

Chapter 29

Variability of Dynamic Response in Jointed Structures

D. Di Maio, Z. Mitha, J.V. Paul, and X. Chi

Abstract This study focuses on the variability of the dynamic response of jointed structures. It is well known that the dynamic response of joints is prone to variability issues when they are open and closed again. This paper will present one numerical example and two experimental ones on different type of structures used for studying this issue of variability. The numerical example will focus on parameters such as torque magnitude and contact area. The analysis, which is linear, will present the changes of natural frequency caused by the variation of these two parameters. The experimental examples will focus on parameters like torque magnitude, torque sequence and number of assembling. Both natural frequency and damping changes will be measured from a number of repeated sequences and analysed using statistical methods.

Keywords Variability • Repeatability • Jointed structures • Dynamic response

29.1 Introduction

This research work focuses on the variability of dynamic response for jointed structures. Joints are convenient for assembling and maintaining complex engineering machines. This research is focused on the issues related to the variability of the dynamic response when joints are opened and closed several times, which happens in any regular maintenance. This concept of variability is coined by the term “repeatability”, where manufacturers attempt to maximise the repeatability of a structure in order to minimise the variability.

Joints are not always modelled because of the excessive time requirement and computational effort needed. The simplest solution to this problem, is to fully join the parts together assuming no relative motion. Hence the calculation of natural frequencies will be limited within a theoretical model, as the variability caused by this relative motion will be limited. This relative motion can be determined by several parameters such as torque, contact area, material type, bolting sequence and several others. Hence from an experimental view point several parameters can be investigated, whereas from a numerical one this number can be smaller. The major restriction is caused by the nonlinear dynamic behaviour of the contact conditions, which the modern FE solver cannot tackle yet. This brief overview shows how complex joints can be. Furthermore, studies on variability are very limited due to their time consuming nature and so literature is scarce. Instead, much research is carried out on establishing laws for the dynamic behaviour of jointed structures since it is a nonlinear phenomenon that is much more appealing to the scientific community [1–3] and [4]. Nevertheless, the variability of dynamic response in flexible structures might be more sensitive for certain response modes than others and, therefore, any nonlinearity associated to that variability is more challenging as well as fundamental to study.

This work will present one numerical work and two experimental ones. Natural frequencies were calculated and measured in all the three test cases; the loss factor was measured in the experimental test case. The numerical work was focussed on two parameters such as bolt preload and the contact area designed for the assembly of the two parts. The experimental works focussed on several parameters such as torque level, bolting sequence, number of number of repetitions. Tests were carried out under linear response conditions so as to be able to calculate the natural frequency and damping loss factor by modal analysis. The large amount of data was processed by statistical methods in order to capture the standard deviation from the mean value calculated from several repetitions.

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29.2 Test Structures and Setup

Two different test structures were designed and made for this experimental work, as shown in Fig. 29.1a, c. These structures were freely suspended and a shaker was attached to one of the extremities. Due to the continuous disassembly and reassembly of the structures, it was decided to attach the shaker in such a way that would minimise setup difficulties. The solution applied in these cases was to have a powerful permanent magnet installed at the force gauge so as to bond the shaker to the structures by a magnetic force. Some repeatability checks were carried out in order to assure the correct force transmission every time the gauge was disconnected; this is shown in Sect. 29.4.1. The level of the excitation forces were set to a low amplitude so as to avoid any activation of nonlinearities. The test setup is shown in Fig. 29.2.

Regarding the FE model used for the numerical work some information about the meshing dimension are provided; ABAQUS software was used for this piece of work. Firstly the element shape of the mesh for all the following tests is tetrahedral as it was impossible to perform accurate meshes if a hexahedral element shape was used on a structure

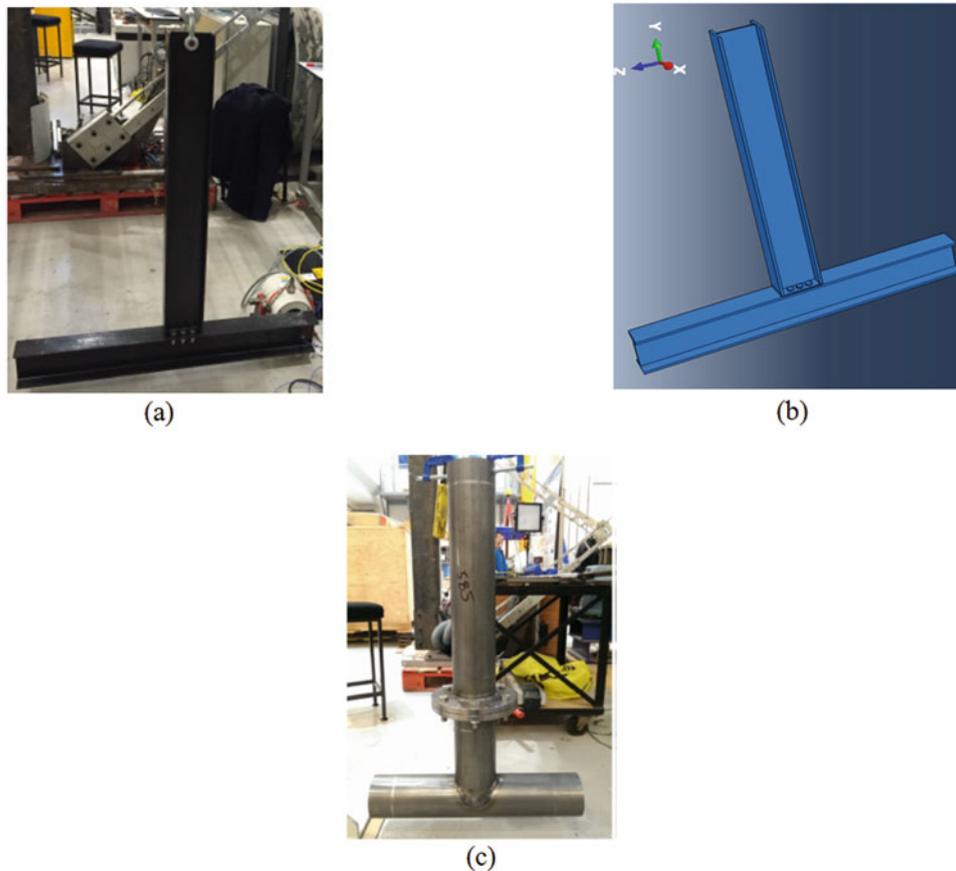


Fig. 29.1 Test structures. (a) I-beam in T shape assembly. (b) FEM of the type (a). (c) Pipes with bolted flanges

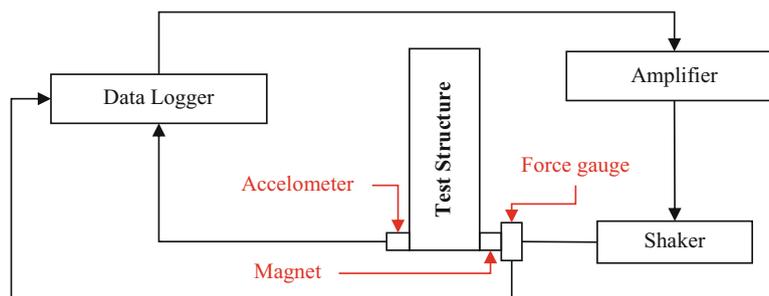


Fig. 29.2 Test setup

with complicated geometry, especially when circular patterns were involved. The element size was determined from mesh convergence, which is 8 mm globally with minimum size control factor 0.01 of the global element size. The element size for bolts is auto-calculated 3.4 mm with 0.1 minimum size control factor by ABAQUS.

Measurements were made up to 1 kHz within which several modes were available for the down selection. Instead, the FE analysis was carried out using the first six mode shapes. The next sections will present some of the results obtained from each test case studied and discussion will be provided to the test case studied.

29.3 FE Analysis of I-Beam in T Shape Assembly

The mode shapes for the structure were calculated and presented in Fig. 29.3. These modes were used for calculating the new natural frequencies where a parameter, such as the bolt preload, was used instead of the fully constrained conditions. This section will present four cases where the preload, the size of the contact area, the size of the bolt body and the size of the bolt head were changed for simulating the new natural frequencies of six mode shapes.

Figure 29.4 shows the effect of the bolt preload on the natural frequencies of the six mode shapes. The largest preload was set to 500kN and the smallest 1 N. As expected some modes were minimally affected by these changes but other ones were more sensitive.

Figure 29.5 shows the effect of the size of the bolt head diameter on the natural frequency. For this case the bolt preload was set up to 20kN. Most of the modes were insensitive to these changes, but Mode 4 was highly responsive.

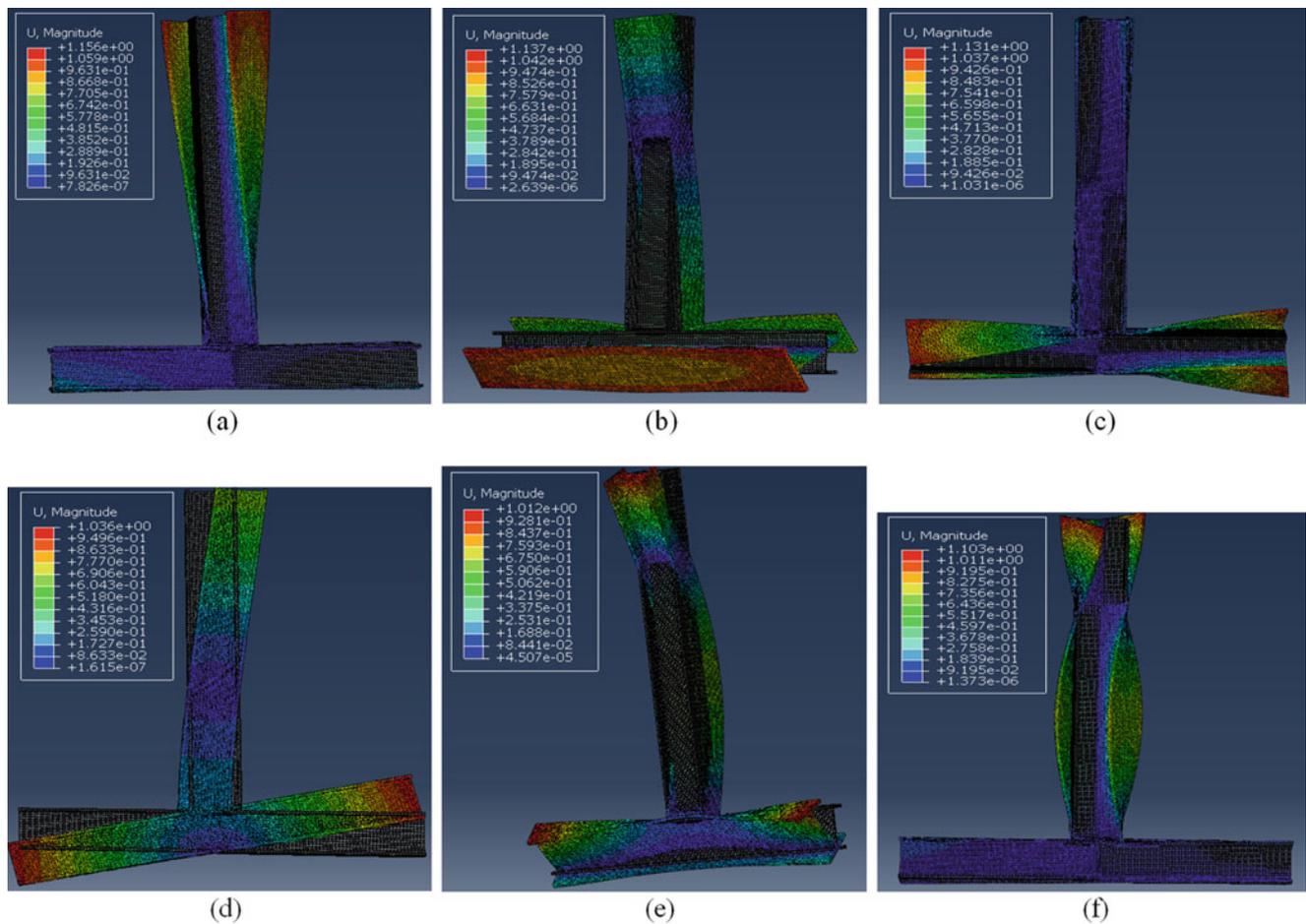


Fig. 29.3 Mode shapes and natural frequencies of the test structure. (a) Mode at 67.5 Hz. (b) Mode at 98.2 Hz. (c) Mode at 124.2 Hz. (d) Mode at 144.2 Hz. (e) Mode at 244.1 Hz. (f) Mode at 320.4 Hz

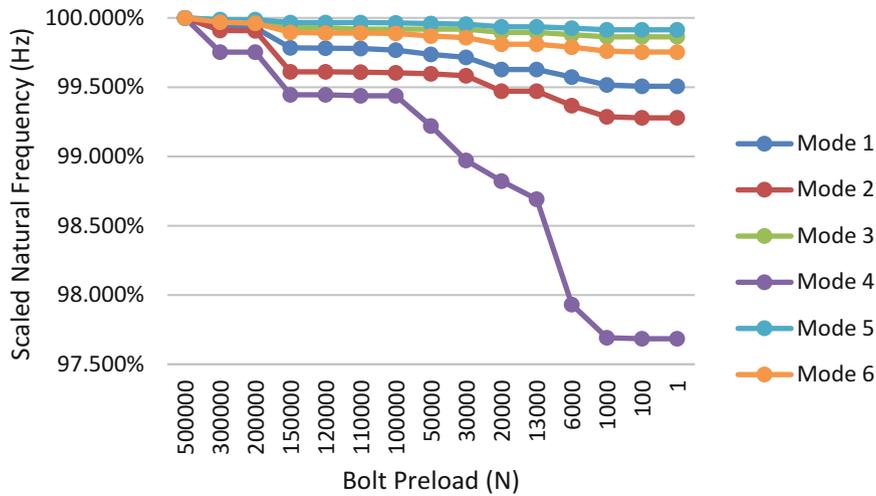


Fig. 29.4 Effect of bolt preload on the natural frequency

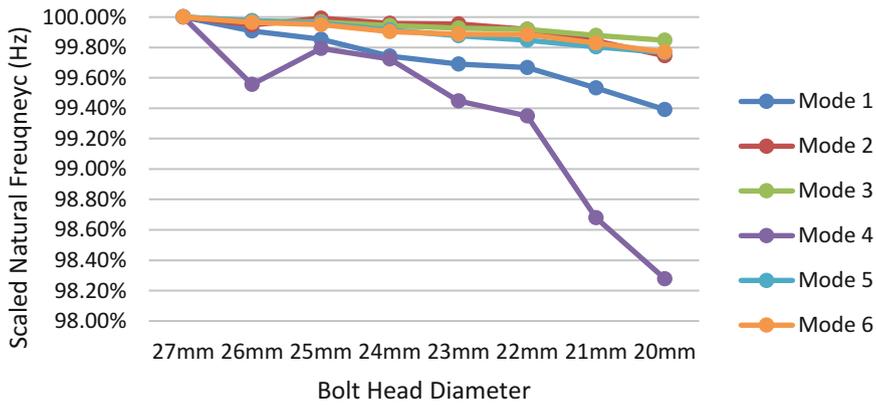


Fig. 29.5 Effect of the size of the bolt head diameter on the natural frequency

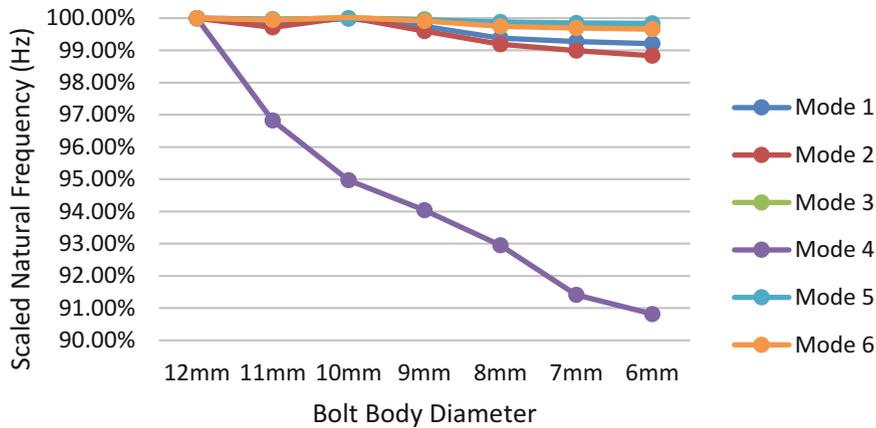


Fig. 29.6 Effect of the size of the bolt body on the natural frequency

Figure 29.6 shows the effect of the size of the bolt body on the natural frequency. Even for this case the bolt preload was set up to 20kN. Despite most of the modes being insensitive to this parameter, Mode 4 once again shows the highest relative frequency shift.

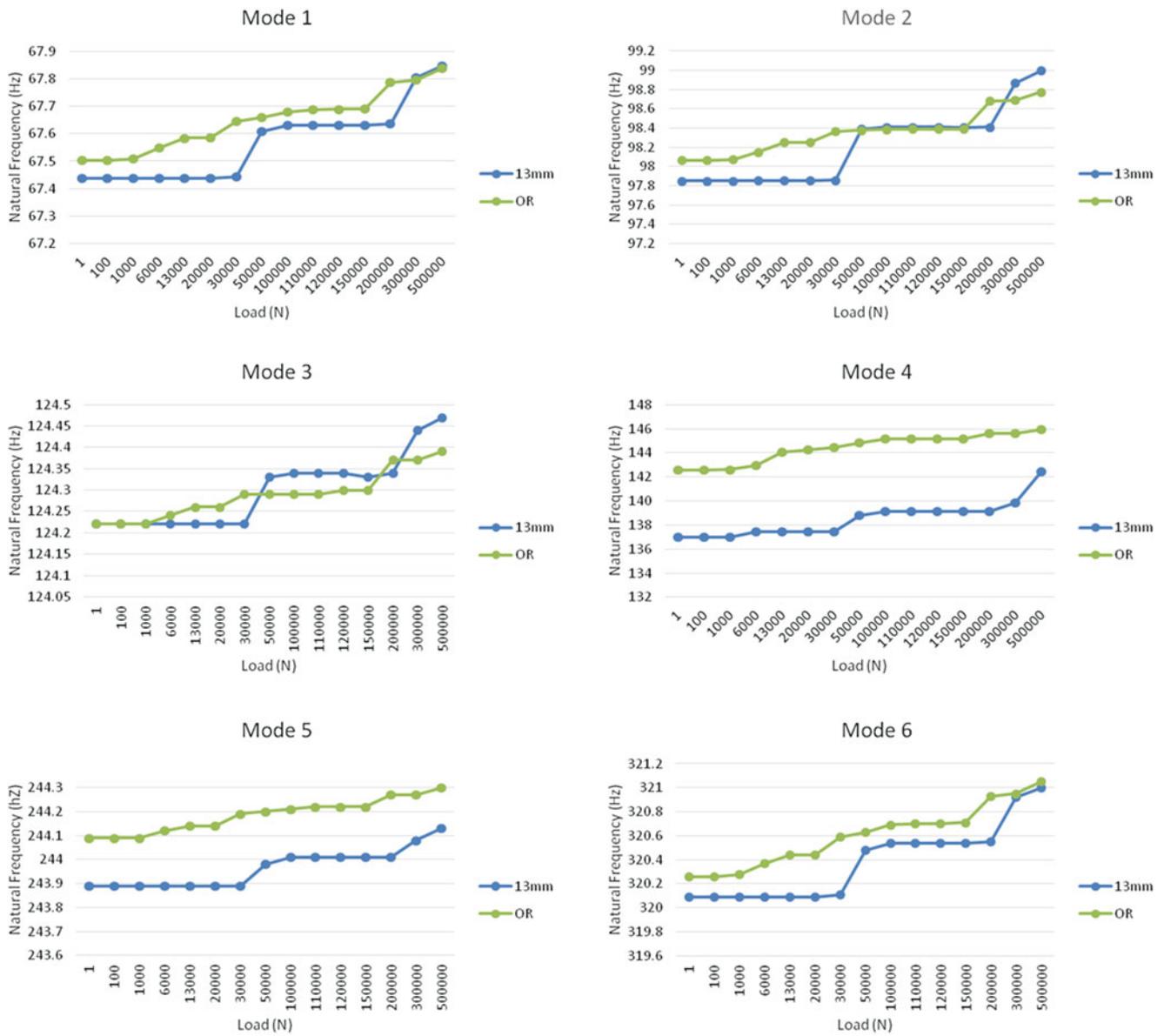


Fig. 29.7 Effect of the size of the contact area on the natural frequency

Finally, Fig. 29.7 shows the effect of the size of the contact area on natural frequency for all modes. One set of tests are presented here, where the diameter of the bolted holes being cut was set to 13 mm. For each structure with a varying contact area, a full preload test was performed. The results were then compared to the data from the preload tests of the original structure (referred to as “OR” within the legend).

These FE analyses showed that Mode 4 was the most sensitive to the variation of the parameters, as presented in Figs. 29.4, 29.5, and 29.6. However, the reduction of contact area showed a different relationship where all modes were fairly insensitive to any preload used for the bolt. This seems to suggest that the reduced contact area generates more local stiffness which in turns makes the natural frequency less variable. This set of examples shows how much an improved level modelling adds important value to the study of the variability of the dynamic response.

29.4 Experimental Works

This section will report the two experimental cases by presenting the most interesting data analysis.

29.4.1 Bolted Flange Joints (BFJs)

Bolted Flange Joints (BFJs) are used nearly in all industrial piping systems including in oil and gas plants which are considered as high-risk facilities. These connections represent leak relevant positions, where a single failure may lead to catastrophic damage. Hence, the correct functioning of BFJs is required to ensure the overall performance of such facilities and to avoid possible accidents. Recent studies have shown a high vulnerability of piping systems and their components, including joints, to seismic and non-seismic vibrations (such as those induced by rotating machinery). Pipeline failures account for the majority of oil-field disasters that have led to destruction of lives and environment. Hence, there is a pressing need to better understand the dynamics of bolted flanges. Figure 29.1c shows the test structure, which is made of two pipes connected by bolted flanges. Six M16 bolts were used to connect the two flanges. Four mode shapes were selected for the experimental testing (Fig. 29.8).

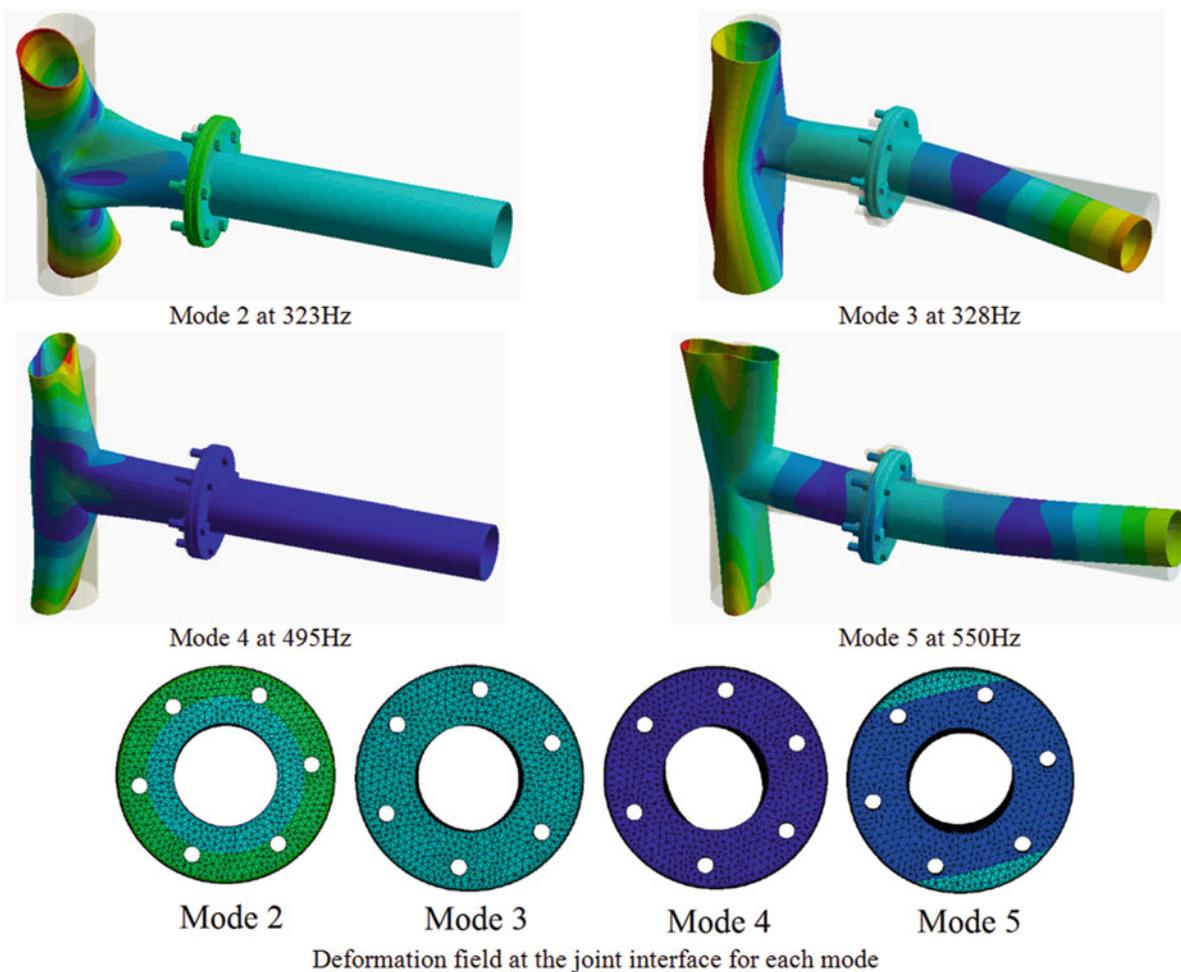


Fig. 29.8 Mode shapes and flange deformation

A series of tests were performed to study the variations in natural frequency and damping where certain parameters that influence the dynamics of the joints were varied. Three parameters were determined to be of interest:

1. Bolt preload
2. Tightening sequence
3. Differential torque

These tests were performed to quantify the sensitivity of the modes to each of these parameters and to determine how they affect the repeatability of the modal parameters.

All measurements are prone to systematic errors which can be environmental changes or imprecise calibrated measurement instruments. Repeated measurements do not reduce systematic error and hence care must be taken to avoid it. In addition to this, there can also be random errors that are caused by unknown changes in the experiment and are hence inherently unpredictable. A series of tests were performed to quantify the error in both natural frequency and loss factor. The structure was bolted with a preload of 10 Nm. This value of torque was chosen as the joint seems to induce the least repeatability at lower preloads. After each test, the structure was detached from the shaker and accelerometer, taken off the bungee cables and then re-attached so as to simulate all the previous experimental conditions except for the disassembly of the joints. These observations, presented in Fig. 29.9, give weight to the assumption that the errors caused by changes in the environment or variations in the suspension of the structure are insignificant compared to the effect that changes in the joint interface has on the modal properties of the structure.

In this section, the effect of bolt-preload on the modal parameters of the pipe section is investigated. The structure was repeatedly detached and assembled to perform a series of tests. The preload torque was varied through 10, 20 and 30 Nm for different series of tests. The natural frequency and damping were estimated from the inherent FRFs obtained (Figs. 29.10 and 29.11).

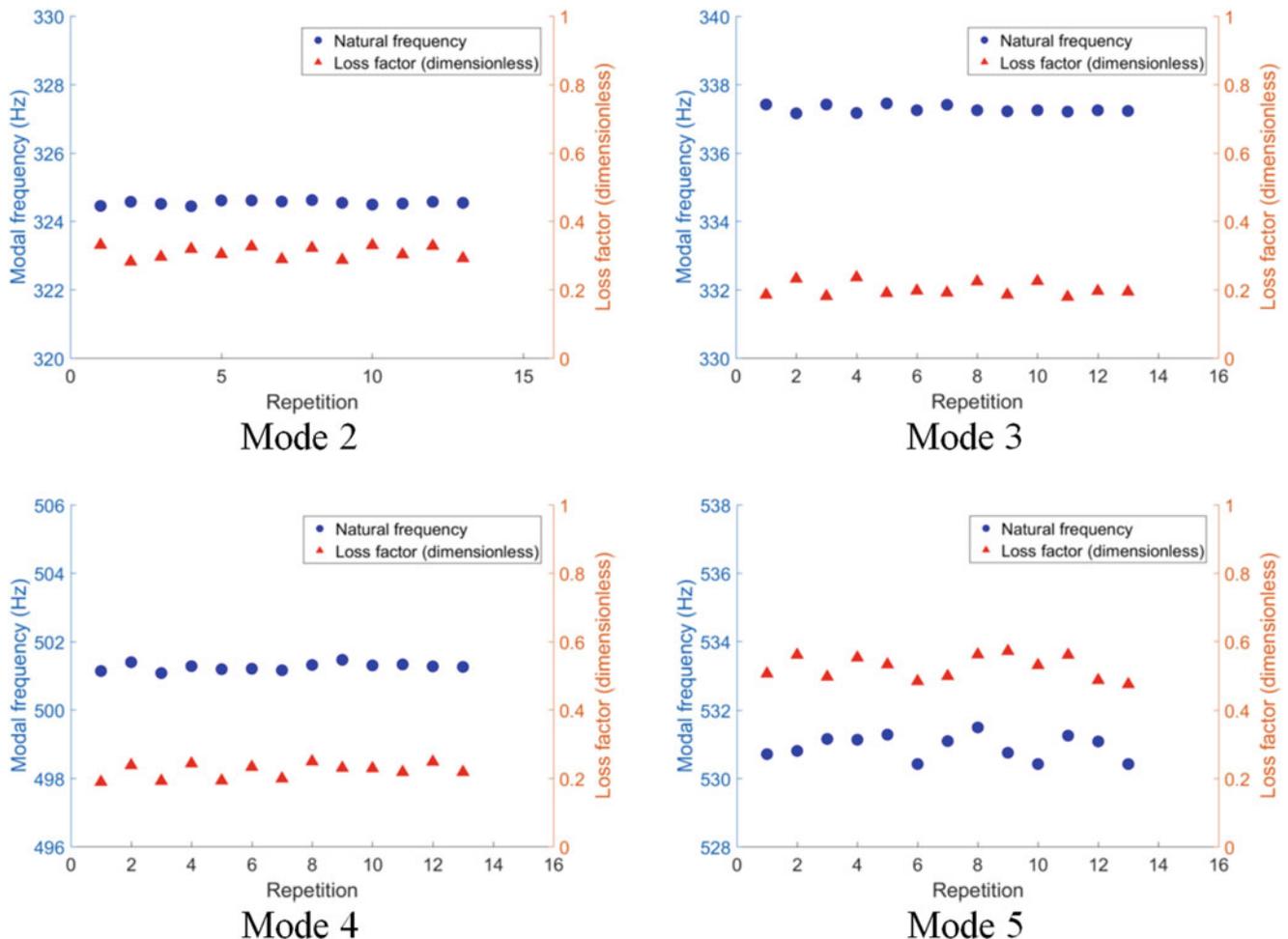


Fig. 29.9 Scatter plots of modal data for error analysis

In this section, the effect of bolt tightening sequence on the modal parameters of the pipe section is investigated. The structure was repeatedly detached and assembled to perform a series of tests. The bolt preload was kept constant at 10 Nm, since the scattering of data points was maximum at low bolt-preloads (as seen in previous section) and any trends in data are easier to spot. The natural frequency and damping were estimated from the inherent FRFs obtained (Fig. 29.12).

In this section, the variation of the modal parameters of the pipe section when combinations of bolt preloads were applied on the joint, is explored. The structure was repeatedly detached and assembled to perform a series of tests. The tightening sequence was kept constant for all the tests. The natural frequency and damping were estimated from the inherent FRFs obtained (Figs. 29.13 and 29.14).

This section presents a study of the repeatability of the modal behaviour of a bolted flange when various parameters that affect the contact condition of the joint were changed. Three parameters and their effects were explored – bolt preload, torque sequence and torque configuration, respectively. The results from the experimental analysis show that the mode-shape and the stress distribution at the flange interface play a critical role in the variability of modal parameters. Also it is noticed that repeatability of modal behaviour varies from mode to mode and from parameter to parameter. Some modes exhibited greater sensitivity to certain parameters than others. Numerical analysis revealed that Modes 2 and 5 have non-uniform stress distribution at the joint interface. This corresponded well with the large scattering of modal data and non-repeatability of the modal dynamics for these two modes. When the overall torque on the flange is increased, the joint becomes rigid and the variability in natural frequency and loss factor decreases.

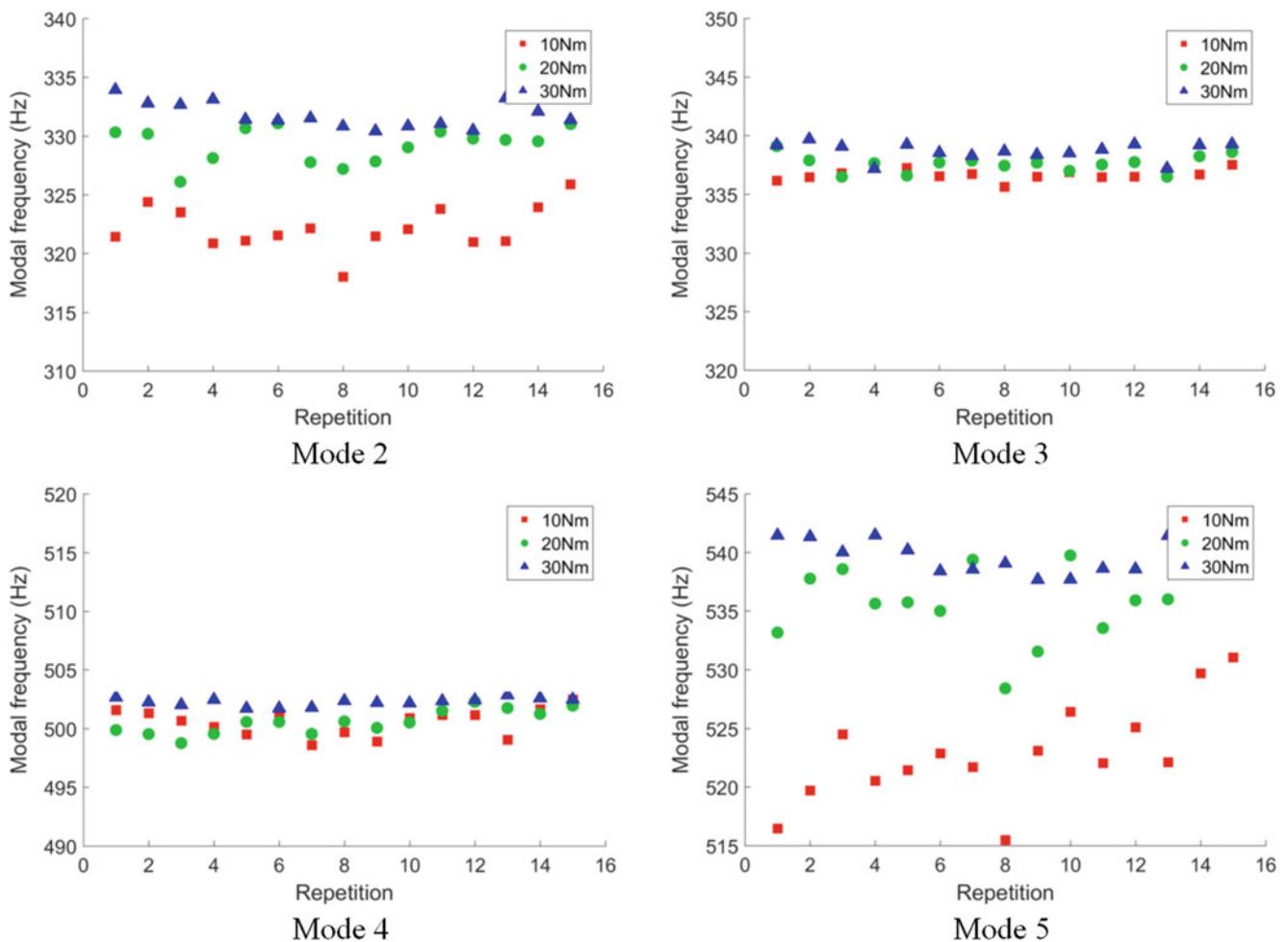


Fig. 29.10 Variability of the natural frequency and loss factor

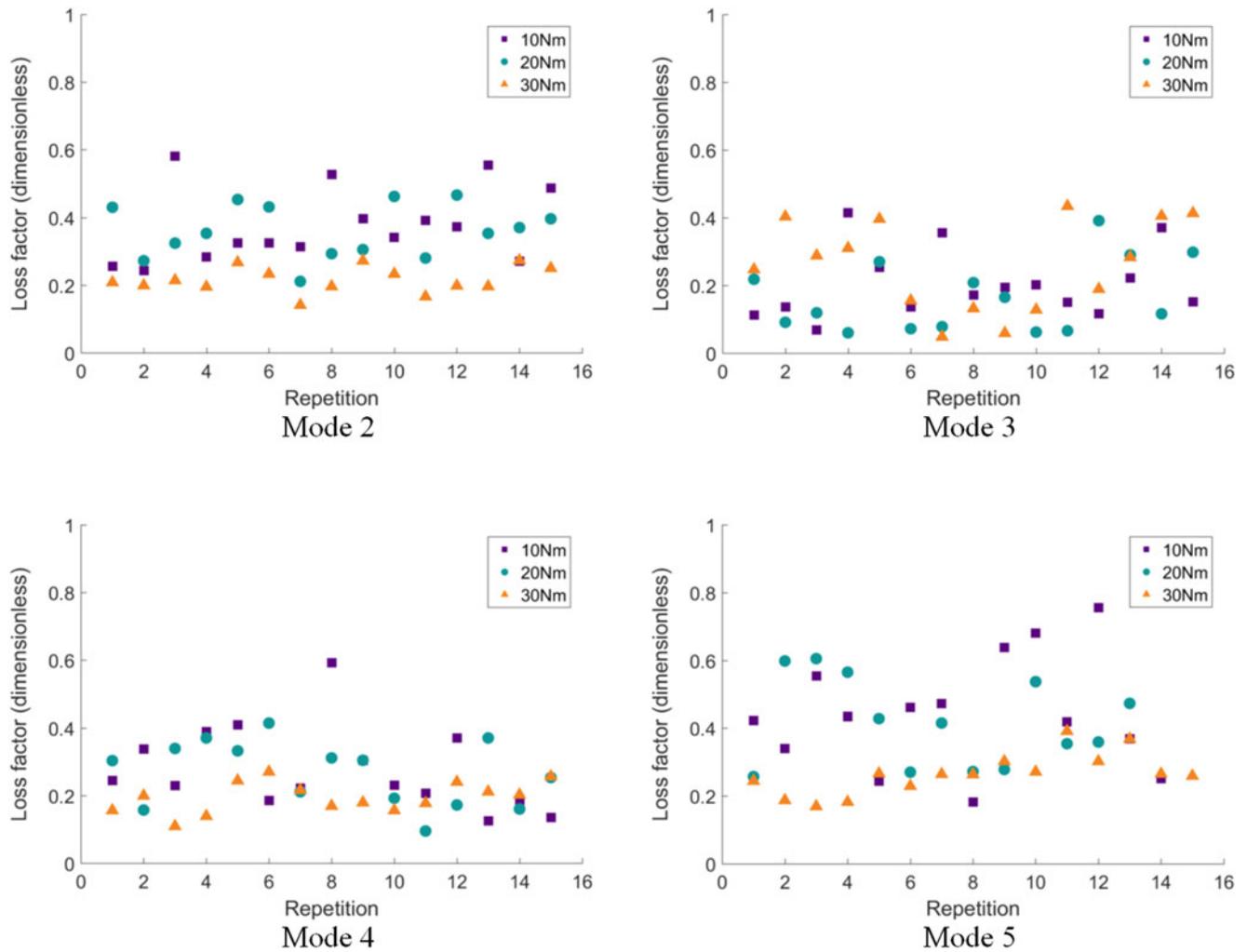


Fig. 29.10 (continued)

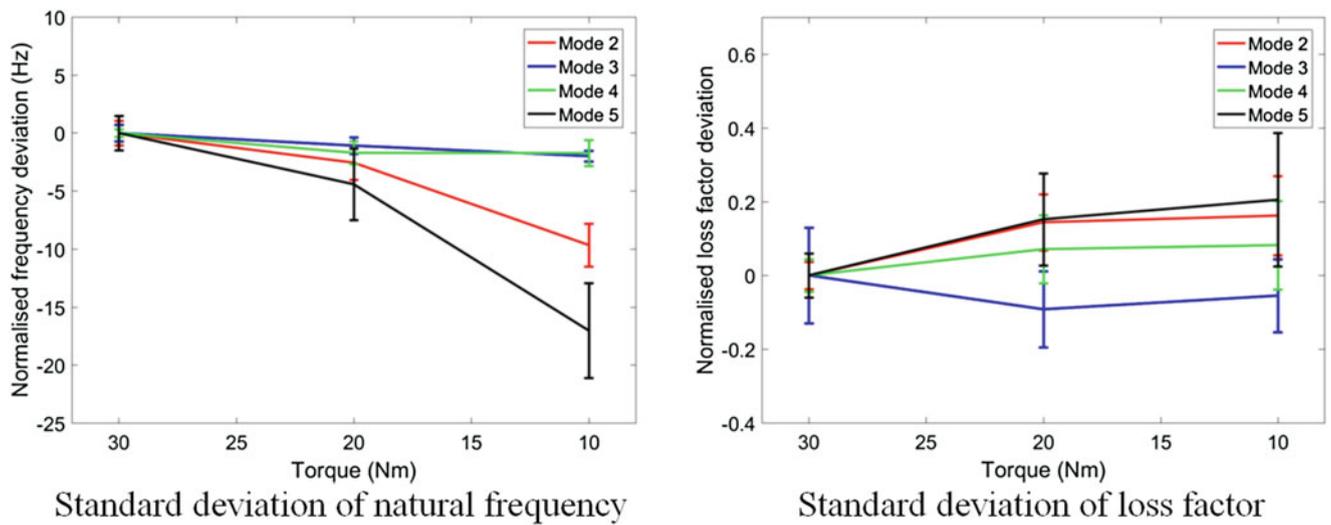
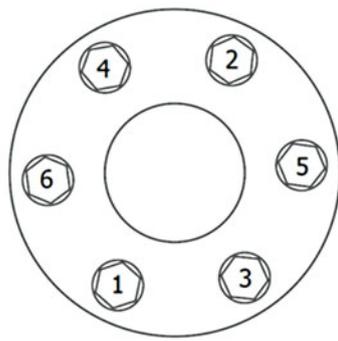
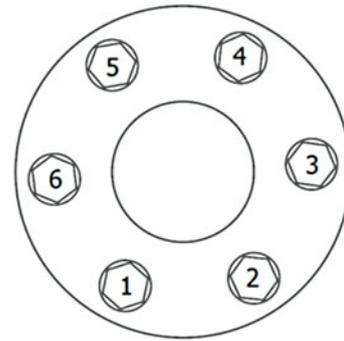


Fig. 29.11 Standard Deviation



Tightening sequence 1



Tightening sequence 2

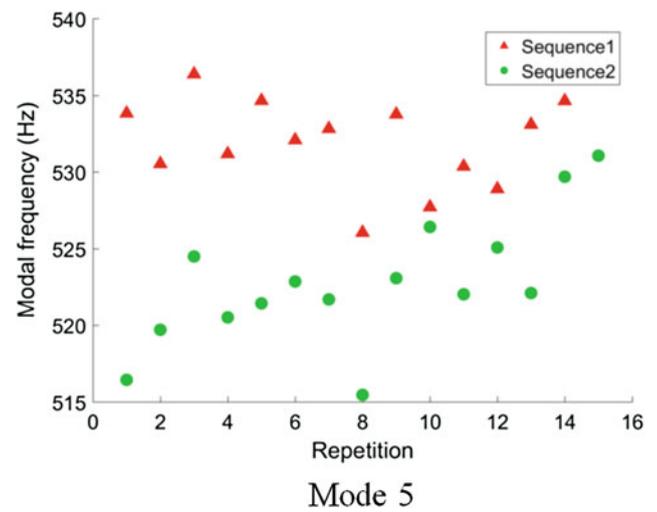
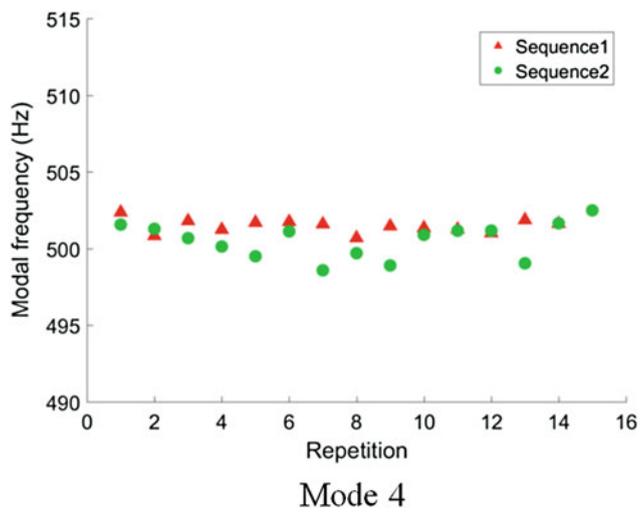
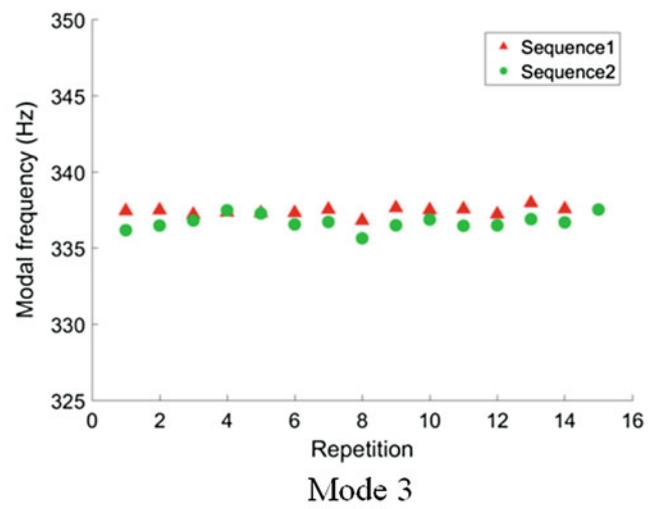
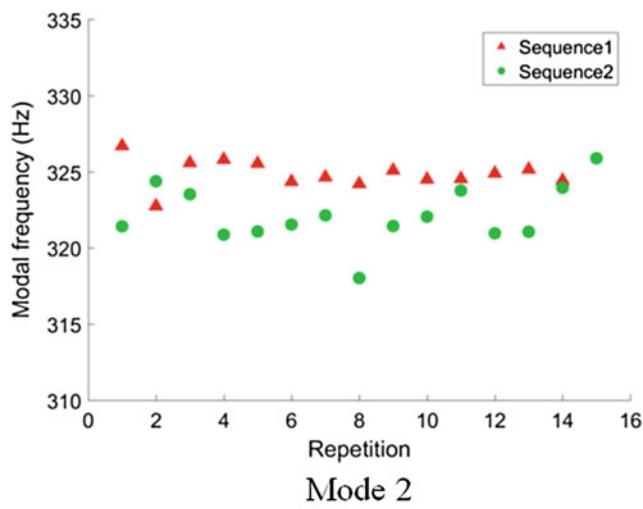


Fig. 29.12 Two bolt-tightening sequences used for the natural frequency and loss factor analysis

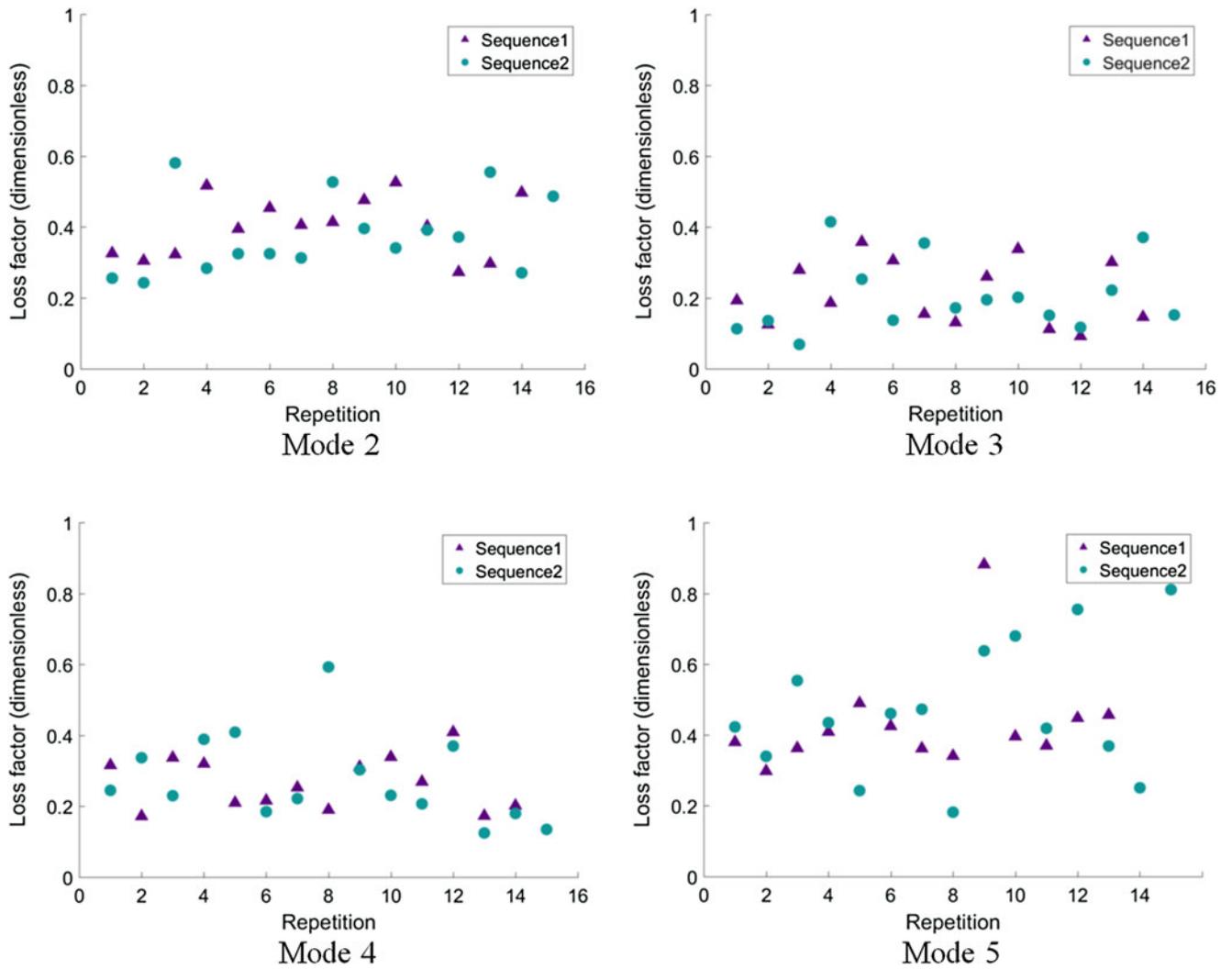


Fig. 29.12 (continued)

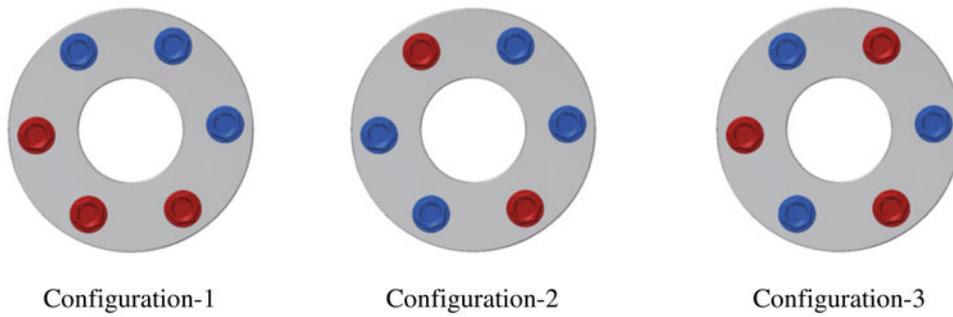


Fig. 29.13 Three different combinations of low and high bolt pre-loads used for analysis (Redbolts are torqued to 20 Nm while Bluebolts are torqued to 10 Nm)

29.4.2 I-Beam in T Shape Assembly

A T-shaped assembly was chosen to evaluate the construction of a beam to column connection. This involved the horizontal I-beam cross section being jointed to the side of the vertical I-beam. In order to make this possible, an extra interface was needed to bolt the I-beams together. Therefore an end plate, composed of mild steel, was welded to the horizontal I-beam face. This would then be bolted to the vertical I-beam with six M12 bolts, as shown in Fig. 29.1a. Once the structure was prepared, two modes were selected for testing, one at 220 Hz and other at 750 Hz. The structure was then disassembled and reassembled 15 times for each of the five torque settings while measurements of natural frequency and damping were taken.

Examination of Fig. 29.15a, b shows all the data values gathered for Mode 1. Clearly there is a large spread of data, most notably in Fig. 29.15a, where several data points occurred around 235 Hz while the majority were found at 220 Hz. These outliers at 235 Hz appeared for all torque settings, regardless of their value. This disparity between values at 220 Hz and 235 Hz seems to suggest systematic error as the natural frequency of structure should not theoretically change by such a large amount for all torque values. The most likely explanation is that the mode is highly sensitive to testing. This explanation agrees with data in Fig. 29.16a where no clear outliers occurred for Mode 2, despite data being measured for the exact same samples. As a result, these outliers for natural frequencies and their corresponding loss factors, were ignored from further analysis, as they would unfairly affect the mean and standard deviations calculated for comparison and as shown in Fig. 29.15c–f.

The correlation coefficient, ρ , shows a value close to 1 for Fig. 29.15c, suggesting a positive correlation between torque preload and natural frequency. Furthermore, the correlation of determination, R^2 , is also close to 1 indicating a linear

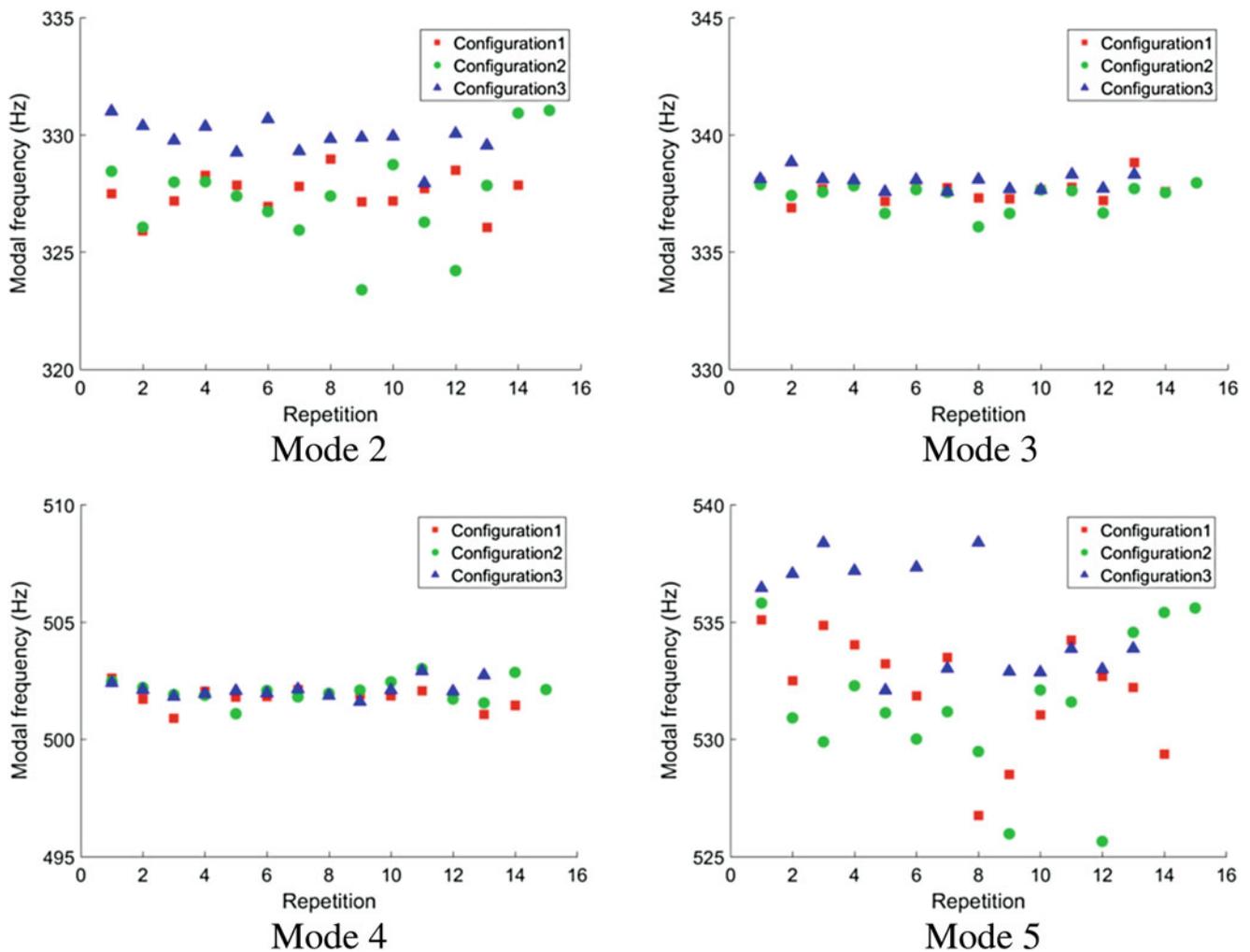


Fig. 29.14 Natural frequency and loss factor variability

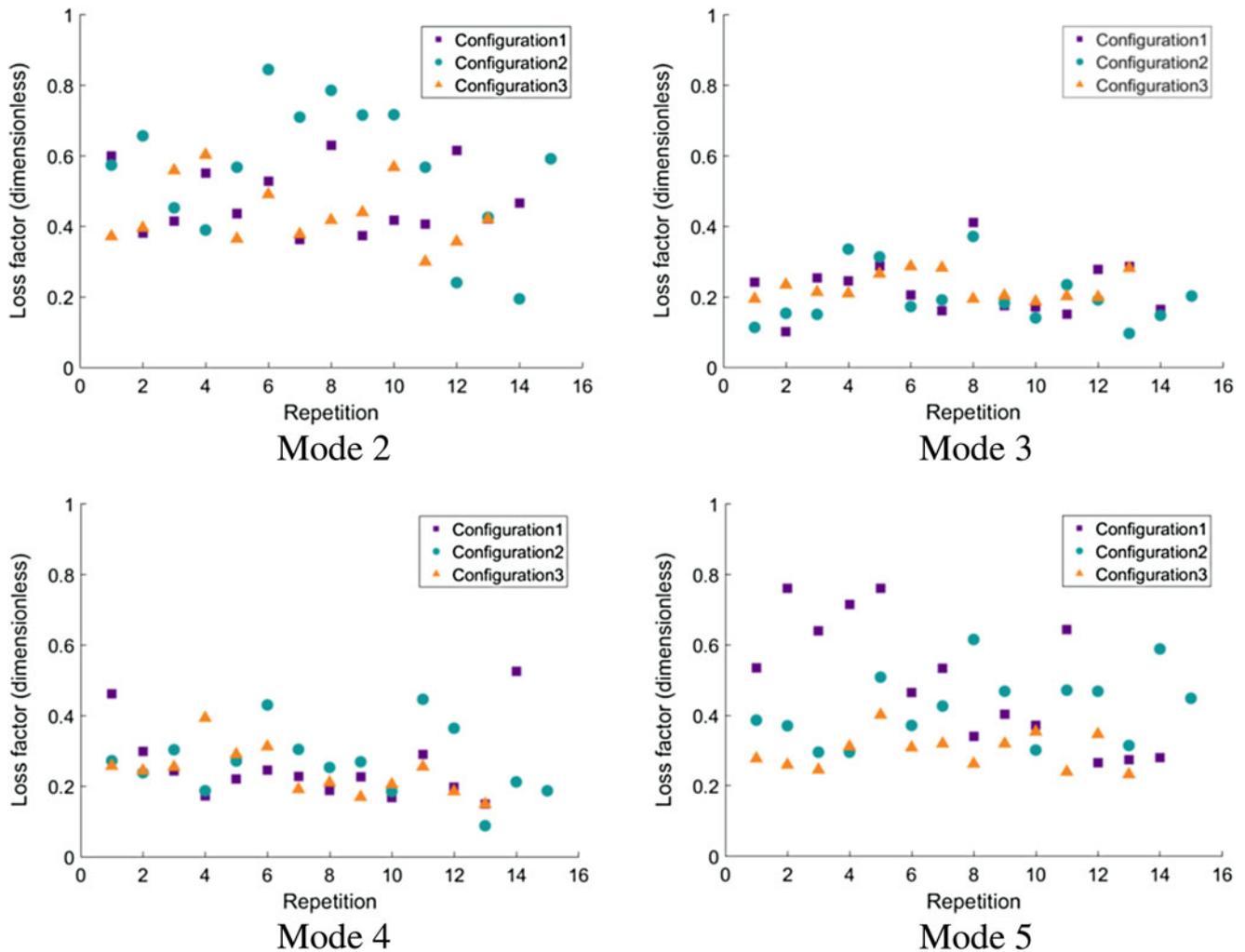


Fig. 29.14 (continued)

relationship between the two variables. This is consistent with dynamic theory, as the higher the torque preload, the more stiff the structure and therefore the higher the natural frequency. Figure 29.15d shows a similar linear relationship between torque and loss factor, except it is in the negative direction shown by its correlation coefficient close to -1 . Given that loss factor is a representation of mechanical damping, the higher the torque preload, the stiffer the structure, the less energy is dissipated by the system and therefore the lower the mechanical damping and loss factor of the mode. Given the linear relationships of both natural frequency and loss factor to torque, this behaviour is validated by dynamic theory.

Figure 29.15e, f show how the standard deviation changes with constant torque preload. Standard deviation is a measure of repeatability as the higher the standard deviation of a sample, the larger its spread in data and hence the less repeatable it is. Both graphs have a negative correlation coefficient of -0.9655 and -0.9484 respectively, indicating that the standard deviations of natural frequency and loss factor decrease with torque. Therefore the repeatability of the structure increases with torque preload. As a bolted surface becomes tighter and more rigid, the ability of the structure to twist, turn or displace in any manner reduces; as a result it is not surprising that this trend is observed. The R^2 value of Fig. 29.15e means that 93.21% of the variance in natural frequency standard deviation can be explained by a linear relationship between the torque and standard deviation. Although a linear relationship could explain the trend in repeatability, visually it seems more likely that the repeatability is increasing at a greater rate between torques, as the gradient of the line plot becomes steeper and steeper. Given that only 4 data points are plotted, it is hard to be certain of this, but a linear relationship for repeatability also seems to be unsupported by Fig. 29.15f, where the R^2 value is less than 0.9 and visually there is a considerable jump in the standard deviation of loss factor between 20 and 40 Nm. Therefore there does not seem to be a linear relationship between repeatability and modal behaviour. As mentioned, both sets of data do suggest that repeatability increases with

torque preload, but it is not clear in what fashion or whether a predictable model can be suggested by these results. For this particular mode, it does appear that the repeatability of natural frequency increases at a greater rate between torques indicating that torque preload should be set to 60 Nm or higher in order to maximise repeatability. For loss factor, a decrease of 43.9% in standard deviation was observed between 20 and 40 Nm, suggesting a torque preload of 40 Nm or higher should be used to maximise repeatability.

All the experimental data for Mode 2 is plotted in Fig. 29.16a, b. Unlike Mode 1, both loss factor and natural frequency appear to have no outliers and a relatively smaller spread in data values. From the onset, this suggests that the mode is relatively stable with a high level of repeatability. The lack of outliers means that all data points are valid for statistical analysis. Further examination is therefore needed to determine if any trends can be used to model repeatability.

Figure 29.16c, d show how the mean natural frequency and mean loss factor of Mode 2 vary with constant torque preload. Figure 29.16c has a ρ value of 0.9994 indicating a strong positive correlation between torque preload and natural frequency. Furthermore, its R^2 value of 0.9988 suggests a linear relationship between the two variables. These results conform to vibration theory where the higher the torque preload, the stiffer the structure and the higher its natural frequencies. Figure 29.16d has a ρ value of -0.9870 showing a negative correlation between loss factor and torque preload. Similarly a high R^2 value of 0.9742 was calculated, suggesting a linear relationship between the two variables. This is also consistent with vibration theory as the higher the torque preload, the less energy dissipated during vibration and the lower the loss factor.

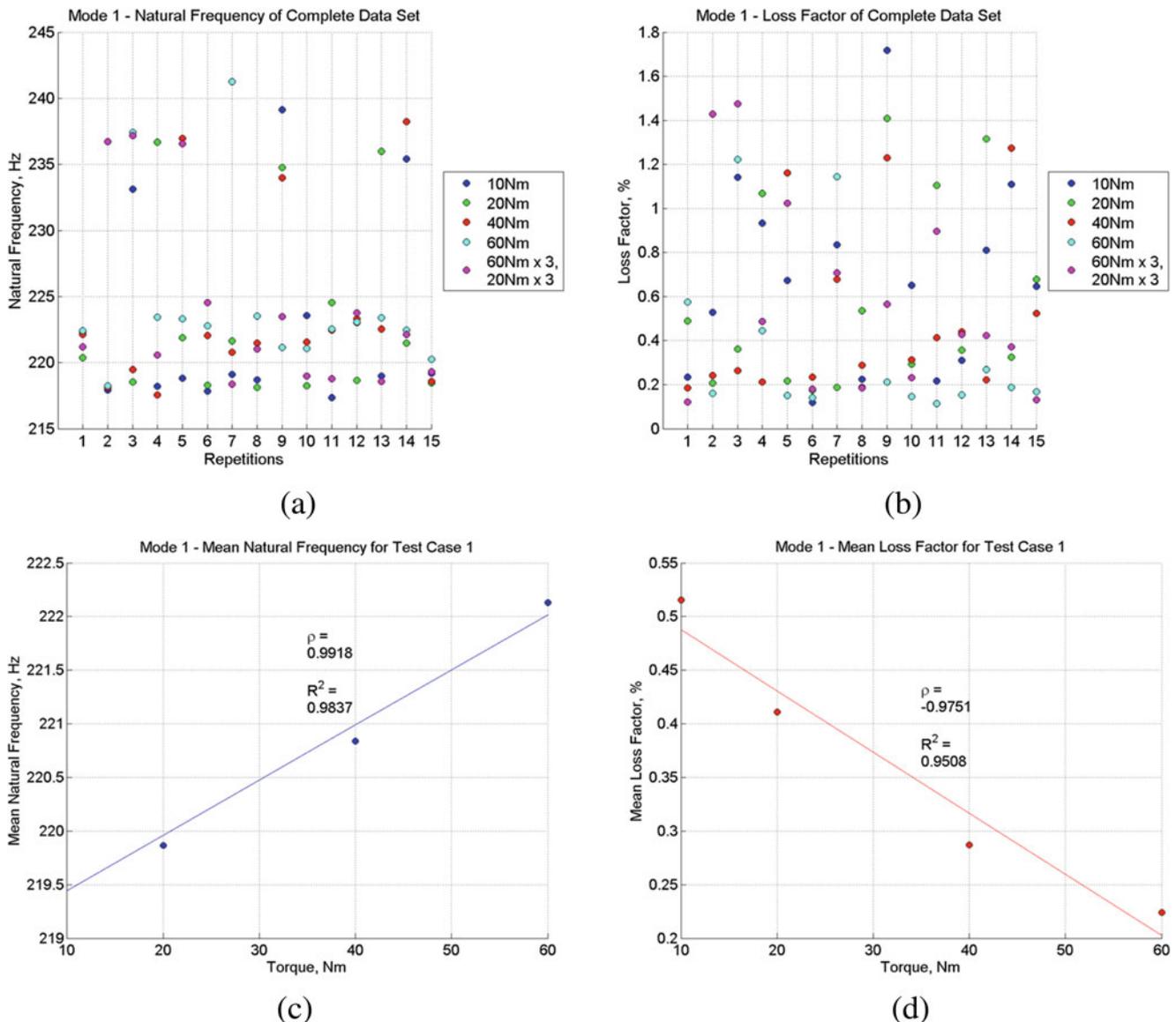


Fig. 29.15 Natural frequency and damping for mode at 220 Hz

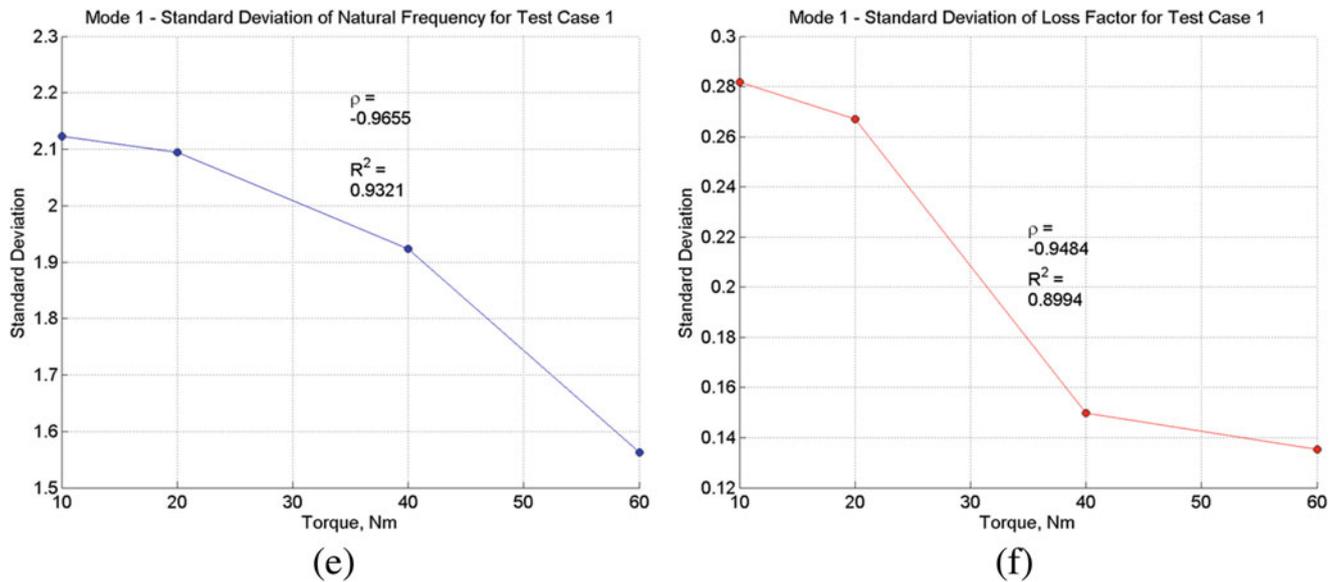


Fig. 29.15 (continued)

Understanding how the standard deviation of the natural frequency and loss factor change is vital to understanding how repeatability changes, as the smaller the spread in data, the more repeatable the modal behaviour. This is illustrated by Fig. 29.16e, f where both standard deviations of the natural frequency and the loss factor change with torque preload. Visually both have similar shapes and correlation coefficients (-0.7124 & -0.7797) suggesting a relationship between modal properties and torque preload i.e. the repeatability of both natural frequency and loss factor decrease in tandem with torque preload. It is unsurprising that the correlation coefficient is negative because the higher the torque preload, the tighter the bolts, the more rigid and secure the structure, and less likely it is to deviate from its standard modal behaviour. The R^2 values of both graphs are relatively low suggesting that a linear relationship between repeatability and torque preload does not exist. Both do show dramatic jumps in standard deviation between 10 and 20 Nm. This indicates that the repeatability of mode increases significantly between these torque values and that a minimum of 20 Nm should be used in order to increase repeatability. Although the R^2 values indicate a non-linear model for repeatability, if one were to disregard the data points at 10 Nm and focus on the torque preloads onwards, visually a linear relationship would be reasonable to suggest for both natural frequency and loss factor. This means that repeatability could increase after a particular torque (20 Nm in this case) and then follow a linear relationship in terms of further increase. By disregarding 10 Nm and calculating the R^2 values for the data points at 20, 40 and 60 Nm, one can see if a linear relationship does exist between repeatability and modal behaviour from 20 Nm onwards. A value of 0.7826 for natural frequency and 0.9967 for loss factor was produced. This new R^2 value for loss factor suggests a linear relationship as it is close to 1, while the new R^2 value for natural frequency suggests the opposite as it is relatively low. Given that both contradict each other, it is inconclusive whether repeatability can be modelled to be linear from a point onwards.

29.5 Discussion of the Results

This work presented two types of structures usually designed in mechanical engineering. The simplicity of the assembly posed a question about the effect of the bolted joints on the variability of the dynamic response. The work is split in two parts, one numerical and one experimental. The joints presented in here are not usually modelled in practice where components are often bonded together. This design choice is simple and makes the model faster to run simulations. Instead, from a practical view point, maintenance aims at disassembling and reassembling the joints numerous time. Hence, the questions are about (i) what happens if they are modelled and (ii) how repeatable is the dynamic response if the joint is opened and closed several times.

The numerical work was focused on four parameters (preload, the size of the contact area, the size of the bolt body and the size of the bolt head), two of which are more relevant since the bolt head and body diameters are standardized and hardly changeable. The FE analysis is also based on linear response conditions. The change in the preload has shown that some

modes are more sensitive than others, in particular Mode 4, to the changes applied. Mode 1 and Mode 2 were also sensitive to this parameter variation. By looking at the mode shapes it is possible to infer that Mode 4 seems to stress the bolt because of the in-plane bending with a large inertia created by the motion of the two beams; so the bolts take most of the load. Similar observation could be drawn by looking at Modes 1 and 2. However, in this case Mode 1 is the least sensitive and this is probably due to the torsional mode of the up-right beam. Interestingly, when the contact areas between the bolted parts were reduced and the preload was again varied between 1 N and 500,000 N, the natural frequencies of the modes become less variable than before. This can be explained due to the increased pressure distribution and therefore higher local contact stiffness.

The experimental work was conducted under low level of excitation forces so as to measure linear responses. It is well known that joints show typical nonlinear responses but these were not taken into account at this stage. So, the work was confined to the understanding of the variation of natural frequency and loss factor due to the opening and closing of the joints. Four modes were analysed for the pipe assembly whereas only two modes for the I-beam assembly. It is also clear from the experimental examples that some response modes are more sensitive than others. This evident for the jointed pipe in Sect. 29.4.1 which shows that Modes 3 and 4 are insensitive to the assembly operation while the others produce much

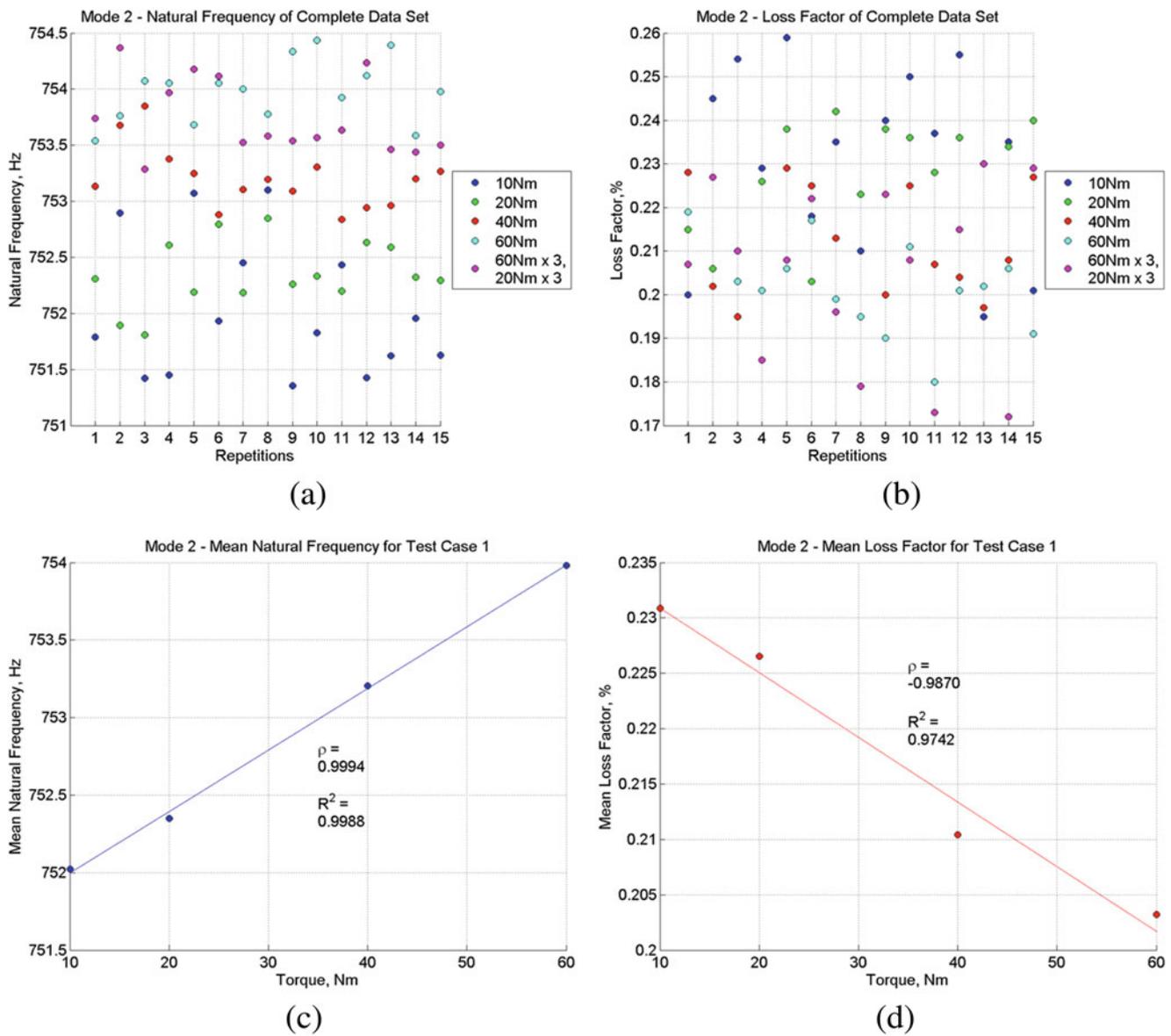


Fig. 29.16 Natural frequency and damping for mode at 750 Hz

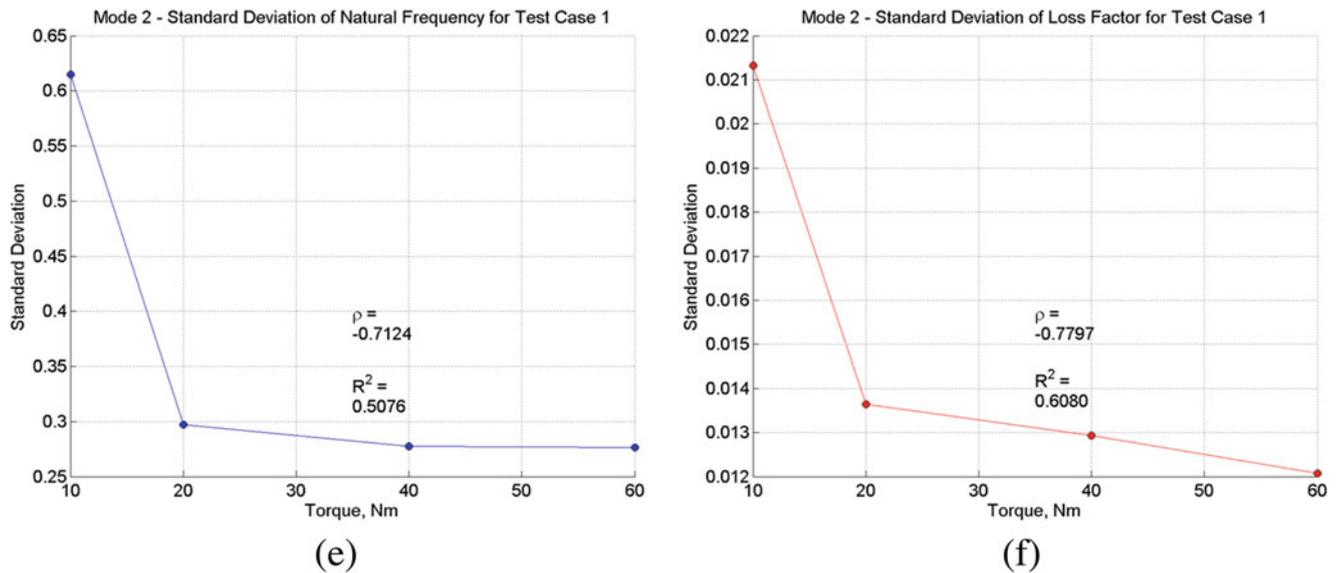


Fig. 29.16 (continued)

higher variability in both frequency and damping. The experimental outcome could be partially expected by inspection of the deformation of the flange as shown in Fig. 29.8. In this Figure it is possible to see that Modes 3 and 4 present the least deformation of the flanged area and so joints would be the least exercised during the vibration loading; hence the higher level of repeatability. Similarly, but less evident, it is presented for the I-beams in Sect. 29.4.2. There, two modes were analysed and Mode 1 showed a poorer standard deviation of the natural frequencies as shown in Fig. 29.15e, than Mode 2 as presented in Fig. 29.16e. Both show that an increased torque level makes the natural frequency of the assembly increasingly less variable. In both experimental cases the damping loss factors present significant scatter, in some cases more bounded but in others highly variable. This was somehow expected since a number of factors can influence the variance of the loss factor, which is not just due to the jointed areas, for example the method of suspension can play an important contribution.

29.6 Conclusions

This paper presented a research work on the variability of dynamic response of jointed structures. The aim was not to investigate the nonlinear dynamics of joints but, instead, to observe how variable both natural frequency and loss factor are when the joint is open and closed several times. Assembled structures are maintained and it is common to open and close joints. The major challenge is given by the large variability of both frequency and damping this will create a level of aleatory uncertainty. It is possible to say from an experimental point of view that some response modes presented less variability to the assembly procedure than other modes investigated. The true physics is not identified but an explanation can be given by saying that level of deformation of the jointed interfaces is smaller for some modes than for others. Whichever contact stiffness at the interface and any consequent stick-slip condition that follows will be mode dependent and so some modes will be less sensitive to those conditions and thus resulting in less variable natural frequency.

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