Experimental determination of the natural frequencies of a full scale double layer grid with ball joint system

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SUMMARY:
One type of space structures known as double layer grids are the structural systems that their actual responses obtained through experimental measurements are rather different from analytical responses. This is because of some uncertainties in these structural systems that cannot be considered in analysis. In the present work, a series of modal testing have been done on a full scale double layer grid with ball joint system, in order to measure its actual natural frequencies. The structure was suspended from four points using suitable springs to simulate free support conditions. By exciting the structure with an impulse hammer and measuring input force together with output acceleration, frequency response functions were recorded at different degrees of freedom in the frequency range of 0 to 200 Hz. The obtained results show relatively complex dynamic behavior for the double layer grid with many close modes and high damping values in some frequency ranges.

Keywords: Double layer grid, Ball joint system, Modal testing, Natural frequencies

1. INTRODUCTION

Double layer grids are an important family of space frames used to cover large spaces. For ease of handling, flexibility in fabrication and speedy on-site erection, these structures are mainly prefabricated. Therefore, the components of double layer grids are normally mass produced in factory with a high standard of quality control. Several industrialized systems have been developed and applied in construction of double layer grids and one of the most popular of these is ball joint system.

Natural frequencies are important global properties of a structure that include stiffness and mass properties. They have an important role on the behavior of a structure under dynamic loading. Moreover, natural frequencies are extensively used in finite element model updating and damage assessment of existing structures. Chellini et al. (2010) used vibration frequencies of the first four modes and relative mode shapes for updating a finite element model of a high ductile steel-concrete composite frame and to perform damage assessment. Jaishi and Ren (2007) used natural frequency and modal strain energy residues in a model updating problem. To test a proposed updating algorithm, Basaga et al. (2011) used five natural frequencies of experimental models for finite element model updating. Dilena et al. (2011) utilized the results of experimental modal analysis including first few vibration frequencies and mode shapes to determine boundary conditions and estimate cracking effects of a single span bridge using model updating method.

In double layer grids constructed from ball joint system, the conventional methods of analysis, based on the assumption that the joints are either full rigid or ideally pinned, do not yield correct approximations of actual natural frequencies of the structure. Behavior of joints has significant effect on the response of double layer grids (Davoodi et al., 2007) (Pashaee et al., 2006) and to get a more accurate estimation of the structure response, the effect of joints should be considered in modeling (Fan et al., 2012). The joint behavior includes many uncertainties, some of them are: manufacturing tolerances and discontinuities in the joint components, different degrees of bolt tightness in the joints, and so on. Since these uncertainties cannot be considered easily in analysis, it is more appropriate to obtain dynamic properties of the double layer grid using experimental methods.

In the present study, a double layer grid with ball joint system was constructed from the components which are generally utilized in practice. Modal testing was carried out on the grid in free support condition and its frequency response functions were measured at appropriate degrees of freedom. Frequencies of first twelve vibration modes of the grid were obtained through experimental modal analysis.

2. DOUBLE LAYER GRID WITH BALL JOINT SYSTEM

For this study, a double layer grid with a standard configuration of two way on two way with ball joint system were made. The components used in the grid are the same as those used in practice. The general view and the plan of the grid are shown in Fig. 2.1a and 2.1b respectively. In the figure, top layer members are shown with solid lines while bottom layer members and web members are shown with broken lines and dotted lines respectively. The horizontal center to center distance of adjacent nodes in each layer of the grid is 1.414 m and distance between the top and bottom layers is 1 m. The grid consists of 96 members and the approximate weight of the structure is 8550 N. All the members used in the grid are identical.

(a) (b)

Figure 2.1. (a) General view and (b) plan of the double layer grid

As shown in Fig. 2.2, each member consists of a steel tubular part and end connectors. The tubular part has outer diameter of 7.64×10^{-2} m and wall thickness of 0.35×10^{-2} m. Details of the end connector are shown in Fig. 2.3. The forged steel ball has ten threaded holes at different angles and is located at the intersection of longitudinal axes of connected members. The conical end piece is welded to the end of tubular part. The high tensile bolt passes through the conical end piece and is screwed into the ball with the aid of the sleeve. The dowel pin constrains rotation of bolt to the sleeve, allowing turning of the bolt. The windows on the sleeve permit movement of dowel pin and indicate penetration of the bolt in the ball. After all the members of the grid have been assembled, the bolt at each joint is tightened in a series of steps by twisting the corresponding sleeve, so that the nonlinear effects of the joint are reduced. If the bolts are not tight enough, the nonlinear effects will be considerable even in low excitation levels and this will lead to difficulties in measurements and experimental modal analysis.

In dynamic behavior of a double layer grid, the ball joint system (end connector) can be subjected to axial or non-axial forces. The joint behavior is different depending on type of the force applied to the joint. In reality, before external loads applied to the structure, tightening of bolt develops prestress in the joint that leads to a tension force in the bolt and a compressive force in the sleeve. The force that is transferred through the joint will be the consequent of this prestress and the force in members resulting from subsequent external loading of the structure. Moreover, due to unavoidable inaccuracy in geometric dimensions of components, gaps will be created at contacting surfaces of the sleeve with the conical end piece and the ball. The width of this gaps influences force transfer mechanism. A double layer grid includes many joints with unknown degrees of bolt tightness and indefinite gap widths between their components. Therefore, due to these inevitable uncertainties, analytical estimations of dynamic properties of a double layer grid constructed from ball joint system are usually erroneous. For this reason, in the present study, natural frequencies of the grid are obtained experimentally.

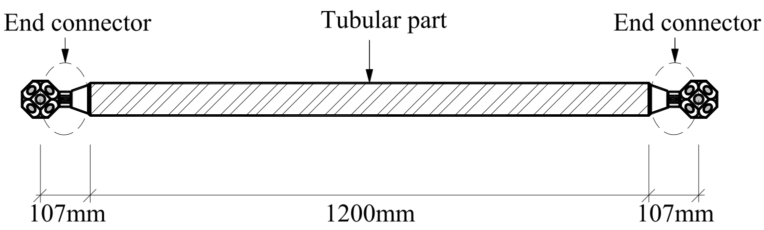


Figure 2.2. A member of the double layer grid

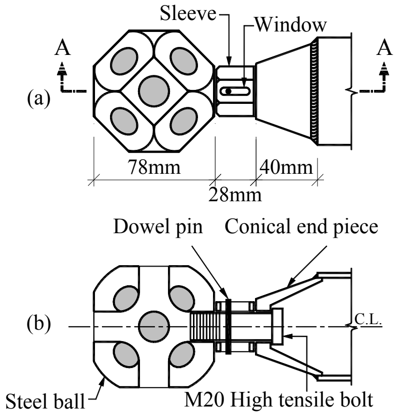


Figure 2.3. Details of the end connector

3. MODAL TESTING

Frequency response functions (FRFs) of the double layer grid were obtained in the frequency range of 0-200 Hz through modal testing. To minimize the effects of support conditions on the properties of the structure, the grid was tested in an approximately free condition. This support condition has more reliable operation than grounded support condition during testing. To provide a suspension system which closely approximates the free condition, the grid was supported on four soft springs. Optimum suspension locations were determined by MODPLAN program from MODENT 2002 suite (ICATS, 2002). The locations with low average modal displacement response will provide good suspension locations. Four of these locations, as shown in Fig. 3.1 with four hollow squares at four nodes in the top layer of the grid, were selected for supporting the grid. Considering noticeable mass of the grid, appropriate steel springs were provided for suspension system, one of which in the attached state has been shown in Fig. 3.2. The spring stiffness was selected such that the highest rigid body mode frequency was less than 10-20% of that for the lowest flexible mode (Ewins, 2000).

The measurement equipments used in modal testing have been shown in Table 3.1. Excitation was applied through an impulse hammer integrated with a force transducer and the resulting response of the grid was measured through three attached accelerometers in horizontal X, horizontal Y and vertical Z directions. The excitation and response input signals were recorded by a four channel spectrum analyzer for T=16 s and processed to calculate frequency response functions with a frequency resolution of Δf=0.0625 Hz.

Table 3.1. Measurement equipments for modal testing

Spectrum Analyzer	Impulse Hammer	Accelerometers
B&K PULSE 3560C (3109+7533 Modules)	AP Tech AU02	DJB A/120/V

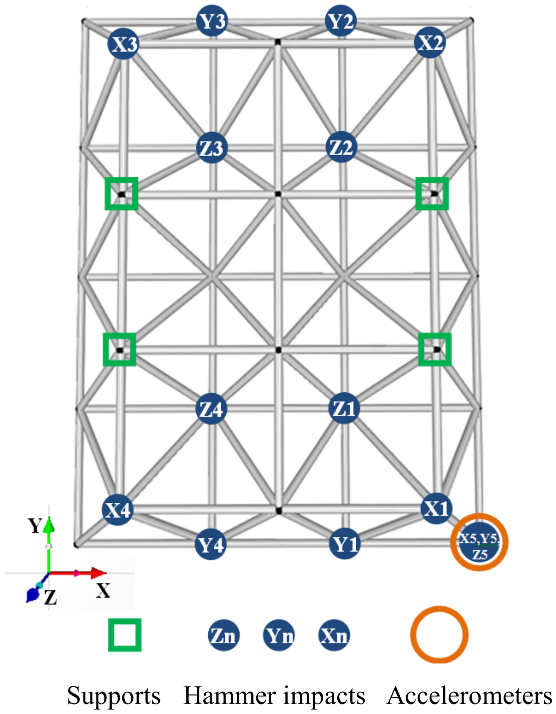


Figure 3.1. Location of supports, hammer impacts and accelerometers

Figure 3.2. Support system of the grid

The FRFs were measured by applying impact and measuring response in all of the three X, Y and Z directions. The balls in the grid with maximum average modal acceleration response were determined by the MODPLAN program separately in three different directions. The balls located at four corners of the bottom layer of the grid have the above property in all the three directions and one of them, which has been shown with a hollow circle in Fig. 3.1, was selected to attach three accelerometers. Fig. 3.3 shows the attached accelerometers in three directions to this ball of the grid. Optimum impact locations were determined by the MODPLAN program separately in three different directions, based on not standing on the nodal points of mode shapes and low average modal velocity response of the structure. These locations have been shown with solid circles of X1 to X4, Y1 to Y4 and Z1 to Z4 in Fig. 3.1, in which the letter represents impact direction and the digit represents the number of impact in the relevant direction. Moreover, since point FRFs (in which response and excitation coordinates are coincident) are important in experimental modal analysis, the grid was excited next to the accelerometers in three directions to measure point FRFs. These impact locations have been shown with solid circle of X5,Y5,Z5 in Fig. 3.1. With a roving impact test scenario (moving hammer and fixed accelerometers), impacts were applied at the pre-mentioned locations one at a time and three FRFs were recorded each time. Each recorded FRF is the average of 5 similar measurements and averaging more number of measurements had little effect on the FRF and its coherence function. The magnitude of impact was adjusted to achieve a good signal to noise ratio and to develop no important nonlinearities in the structure and was in the range of 238.9 N to 477.8 N. Using rubber tip and weight extender for the hammer, frequency spectrum of the impact force was nearly flat up to about 400 Hz and this shows even input energy has been provided to excite the structure in the desired frequency range of 0-100 Hz. The quality of measured data was checked by conventional methods such as repeatability and reciprocity.

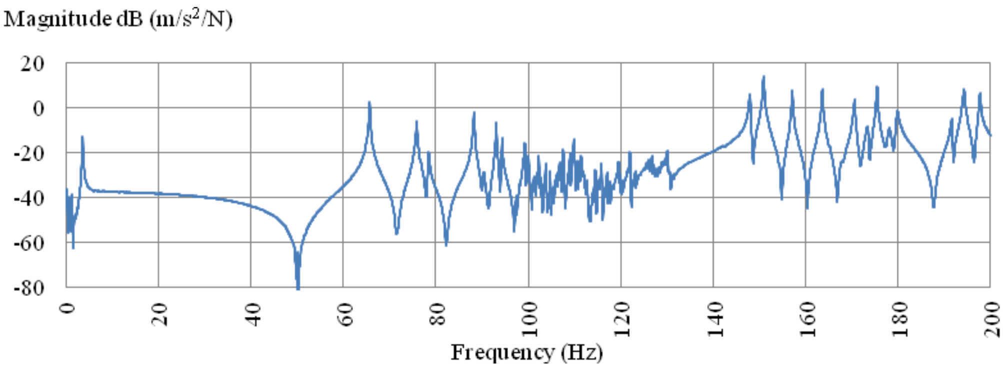
Figure 3.3. Three accelerometers to measure response of the grid in different directions

4. RESULTS AND DISCUSSION

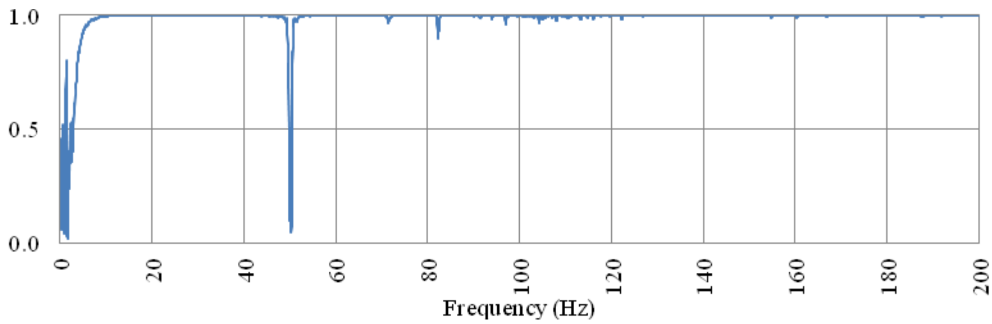
In modal testing of the double layer grid, a total of 45 FRFs was recorded; each of which is identified by the name 'A-B'. A can be X1 to X5, Y1 to Y5 or Z1 to Z5 representing direction and location of the hammer impact, and B can be X5, Y5 or Z5 representing direction and location of the measured acceleration (Fig. 3.1). Four experimental FRFs of the double layer grid, two point FRFs and two transfer FRFs, have been shown in Figs. 4.1 to 4.4 together with the relevant coherence functions. For a point FRF, there must be an anti-resonance after each resonance which is clear in Figs. 4.1a and 4.2a. In a well made measurement, the coherence is unity away from anti-resonances which is clear in Figs. 4.1b to 4.4b.

A general observation of the obtained FRFs shows that three distinct zones can be identified for frequency response of the double layer grid in the frequency range of 0-200 Hz:

- The first zone, from 0 Hz to around 100 Hz, includes the first flexible vibration mode with the frequency of about 3.5 Hz. After that, there is a comparatively vast region up to about 65 Hz in which no vibration mode exists and therefore frequency of excitation has no amplification effect on the response amplitude in this region. Then, relatively well separated vibration modes appear in the FRFs.

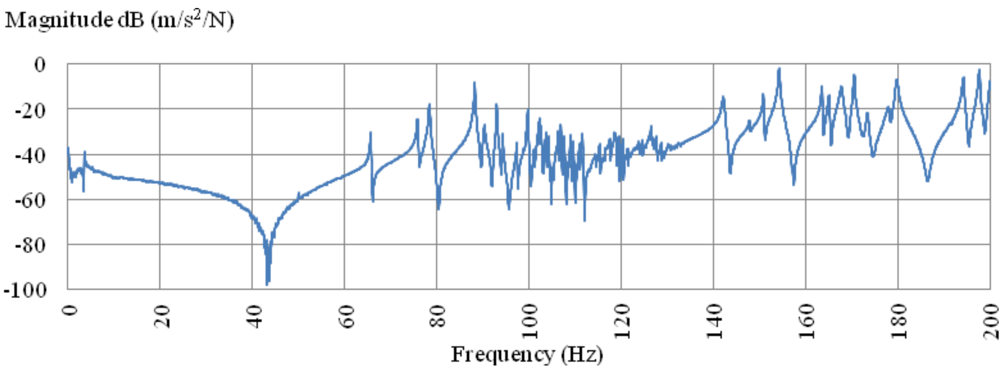


(a)



(b)

Figure 4.1. (a) Point FRF Z5-Z5 (b) Coherence function



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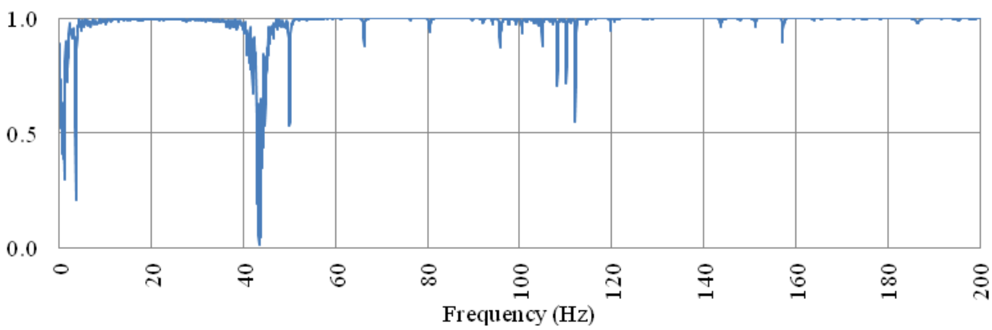
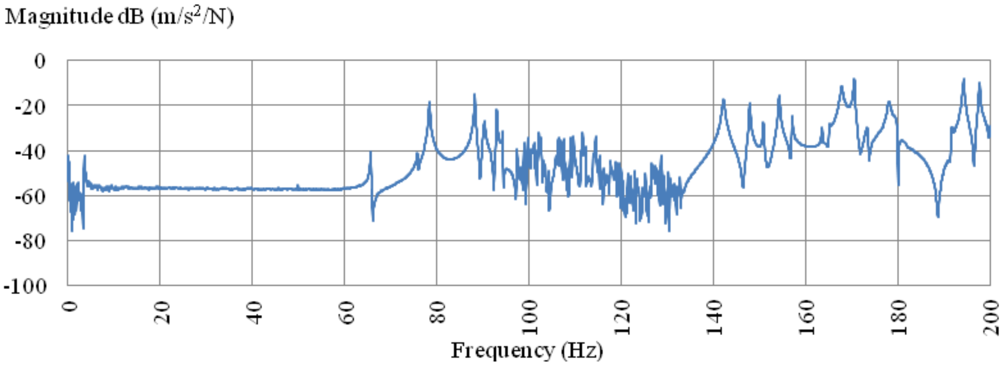


(b)

Figure 4.2. (a) Point FRF Y5-Y5 (b) Coherence function



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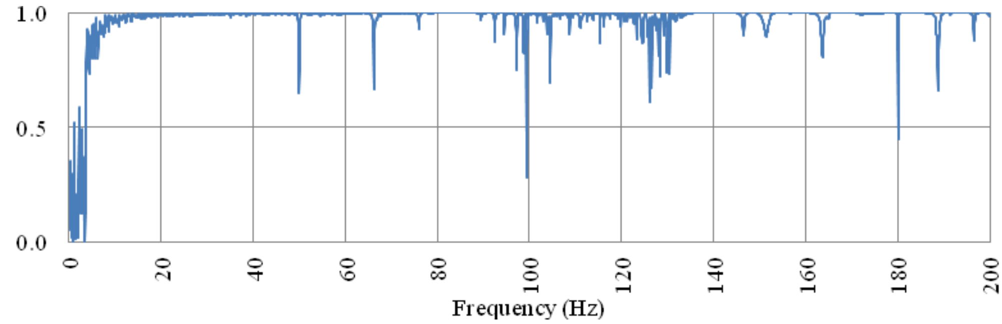
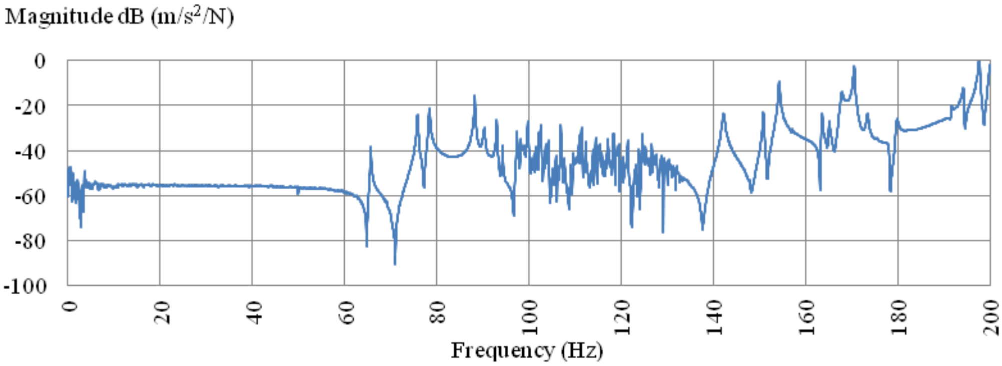
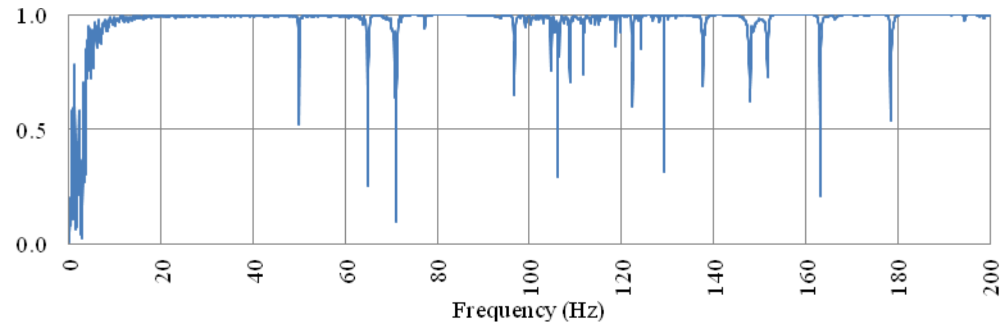


(b)

Figure 4.3. (a) Transfer FRF X1-X5 (b) Coherence function



(a)



(b)

Figure 4.4. (a) Transfer FRF Y1-X5 (b) Coherence function

- The second zone, around 100-130 Hz, includes many modes with close vibration frequencies. Modal damping values are high in this zone, so that difference between resonance and anti-resonance amplitudes are low. Behavior of the grid is complicated if excited in this zone, because the modes are coupled here and many of them contribute to the total response of the structure.
- The third zone, from around 130 Hz to 200 Hz, includes well separated and distinct vibration modes with normal damping values.

Frequencies of the first twelve vibration modes of the double layer grid were extracted from frequency response functions obtained through modal testing. That is the number of all the vibration modes in the frequency range of 0-100 Hz except rigid body modes. To extract natural frequencies of the grid, experimental modal analysis (EMA) was carried out using MODENT 2002 suite. EMA started with analyzing some point and transfer FRFs separately using CIRCLE-FIT SDOF method to get a feel for the modes of the system. Then, simultaneously analyzing all the 45 measured FRFs in X, Y and Z directions using GLOBAL-M MDOF method, the values of twelve natural frequencies of the grid were obtained as shown in Table 4.1. Since the grid was excited in three directions with the selection of impact and response locations such that all the vibration modes participate in the measured FRFs, all the vibration modes of the grid must be identified in the frequency range of interest.

Table 4.1. Experimental natural frequencies of the grid in the range of 0-100 Hz

Mode Number	1	2	3	4	5	6	7	8	9	10	11	12
Frequency (Hz)	3.688	65.81	75.94	78.50	88.31	90.44	93.13	94.38	97.44	98.25	99.31	99.81

5. CONCLUSION

In the present work, frequency response functions of a freely supported double layer grid constructed from ball joint system were measured. The components used in construction of the studied grid were similar to those which are usually utilized in practice. So, the studied double layer grid includes all the actual uncertainties of this family of structures. Measured degrees of freedom were selected so that all the vibration modes of the grid in the frequency range of interest are excited. Frequencies of vibrations modes were extracted by experimental modal analysis. In the frequency range of 0-200 Hz, vibration modes of the grid are very close together with high damping values in certain range and well separated having normal damping values in other ranges.

REFERENCES

Basaga, H.B., Türker, T. and Bayraktar, A. (2011). A model updating approach based on design points for unknown structural parameters. *Applied Mathematical Modelling* **35:12**,5872-5883.

Chellini, G., Roeck, G.D., Nardini, L. and Salvatore, W. (2010). Damage analysis of a steel-concrete composite frame by finite element model updating. *Journal of Constructional Steel Research* **66:3**,398-411.

Davoodi, M.R., Pashaei, M.H. and Mostafavian. S.A. (2007). Experimental study of the effects of bolt tightness on the behaviour of MERO-type double-layer grids. *Journal of the International Association for Shell and Spatial Structures* **48:1**,45-52.

Dilena, M., Morassi, A. and Perin, M. (2011). Dynamic identification of a reinforced concrete damaged bridge. *Mechanical Systems and Signal Processing* **25:8**,2990-3009.

Ewins, D.J. (2000). Modal testing: Theory, Practice and Application (Second Edition), Research Studies Press Ltd, Baldock-Hertfordshire-England.

Fan, F., Ma, H., Chen, G. and Shen, S. (2012). Experimental study of semi-rigid joint systems subjected to bending with and without axial force. *Journal of Constructional Steel Research* **68:1**,126-137.

ICATS (2002). www.icats.co.uk.
Jaishi, B. and Ren, W.X. (2007). Finite element model updating based on eigenvalue and strain energy residuals using multiobjective optimisation technique. *Mechanical Systems and Signal Processing* **21:5**,2295-2317.
Pashaei, M.H., Davoodi, M.R. and Nooshin, H. (2006). Effects of Tightness of Bolts on the Damping of a MERO-Type Double Layer Grid. *International Journal of Space Structures* **21:2**,103-110.