Finite Element Modelling and Updating for Bolted Lap Joints

Rohaizat Omar[1,2]
Muhamad Norhisham Abdul Rani[1*]
Wan Imaan Izhan Wan Iskandar Mirza[1]
Mohd Azmi Yunus[1]
Mohd Hakimi Othman[1,2]
[1]*Structural Dynamics Analysis & Validation (SDAV)*
Faculty of Mechanical Engineering, Universiti Teknologi MARA
[2]*Machinery Technology Centre, SIRIM Industrial Research*

**mnarani@salam.uitm.edu.my*

ABSTRACT

Bolted joints have been widely used in the automotive and aerospace industries to join structural components due to its easy assembly method and low cost. However, the effect of the presence of bolted joints in industrial structures, regarding the dynamic response, has not been extensively studied, especially the efficient and economical modelling of the bolted joints itself. Therefore, this paper is put forward efficient and economical modelling for the bolted joints and interfaces affected regions of an assembled structure namely bolted lap joints. The finite element (FE) model of the bolted lap joints comprising the structural components, elements of the bolts, interfaces elements and the affected region of the interfaces were developed. Experimental modal analysis (EMA) was performed to extract the natural frequencies and mode shape of the physical lap joints' components and the assembled structure. The FE modal analysis was conducted for the initial FE models of the structural components and the assembled structure, and there were errors obtained when the modal analysis results and the EMA results were compared. FE model updating procedure was used to minimise the errors in the initial FE models of structural components and assembled structure. Results show that the bolts' material properties, stiffness values at the joint interfaces and the material properties of the interfaces affected regions have played a major role in ensuring the accuracy of the prediction of the dynamic behaviour of the bolted lap joint.

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Introduction

Bolted lap joints are the essential and critical elements in the structural assembly that have been widely used in various types of mechanical systems. The accuracy of the finite element models of the assembled structures with bolted lap joints is significantly influenced by the accurate and efficient representation of the bolted joints in the models [1]. The dynamic behaviour of the assembled structures markedly depends not only on their dimensions and material properties but also highly depends on the parameters of the joints' connecting elements in between the components. Although the bolted joints crucially play the important part to increase damping properties and to minimise resonance magnitude of the assembled structures, but their dynamic behaviour has not been predicted efficiently [2], [3].

There are several modelling approaches of the bolted joints that have been suggested by researchers [4], [5]. Different kinds of FE models to represent bolted joints have been studied. They are the solid bolt model, coupled bolt model, spider bolt model, RBE bolt model, hybrid bolt model and no-bolt model [6], [7]. There are models in which their elements are based on the calculated bolt stiffness value [1], [8], [9] and a linearized version of Hertzian contact theory which incorporates contact stiffness between bolt and hole [10]. Most of the researches modelled the bolt shank as CBAR or CBEAM element and modelled the connection of the bolt head and nut to the plate using either RBEs or line elements. However, the interfaces of the joints are also play significant roles in determining the accurate behaviour of the bolted joints.

Joint interfaces are also an important part of every assembled structure and modelling the interface area precisely is very challenging work. Appropriate modelling for the interfaces of the assembled structure with bolted joints has continuously been investigated by researchers because the mechanical contact at joint interfaces are not appropriately modelled and it contributes a significant effect to the structural dynamic response [11]–[13]. To some extent, finding a suitable element to accurately represent the joint interfaces is more challenging and requires more efforts compared to modelling the individual components of the assembled structure [14].

There are several modelling approaches that have been investigated to represent joint interfaces such as spring-damper [15], [16], offset dimension [17], generic element [18], [19] Jenkins element or Iwan model [20]–[22] and interface element [4], [23], [24]. The interface element is a noticeable method to model the joint interfaces. Recently, instead of interface element, the concept of interface affected regions of bolted joints has received much attention by researchers in order to simulate the dynamic behavior of bolted joints.

The interface affected regions of the bolted joints have been investigated to simulate and update the structural dynamic behavior by using models with special elements to represent it such as beam-bar element [25], contact zone element [26], partitioned thin layer element [27] and connective layer element [28]. These special elements merge the neighboring contact surfaces of the substructures. The efficiency of the bolted joint model shall be enhanced by defining the contact bodies as sub-parts of the joint affected region [29]. These recent studies show that the quality of bolted joints interface simulation depends on parameters such as the thickness and density of the joint affected region in addition to its elasticity properties.

This paper focuses on the identification of the dynamics behaviour of the bolted lap joints by developing the appropriate FE model and update the parameters of the individual components' model, bolting elements, interface elements and its affected regions properties. FE model updating is used to improve the accuracy and reliability of the initial FE model, so that the predicted dynamic behaviour matches as close as possible to the experimental measured dynamic properties.

Lap Joint Geometry, Properties and FE Model

The 3D computer-aided design (CAD) model of a simple bolted lap joints was developed as shown in Figure 1. The FE model of bolted lap joints was developed (**Error! Reference source not found.**) and analysed by using NX 7.5 Advanced Simulation with NX Nastran as the solver. The meshing of the plate was created by using 2673 numbers of QUAD8 thin shell elements of size 5 mm. Thin shell element type was chosen to minimise the numbers of the nodes used for the analysis of the model. The element size of 5 mm was used for the development of the FE models after performing several convergent tests. The upper plate is named as Plate A while the bottom plate is Plate B. Material properties for the plates and bolts are tabulated in **Error! Reference source not found.** and **Error! Reference source not found.** respectively.

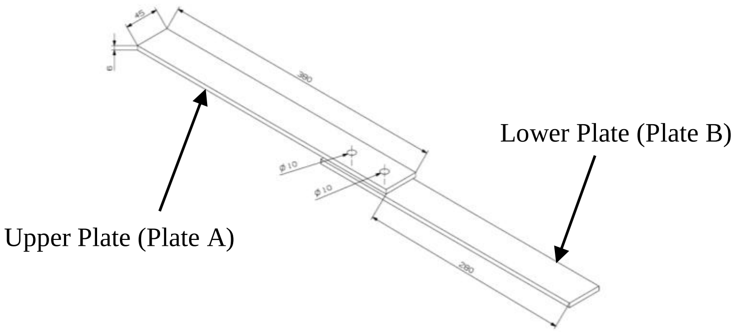

Figure 1: Geometry of the bolted lap joints

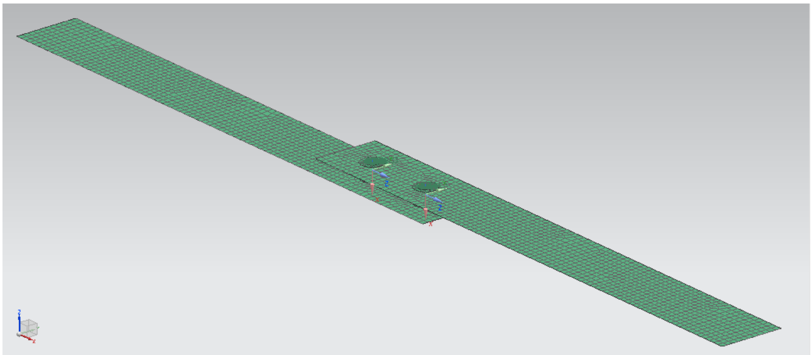

Figure 2: Finite element model of the bolted lap joints

Table 1: Material properties of Plate A and Plate B [30]

Properties	Type/Value
Material	Aluminium 6061
Modulus of Elasticity	68,980 N/mm^2
Poisson’s Ratio	0.33
Mass Density	2.711E-6 kg/mm^3

Table 2: Material properties of bolts [30]

Properties	Type/Value
Material	Stainless Steel
Modulus of Elasticity	190,000 N/mm^2
Poisson’s Ratio	0.3
Mass Density	7.9E-6 kg/mm^3

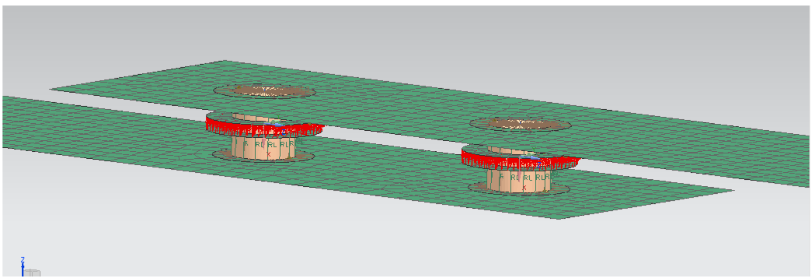

Figure 3: Bolts and interface elements modelling

Bolts were modelled using CBEAM elements for the bolts’ shank with PBEAM property, and RBEs were used to represent bolts’ heads and nuts. The interfaces connecting elements of the joints were modelled using CELAS elements with PELAS property of stiffness [31], [32]. The properties’ parameters used for the modelling are as in Table 3: Physical properties entry

Property	Parameter	Value
PBEAM	Radius	5 mm
	Area (A)	78.5398 mm2
	Moment of Inertia (Iz, Iy)	490.8738 mm4
	Torsional Constant (K)	981.7577 mm4
PELAS	Translational Stiffness	239 N/mm

.

Table 3: Physical properties entry

Property	Parameter	Value

PBEAM	Radius	5 mm
	Area (A)	78.5398 mm^2
	Moment of Inertia (I_z, I_y)	490.8738 mm^4
	Torsional Constant (K)	981.7577 mm^4
PELAS	Translational Stiffness	239 N/mm

Interfaces affected regions of the bolted lap joints are the regions of the contact faces in between Plate A and Plate B, as shown in Figure 4 with circles. The initial thickness for each of the affected region was designed to be 2 mm and there were 2 regions selected in each Plate A and Plate B. The material properties of the affected regions are following the updated material properties of the Plate A and Plate B, which have been updated before the study proceed with the updating processes of the assemble lap joint. In the FE modelling, the thickness of these affected regions is modelled as shell element.

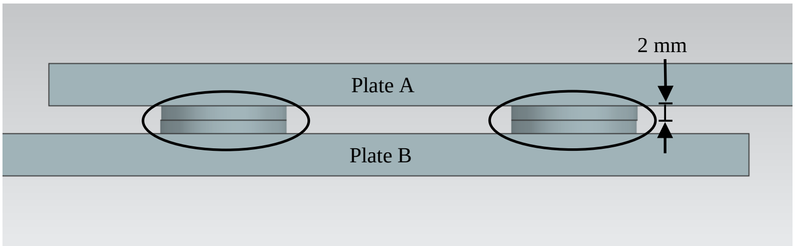

Figure 4: Thickness of the interface affected regions

FE Model Updating

Normal modes analysis was carried out by using NX Advanced Simulation SEMODES 103 with NX Nastran solver to compute the first 10 natural frequencies and mode shapes. They were used as the initial FE results in this study. The DESOPT 200 – Model Update in NX FE Model Updating was used for the model updating procedure. In this work, the purpose of using the model updating procedure was to reconcile the finite element models with the experimental data [33]. The objective function of the model updating procedure used in NX FE Model Updating is mathematically expressed as

$$f\left(\Delta DV_j\right) = min\left(\sum_{i=1}^{N_\tau} A_i|\epsilon_i| + O\sum_{j=1}^{N_{DV}} B_j\left|\Delta DV_j\right|\right) \qquad (1)$$

where:
ΔDV_j is the j^{th} design variable change
ϵ_i is the i^{th} target error that depends on the design variable changes ΔDV_j.
N_τ is the total number of active optimization target
A_i is the weight of the i^{th} target
O is the overall design variable weight
N_{DV} is the total number of free design variables
B_j is the weight of the j^{th} design variable

In this study, the finite element model updating procedure was firstly carried out for the individual plates (Plate A and Plate B). Therefore, the errors presented in the FE models of the plates as a result of the invalid assumption about the material properties of the individual plates were minimised before the FE models were assembled as a lap joint. In other words, the errors in the FE models of the components of an assembled structure, in this study, the components used which are plates A and B must be minimised with the acceptable level of accuracy so that the resulting errors in the finite element model of the assembled plate or lap joint can be easily directed to the uncertainties in modelling for bolts and interfaces and also interfaces affected regions. The updating procedure used in this study was divided into two stages. The first stage involved in updating the bolts and interfaces element parameters. The second stage was the updating of the interfaces affected regions.

Experimental Modal Analysis

The experimental modal analysis was performed on a simply bolted lap joints to extract modal parameters which are the natural frequencies and mode shapes. The tests were carried out in two phases which are on the component level and then on the assembled structure. The pieces of equipment used in the test are the LMS system, LMS Test.Lab software, impact hammer & accelerometers. The experimental setup for the assembled structure (bolted lap joint) is shown in Figure 5 in which the Plate A (upper plate) and Plate B (bottom plate) were joined by using stainless steel bolts and nuts. The assembled structure was suspended to the test rig by using rubber bands to simulate free-free conditions.

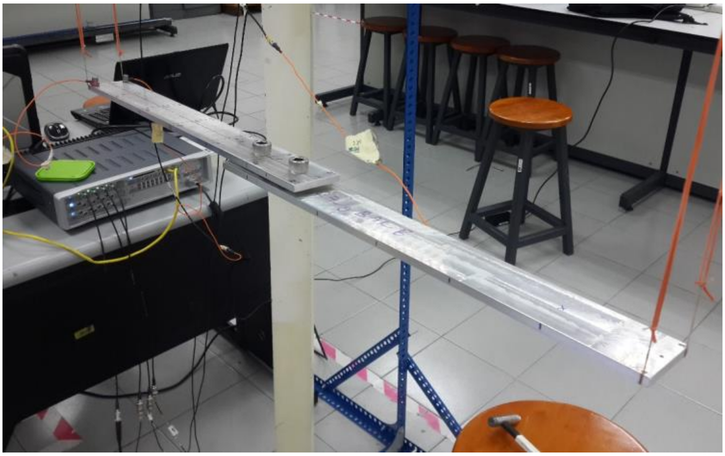

Figure 5: Experimental modal analysis setup

Results and Discussion

Modelling and predicting the dynamic behaviour of bolted structures presented and demonstrated in previous studies [25], [26], [34] using the finite element method revealed that analytical results obtained from the method were not in agreement with the experimental counterparts. The disagreement was a result of the invalid assumptions about the model properties used in the finite element model of the bolted structures [33]. Therefore, finite element model updating methods have been widely used by researchers to improve the confidence in the analytical models.

In this study, the modal parameters of interest which are the natural frequencies and mode shapes of the bolted lap joint were obtained using the finite element method and experimental modal analysis. Shell elements (CQUAD8) were used to construct the initial finite element model of the bolted lap joint. Different types of the 1D element were used to model the bolted joints in the bolted lap joint. Two stages of model updating procedure were required in the attempt to reconcile the initial finite element model in the light of the measured data. The comparison of the numerical and experimental results and the updated parameters of the Plate A, Plate B and the assembled structure are tabulated in

Table 4 : Comparison of experiment and FE analysis of Plate A

	I	II	III	IV	V	VI
Mode	Experiment (Hz)	Initial FE (Hz)	Error (%) between I & II	FE MAC	Updated FE (Hz)	Error (%) between I & V

1	214.845	215.710	0.403	0.990	215.006	0.075
2	592.531	594.724	0.370	0.983	592.471	0.010
3	1046.045	1035.030	1.053	0.990	1050.728	0.448
4	1161.442	1166.718	0.454	0.962	1161.513	0.006
5	1532.718	1541.000	0.540	0.995	1538.000	0.345
6	1917.250	1928.211	0.572	0.942	1918.077	0.043
7	2122.070	2091.855	1.424	0.984	2122.035	0.002
8	2859.246	2876.193	0.593	0.905	2858.613	0.022
9	3240.377	3188.572	1.599	0.982	3231.621	0.270
10	3917.588	3932.115	0.371	0.986	3930.000	0.317
	Total Error		7.378			1.537

Table 5: Comparison of experiment and FE analysis of Plate B

	I	II	III	IV	V	VI
Mode	Experiment (Hz)	Initial FE (Hz)	Error (%) between I & II	FE MAC	Updated FE (Hz)	Error (%) between I & V
1	214.927	215.707	0.363	0.993	214.469	0.213
2	591.069	594.702	0.615	0.986	591.015	0.009
3	1042.679	1034.989	0.738	0.987	1045.874	0.306
4	1157.761	1166.665	0.769	0.967	1158.741	0.085
5	1533.322	1541.000	0.501	0.993	1533.000	0.021
6	1910.919	1928.134	0.901	0.955	1913.686	0.145
7	2112.324	2091.718	0.976	0.988	2112.346	0.001
8	2852.658	2876.078	0.821	0.928	2852.356	0.011
9	3222.355	3188.412	1.053	0.987	3217.264	0.158
10	3919.366	3932.100	0.325	0.964	3917.000	0.060
	Total Error		7.061			1.009

Table 6: Updated parameters for Plate A

Parameter	Initial Value	Updated Value	Unit
Young's Modulus	68,980	68,497.14	MPa
Poisson's Ratio	0.33	0.2805	Unitless
Mass Density	2.711×10^{-6}	2.708×10^{-6}	kg/mm^3

Table 7: Updated parameters for Plate B

Parameter	Initial Value	Updated Value	Unit
Young's Modulus	68,980	68,221.22	MPa
Poisson's Ratio	0.33	0.2864	Unitless
Mass Density	2.711 x 10^{-6}	2.711 x 10^{-6}	kg/mm^3

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FE Model Updating of Plate A and Plate B

The first 10 modes for the experiment modal test and initial FE modal analysis results are compared for Plate A and Plate B. The total errors for Plate A is 7.378% meanwhile for Plate B is 7.061%. The MAC values for all modes for Plate A and Plate B are more than 0.9 which show that the mode shapes of the experimental and finite element modal analysis have very good correlation. However, the total errors need to be reduced by using model updating process. The steepest descent algorithm has been used as the optimizer to update the parameters of the models of both plates. The updated parameters are the Young's modulus, Poisson's ratio, and mass density. Comparison of results including the updated FE results is shown in

Table 4 : Comparison of experiment and FE analysis of Plate A

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2	592.531	594.724	0.370	0.983	592.471	0.010
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8	2859.246	2876.193	0.593	0.905	2858.613	0.022
9	3240.377	3188.572	1.599	0.982	3231.621	0.270
10	3917.588	3932.115	0.371	0.986	3930.000	0.317
Total Error			7.378			1.537

Table 5: Comparison of experiment and FE analysis of Plate B

	I	II	III	IV	V	VI
Mode	Experiment (Hz)	Initial FE (Hz)	Error (%) between I & II	FE MAC	Updated FE (Hz)	Error (%) between I & V
1	214.927	215.707	0.363	0.993	214.469	0.213
2	591.069	594.702	0.615	0.986	591.015	0.009
3	1042.679	1034.989	0.738	0.987	1045.874	0.306
4	1157.761	1166.665	0.769	0.967	1158.741	0.085
5	1533.322	1541.000	0.501	0.993	1533.000	0.021
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7	2112.324	2091.718	0.976	0.988	2112.346	0.001
8	2852.658	2876.078	0.821	0.928	2852.356	0.011
9	3222.355	3188.412	1.053	0.987	3217.264	0.158
10	3919.366	3932.100	0.325	0.964	3917.000	0.060
	Total Error		7.061			1.009

Table 6: Updated parameters for Plate A

Parameter	Initial Value	Updated Value	Unit
Young's Modulus	68,980	68,497.14	MPa
Poisson's Ratio	0.33	0.2805	Unitless
Mass Density	2.711 x 10-6	2.708 x 10-6	kg/mm3

Table 7: Updated parameters for Plate B

Parameter	Initial Value	Updated Value	Unit
Young's Modulus	68,980	68,221.22	MPa
Poisson's Ratio	0.33	0.2864	Unitless
Mass Density	2.711 x 10-6	2.711 x 10-6	kg/mm3

for Plate A and in **Error! Reference source not found.** for plate B. It shows that the error for the updated FE model is reduced to 1.537% for Plate A. Meanwhile, the error for Plate B is reduced to 1.009%. The updated parameters' values are as shown in **Error! Reference source not found.** and **Error! Reference source not found.** for Plate A and Plate B respectively.

Results show a significant reduction in Poisson's ratio and a slight reduction in Young's modulus for both plates. Note that the mass density of plate A is slightly less than the initial value while the mass density for Plate B has not changed after updating process. This process gives an accurate modelling of the Plate A and Plate B before proceed to the updating processes for the assembled plates.

Table 4 : Comparison of experiment and FE analysis of Plate A

	I	II	III	IV	V	VI
Mode	Experiment (Hz)	Initial FE (Hz)	Error (%) between I & II	FE MAC	Updated FE (Hz)	Error (%) between I & V
1	214.845	215.710	0.403	0.990	215.006	0.075
2	592.531	594.724	0.370	0.983	592.471	0.010
3	1046.045	1035.030	1.053	0.990	1050.728	0.448
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8	2859.246	2876.193	0.593	0.905	2858.613	0.022
9	3240.377	3188.572	1.599	0.982	3231.621	0.270
10	3917.588	3932.115	0.371	0.986	3930.000	0.317
Total Error			7.378			1.537

Table 5: Comparison of experiment and FE analysis of Plate B

	I	II	III	IV	V	VI
Mode	Experiment (Hz)	Initial FE (Hz)	Error (%) between I & II	FE MAC	Updated FE (Hz)	Error (%) between I & V
1	214.927	215.707	0.363	0.993	214.469	0.213
2	591.069	594.702	0.615	0.986	591.015	0.009
3	1042.679	1034.989	0.738	0.987	1045.874	0.306

4	1157.761	1166.665	0.769	0.967	1158.741	0.085
5	1533.322	1541.000	0.501	0.993	1533.000	0.021
6	1910.919	1928.134	0.901	0.955	1913.686	0.145
7	2112.324	2091.718	0.976	0.988	2112.346	0.001
8	2852.658	2876.078	0.821	0.928	2852.356	0.011
9	3222.355	3188.412	1.053	0.987	3217.264	0.158
10	3919.366	3932.100	0.325	0.964	3917.000	0.060
	Total Error		7.061			1.009

Table 6: Updated parameters for Plate A

Parameter	Initial Value	Updated Value	Unit
Young's Modulus	68,980	68,497.14	MPa
Poisson's Ratio	0.33	0.2805	Unitless
Mass Density	2.711×10^{-6}	2.708×10^{-6}	kg/mm^3

Table 7: Updated parameters for Plate B

Parameter	Initial Value	Updated Value	Unit
Young's Modulus	68,980	68,221.22	MPa
Poisson's Ratio	0.33	0.2864	Unitless
Mass Density	2.711×10^{-6}	2.711×10^{-6}	kg/mm^3

FE Model Updating of Bolted Lap Joint

In this study, the updated finite element models of Plate A and Plate B were joined to form a lap joint structure with pre-defined interface area on both mating sides. In the first stage of the model updating of the lap joint, the material properties of the bolts and the translational stiffness property of the CELAS elements, representing the interfaces, were used as the updating parameters. Genetic algorithm was used as the optimizer for updating the lap joint. The comparison of natural frequencies between the initial FE, experiment and updated is tabulated in Table 8: Comparison of experiment and FE analysis of lap joint (1st stage)

	I	II	III	IV	V	VI

Mode	Experiment (Hz)	Initial FE (Hz)	Error (%) between I & II	FE MAC	Updated FE (Hz)	Error (%) between I & V
1	69.37	70.68	1.89	0.995	70.50	1.63
2	189.40	200.70	5.97	0.988	198.60	4.86
3	374.10	377.80	0.99	0.582	376.90	0.75
4	440.70	442.10	0.32	0.879	439.00	0.39
5	580.40	604.30	4.12	0.972	601.30	3.60
6	643.20	630.90	1.91	0.823	630.00	2.05
7	963.10	962.80	0.03	0.762	961.00	0.22
8	973.20	1021.00	4.91	0.798	1021.00	4.91
9	1168.00	1199.00	2.65	0.880	1195.00	2.31
10	1381.00	1401.00	1.45	0.454	1400.00	1.38
	Total Error		24.24			22.09

Table 9: Updated parameters for lap joint (1st stage)

Property	Parameter	Initial Value	Updated Value	Unit
Material (Bolt)	Young's Modulus	190,000	168,150	N/mm2
	Mass Density	7.90E-06	8.97E-06	kg/mm3
	Poisson's Ratio	0.3	0.3024	unit less
PELAS (Interface)	Translational Stiffness	239	160.608	N/mm

Table 10: Comparison of experiment and FE analysis of lap joint (2nd stage)

	I	II	III	IV	V	VI
Mode	Experiment (Hz)	Initial FE (Hz)	Error (%) between I & II	FE MAC	Updated FE (Hz)	Error (%) between I & V
1	69.37	70.50	1.63	0.995	70.48	1.60
2	189.40	198.60	4.86	0.988	198.60	4.86
3	374.10	376.90	0.75	0.582	376.80	0.72

4	440.70	439.00	0.39	0.879	438.90	0.41
5	580.40	601.30	3.60	0.972	601.20	3.58
6	643.20	630.00	2.05	0.823	630.00	2.05
7	963.10	961.00	0.22	0.762	960.80	0.24
8	973.20	1021.00	4.91	0.798	1021.00	4.91
9	1168.00	1195.00	2.31	0.880	1194.00	2.23
10	1381.00	1400.00	1.38	0.454	1400.00	1.38
	Total Error		22.09			21.98

Table 11: Updated parameters for lap joint (2nd stage)

Property	Parameter	Initial Value	Updated Value	Unit
Material Plate A	Young's Modulus	68,497.14	65,277.74	N/mm2
	Density	2.708E-06	2.827E-06	kg/mm3
	Poisson's Ratio	0.2805	0.2819	Unitless
PSHELL Plate A	Thickness	2	1.98	mm
Material Plate B	Young's Modulus	68,221.22	64,673.70	N/mm2
	Density	2.711E-06	2.830E-06	kg/mm3
	Poisson's Ratio	0.2864	0.2878	Unitless
PSHELL Plate B	Thickness	2	1.958	mm

. It was found that the total error recorded in the updated FE model of the lap joint was reduced from 24.24% to 22.09%. The updated values of the parameters used in the updating procedure are as shown in **Error! Reference source not found.** from which it was shown that there was a significant reduction in the Young’s modulus and significant increment in mass density of the bolts. The achievement revealed that the bolts and nuts used to assemble the plates contributed significantly to the dynamic behaviour of the assembled structure.

The FE model of the updated lap joint obtained from the 1st stage of model updating procedure was used again in the 2nd stage of the procedure by focusing on the interfaces affected regions. The purpose of the 2nd stage model updating was to improve the accuracy of the predicted natural frequencies. The material properties of the interfaces affected regions of Plate A and Plate B, and the thickness of the PSHELL property of the interface affected region was chosen as the updating parameters. Comparison of results between the initial FE model, updated FE model obtained from the 2nd stage and experiment is shown in **Error! Reference source not found.**. It was found that the total error demonstrated by the updated FE model of the lap joint was slightly reduced from 22.09% to 21.98%. The values of the updated parameters are shown in **Error! Reference source not found.**. The significant reduction in the Young's modulus and increment of the mass density and Poisson's ratio revealed that the use of the parameters contributed to the structural stiffness reduction in the bolted joint region. Furthermore, the slight reduction in the thickness regions shows that the quality of the bolted lap joints also depends on the thickness variations, the effect which has rarely been considered in the actual industrial practise.

Table 8: Comparison of experiment and FE analysis of lap joint (1st stage)

	I	II	III	IV	V	VI
Mode	Experiment (Hz)	Initial FE (Hz)	Error (%) between I & II	FE MAC	Updated FE (Hz)	Error (%) between I & V
1	69.37	70.68	1.89	0.995	70.50	1.63
2	189.40	200.70	5.97	0.988	198.60	4.86
3	374.10	377.80	0.99	0.582	376.90	0.75
4	440.70	442.10	0.32	0.879	439.00	0.39
5	580.40	604.30	4.12	0.972	601.30	3.60
6	643.20	630.90	1.91	0.823	630.00	2.05
7	963.10	962.80	0.03	0.762	961.00	0.22
8	973.20	1021.00	4.91	0.798	1021.00	4.91
9	1168.00	1199.00	2.65	0.880	1195.00	2.31
10	1381.00	1401.00	1.45	0.454	1400.00	1.38
	Total Error		24.24			22.09

Table 9: Updated parameters for lap joint (1st stage)

Property	Parameter	Initial Value	Updated Value	Unit
Material (Bolt)	Young's Modulus	190,000	168,150	N/mm^2
	Mass Density	7.90E-06	8.97E-06	kg/mm^3
	Poisson's Ratio	0.3	0.3024	unit less
PELAS (Interface)	Translational Stiffness	239	160.608	N/mm

Table 10: Comparison of experiment and FE analysis of lap joint (2nd stage)

	I	II	III	IV	V	VI
Mode	Experiment (Hz)	Initial FE (Hz)	Error (%) between I & II	FE MAC	Updated FE (Hz)	Error (%) between I & V
1	69.37	70.50	1.63	0.995	70.48	1.60
2	189.40	198.60	4.86	0.988	198.60	4.86
3	374.10	376.90	0.75	0.582	376.80	0.72
4	440.70	439.00	0.39	0.879	438.90	0.41
5	580.40	601.30	3.60	0.972	601.20	3.58
6	643.20	630.00	2.05	0.823	630.00	2.05
7	963.10	961.00	0.22	0.762	960.80	0.24
8	973.20	1021.00	4.91	0.798	1021.00	4.91
9	1168.00	1195.00	2.31	0.880	1194.00	2.23
10	1381.00	1400.00	1.38	0.454	1400.00	1.38
	Total Error		22.09			21.98

Table 11: Updated parameters for lap joint (2nd stage)

Property	Parameter	Initial Value	Updated Value	Unit
Material Plate A	Young's Modulus	68,497.14	65,277.74	N/mm^2
	Density	2.708E-06	2.827E-06	kg/mm^3
	Poisson's Ratio	0.2805	0.2819	Unitless
PSHELL Plate A	Thickness	2	1.98	mm
Material Plate B	Young's Modulus	68,221.22	64,673.70	N/mm^2
	Density	2.711E-06	2.830E-06	kg/mm^3
	Poisson's Ratio	0.2864	0.2878	Unitless
PSHELL Plate B	Thickness	2	1.958	mm

Conclusions

Authors have demonstrated the attempt to model bolted joints using an efficient and economical procedure and the use of model updating for reconciling the FE model of the bolted joints with the experimental data.

The parameters of the FE models of the individual components, bolting elements and interface elements have been successfully used in the updating procedure to determine an efficient FE model of the lap joint.

This study revealed that the bolts' material properties, stiffness values, especially at the joint interfaces and the properties of the interfaces affected regions has played an important role in ensuring the accuracy of the prediction of the dynamic behaviour of the bolted lap joint.

Furthermore, the accuracy of prediction of the dynamic behaviour probably could be improved further if the boundary condition and damping effect of the interfaces between the assembled plates were included in the FE model of the bolted lap joint.

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