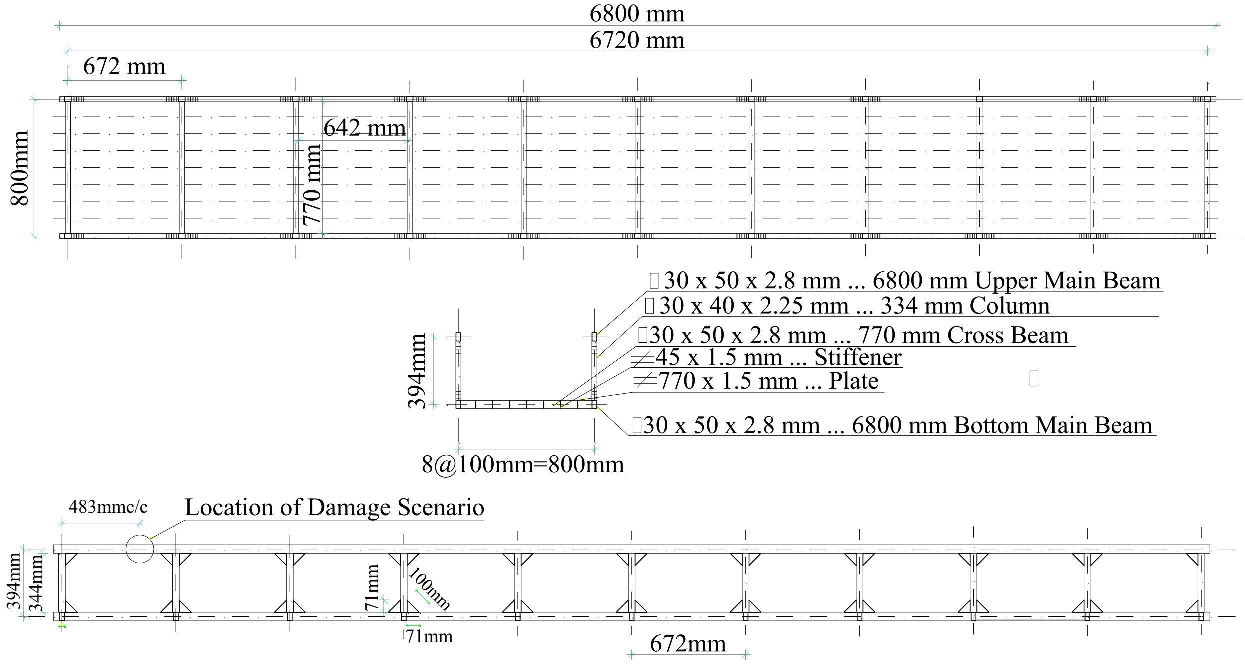
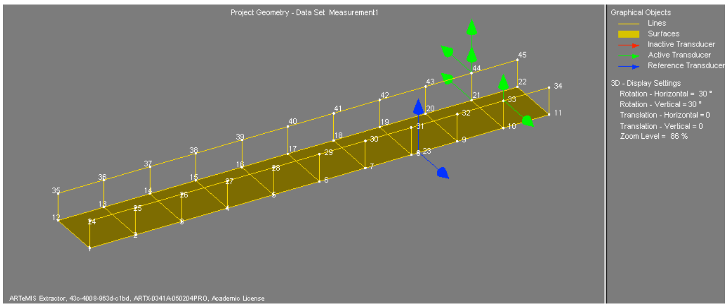


Figure 2. Geometry of the adopted Vierendeel bridge model

3. Simulation of ambient vibration excitation

Simulation of ambient vibration excitation of the Vierendeel bridge model structure is carried out by authors and staff of the laboratory for structures of Faculty of Civil Engineering at the University of Belgrade. The model is prepared to distribute the points of measurements in suitable positions to reflect the actual behaviour through real mode shapes of the model under vibration. In the case of small structures, just up to 10 points are sufficient, while in the case of large structures up to 60, or more, test points is required for representation relevant mode shapes. However, there are no clear guidelines of number of test points, and it depends on structural type, design, and other factors as mentioned in ARTeMIS guide [3]. The measurements points are divided to 10 sets to represent all 10 bays in the model due to the complexity of the adopted 3D-model. Also, the reason of using 10 sets is due to the available number of accelerometers during the experimental test. The 10 sets consist 41 total measured movements including the movements of reference point, as shown in Figure (3).



3D - Display Settings
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Figure 3. Layout of the distributed measured movements in the second set of Vierendeel bridge structural model

The movements of reference point are fixed throughout all the 10 sets of measurements because of the requirements of the data analysis process. Each set contains 8 measured movements to simulate the motion of these selected points. The eight points are distributed to 4-vertical movements and 4-horizontal movements. The longitudinal movement is neglected due to the lower effect for this movement. The distribution of measured points takes into account the space movement of the model, thus, two points are selected on upper main beams and the other two points are on the lower main beams including the reference point, as shown in Figure (3) and Figure (4).

Figure 4. Positions of measurement points in one set with reference point for the model and acquisition system with laptop

The required devices for the ambient vibration measurements are supplied to conduct the experimental test and record the dynamic response data of the model. The devices include, data acquisition, PC computer, accelerometers, shaker and voltage regulator, as shown in Figure (4). A set of eight Silicon Design Model-2240 accelerometers are used with high quality cables or a transmission system, all are connected up to a high quality data acquisition system. The data acquisition device, has 8 channels, battery powered, Hottinger Baldwin Messtechnik - HBM data acquisition system is used for recording the measurements. The shaker device is installed between the supports during the test, as shown in Figure (5), also the figure shows installation of two used accelerometers during the test.

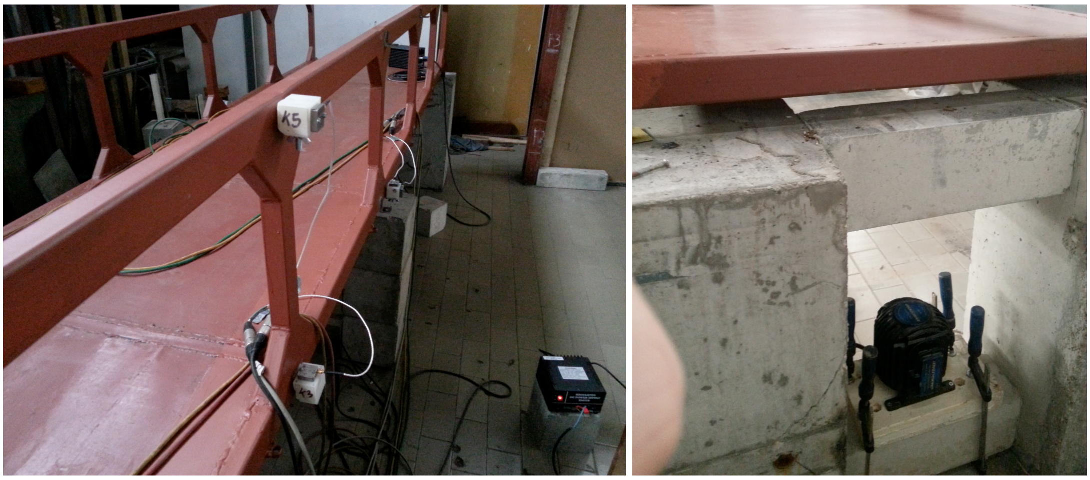


Figure 5. Accelerometer installed on the measured point of the model and shaker device to simulate ambient vibration installed over the support

The measure parameters which are used in the test, sampling frequency, cut-off frequency and intensity level were 600 Hz, 200 Hz and 7, respectively. The used software for data recording is CAT-MAN software which supplied with the data acquisition device. Each set of measurements requires 20 minutes for complete recording, which produce a file contains about 1000000 rows and 8 columns of acceleration values which represents acceleration time history

4. Experimental analysis of the Virendeel structural model

The extraction of medal properties was made by ARTeMIS software extractor. This extractor software includes technique depend on frequency domain, FDD, with their results represented by natural frequencies, mode shapes and damping ratio as mentioned in ARTeMIS guide [3].

4.1. Extraction methods of model modal properties

The idea of the FDD technique is to perform an approximate decomposition of the system response into a set of independent single degree of freedom (SDOF) systems as mentioned in ARTeMIS guide [3]. As the data is recorded, the operation of data processing is conducted by FDD depending on several chosen parameters. In this study, the adopted parameters used in experimental analysis are low pass filter and frequency lines. There are several values of frequency line of processing data in extractor software. Three values of frequency line are adopted 2048, 4096 and 8192 in order to get more confidence to the obtained results during the analysis of each iteration. The FDD technique depends in its estimation to extract modal properties on the way of peak picking process which uses the peaks of the resulted spectral density matrix as an indicator for the candidate available modes. Each extracted mode should be examined by the value of MAC that correlates each mode with another, during the selection process

4.2. Analysis results of adopted model

For the modal properties estimation using FDD technique, the frequency line value is 8196 and 4096 for the state of model with low pass filter for data processing. and with low pass filter for data processing. Application of the pick picking procedure, for estimating modal properties from spectral density matrices of the data analysis for the adopted model using FDD, is shown in Figure (6). Four modes are adopted in the present study, which are sufficient to reflect the dynamic behaviour of the model.

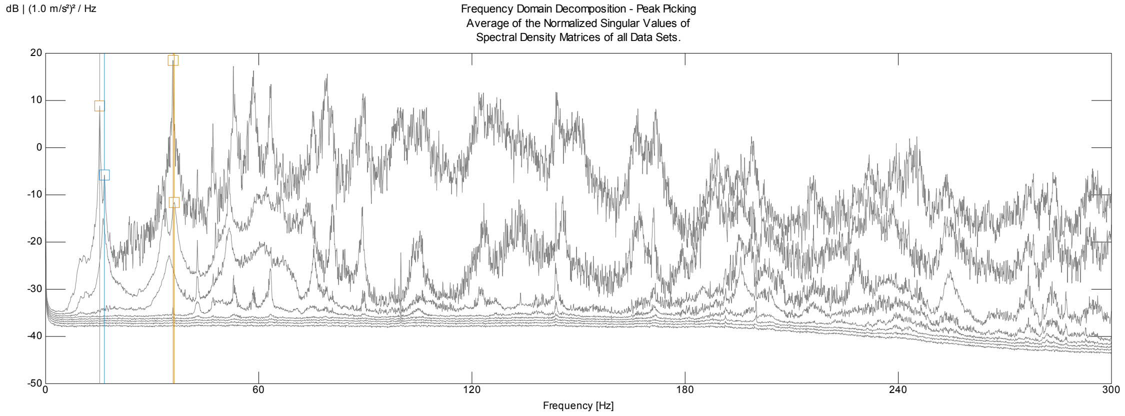


Figure 6. The picked values of modes by the peak picking procedure in spectral density matrix for the adopted model

For verification purposes, values of MAC for the adopted model is represented by bar charts to give an indication for the relationship between each two modes. Figure 7 shows the correlation between each two extracted modes using FDD technique for the model. Results of MAC values in Figure (7) verify the validity of the extracted modes with the respect to their stability.

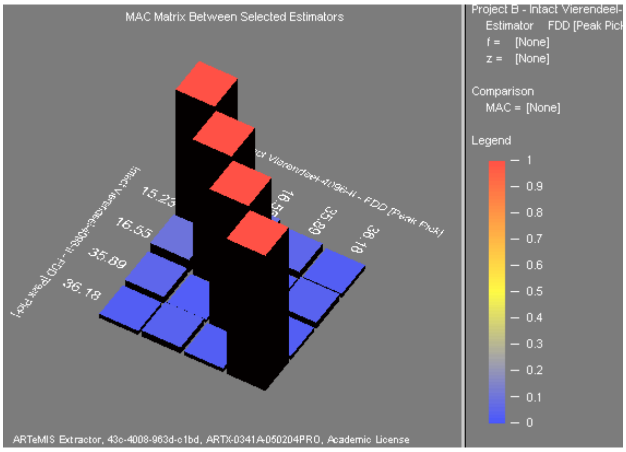
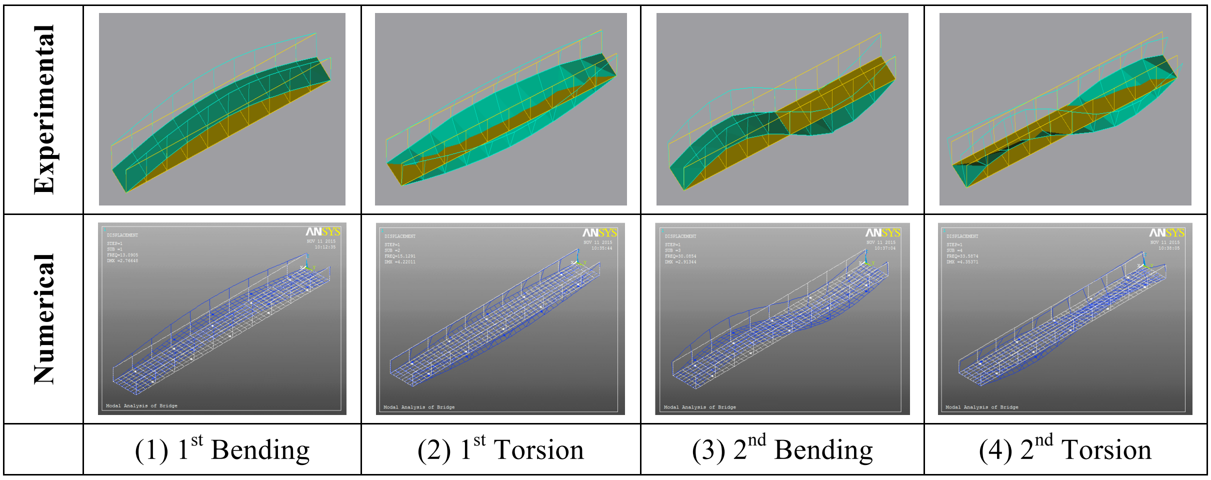


Figure 7. MAC verification of the extracted modes by FDD technique for the adopted model

The results of the mode shapes and their characters for the adopted intact model using FDD technique are shown in Figure (8). The extracted modal frequencies by FDD technique for the intact model are listed in Table (1).



(1) 1st Bending (2) 1st Torsion (3) 2nd Bending (4) 2nd Torsion

Figure 8. Estimated mode shapes and their characters for the intact model using FDD technique experimentally and FE analysis numerically

It is evident from Table (1), all values of damping ratio are within the limits of recommendations for the damping ratio of stable modes which refer to 5% as a maximum value as mentioned in ARTeMIS guide [3]. This gives an indication that the extracted modes by FDD technique, with accepted values of damping ratios, are stable modes and can be used for structural purposes. Therefore, the convergence between values of natural frequency extracted by FDD techniques verify that the FDD technique is accurate for modal estimation. Hence, the FDD technique is adopted in the present study due to its efficiency and simplicity, and damping ratio is not included in proposed procedures.

Table 1. Experimental extracted natural frequency values and damping ratios for the intact model using FDD techniques

No. of mode	Mode shape	Natural Frequency(Hz) using FDD	Damping Ratios (%)
1	1st Bending	15.230	0.485
2	1st Torsion	16.550	1.043
3	2nd Bending	35.890	0.207
4	2nd Torsion	36.180	1.478

5. Numerical analysis and calibration process

5.1. FE model analysis for the adopted model

The numerical analysis of the adopted model was carried out using ANSYS-software, by creating FE model with 1402 elements using Beam4 element type. Different element lengths are applied to simulate the element model dimensions. Those different lengths are used to decrease the number of degrees of freedom in the created FE model. For the main lower and upper edge beams, 42 mm length is used, while, for the columns two lengths are applied. For stiffer column elements in the lower and upper end of each column, a 60 mm length is used to simulate the additional stiffeners and 54.5 mm length for other parts of columns. On the other hand, for transverse main beams and hidden beams a 100 mm element length is used while, for internal longitudinal stiffener beams a 168 mm is used. The hidden beams represent additional elements with zero mass density that added in the FE model only to suppress the local modal behaviours. The results of modal analysis, natural frequency and mode shapes, for the initial FE model are listed in Table 2. The mode shapes and their characters for the adopted model are shown in Figure (8).

The values of differences in natural frequencies of numerical modal analysis of FE model compared with those extracted from experimental analysis for the intact initial FE model, are listed in Table (2).

Table 2. Numerical natural Frequency values and the differences between experimental and numerical for the intact initial model

	Experimental Freq (Hz)	Initial Numerical Freq (Hz)	Difference in Freq (Hz)
1	15.230	17.250	-2.020
2	16.550	18.123	-1.573
3	35.890	40.825	-4.935
4	36.180	40.896	-4.716

It clear obvious fromn Table (2), that the differences are higher in the third and fourth modes and in this case need calibration process to reduce them to be closer.

5.2. Proposed calibration procedure

The calibration process between experimental and numerical estimates of the modal properties is conducted to minimize the difference between them. For this FE model, a proposed procedure of calibration is applied using SA and TS optimization methods with selected target function. The adopted target functions depending on a changing in natural frequencies only, during updating the selected parameters of the model, are defined in Equations (1) and (2) for the proposed procedures using SA and TS, respectively. The target in Equations (1) and (2) minimizes the sum of direct and relative squared differences, respectively, between numerically updated and experimentally extracted natural frequency values as an optimum solution, as following:

$$Obj\_fun = \sum_{i=1}^{n} \left(f_i^{exp} - f_i^{updated} \right)^2 \quad (1)$$

$$Obj\_fun = \sum_{i=1}^{n} \left(\frac{f_i^{exp} - f_i^{updated}}{f_i^{exp}} \right)^2 \quad (2)$$

where, f_i^{exp} and $f_i^{updated}$ represent natural frequencies extracted experimentally and estimated numerically for the i^{th} mode, respectively, and n is the number of included modal frequencies in calibration process, in this study four modal modes $n = 4$ are included.

For the proposed calibration procedure using SA method, eight parameters of the model, represent the effect of flexural stiffness and density of the model material, are selected. The included parameters are: thickness of rectangular hollow section for main lower and upper beams; equivalent height of rectangular hollow section for stiffener part of main beams; thickness of T-section for longitudinal internal beams; width of hidden transverse beams; thickness of rectangular hollow section for columns; equivalent height of rectangular hollow section for stiffener part of columns; modulus of elasticity and density of steel material.

For the proposed calibration procedure using TS method, only three parameters are used. The selected parameters are thickness of rectangular hollow section for main lower and upper beams, equivalent height of rectangular hollow section for stiffener part of main beams and columns, and modulus of elasticity.

Figure (9) shows the significant improvement of target functions during calibration procedure using SA and TS optimization methods.

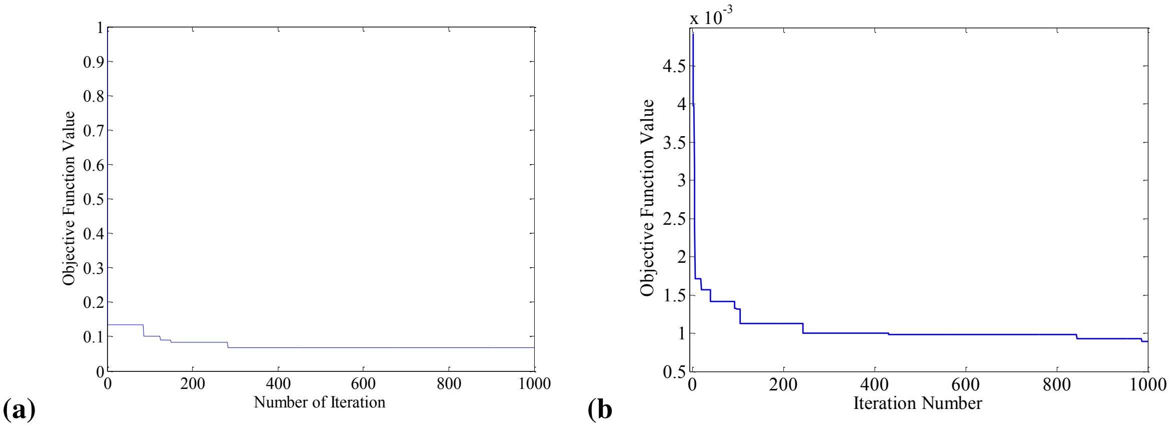


Figure 9. Improvement in the minimum difference in natural frequencies for the model during optimization process by, (a) SA method and (b) TS method

The optimum values of parameters by calibrating using SA method are: thickness of rectangular hollow section for main lower and upper beams of 2.7 mm; equivalent height of rectangular hollow section for stiffener part of main beams of 90 mm; thickness of T-section for longitudinal internal beams of 1.5 mm; width of hidden transverse beams of 95 mm; thickness of rectangular hollow section for columns of 2.3 mm; equivalent height of rectangular hollow section for stiffener part of columns of 115 mm; modulus of elasticity of 200 GPa; mass density of steel material 8000 kg/m3.

For TS calibration process, the optimum model parameters are 2.93 mm, 64 mm and 190.5 GPa for the thickness of the main hollow sections, depth of the stiffened elements in beams or columns and modulus of elasticity, respectively.

The final calibrated modal frequency values, for proposed procedure using SA and TS methods, are represented in Table (3), also, the table shows the differences in natural frequency values between experimental and numerical calibrated values.

Table 3. Calibrated frequency values and the differences for both proposed procedure using SA and TS for the model

Mode No.	Experimental values of natural frequencies (Hz)	Original values of natural frequencies (Hz)	Differences (Hz)	Calibrated values of natural frequencies (Hz) by SA	Differences (Hz)	Calibrated values of natural frequencies (Hz) by TS	Differences (Hz)
1	15.230	17.250	-2.020	15.475	-0.245	15.254	-0.024
2	16.550	18.123	-1.573	16.618	-0.068	16.691	-0.141
3	35.890	40.825	-4.935	35.788	0.102	35.160	0.730
4	36.180	40.896	-4.716	36.25	-0.07	36.906	-0.726

The convergence in values of natural frequencies after the application of proposed calibration processes by SA and TS methods is shown in Figure (10).

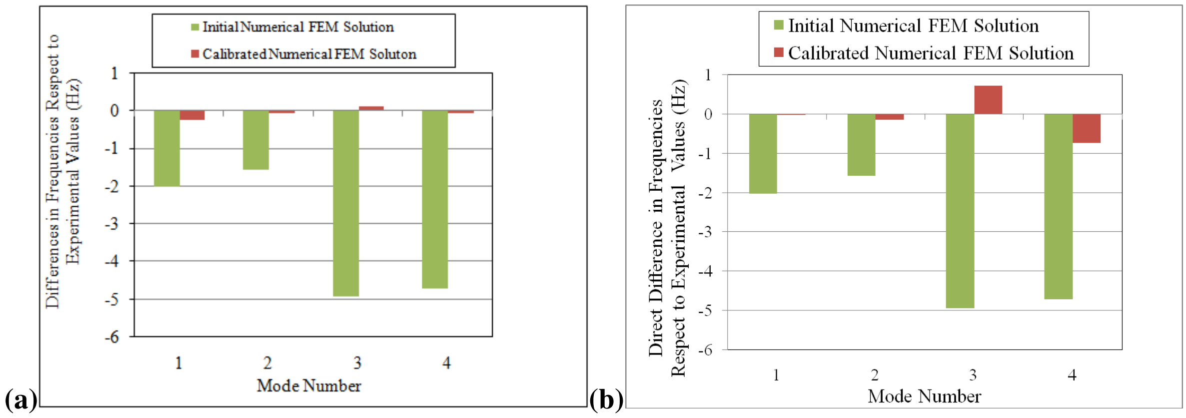


Figure 10. Convergence in calibrated natural frequencies for the model using, (a) SA method and (b) TS method

6. Conclusion

In the present study, experimental and numerical analyses of the Vierendeel bridge model are conducted. Estimation modal properties using FDD technique is efficient with accurate results and a simple technique. Using few numbers of accelerometers (transducers) is sufficient and suitable to reflect actual behaviour during data measuring under simulated ambient excitation of the model. The shaker device produces adequate excitation for the adopted model to extract modal properties using professional extractor of ARTeMIS software. This software, with all its parameters, presents modal results clearly, easily and understandably. The creating of FE model in ANSYS software, gives reliable and acceptable modal properties with respect to the experimental result of the model. After implementation of the proposed calibration process, high convergence is achieved between updated numerical and estimated experimental modal properties for the model. The number of the included parameters in calibration process is important and effective in convergence of final updated results.

7. Acknowledgments

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