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Damage assessment on frame structure with bolted joints based on experimental modal analysis

M H N Izham¹, M S M Sani^{1,2*}, M N Abdul Rani³ and M A Yunus³

¹Advanced Structural Integrity and Vibrational Research Group (ASIVR), Faculty of Mechanical Engineering, Universiti Malaysia Pahang (UMP), 26600 Pekan, Pahang, Malaysia

²Automotive Engineering Centre, Universiti Malaysia Pahang (UMP), 26600 Pekan, Pahang, Malaysia

³Structural Dynamics Analysis and Validation (SDAV), Faculty of Mechanical Engineering, Universiti Teknologi MARA (UiTM), 40450 Shah Alam, Selangor Malaysia

*Corresponding author: mshahrir@ump.edu.my

Abstract. Bolted joint commonly being used as a mechanical joint to connect two or more mechanical components which bring an interest to this study. The complexity of joint element plays an important role in the dynamic investigation. Structural damage happens and often it's too late to react to it and early detection of structure failure (damage) is beneficial. This paper aims to study the differences between undamaged and damage frame structure with bolted joints. Frame structure consists of 4 angle bar and 16 flat bars fabricated with stainless steel material is used. Total of 32 pcs of M6 screw and nuts are used together with structure. Damage often alter the mode shapes and reduce the natural frequencies. Natural frequencies and mode shapes of both undamaged and damaged data obtained by experimental modal analysis is correlated. Frequency drop is observed on natural frequencies after being correlated and as well as the mode shapes changed occurs on the undamaged and damages structure. Frame structure with damage on the joints able to detect the frequency drops and alter the modes shapes.

1. Introduction

Frame structure often used as a structure in the industry due to the cost of the design and has good reputation in terms of rigidity to bear the load. Application of frame structure covers varies range in the industry such as building supports, transportation or towers. Is manufactured with a combination of at least few L bars and flat bars to build a complete frame structure. structure. Frame structure without doubts, is an essential mechanical structure that plays an important role in defending the load from collapse [1, 2]. Without the joint to connect other component, it would not be a complete frame structure, hence few types of connections been offered in the industry such as weld, rivet or bolt. With bolted joints being the most connection used in the industry based on the cost of the material as well as the process with the idea of serviceability. Less human dependencies also make it among one of the majorly used connection in the industry.

Experimental modal analysis (EMA) is a method to determine the modal parameters or vibration characteristic. This characteristic which can be identified by either impact hammer or shaker test are natural frequency, mode shape and damping ratio. Impact hammer or shaker is used to excite the structure where the output response is measured by accelerometers with the Fast Fourier Transform



(FFT) analyzer and the modal parameters is extracted frequency response function (FRF) [3, 4]. Experimental modal analysis being used to determine modal properties of structure with two different material which alloy and magnesium involving friction stir welding as the joint [5] and frame structure is also used to collect the modal parameters using impact hammer test [6] which results to updating of the structure without joint strategy.

Damage of the structure can lead to a serious issue if it's involving the integrity of the structure, early detection of damage can presence to prevent further problem to the structure. This makes damage on a structure is one of the most discussed topic in the industry nowadays, damage can occurs either on the structure itself or its joints [6]. Damage often alter the model parameters of the structures with the fact of most sensitives parameter is natural frequencies [7, 8]. It has been established in the world there are multiple attempts to identify the damage with the assisting of vibration technique. According to a previous study of damage detection through a frequency change, damage detection would be likely suitable for structure with lower vibration modes and suggest changes in frequencies only may not be sufficient for a unique detection on location of a damage [9]. Changes in modes curvatures is also used as a method to identify or locate the damage on a structure [10], where another study proves the usage of frequencies shift (FRESH) path to do a damage detection analysis which combining effects of frequency shifting and amplitude changes [11]. There are others several methods using natural frequencies from FRF to detect the change of structure characteristic as well [12, 13].

This paper aim to study the differences between the undamaged and damaged structure of frame structure with bolted joints in terms of experimental modal analysis which focusing on natural frequency and mode shape. The scope of undamaged and damaged is defined on the bolted joints itself. Undamaged being defined as a bolted tightened with a control torque and damage is defined as a looseness on the bolted joints but the flat bars are remained intact in the original position with an ability to rattles when external force is applied on the structure.

2. Structural Setup

Frame structure is a simplified model of a communication tower which involves bolted joints to connect two or more components. The structure consists of 4 L/angle bars, 4 metal plates and 16 flat bars with a 4mm thickness across all component. Image of frame structure is shown in Figure 1. Total of 32 pcs of M6 screw together with nuts to complete the frame structure with a control torque of 8-9 Nm on undamaged structure.



Figure 1. Frame structure with bolted joints.

Table 1 shows the dimension of each component of frame structure. Stainless steel SUS 304L is selected as a frame structure and table 2 below is shows the material properties of frame structure. Boundary set as fixed-free boundary condition to replicate the actual model of communication tower which shown in Figure 1, with 4 plates is used to secure the structure to the ground.

Table 1. Frame structure parts dimension.

Description	L Bar, mm	Straight Bar, mm	Flat Plate, mm
Length	1000	488	-
Width	40 x 40	30	100 x 100
Thickness	4	4	4

Table 2. Dimension and material properties of frame structure.

Properties		Value
Material properties (SUS304L)	Young's modulus, E (GPa)	190
	Density (kg/m ³)	8000
	Poisson ratio	0.29

3. Experimental modal analysis

Experimental modal analysis is used to identify the modal parameters (natural frequencies and mode shape) which also known as modal testing. This method is used in the world in early 1970's [14]. Two methods of modal testing are impact hammer and shaker, where both are seeking for the same objective which is modal parameters. In terms of discrepancies between the two method itself, 5% of discrepancies is capture among the two methods [15]. Hence the tools used to excite the structure in this study is impact hammer, two data acquisition system (DAQ) and two sets of tri-axial accelerometer. Figure 2 displays the equipment used for modal testing with rack being used. Rack is considered in this study due to a better consistency of knocking, hence less knocking is required to completely excites the structure.

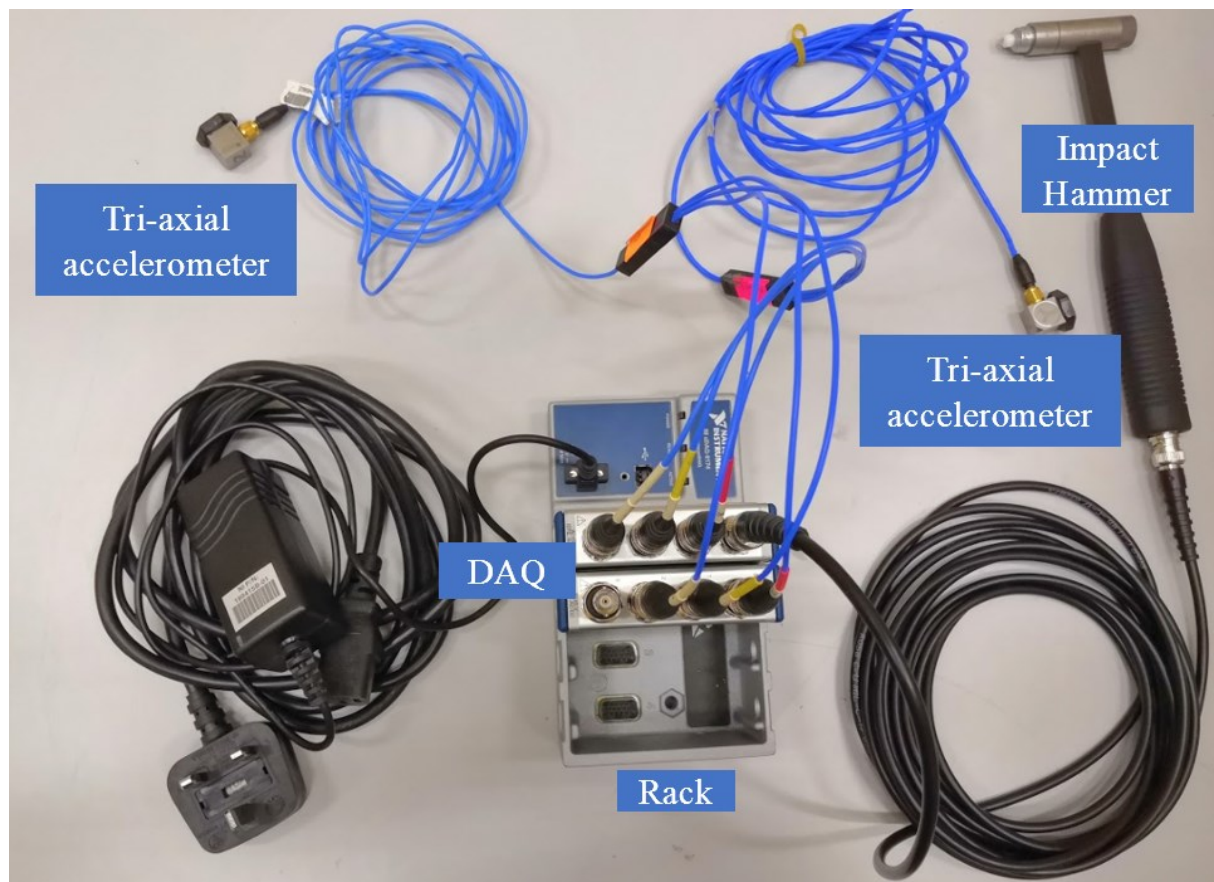


Figure 2. Modal testing equipment.

60 grid points of excitation is distributed evenly on the frame structure with a used of ME' Scope VES software. Figure 3 shows the 60 points that is assigned on the frame structure, same points is mark on the real physical frame structure. This is to ensure the results is tally with the points of measurement.

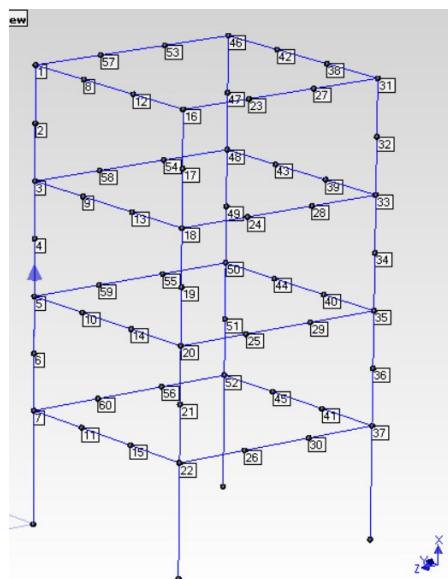


Figure 3. Frame structure with grid points.

4. Data correlation of damage vs undamaged frame structure with bolted joints

In this study, damage is focused on the joint itself instead of structure. Bolted joint is intentionally being loosening to simulate the damage condition on the frame structure. Undamaged structure condition is defined as a flat bar is still intact on the structure with a tightening torque of 8-9Nm whereby damages explain about the structure with a loose bolted connection and no torque is set on this condition. Figure 4 represent the structure with flat bar selected to be loosen with an arrow pointing to the impacted components and Figure 5 shows the detail image of loose bolted joints to simulate the damage condition.

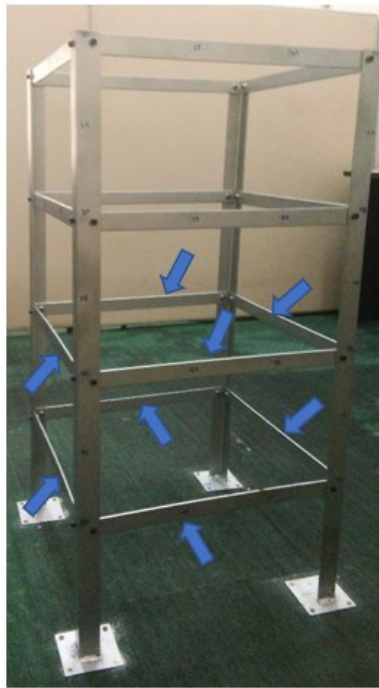


Figure 4. Damage condition of Frame structure.



Figure 5. Detail image of damage condition on bolted joints.

Total of 16 bars used in the frame structure, which a single bar consists of 2 screws with 2 nuts. 50% (16 out 32) of total screws is set to loosening to simulate the damage condition which this will makes total of 8 flat bars is loose.

Data obtained from EMA is correlated to analyse the discrepancies of undamaged vs damaged. Total of 6 modes are collected with a frequency range of 0 – 100 Hz which is tabulated on Table 3 while Figure 6 demonstrated the graph plotted.

Table 3. Percentage of variation between undamaged and damaged.

Modes	EMA Natural Frequency (Hz)		
	Undamaged	Damaged	Variation, (%)
1	26.5	21.5	18.87
2	39.5	30.7	22.28
3	56.1	51.8	7.66
4	66.7	56.5	15.29
5	71.7	68.1	5.02
6	90.1	86.4	4.11
Average Error (%)			12.21

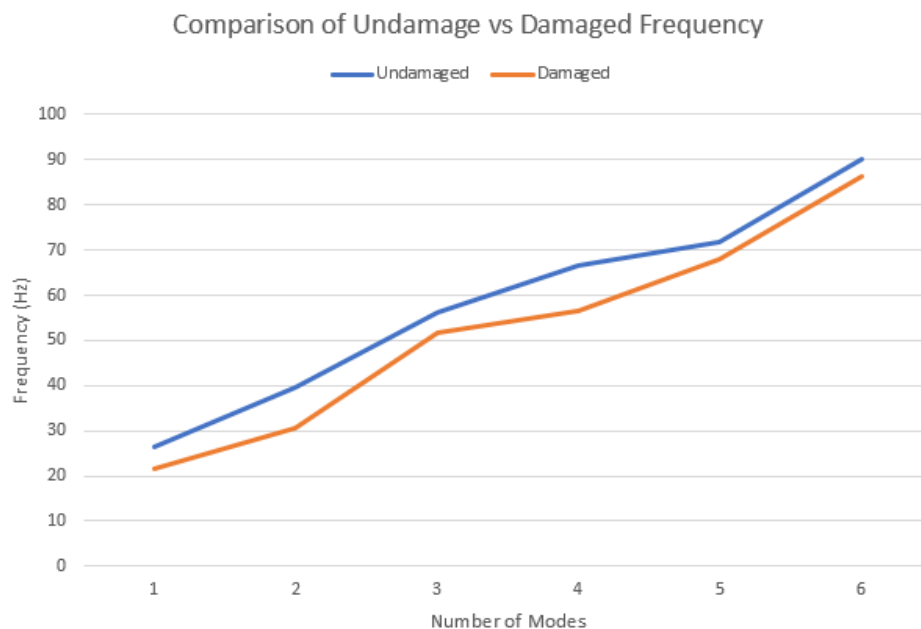
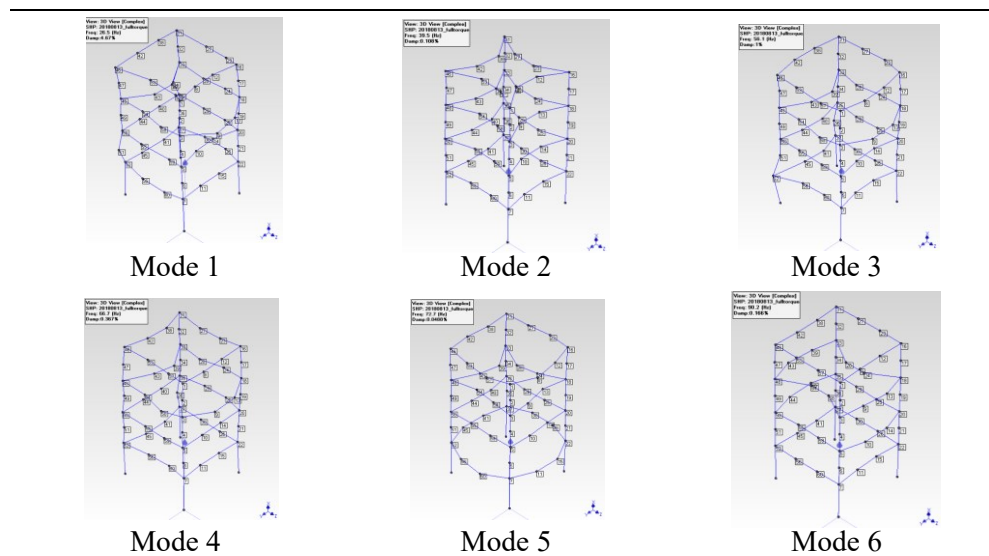
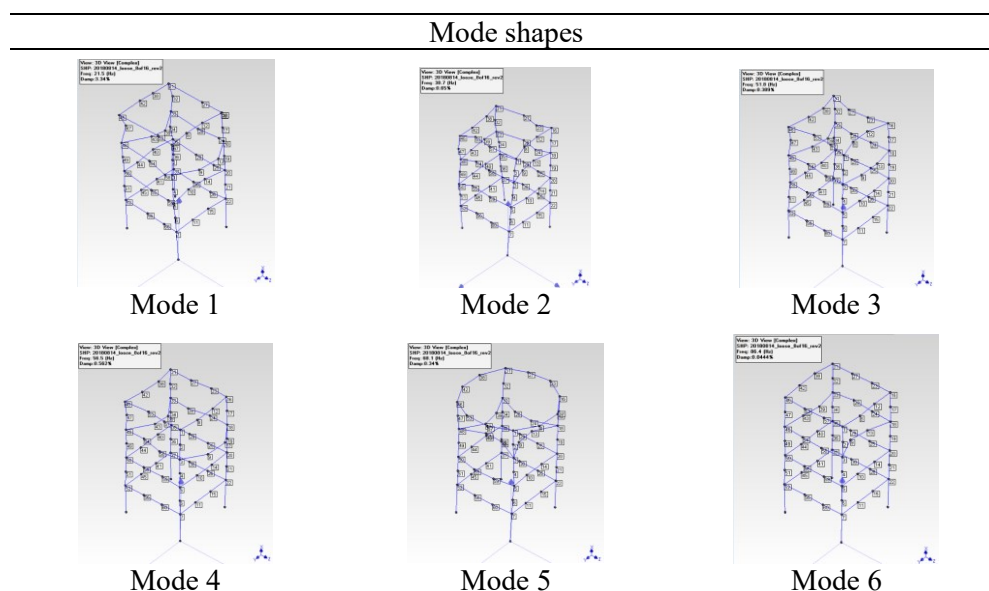


Figure 6. Comparison of EMA undamaged and damaged in natural frequencies

The result above shows there is a change in the natural frequencies, where all 6 modes shows a drop in natural frequency. Average variation is 12.21% and the significant changes happens on the mode 2 where 22.28% is recorded. Table 4 exhibit the modes shapes of undamaged and table 5 represents the mode shapes of damaged within the frequency range of 0-100Hz.

Table 4. Mode shapes of undamaged frame structure with bolted joints.

Mode shapes

**Table 5.** Mode shapes of damaged frame structure with bolted joints.

The significant change happens on mode 2 where from bending it change to torsion mode. Mode 1, 3,4,5 and 6 remain unchanged which is bending be it damaged or undamaged.

5. Conclusions

This paper aims to study the correlation between undamaged vs damaged natural frequencies and mode shapes of the test structure with experimental modal analysis. The damage is simulate on the bolted joints of the strucutre, bolts (16 out of 32 boltes) has been loosen wihtout any torque requirement been control that makes the flat bar becomes loose but still attached to the structure. Undamage strucure is setup with a control torque (8-9 Nm) applied on the bolted. The test strucure is excite with an impact hammer testing to idntiyy the modal parameters. 6 Modes with the frequency range setup within 0-100 Hz is observed has a dropped in frequency when damage is introduced into the frame structure with bolted joints. Total average of variation is recoreded to be 12.21%. Same goes to the mode shapes, damage has altered the mode shapes of the testing structure whereby only mode 2 is having a change in the mode shape where the other 5 mods shapes reamain unchanged.

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