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Updating of the Dynamic Behaviour of an Assembled Structure with Bolted Joints in Light of EMA Results

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Abstract. Bolted joints, which contribute significantly to minimise the magnitudes of resonant peaks of assembled structures and give easy-to-install and uninstall, have been widely used in various types of mechanical structural assembly and. However, modelling of an individual bolted joint within a large assembled structure has always been problematic, especially when it comes to predicting dynamic behaviour. The aim of this paper is to put forward an idea of efficiently and economically modelling of bolted joints of an assembled structure focusing on the bolting and assembly interfaces. The finite element (FE) models of individual components (Plate A and Plate B), bolting and assembly interfaces were developed using the NX11 Simcenter 3D software. Normal modes analysis was carried out for the initial FE models of the individual components and the assembled structure. Experimental modal analysis (EMA) was performed to determine the modal parameters of the individual components and assembled the structure. It was found that a low correlation between the initial FE models and EMA has been recorded. The initial FE models were then tuned in the light of EMA results in order to improve their accuracy and reliability. The proposed updating procedure has been successfully used in improving the low correlation which is largely due to the inaccurate modelling of the bolted joints.

1. Introduction

One of the essential features of bolted joints is easily assembling and dissembling. For this reason, bolted joints have been widely used in assembled structures. In addition, bolted joints play a significant role in the structural, dynamical response. Although bolted joints are important for energy dissipation of structures and alterations in structural damping [1] but efficient and economical representation of an individual bolted joint within a large assembled structure has always been troublesome and difficult, particularly for the prediction of dynamic behaviour.

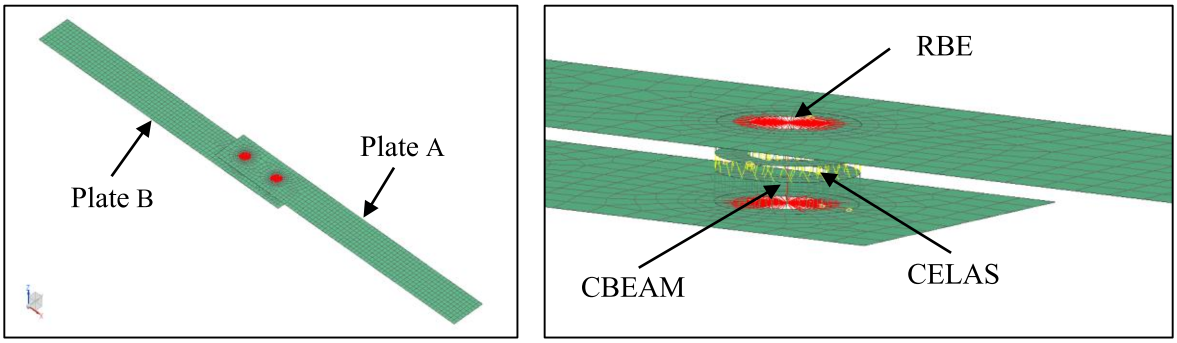
The dynamic behaviour of an assembled structure with bolted joints can be predicted efficiently with the appropriate FE modelling. There are several factors which can contribute to the development of an efficient FE modelling of the bolted joints such as bolt modelling and joint interfaces [2-5]. However, very little attention has been paid to the development of an efficient FE model of an assembled structure with bolted joints and integrate the proposed method with the FE model updating procedure.

This work is concerned with the idea of bringing forward an efficient and economical modelling method for the bolted joints of an assembled structure focusing especially on the bolting and the assembly interfaces. FE model updating is used to update the initial FE results in the light of experimental data and to improve the accuracy and reliability of the FE model of the assembled structure with bolted joints which could be used for subsequent analyses.

2. FE Modelling and Analysis

The FE modelling and analysis was carried out by using the NX11 Simcenter 3D software. The identical FE models of the steel plates, named as Plate A and Plate B, were developed. The meshes of each plate were created by using 1288 CQUAD8 elements with the element size of 5 mm. The element size was used after several convergent tests were performed. Normal modes analyses for the plates A and B were conducted by using the solution type of SOL 103 Real Eigenvalues in order to characterise the first ten natural frequencies and mode shapes of the plates. The predicted results were used as the initial FE results in this study. The initial FE results were then compared with the measured results of the plates obtained from EMA. The FE model updating procedure was employed to reduce the errors introduced in the initial FE models as a result of invalid assumptions about model properties.

The updated FE models of Plate A and Plate B were assembled together to form a simple lap joint which is called an assembled structure with bolted joints in this work (figure 1). In modelling of the physical stainless-steel bolts and nuts, they were represented by the CBEAM element for the bolts' shank and RBEs for bolts' heads and nuts. The interfaces of the assembled structure were modelled using CELAS elements. The same procedures for FE analysis and model updating were exercised for the FE model of the assembled structure with bolted joints.



(a) (b)

Figure 1. (a) Finite element model of the assembled Plate A and Plate B; (b) Representation of bolt, nut and assembly interface.

3. Experimental Modal Analysis (EMA)

The modal parameters, which are the natural frequencies and mode shapes, of Plate A, Plate B and the assembled structure with bolted joints were characterised by performing the EMA. The experimental setup for the assembled structure is shown in figure 2(a). Plate A and Plate B were joined by using the stainless steel M10 bolts and nuts. The components and assembled structural component under test were suspended to the test rig by using rubber bands to simulate free-free boundary conditions. The equipment used to characterise the modal parameters were the LMS system, LMS Test.Lab software, impact hammer & accelerometers as shown in figure 2(b).

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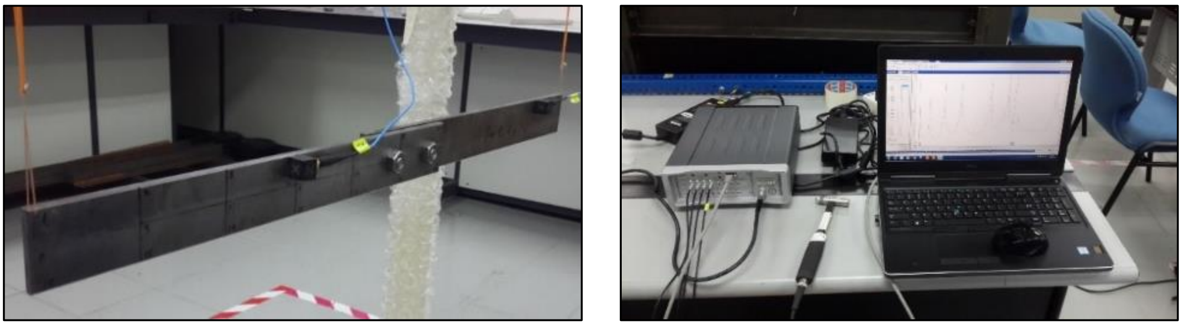

(a) (b)

Figure 2. (a) Experimental set up for the assembled structure with bolted joints; (b) Testing equipment for EMA.

4. FE Model Updating

FE model updating is used to improve the accuracy and reliability of the initial FE model, so that the predicted dynamic behaviour obtained from the updated FE model matches as close as possible to the measured dynamic properties [6-7]. Material and physical properties, such as Young's modulus, Poisson's ratio, shear modulus and mass density, are used as the updating parameters. Those parameters, which are sensitive to the finite element model's stiffness and mass properties [8], shall be systematically adjusted within the identified range to match the experimental results as closely as possible.

In this study, the SOL 200 Model Update of NX 11 Simcenter 3D was used in the attempt to update the FE models of Plate A, Plate B and an assembled structure with bolted joints. The first ten natural frequencies were included in the objective function as in equation (1) [9-10] to minimise the errors between the predicted and measured natural frequencies:

$$min \sum_{i=1}^{m} W_i \left(\frac{\omega_i^n}{\omega_i^e} - 1 \right)^2 \tag{1}$$

where ω_i^n is the i-th predicted frequency, ω_i^e is the i-th measured frequency, the weightage, W_i is set to unity and $i = 1,\ldots,10$.

5. Results and Discussion

In this work, the FE method and EMA were used to obtain the natural frequencies and the mode shapes of Plate A, Plate B and the assembly of both Plate A and Plate B. The FE model updating procedure was carried out in the effort to update the results of the initial FE models of Plate A, Plate B and the assembled structure in the light of the measured counterparts. The comparison of results between the measured, initial FE and updated FE, the updated parameters of Plate A, Plate B and the assembled structure are tabulated in table 1 to table 6.

5.1. FE Model Updating of Plate A and Plate B

The results of the natural frequencies and mode shapes obtained from the EMA and initial FE models for the first ten modes of Plate A and Plate B were compared. The total error for Plate A is 39.417% meanwhile for Plate B is 43.113%. The steepest descent algorithm was used as the optimizer to update the parameters of the FE models of both plates in order to reduce the total errors. The most sensitive parameters identified for the updating are the Young's modulus, Poisson's ratio and mass density. The comparison of results including the updated FE is shown in table 1 for Plate A, and in table 3 for Plate B. For Plate A, it was found that the error in the updated FE model has been successfully reduced from 39.417 to 4.271%. Meanwhile, the error of 43.113% in Plate B has been significantly decreased to 5.23%. The updated values of the parameters are shown in table 2 and table 4 for Plate A and Plate B respectively. It was revealed that there is a slight reduction in mass density and Poisson's ratio while an increment was noticed in the Young's modulus for both plates A and B. This process gives an accurate modelling of the Plate A and Plate B before progress to the updating process for the assembled structure.

Table 1. Comparison of experimental, initial FE and updated FE for Plate A.

Mode	I. Experiment (Hz)	II. Initial FE (Hz)	III. Error between I & II (%)	IV. Initial FE MAC	V. Updated FE (Hz)	VI. Error between I & V (%)
1	225.992	215.992	4.425	0.969	225.098	0.396
2	623.044	596.321	4.289	0.915	621.306	0.279
3	1096.832	1045.870	4.646	0.913	1096.350	0.044
4	1221.802	1171.210	4.141	0.772	1219.890	0.156
5	1581.957	1542.180	2.514	0.671	1607.710	1.628
6	2015.090	1935.790	3.935	0.852	2015.480	0.019
7	2216.766	2115.930	4.549	0.938	2217.310	0.025
8	3002.219	2886.310	3.861	0.881	3003.870	0.055
9	3375.650	3225.620	4.444	0.981	3378.800	0.093
10	4041.950	3936.380	2.612	0.840	4105.650	1.576
	Total Error		39.417			4.271

Table 2. Updated parameters for Plate A.

Parameter	Initial Value	Updated Value	Unit
Young's modulus	200000	206400	MPa
Poisson's ratio	0.32	0.302	Unitless
Mass density	7.850E-06	7.458E-06	kg/mm^3

Table 3. Comparison of experimental, initial FE and updated FE for Plate B.

Mode	I. Experiment (Hz)	II. Initial FE (Hz)	III. Error between I & II (%)	IV. Initial FE MAC	V. Updated FE (Hz)	VI. Error between I & V (%)
1	227.041	215.998	4.864	0.958	226.864	0.078
2	626.170	596.143	4.795	0.929	626.046	0.020
3	1099.010	1046.010	4.823	0.899	1099.210	0.018
4	1229.100	1170.520	4.766	0.828	1229.010	0.007
5	1582.200	1542.290	2.522	0.604	1620.060	2.393
6	2027.970	1934.670	4.601	0.877	2030.960	0.147
7	2223.820	2116.590	4.822	0.908	2223.890	0.003
8	3021.030	2885.450	4.488	0.890	3028.390	0.244
9	3390.110	3226.740	4.819	0.913	3389.750	0.011
10	4042.010	3936.400	2.613	0.674	4135.360	2.309
	Total Error		43.113			5.230

Table 4. Updated parameters for Plate B.

Parameter	Initial Value	Updated Value	Unit
Young's modulus	200000	209400	MPa
Poisson's ratio	0.32	0.316	Unitless
Mass density	7.85E-06	7.45E-06	kg/mm^3

5.2. FE Model Updating of Assembled Structure

In this work, the updated FE models of Plate A and Plate B were joined to form a simple lap joint as an assembled structure. In the FE model updating of the assembled structure, the material properties of the bolts and the translational stiffness property of the CELAS elements for the interfaces were found to be the most sensitive parameters and were used as the updating parameters. A genetic algorithm was used as the optimizer for the updating of the assembled structure. The comparison of results including the updated FE is tabulated in table 5. It was found that the total error recorded in the updated FE model of the assembled structure has been reduced from 21.093% to 18.874%. The updated values of the parameters used in the updating procedure are shown in table 6 from which it is revealed that there is a significant increment in the Young's modulus and shear modulus while a reduction in the mass density of the bolts is noted. In addition, there is also a slight increment in the value of the translational stiffness of the interfaces. This achievement discovered that the bolts and nuts used to assemble the plates contributed significantly to the dynamic behaviour of the assembled structure.

Table 5. Comparison of experimental, initial FE and updated FE for assembled plates.

Mode	I. Experiment (Hz)	II. Initial FE (Hz)	III. Error between I & II (%)	IV. Initial FE MAC	V. Updated FE (Hz)	VI. Error between I & V (%)
1	75.075	74.308	1.022	0.982	74.491	0.778
2	200.766	203.724	1.473	0.939	203.785	1.504
3	404.924	396.609	2.053	0.991	397.560	1.819
4	469.304	447.814	4.579	0.950	451.992	3.689
5	630.771	628.602	0.344	0.971	629.301	0.233
6	674.388	649.156	3.741	0.961	651.654	3.371
7	1034.640	1007.230	2.649	0.941	1009.680	2.412
8	1053.230	1060.560	0.696	0.911	1061.550	0.790
9	1276.950	1252.120	1.944	0.948	1255.760	1.659
10	1435.090	1472.260	2.590	0.936	1472.680	2.619
	Total Error		21.093			18.874

Table 6. Updated parameters for assembled plates.

Property	Parameter	Initial Value	Updated Value	Unit
Material	Young's modulus	193000	235619	N/mm^2
(Bolts)	Shear modulus	75000	92150	N/mm^2
	Mass density	7.86E-06	7.49E-06	kg/mm^3
PELAS (Interfaces)	Translational stiffness	300	301.2	N/mm

6. Conclusions

The attempts to model bolted joints using an efficient and economical procedure via the FE model updating procedure in the light of the results of EMA are presented and have been successfully performed. The parameters of the FE models of Plate A, Plate B, bolting elements and interface elements have been successfully used in the updating procedure to determine an efficient FE model of the assembled structure. This study revealed that the bolts' material properties and stiffness values at the joints interfaces have played a crucial role in ensuring the accuracy of the prediction of the dynamic behaviour of the assembled structure with bolted joints. Furthermore, the accuracy of prediction of the dynamic behaviour probably could be improved further if the boundary conditions and damping effects of the interfaces between the assembled plates were included in the FE model of the assembled structure with bolted joints.

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