Structural dynamic investigation of frame structure with bolted joints

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Abstract. Frame structure is widely used in many engineering structures. Besides, vibrational problem is one of the main challenges in industry. Bolted joints are commonly used in industry to connect two or more mechanical parts and it plays a significant role in the dynamics characteristic of the structure. This study aims to perform a model updating procedure on a portal frame structure which consists of bolted joints. Modal parameters such as the natural frequencies, mode shapes and damping ratios are gathered through finite element analysis (FEA) and experimental modal analysis (EMA). Frame structure is set to be fixed-free boundary condition and equivalence of nodes is performed at the area of bolted joints. Correlation between these two sets of data is carried out. With the selected parameters identified to perform model updating on the structure by using sensitivity analysis, the discrepancies in natural frequencies were reduced between FEA and EMA.

1 Introduction

Space frame structure is widely used as engineering structure. The application covers wide range of usage such as roofing, sports arena, transportation support, building supports, communication tower, defence tower and etc. Various application/function applies on the frame structure but how rigid/strong will the structure able to withstand the load. Structures are usually used to overcome the large moment due to the applied loading. In past few decades technology has driven frame structure to be more competitive to meet the current world requirement such as lightweight and economical, at the same time to maintain the stability of the structure [1–3].

Structural systems or space frame structure is build up or assemble of many components. One of the most important roles on frame structure is the joint. A mechanical joint is a section of a structure which was used to connect one component or more. Few types of connections such as weld, bolt and thread are used for frame structure. Joints will usually consume 15-30% of the steel consumption which lead to high cost [2].

Bolted connection is commonly used in the industry, easy to assemble/disassemble and low cost is what making it popular among user. Figure 1 shows the frame structure with bolted

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joints with fixed boundary condition at the base of the structure. Frame structure with bolted joints definitely vibrates. In order to perform dynamic investigation of frame structure with bolted joints, finite element analysis was used in the early stage of the study.

Fig. 1. Frame structure with bolted joints.

Finite element method is common computer aided software used in industry and commonly used method to simulate the performance of the product/structure in early engineering design stage. Finite element analysis (FEA) famously used in strength and stress analysis, and lately dynamic investigation has brought interest to industry to simulate the product performance. FEA is used in industry to gain confidence level in early designing stage and to analyses the product performance and definitely to predict the dynamic characteristic of the structure. It's a common practice to use FEA to predict the product performance or dynamic characteristic and few studies have been using FEA method to gain data of the structures/products [4–7].

Experimental modal analysis (EMA) is a process to describe the vibration characteristic, vibration characteristics are divided into three which are natural frequency, damping ratio and mode shape which also called as modal parameters. Experimental modal analysis has been used since early 1970's [8]. Structure is excited by a force using tool called impact hammer and the output response will be measured by accelerometers with the fast fourier transform (FFT) analyzer, modal parameters will be extracted from the frequency response function (FRF) [8–10].

FEA method often have discrepancies between the experimental value [11] hence model updating is required to minimize the discrepancies between numerical studies and experimental. Before model updating fall in place, few most common errors in numerical studies need to be addressed such as model structure errors, model parameters errors and model order errors [12]. Model updating is a process adjusting selective parameters in finite element to reduce the results discrepancies between FEA and EMA [13].

Performing model updating by trial and error approach has been the technique classically [13], hence there are few exploration of model updating techniques has been studied by then [4,11–18]. Model updating applied on structural dynamic [19] explained general concept of FEA model updating and model updating method. Parameters are adjusted in model updating process [20-21] to reduce the discrepancies. Sensitivity analysis

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is one of the model updating technique develops algorithm to optimize the model updating technique, only sensitive parameters is selected to minimize the discrepancies [13, 22].

In this project, investigation on dynamic properties of space frame structure will be carried out to determine modal properties in numerical analysis and experimental. One of the approached to solve model updating is to use sensitivity method. Sensitivity method is focusing on the approach of model updating problem. Furthermore, model updating will be used to minimize the discrepancies between experimental modal analysis and finite element analysis.

2 Experimental modal analysis

Increasing development of data acquisition and processing capabilities has led to major advances in the experimental realm of the analysis, widely known as modal testing. Modal parameters such as natural frequency, mode shape and damping ratio were extracted using modal testing. The experiment was carried out in fixed-free boundary condition. The upper part of the structure is in free condition while the base structure is in fixed condition. The portal frame structure was divided into 48 grid points in order to achieve adequate spatial resolution of global structural mode shapes. The impact location and measurement points were carefully chosen in order to avoid nodal points. Figure 2 displays the location of grid points on the portal frame structure.

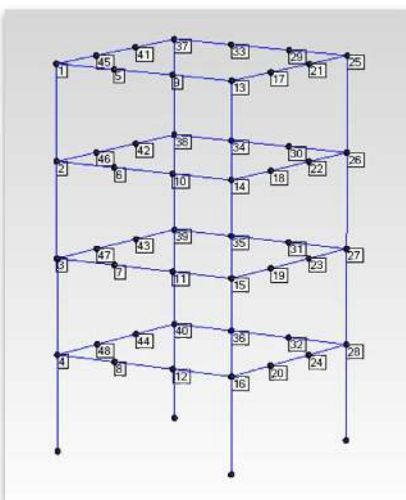

Fig. 2. Portal frame structure with lebeled grid points.

The excitation method used in this paper is impact hammer testing with roving accelerometer. The impact hammer with force transducer attached on its head used to excite the structure. The response was detected by tri-axial accelerometer attached on the structure and data analyser was used to convert the signal response which was in time domain to the frequency domain which the equipment shown in Figure 3.

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Fig. 3. Equipment used for EMA.

Natural frequency and mode shapes were extracted using curve fitting method from ME'scopeVES software and being tabulated in Table 1

Table 1. Experimental natural frequencies results.

Mode	Natural Frequency (Hz)
1	34.5
2	40.0
3	57.9
4	65.8
5	81.4

3 Finite element analysis

Computer aided design (CAD) model of the frame structure was created by using CATIA software before the model was converted into FEA model. FEA was performed by using MSC Nastran/Patran software. The FEA model of the frame structure composed of 3476 nodes and 2760 shell elements (CQUAD4). Geometrically, the model consists of 4 angle-bars and 16 flat bars which their properties is stated in Table 2. Equivalence of nodes was performed at the area of bolted joints in the model in order to represent the rigidity of joints in the structure.

Boundary condition and external forces were assigned to the model as the model was let to exist in fixed-free boundary condition. Structure base is in fixed condition by wall plug. Calculation of modal properties in MSC.Natran/Patran was done by using SOL 103, which is the solution for normal modes analysis. By using the normal modes analysis, the natural frequencies and mode shapes of the structure can be computed. In normal modes analysis, the equation of motion is stated as Eq. (1).

$$\boldsymbol{M}u + \boldsymbol{K}u = 0 \quad (1)$$

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where **K** and **M** are stiffness and mass matrices respectively. These system matrices are computed automatically by MSC Nastran/Patran, based on the geometry and properties of the FEA model. By assuming a harmonic solution, the equation from above can be reduced to an eigenvalue problem which is stated as below.

$$[\boldsymbol{K} - \lambda_i \boldsymbol{M}]\{\phi_i\} = 0 \quad (2)$$

Where $\{\phi\}$is the eigenvector (mode shape) corresponding to the eigenvalue λ (natural frequency). Each eigenvalue is proportional to a natural frequency and is corresponding to eigenvector. The eigenvalues are related to the natural frequencies as

$$f = \frac{\sqrt{\lambda_i}}{2\pi} \quad (3)$$

The constructed finite element model as viewed in graphic interface of MSC Nastran/Patran software is as shown in Figure 4 and results of FEA is obtained as shown in Table 3.

Table 2. Material properties of frame structure.

Structure	Properties		Value
Angle bar	Material properties (low carbon steel)	Young's modulus, E (GPa)	180
		Density (kg/m^3)	7860
		Poisson ratio	0.3
	Physical properties	Length (mm)	1000
		Width (mm)	37.5
		Thickness (mm)	4.0
Flat Bar	Material properties (low carbon steel)	Young's modulus, E (GPa)	180
		Density (kg/m^3)	7860
		Poisson ratio	0.3
	Physical properties	Length (mm)	500
		Width (mm)	25.0
		Thickness (mm)	6.0

4 Correlation of experimental and numerical results

The results of FEA often have discrepancies between the experimental [11], hence the results obtained from FEA and EMA will be correlated, where discrepancies between both result will be compared and the percentage error will be captured.

Table 4 shows the correlation of natural frequency from different modes between experimental vs numerical value of frame structure with bolted joints. Results observed the percentage of error which recorded highest of 16.29% on mode 1 and lowest of 0.23% on mode 4. Mode shape in between FEA and EMA is presented in table 5.

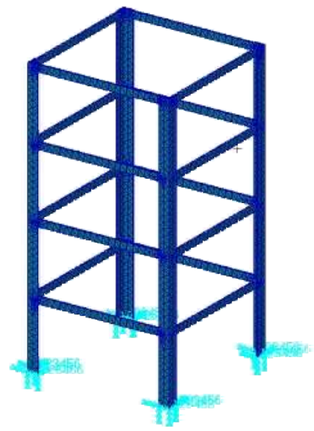


Fig. 4. Frame structure of FEA model.

Table 3. FEA natural frequency results.

Mode	Natural Frequencies (Hz)
1	40.12
2	43.77
3	54.65
4	65.95
5	86.33

Table 4. Correlation of natural frequencies between EMA and FEA.

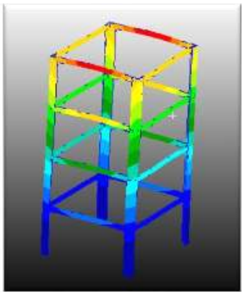
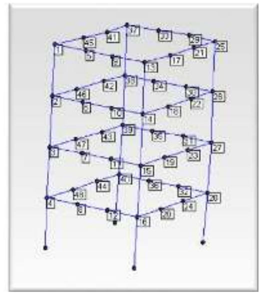
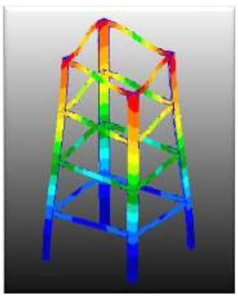
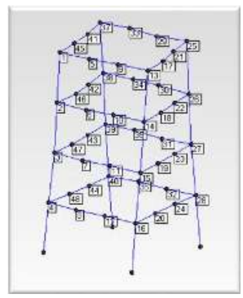
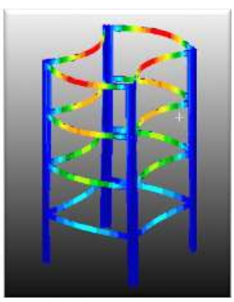
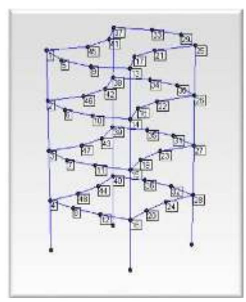
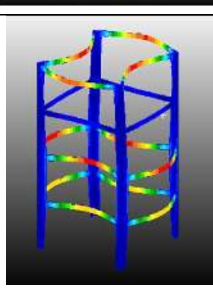
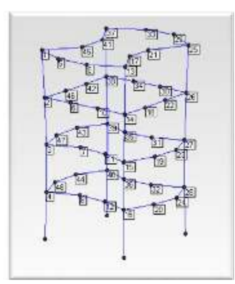
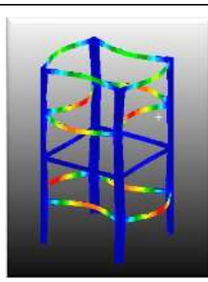
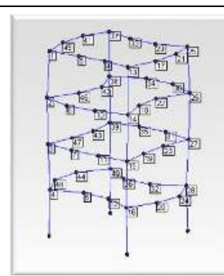
Mode	Natural Frequency (Hz)		Percentage of error (%)
	EMA	FEA	
1	34.5	40.12	16.29
2	40.0	43.77	9.43
3	57.9	54.65	5.61
4	65.8	65.95	0.23
5	81.4	86.33	6.06
		Total Error	37.62

Model updating is a process adjusting selective parameters in finite element to reduce the results discrepancies between FEA and EMA [13]. The target of correlation is to minimize the percentage of error in between FEA and EMA. This can be completed by performing the model updating. The optimization algorithm called SOL 200 has been used in this study. The objective function is constructed as Eq. (4).

$$g(x)=\sum_{i=1}^{n} W\left(\frac{w_i^e}{w_i^a}-1\right)^2 \tag{4}$$

where w_i^e and w_i^a are the experimental and computational natural frequencies respectively, with W as the real positive weighing factor.

Table 5. Correlation mode shape between FEA and EMA.

Mode	Mode shape	
	FEA	EMA
1		
2		
3		
4		
5		

Performing model updating with a selection of sensitive parameters is very crucial in order to minimize the discrepancies. Which resulting to four parameters has been picked in this study, which are Modulus Young, poison ratio and thickness of the angle and flat bar.

Table 6 below is presenting the results prior to model updating of the frame structure, comparison of natural frequencies performed in FEA between before and after model updating. The significant errors were observed on mode 1, upon model updating the error rate reduces from 16.29% to 10.52%. Mode 4 showing an increasing percentage of error, but other modes shows a significant reduction in percentage of error.

Table 6. Comparison of natural frequencies values between initial and updated results.

Mode	EMA Natural Frequency (Hz)	Initial FEA results		Model updating FEA results	
		Natural Frequency (Hz)	Error (%)	Natural Frequency (Hz)	Error (%)
1	34.5	40.12	16.29	38.13	10.52
2	40.0	43.77	9.43	42.98	7.45
3	57.9	54.65	5.61	56.04	3.21
4	65.8	65.95	0.23	64.80	1.52
5	81.4	86.33	6.06	82.29	1.09
		Total Error	37.62	Total Error	23.79

Four parameters have been identified to reduce the discrepancies between EMA and FEA natural frequencies via model updating procedure. Table 7 shows the deviation of the updating parameter and it explains that young modulus, poison ratio and thickness play an important role to reduce the discrepancies. Flat bar thickness shows higher sensitivity value when sensitivity analysis was performed.

Table 7. Changes of updating parameters from the initial values.

Parameter	I	II	Changes (%) = |(II-I)/I| x 100
	Initial value	Updated value	
Young's modulus (GPa)	180	162	10
Poison Ratio	0.3	0.33	10
Angle Bar Thickness (m)	0.004	0.0039	2.5
Flat Bar Thickness (m)	0.006	0.0065	8.3

5 Conclusions

This study is to focus on reducing the discrepancies between EMA and FEA on frame structure. With the fixed-free boundary condition applied on the frame structure with bolted joints, fixed boundary was applied on the base of the structure and equivalence of nodes is performed at the area of bolted joints in FEA. Four parameters were chosen in this study for updating parameters. Parameters assumption has been made in earlier phase when performing FEA which resulting to discrepancies in natural frequencies, with updating procedure this gap is narrow down.

The discrepancies between EMA and FEA have been brought down by applying the model updating technique using sensitivity analysis optimization. This finding can be further improved by focusing updating on the joint, defining the joint element can probably reduce the discrepancies between EMA and FEA.

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