

Different Torque Settings and Their Effect on the Vibration Characteristics of a Bolted Structure

W.I.I. Wan Iskandar Mirza¹, N.A. Jebat¹, M.N. Abdul Rani¹, M.A. Yunus¹, M.A.S Aziz Shah¹ & M.S.M. Sani²

¹Structural Dynamics Analysis & Validation (SDAV), School of Mechanical Engineering, Collage of Engineering, Universiti Teknologi MARA (UiTM), 40450 Shah Alam, Selangor, Malaysia

²Faculty of Mechanical & Automotive Engineering Technology (FTKMA), Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia,

*Corresponding email: mnarani@uitm.edu.my

ABSTRACT

The vibration characteristics of a bolted structure are very sensitive to the preload applied when the bolts are tightened. This study investigates how different torques affect the vibration characteristics of a bolted structure. The structure consists of two beams connected by two bolted joints. This study is conducted using different tightening configurations: self-tightening, hand-tightening and different torque values between 1 Nm and 15 Nm. Based on the configurations, the frequency response functions (FRFs) of the structure obtained from experimental modal analysis (EMA) are observed to analyse the changes in the vibration characteristics of the structure. Shaker testing is performed on the structure under free-free boundary conditions. A FE model of the structure developed is used to calculate the natural frequencies and mode shapes, which are used for validation. A comparison between the natural frequencies of FE and EMA shows that they increase with increasing torques. The comparison also shows that the 8th mode, which is a torsional mode, is more sensitive to torque changes compared to other modes. Another striking finding of this study is that a decrease in damping values with increasing torque is observed in the experimental FRFs of the structure. The results of this study show that different torque settings lead to different vibration characteristics of the structure.

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INTRODUCTION

Mechanical connections play a crucial role in ensuring the performance and safety of engineering structures. Bolted joints are one of the most commonly used mechanical connections in engineering structures due to their high load-bearing capacity, low cost, ease of handling and maintenance, and adaptability [1]–[3].

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In practice, bolted joints used in the assembly of components and substructures into assembled structures require different torques. Furthermore, the torques required for bolted joints to clamp components are highly dependent on the actual applications of the bolted structures. In certain cases, the same bolted structure may be used for different applications requiring adjustment of torque settings.

Furthermore, previous studies [4]–[6] have shown that different torques used in bolted structures lead to a large variability in the vibration characteristics of bolted structures. Therefore, the experimental vibration characteristics of a bolted structure based on a specific torque setting are usually not suitable as a benchmark for a subsequent analysis of the same bolted structure with different torque settings [3], [5], [6]. However, detailed experimental and numerical investigations are required for the same bolted structure that requires different torque settings in different applications [7]–[9]. In this paper, the effects of the vibration characteristics of an aluminium bolted structure at different torque settings are investigated. The investigations are carried out using experimental modal analysis and the finite element method.

Physical Test Bolted Structure

Figure 1 shows the aluminium bolted structure with a length of 380 mm, a thickness of 6 mm and a width of 45 mm. Two M10 stainless steel bolts and nuts are used in the bolted structure. Using a mechanical torque range, different tightening torques from 1 Nm to 15 Nm were applied to the bolted structure. The vibration characteristics of the bolted structure were determined for each torque setting using the EMA.



Figure 1. Physical test bolted structure

FINITE ELEMENT MODEL

The computer-aided design (CAD), Catia V5 was used to develop the 3D model of a double bolted structure shown in Figure 2.

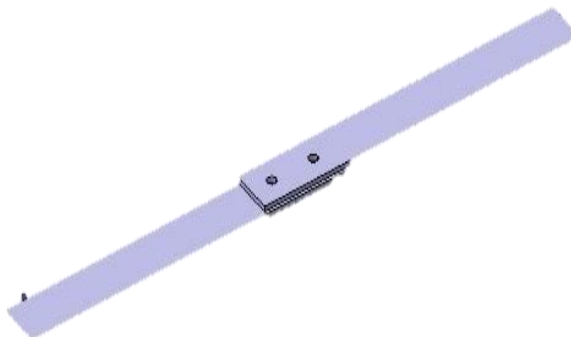


Figure 2. 3D model of the bolted structure using Catia V5.

The FE model of the aluminium bolted structure was developed and analysed using MSC PATRAN/NASTRAN. The FE model consisted of 53494 elements and 65787 nodes. Table 1 shows the material properties of the beams. The bolted joints were modelled using 1D CBEAM elements and RBE3 connectors, as shown in Figures 4 and 5.

Table 1: Material properties of the beams

Properties	Value/Type
Material	Aluminium 6061
Modulus of Elasticity	70,000 MPa
Poisson's Ratio	0.3
Mass Density	2850 kg/m ³

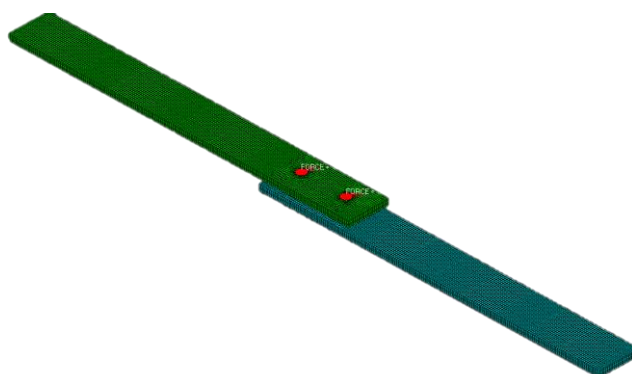


Figure 3. FE model of the bolted structure

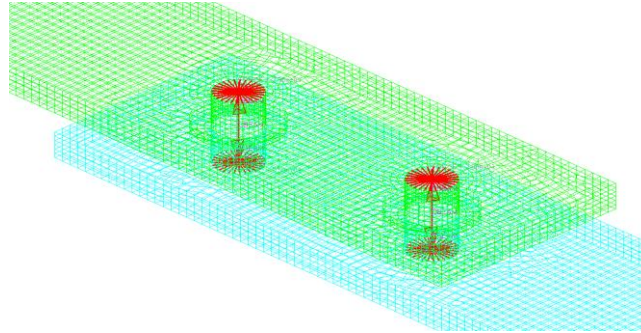


Figure 4. CBEAM element of the bolted joints

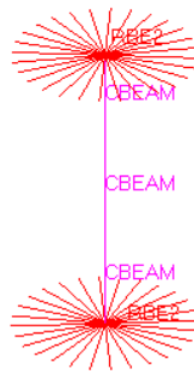


Figure 5: RBE3 elements

NASTRAN SOL103 based normal modes analysis was used to calculate the natural frequencies and mode shapes of the bolted structure. However, for the FE model of the bolted structure with different torque settings, preload calculations using equations (1) and (2) were required. The bolted torques used in the FE model varied from 1 Nm, 2 Nm, 5 Nm, 8 Nm, 10 Nm and 15 Nm. The contact condition with a torque coefficient of 0.2 was used in equation (2). The nominal diameter of the bolt used was 10 mm. The detailed representation of the preload modelling of the FE model can be found in Figure 6. Table 2 shows the calculated axial bolt forces under the tightening torques of the bolts.

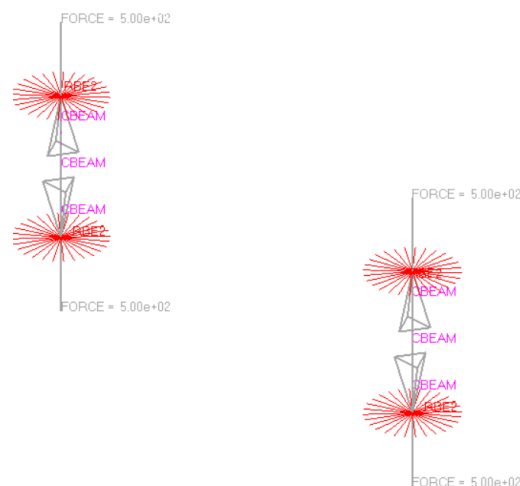


Figure 6. Preload modelling of the FE model of the bolted structure

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$$T = kFd \quad (1)$$

$$F = \frac{T}{kd} \quad (2)$$

Where T=wrench torque (Nm), k=torque coefficient, d=nominal diameter (m), F=axial bolt force (N)

Table 2. Axial bolt force in relation to the bolt tightening torques

Tightening torque, T	Nominal diameter, d	Friction coefficient, k	Axial bolt force, F
1 Nm	0.01 m	0.2	500
2 Nm			1000
5 Nm			2500
8 Nm			4000
10 Nm			5000
15 Nm			7500

The FRFs of the FE model of the bolted structure were derived by using the FRF synthesis method shown in Equation (3), where $\{\phi\}_i$ is the i th mass normalised mode shapes, N is the number of calculated modes, ξ_i is the i th modal damping ratio, and ω_{ni} is i th natural frequency.

$$H_{syn}(\omega_k) = \sum_{i=1}^N \frac{\{\phi\}_i \{\phi\}_i^T}{(\omega_{ni}^2 - \omega_k^2) + j2\xi_i \omega_k \omega_{ni}} \quad (3)$$

EXPERIMENTAL MODAL ANALYSIS

Experimental modal analysis (EMA) was performed on the bolted joint to characterise the modal parameters, i.e. mode shapes, natural frequencies and damping values. The characterisation was performed using the LMS system, LMS Test. Lab software, shaker, force transducer and triaxial accelerometer. The experimental setup for the test structure is shown in Figure 7. The bolted structure was suspended from the test rig with rubber bands to simulate free-free boundary conditions. The excitation frequency used was between 0 and 2000 Hz.

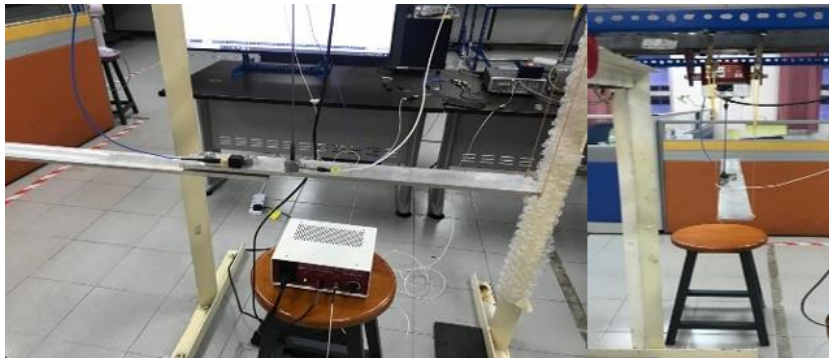


Figure 7. Experimental modal analysis setup of the aluminium bolted structure

RESULTS AND DISCUSSION

The aim of this study was to investigate the effect of applying different torques on the vibration characteristics of a bolted structure. The investigations were carried out using the finite element method and experimental modal analysis. The effect of different torques was investigated in three different cases: (i) natural frequencies of the bolted structure, (ii) mode shapes of the bolted structure and (iii) damping ratios of the bolted structure. Table 3 shows the results of the comparison between the natural frequencies of FE and EMA at different tightening torques from 1 Nm to 15 Nm. The comparison shows that the FE and EMA frequencies increase with the increase of the tightening torque. These results are consistent with the results of [4]. The changes in FE and EMA frequencies were significant at high torques. This is clearly shown in the total error calculated for each torque setting in the bolted structure. For example, the total error for a torque of 15 Nm in Table 3 (f) was higher than for a torque of 1 Nm in Table 3 (a).

Table 3. FE and EMA natural frequencies obtained from different torque settings

(a): Bolt torque 1 Nm				(b): Bolt torque 2 Nm			
Mode No (I)	FE (Hz) (II)	EMA (Hz) (III)	Error (Hz) (IV)	Mode No (I)	FE (Hz) (II)	EMA (Hz) (III)	Error (Hz) (IV)
1	67.61	66.95	0.98	1	67.61	67.05	0.83
2	187.90	186.71	0.63	2	188.40	186.65	0.93
3	361.50	359.68	0.50	3	361.50	361.54	0.01
4	372.70	408.8	9.69	4	372.80	413.85	11.01
5	578.10	556.88	3.67	5	578.60	558.71	3.44
6	597.90	614.83	2.83	6	597.90	618.02	3.37
7	921.20	912.76	0.92	7	921.20	922.5	0.14
8	977.10	932.22	4.59	8	979.10	923.21	5.71
9	1145.00	1134.37	0.93	9	1146.00	1144.21	0.16
10	1362.00	1338.49	1.73	10	1362.00	1336.14	1.90
Total error			26.47	Total error			27.49

(c): Bolt torque 5 Nm				(d): Bolt torque 8 Nm			
Mode No (I)	FE (Hz) (II)	EMA (Hz) (III)	Error (Hz) (IV)	Mode No (I)	FE (Hz) (II)	EMA (Hz) (III)	Error (Hz) (IV)
1	67.62	68.62	1.48	1	67.62	68.79	1.73
2	190.00	186.35	1.92	2	191.50	186.54	2.59
3	361.50	369.71	2.27	3	361.50	371.02	2.63
4	373.10	430.52	15.39	4	373.40	433.53	16.10
5	580.10	563.99	2.78	5	581.60	565.64	2.74
6	598.00	624.43	4.42	6	598.00	626.49	4.76
7	921.30	928.34	0.76	7	921.30	928.68	0.80
8	987.50	935.64	5.25	8	995.30	935.5	6.01
9	1147.00	1158.03	0.96	9	1148.00	1164.4	1.43
10	1362.00	1336.14	1.90	10	1362.00	1338.59	1.72
Total error			37.13	Total error			40.52

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(e): Bolt torque 10 Nm

Mode No (I)	FE (Hz) (II)	EMA (Hz) (III)	Error (Hz) (IV)
1	67.62	68.76	1.69
2	192.50	186.63	3.05
3	361.50	370.98	2.62
4	373.60	433.67	16.08
5	582.60	565.17	2.99
6	598.00	630.06	5.36
7	921.30	928.41	0.77
8	1000.00	938.45	6.15
9	1149.00	1161.54	1.09
10	1363.00	1338.68	1.78
Total error			41.59

(f): Bolt torque 15 Nm

Mode No (I)	FE (Hz) (II)	EMA (Hz) (III)	Error (Hz) (IV)
1	67.62	69.13	2.23
2	194.90	186.09	4.52
3	361.60	372.66	3.06
4	374.10	436.24	16.61
5	585.10	566.99	3.10
6	598.10	627.85	4.97
7	921.30	930.66	1.02
8	1013.00	942.75	6.93
9	1150.00	1168.56	1.61
10	1363.00	1340.53	1.65
Total error			45.71

The effects of different tightening torques represented in the FRFs are shown in Figures 8-13. The comparisons show that the resonance and anti-resonance patterns of FE and EMA were almost identical at all tightening torques. However, the accuracy of the FE FRFs was poor compared to their measured counterparts. The poor correlations are likely due to invalid assumptions about the model properties of the FE model. Another striking result of this study was that the different tightening torques had no effect on the FE mode shapes of the bolted structure. Figure 14 shows the mode shapes of the bolted structure.

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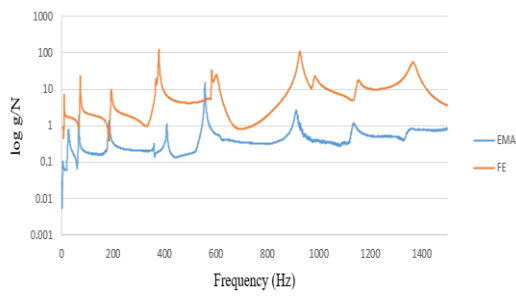


Figure 8. FRF for tightening torque 1 Nm

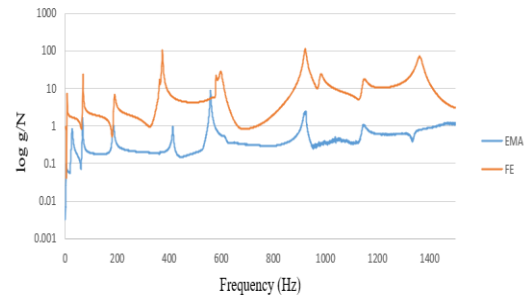


Figure 9. FRF for tightening torque 2 Nm

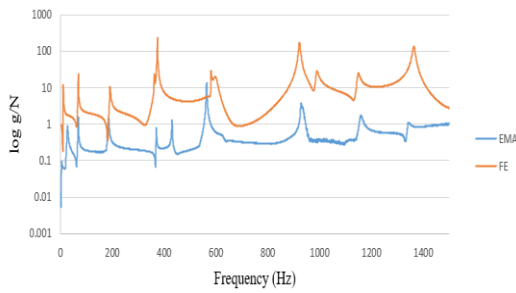


Figure 10. FRF for tightening torque 5 Nm

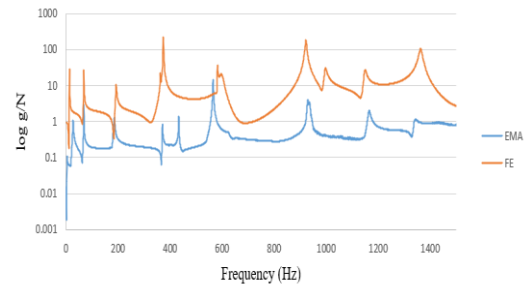


Figure 11. FRF for tightening torque 8 Nm

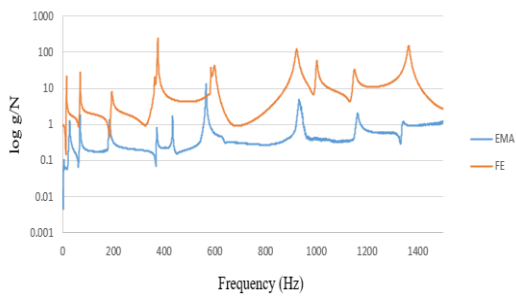


Figure 12. FRF for tightening torque 10 Nm

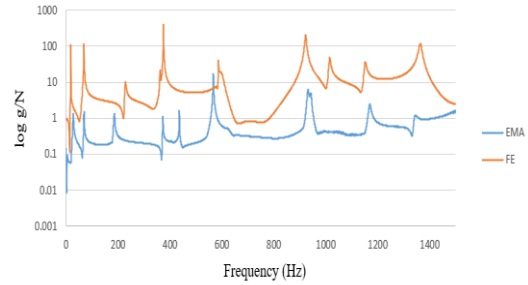


Figure 13. FRF for tightening torque 15 Nm

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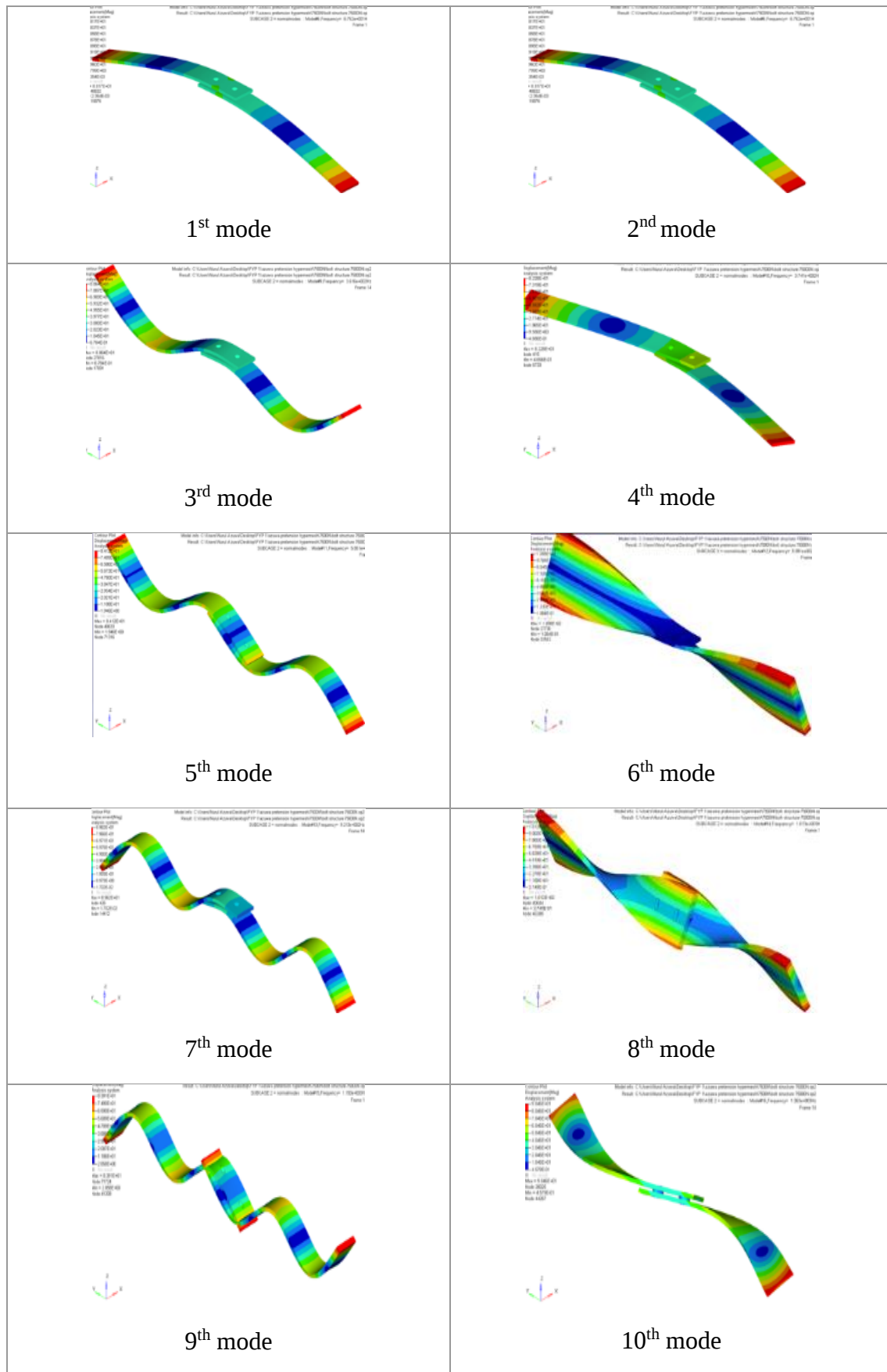


Figure 14. Mode shapes of the bolted structure

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Damping is one of the most important modal parameters in structural dynamics and is usually difficult to calculate accurately. Damping is usually determined from the EMA FRFs. Figure 15 shows the effect of the tightening torques on the modal damping in the FRFs of the bolted structure. The FRFs show that the 8th mode is more sensitive to changes in torque and is shifted to the right, as can be clearly seen in Figure 16. The shift could be due to the increase in stiffness of the mode. Also, the details of the modal damping for each mode due to different torque settings are shown in Table 4. It was observed that the damping ratio decreases as the tightening torque increases. The tendency for the damping ratio to decrease for the 8th mode of vibration was found to be the most acceptable behaviour.

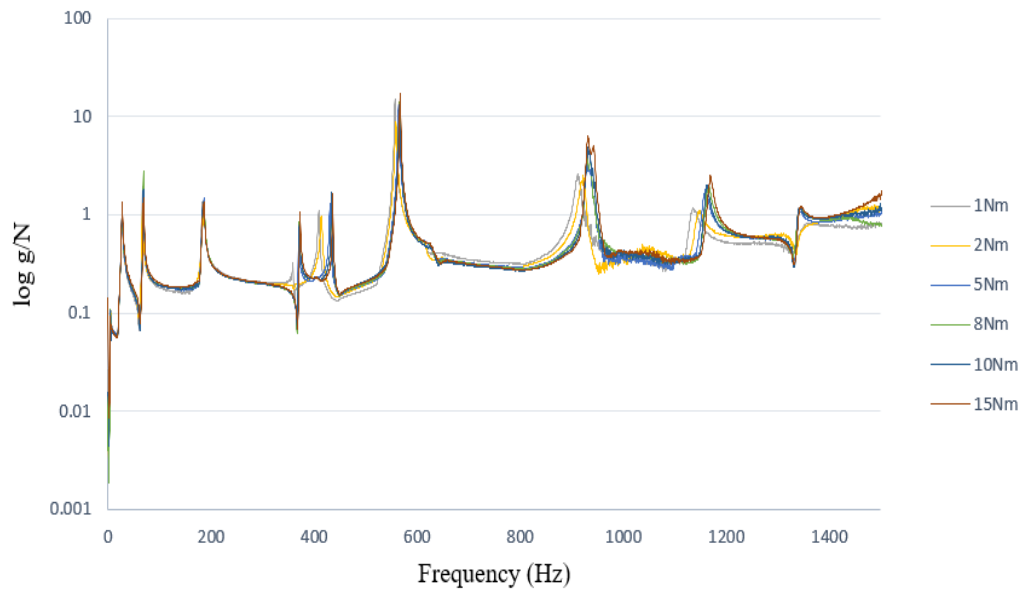


Figure 15. EMA FRFs for different tightening torque settings

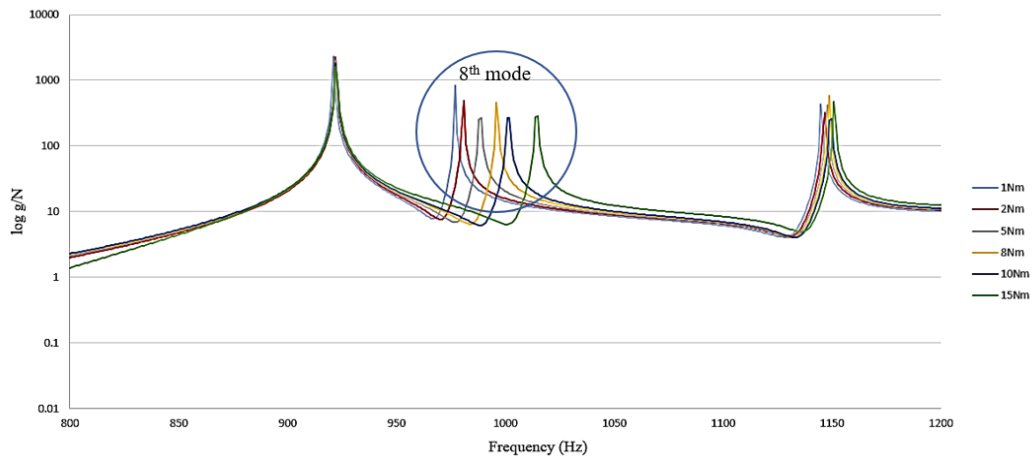


Figure 16. EMA FRF for the 8th mode, resulting from different tightening torques

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Table 4. Comparison of damping ratio, ζ of measured FRFs

Mode No (I)	Damping ratio, ζ						
	Self-loosening (II)	1 Nm (II)	2 Nm (III)	5 Nm (IV)	8 Nm (V)	10 Nm (VI)	15 Nm (VII)
1	0.20	0.41	0.38	0.36	0.08	0.09	0.14
2	0.96	0.88	1.27	0.78	0.81	1.07	0.84
3	3.05	0.22	0.27	0.16	0.18	0.20	0.17
4	2.33	0.26	0.31	0.14	0.11	0.09	0.08
5	1.19	0.15	0.26	0.16	0.13	0.14	0.11
6	1.18	1.13	1.00	1.39	1.37	0.64	1.60
7	3.05	0.50	0.49	0.32	0.32	0.49	0.30
8	0.92	0.76	0.67	0.53	0.49	0.24	0.30
9	1.31	0.70	0.70	0.47	0.44	0.34	0.34
10	1.03	0.90	0.69	0.35	0.46	0.32	0.41

CONCLUSIONS

The effect of applying different tightening torques on the vibration characteristics of a bolted structure is investigated and discussed. The FE and the EMA FRFs were determined and evaluated to determine the changes in modes due to the application of torques (1 Nm, 2 Nm, 5 Nm, 8 Nm, 10 Nm and 15 Nm). It was found that the natural frequencies increased with increasing torque. However, the damping ratio decreased with increasing torque. Another noteworthy finding is that the 8th mode, torsional mode, was most affected when the tightening torque was increased compared to the other modes. The results of this investigation show that different torques have a significant influence on the vibration characteristics of the bolted structure.

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