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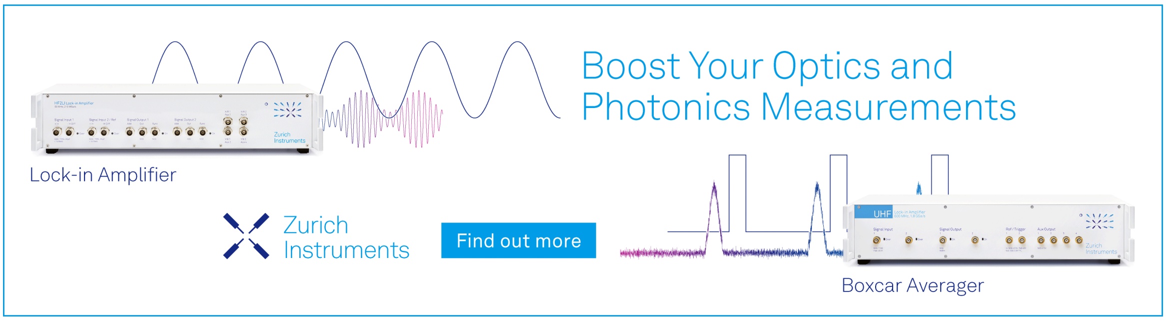

Model Updating of a Bolted Joint Contact Surface Using Thin Layer Element Parameters

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Abstract. The dynamic behaviour prediction scheme of contact surface of bolt joints has found to be extremely difficult to model due the complex behaviour of the structural joints. In this paper, the bolted structure was used with aim to investigate the dynamic behaviour of the bolted structure using practical modelling scheme via finite element modelling and updating method. A simplified FE model of the bolted structure was developed using CBEAM element to represent geometrical shape of the bolt and Thin Layer Element (TLE) was used to represent the contact surface of the bolted structure. Subsequently, the normal mode analysis using NASTRAN103 was used to predict the dynamic behaviour of the FE model. Potential updating parameters of the FE model was analysed by implemented sensitivity analysis formulated in Nastran SOL200. The model updating method is then used to update the initial FE model of the bolted structure based on the experimental modal analysis (EMA) result. The comparison of the results is used in verifying the accuracy of the updated FE model of the bolted joint structure. The result suggested that the CBEAM and TLE can be used efficiently to represent the bolted joints and the contact surface of the bolted joint of the assembled structure.

INTRODUCTION

A full assembled mechanical structure is formed by assembling sub-components of the structure using numerous types of mechanical joints such as rivets, welds and bolts. The function of the mechanical joints is to ensure the reliability of the structure to meet the functionality of the structure. Riveted and welded joints are two types of permanent joints that have significant disadvantages, for instance, the joints need to be destroyed in case of maintenance [1-4]. As an alternative, mechanical fasteners such as bolted joints are commonly used to assemble two components or more to form an assembly body of automotive or aerospace structures.

The use of bolted joints offers several advantages to the integrity of the structure, such as high joint strength combined with flexibility, ease of use and economical pricing. However, the fact that bolted joints are one of the predominant connection methods the excessive vibration effects can cause the system malfunction, structural failure, reduced performance of a system and even early breakdown to the bolted joints of the structure [4-5]. To investigate the dynamic behaviour of the bolt joints of the bolted structure, engineers and designers need to investigate and develop a reliable method to solve the structural dynamics problem in an efficient manner [6]. Understandably, a numerical model based on the finite element method (FE) has proven to be a powerful tool for predicting the dynamic behaviour of bolted joints because of its versatilities [6-8]. Despite the powerful ability of the FE method to simulate the dynamic behaviour of structures, developing a reliable FE model to predict the dynamic behaviour of bolted joints is a challenge. The reason is that the dynamic behaviour of bolted joints is always determined by the complex physical properties of the bolted joints and contact surfaces [9-10]. This complexity affects the overall stiffness of the structure and causes inconsistencies between experimental and predicted results. On top of that, the initial value of FE model

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parameters usually are obtained either from a text book, research publication or material certification. These challenges the reliability of the existing FE model, which affects the accuracy of the prediction results of the whole assembled structure.

The reconciliation method using FE model updating methods is one of the most effective solutions to resolve the inconsistencies in the predicted results of the dynamic behaviour of bolted joints. The FE model updating is a method developed to improve the prediction responses of initial FE model in light of the experimental responses by calibrating influential input parameters using a systematic methodology [10-11]. By applying FE model updating methods, the dynamic behaviour of bolted joints can be effectively improved and accurately predicted. Therefore, to understand and analyse the dynamic behaviour of structures is essential and beneficial to counter this problem, this can be performed through experimental and theoretical methodologies or combination of both approaches [11-12]. However, in the bolt joint connection the initial stiffness value of contact interfaces of bolted joint is hardly to obtain and it can be said as case dependent [13]. Therefore, estimating an appropriate initial value for the properties of the contact interfaces of a bolted structure is a major challenge because it is difficult to obtain comprehensive knowledge about the properties. This is because the bolted structure always exhibits remarkable frictional effects such as slip, loss and play, which effect the overall stiffness of the joints, especially at the contact surface and the bolts. At the same time, the overall stiffness of the joints is very difficult to determine experimentally. Furthermore, oversimplification in FE modelling of bolted structure also leads to inconsistencies in the local stiffness and flexibility of the bolted structure and causing large errors in predicting the dynamic behaviour of the bolted structure. Therefore, the overall stiffness of bolt joints problem becomes a major issue for in representing the uncertainty in a small and well understood region [14-16]. Accurate estimation of the unknown parameters in the structural model is crucial for building the construction of FE model. If the unknown parameters are incorrectly estimated, the FE model may have mathematical errors, such as singularities in the mathematical solution, which may falsify the predicted results. Therefore, the aim of this research was to estimate and improve the uncertain parameters in a FE model of a bolted structure suitable for the subsequent engineering applications of the bolted structure.

EXPERIMENTAL MODAL ANALYSIS

Experimental modal analysis (EMA) is an effective measurement method in the field of structural dynamics to determine and obtain the dynamic behaviour of an existing structure under various dynamic phenomena. In EMA, the measured dynamic behaviour of a structure is described in terms of modal parameters such as natural frequency, mode shape and modal damping. In this paper, the hammer impulse of EMA was performed in free-free boundary conditions to identify the dynamic behaviour such as natural frequencies and mode shapes of (1) the structural components A (oblong shape hole) and component B (bar shape) as shown in Fig. 2. The identification of the dynamic behaviour of the structures using EMA method can be utilised to calibrate and tune the numerical model systematically. However, to achieve acceptable measurement accuracy, the experimental work must be carried out using appropriate techniques [16].

The FRF describes the relationship between the excitation input signal and the output signal of a measurement point on the structure system, as shown in Fig. 1 and the relationship can be described by Equation (1) which shows the FRF $\mathbf{H}(\omega)$ is defined as the ratio between the output response $\mathrm{X}(\omega)$ and the input force $\mathrm{F}(\omega)$.

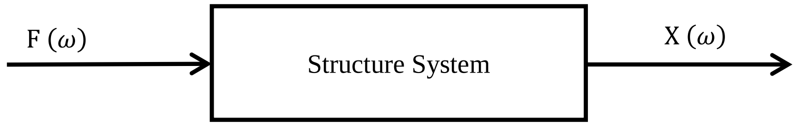


FIGURE 1. Block diagram of FRFs in structure system

$$\{\mathbf{X}(\omega)\} = [\mathbf{H}(\omega)]\{F(\omega)\} \tag{1}$$

On the other hand, the relationship between the response model $\mathbf{H}(\omega)$ and the modal model can be represented in terms of the following equations;

$$\mathbf{H}(\omega) = [\mathbf{K} + i\omega\mathbf{B} - \omega^2\mathbf{M}]^{-1} \tag{2}$$

$$\mathbf{H}(\omega) = \phi[\omega^2 + \omega_n^2 + 2i\omega_n\varsigma_n]^{-1}\phi^{\mathrm{T}} \tag{3}$$

where **K**, **B** and **M** represent the stiffness, damping and mass matrices, respectively, while ω_n, ϕ and ς_n represent the natural frequency, the vector of mode shapes and the modal damping to construct the modal model, respectively, while ω is the excitation frequency of the system.

FIGURE 2. Experimental set-up of bolted structure

FINITE ELEMENT MODELLING AND UPDATING

Finite Element Modelling of Components and Bolted Structure Contact Area

In this paper, the development of the FE model of the bolted structure was carried out in two main phases namely the FE modelling of the structural component A (oblong shape hole) and component B (bar shape). and (2) the FE modelling of the bolted structure. The CBEAM element was used to model the bolted joints of the structure and several contacts models for the bolt contact interfaces of bolted joints investigated namely freeze, slide and thin layer element (TLE) were used to model the contact interface, and the most appropriate model is selected to represent the structure of the bolted joints. The initial stiffness value of contact interfaces of bolted joint for an assembled was investigate by benchmarking the results that were obtained from the experiment. The modelling of the structural components of A and component B were analysed and updated before they were assembled using bolted joints to detect prediction errors in the bolted joints and the structural components. The NASTRAN SOL 103 was used to calculate the dynamic behaviour of the structure. the equation of motion in can be rewritten in matrix form as

$$\boldsymbol{M}\ddot{\boldsymbol{u}}(t) + \boldsymbol{C}\dot{\boldsymbol{u}}(t) + \boldsymbol{K}\boldsymbol{u}(t) = \boldsymbol{p}(t) \tag{4}$$

where $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ are respectively the *n x n* mass, damping and stiffness matrices of the structure system and n represents the number of DOFs resulting from the discretisation of the structure. For normal mode analysis using the FE solver of NASTRAN SOL 103, the equation of motion for undamped free vibration is introduced by eliminating the damping and external load in Equation (5). The equation is reduced as

$$\boldsymbol{M}\ddot{\boldsymbol{u}}(t) + \boldsymbol{K}\boldsymbol{u}(t) = 0 \tag{5}$$

The undamped free vibration equation can be solved by introducing harmonic forms in the numerical solution:

$$\boldsymbol{u} = \phi \sin \omega t \tag{6}$$

and

$$\ddot{\boldsymbol{u}} = -\omega^2 \phi \sin \omega t \tag{7}$$

where ϕ is the predicted eigenvector or mode shape and ω is the predicted natural frequency of the structure. The inclusion of the harmonic forms in the numerical solution means that all the DOFs of the vibrating structure move synchronously. The structural configuration does not change its basic shape during the motion, only its amplitude. Then the harmonic solutions in (6) and (7) are substituted in (5) to form,

$$-\omega^2 \boldsymbol{M}\phi \sin \omega t + \boldsymbol{K}\phi \sin \omega t = 0 \tag{8}$$

which can be simplified to,

$$(\boldsymbol{K} - \omega^2 \boldsymbol{M})\phi = 0 \tag{9}$$

or can be rewritten in the form of eigenvalue problem as,

$$(\boldsymbol{K} - \lambda \boldsymbol{M})\phi = 0 \tag{10}$$

where $\lambda = \omega^2$ and this equation is called the eigen-equation which is a set of homogeneous algebraic equations for the components of the eigen-vector and forms the basis for the eigenvalue problem. From an engineering point of view, the solution form of eigen-equation is a non-trivial in which the $\phi \neq 0$ and satisfy from $\det|\boldsymbol{K} - \lambda \boldsymbol{M}| = 0$. The determinant is zero only for a set of discrete eigenvalues λ_i and for each eigenvalue there is a corresponding eigenvector that satisfies. Therefore, Equation (10) can be rewritten as

$$(\boldsymbol{K} - \lambda_i \boldsymbol{M})\phi_i = 0 \tag{11}$$

where i = 1, 2, 3… and each paired eigenvalue and eigenvector defines a free vibration mode of the predicted structure with eigenfrequencies and mode shapes. The number of possible natural frequencies and mode shapes is equal to the number of DOFs that have mass.

Finite Element Model Updating

In the finite element model updating the physical parameters such as joint stiffness and damping are selected and adjusted based on the sensitivity analysis to minimise the difference between the measured data and the predicted modal/FRF data. The iterative methods set the errors between the FE and the experimental results as the objective function and try to minimise the selected objective function by adjusting the selected update parameters of the FE model under investigation systematically until the updated modal parameters adequately reflect the experimental counterpart [17-21]. The prediction of the dynamic behaviour, such as the natural frequencies and mode shapes of a structure, is achieved by solving the eigen-equation as in equation (11) and the results of the analysis are compared with the experimental results to assess the accuracy and feasibility of the FE model of the structure.

The finite element model updating can be performed using established updating algorithm available in MSC NASTRAN. Prior to this, sensitivity analysis must be conducted to compute the sensitivity matrix as in Equation (12).

Where, θ is the structure parameters at j^{th} iteration such as material and geometrical properties of the structure and $\boldsymbol{S}_j$ is an *m x n* sensitivity matrix at j^{th} iteration containing the 1st derivatives of the eigenvalues ($\partial\lambda_j$) with respect to the structure parameters ($\partial\theta$). The sensitivity matrix can be expressed as follows

$$\boldsymbol{S}_j = \frac{\partial\lambda_j}{\partial\theta} = \phi_j^T \left[\frac{\partial\boldsymbol{K}}{\partial\theta} - \lambda_j \frac{\partial\boldsymbol{M}}{\partial\theta}\right] \phi_j \tag{12}$$

In SOL 200 of NASTRAN, an objective function containing the measured and analytical responses such as natural frequencies and mode shapes is developed to minimise the discrepancies between the measured and analytical responses by implementing partial derivatives in the objective function to obtain global optimum of the function. In this work, the objective function (J) is constructed based on the natural frequencies as follows

$$J = \sum_{i=1}^{n} \left(\frac{\lambda_i^{fe}}{\lambda_i^{ema}} - 1 \right)^2 \quad (13)$$

where, λ_i^{fe} is the i^{th} predicted eigenvalue from FE model and λ_i^{exp} is the i^{th} measured eigenvalue from EMA and n is the number of natural frequencies involved in the updating process. The minimisation procedure is repeated until convergence is accomplished until the difference between the values of the objective function is reduced to an acceptable level of accuracy. The discrepancies between the predicted natural frequencies and the experimental results can be evaluated using the approximation error (δ) according to Equation 14.

$$\delta = \left| \frac{f_{ema} - f_{fe}}{f_{ema}} \right| x\ 100\ \% \quad (14)$$

where f_{ema} and f_{fe} represent the experimental natural frequency and the predicted natural frequency using FE analysis, respectively. The approximation error is calculated in terms of a percentage relative error. However, the evaluation of the accuracy of FE model is not complete without assessing the validity of the predicted mode shapes. To do this, the modes from the experimental and predicted ones must be paired correctly to measure the similarity between the paired modes. The degree of correlation between the vectors of the paired mode shapes obtained from the FE model and EMA can be determined by the values of the Modal Assurance Criterion (MAC). The MAC values between the set of paired mode shapes of the EMA (ϕ_{ema}) and the FE analysis (ϕ_{fe}) can be calculated in matrix form as [21-22],

$$MAC = (\phi_{ema}\phi_{fe}) = \frac{|\phi_{ema}^T \phi_{fe}|^2}{(\phi_{fe}^T \phi_{fe})(\phi_{ema}^T \phi_{ema})}\ x\ 100\ \% \quad (15)$$

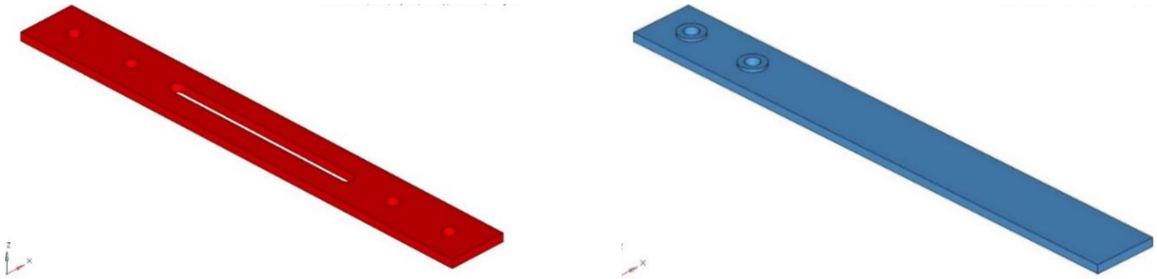
The MAC value is a scalar constant that lies between zero (0) and one (1). A value equal to one indicates a good correlation between the two sets of vectors. The value MAC must lie diagonally between the mode vectors of EMA and FE, with values outside the diagonal equal to zero to confirm a linear relationship and not a cross mode between the mode vectors.

TABLE 1. Material properties of steel bar (oblong shape and bar)

Material Properties	Nominal Values
Young's Modulus (E)	200 GPa
Shear Modulus (G)	80 GPa
Poisson's Ratio (*v*)	0.3
Density (*p*)	7900 kg/m^3

TABLE 2. Specification of the bolts

Material Properties	Nominal Values	Description	Value
Young's Modulus (E)	200 GPa	Quantity	4
Shear Modulus (G)	80 GPa	Mass	0.018 kg
Poisson's Ratio (v)	0.3	-	-
Density (p)	7900 kg/m^3	-	-



(a) Oblong hole (b) Bar shape

FIGURE 3. Individual components (a) Oblong hole and (b) Bar shape

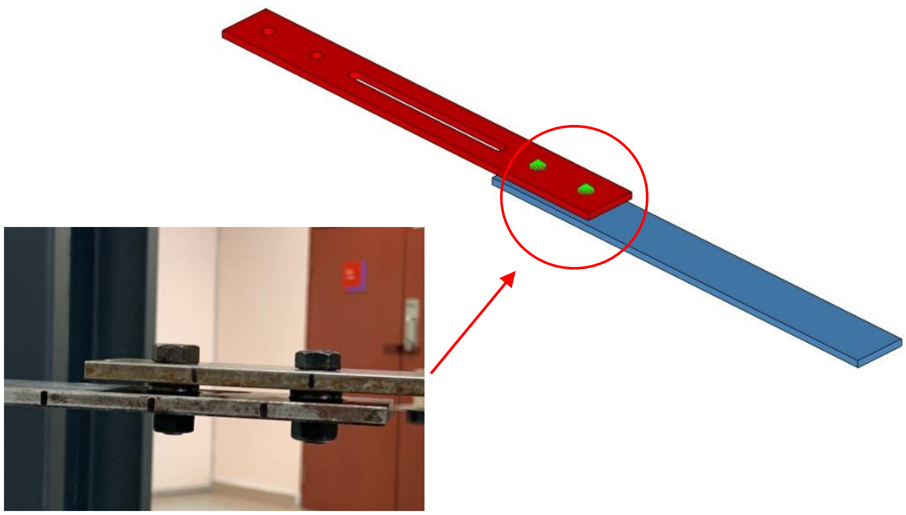


FIGURE 4. Bolted joints of the assembled structure

RESULTS AND DISCUSSION

Main objective of this paper is to propose efficient schemes for accurately predict the contact interfaces of bolted joints model by utilising the CBEAM and thin layer element (TLE) elements. The dynamic behaviour of the structures under investigation were obtained using EMA and FE method respectively. The relative error obtained from the developed FE models were systematically minimised using finite element model method with EMA of the structures under investigation were used as reference in respectively cases. Initially, the relative error in the FE models of components (a) and (b) were updated first prior to assembling process of the components. These works are crucial in order to focusing modelling error on the bolted joints without conspired by the influence of the structure components.

The bolted structure used in this study consisted of two bolted components (oblong hole and bar shape) as shown in Fig. 3 and the nominal values of the material properties of the components are listed in Table 1. Meanwhile the specification of the bolts are shown in Table 2. The identification of the most sensitive parameters of the components and the bolted structure were selected by on the results calculated using NASTRAN SOL200 solver.

The predicted FE and experimental natural frequencies of the component oblong hole (a) and component bar shape (b) are weighed up as tabulated in Table 3 and in Table 4. Only first five modes were utilised in this works. From Table 3, the total relative error recorded for natural frequencies of the FE model of component (a) is reduced from 4.8 percent to 1.0 percent with MAC values (Column IV) of the first five modes are above 0.7. Meanwhile, in Table 4, total relative error recorded for the initial FE model of component (b) is reduced to 3.3 percent from 6.8 percent and the with MAC values of the first five modes are above 0.9. From Table 5, the Young's modulus of component (a) and (b) are increased from 200 Gpa to 203.84 Gpa and 207.4 Gpa respectively.

TABLE 3. Comparison of modal parameters between the EMA and the initial FE of oblong hole

	I	II	III	IV	V	VI
Mode	EMA (Hz)	Initial FE (Hz)	Error (%) [I-II/I]	MAC	Updated FE (Hz)	Error (%) [I-IV/I]
1	211.0	209.4	0.8	96.5	211.47	0.2
2	604.9	598.2	1.1	96.2	604.02	0.2
3	919.1	909.9	1.0	88.0	918.67	0.0
4	1088.	1081.	0.7	76.3	1091.8	0.3
5	1207.	1191.	1.3	94.3	1203.1	0.4
	Total Error		4.8			1.0

TABLE 4: Comparison of modal parameters between the EMA and the initial FE of bar shape

	I	II	III	IV	V	VI
Mode	EMA (Hz)	Initial FE (Hz)	Error (%) [I-II/I]	MAC	Updated FE (Hz)	Error (%) [I-IV/I]
1	225.9	221.5	2.0	98.7	225.52	0.2
2	622.9	613.5	1.5	97.5	624.88	0.3
3	1099.	1075.	2.2	90.4	1098.8	0.1
4	1220.	1208.	1.0	90.6	1230.8	0.8
5	1580.	1581.	0.1	95.5	1609.7	1.9
	Total Error		6.8			3.3

TABLE 5. Updated parameters of structure components (a) and (b)

Parameter	Initial value (GPa)	Updated value (GPa)	Different (%)
Young's modulus (E) of oblong hole component (a)	200	203.84	1.92
Young's modulus (E) of bar shape component (b)	200	207.4	3.62

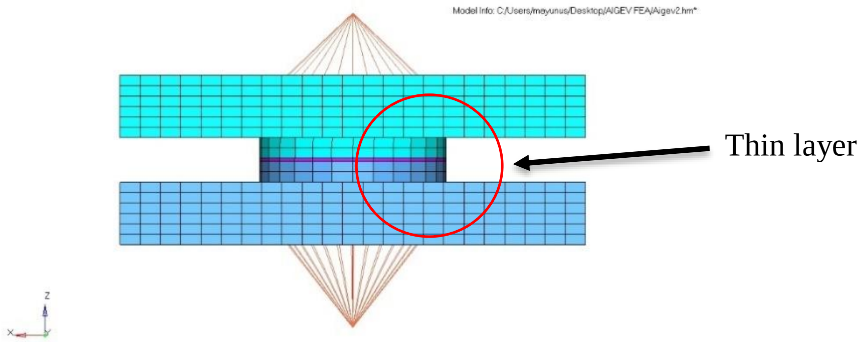


FIGURE 5. Thin layer elements on embossed of bolted joint

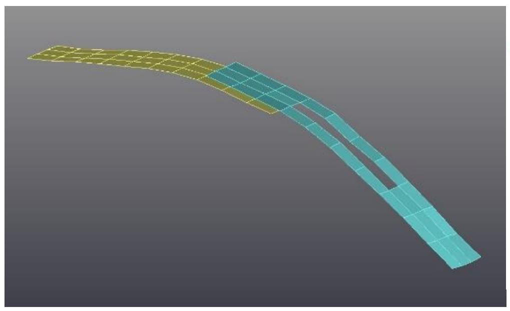
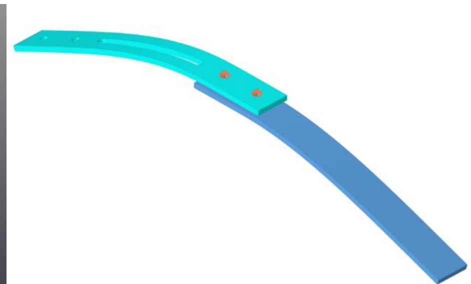
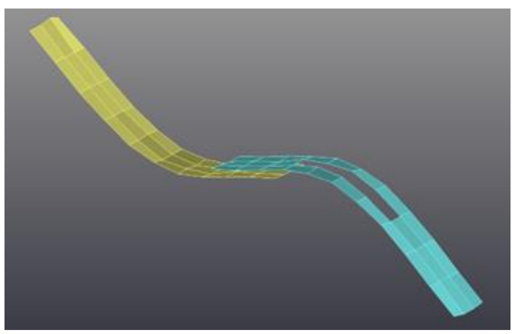
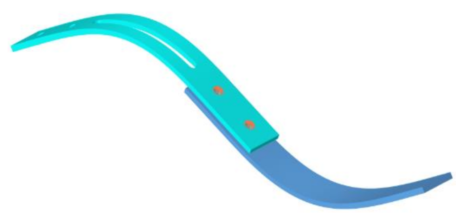
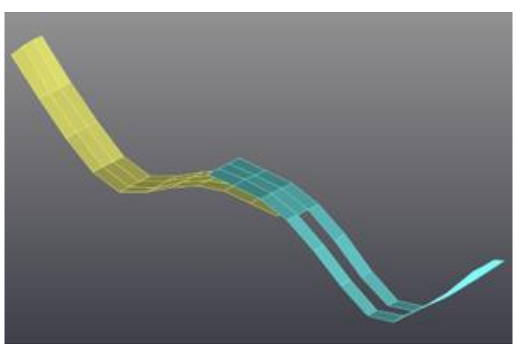
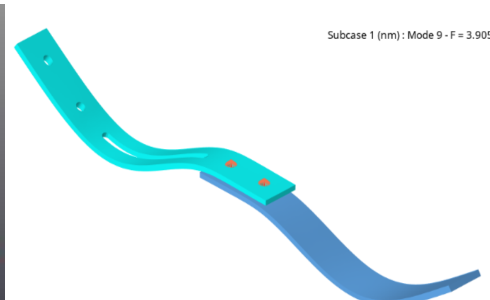
TABLE 6. Comparison of modal parameters between the EMA and the initial FE of bolted structure

	I	II	III	IV	V	VI
Mode	EMA (Hz)	Initial FE of CBEAM (Hz)	Error (%) [I-II/I]	MAC Value	Updated FE (Hz)	Error (%) [I-IV/I]
1	72.59	68.86	5.14	0.96	70.89	2.35
2	197.23	191.57	2.87	0.96	191.87	2.72
3	401.13	378.43	5.66	0.88	390.51	2.65
4	439.77	391.07	11.07	0.76	433.04	1.53
5	596.86	571.83	4.19	0.94	584.61	2.05
6	621.24	598.64	3.64	0.87	603.69	2.82
7	980.89	951.63	2.98	0.92	948.257	3.33
Total Error			35.56			11.30

TABLE 7. Potential updating parameters of the bolted structure

Parameter	**Properties**	**Initial value (GPa)**	**Updated value (GPa)**	**Different (%)**
Bolt Joint	Young's modulus, *E*	200	210	1.05
Thin layer	Young's modulus, *E*	200	210	1.05

The identification of the most sensitive parameters of the bolted structure were selected based on the results calculated using NASTRAN SOL200 solver. Obviously, the potential parameters related to bolts and the TLE element as shown in Fig. 5 were selected such as Young's modulus of bolt and thin layer based on the sensitivity analysis. Significant improvement can be seen in Column VI of Table 6, where the total relative error of the natural frequencies of bolted structure is minimised from 35.5 percent to 11.30 percent. The result proves the capabilities of FE model updating in identifying and correcting invalid initial assumptions made in FE modelling. The results also highlight that, the updated parameters of the Young's and shear modulus are able to improve the first seven natural frequencies and MAC values for bolted structure shows a good correlation of each individual modes as shown in column IV of Table 6 and from comparison of experimental mode with the FE modes of Figure 6.

Mode	Experiment	Finite Element
1		
2		
3		

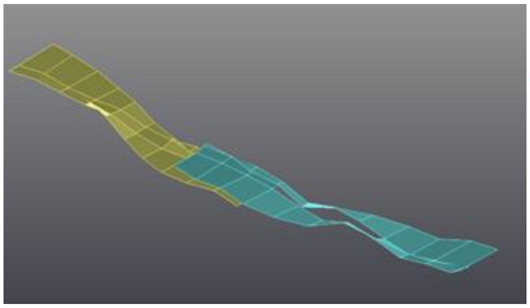
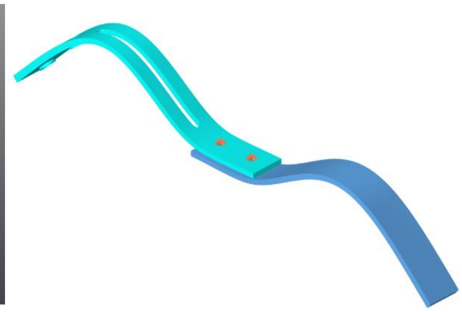
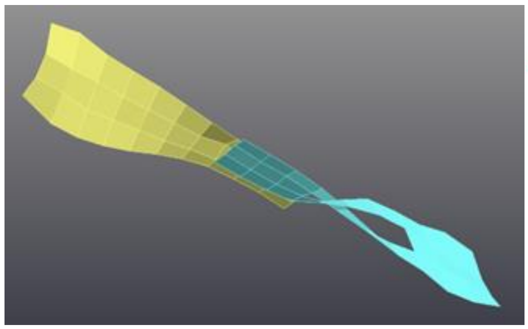
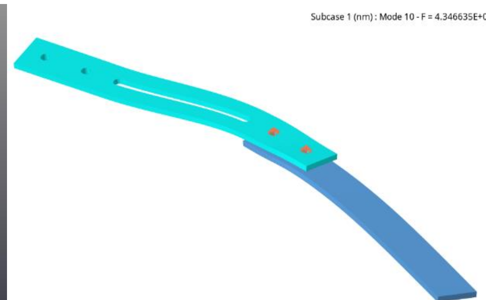
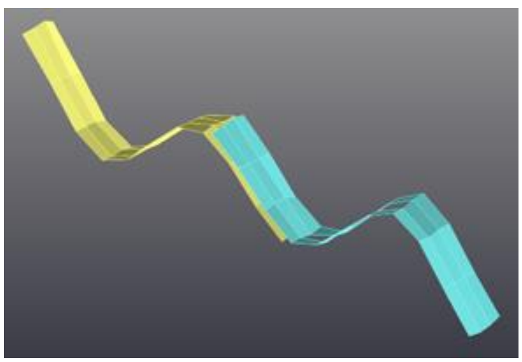
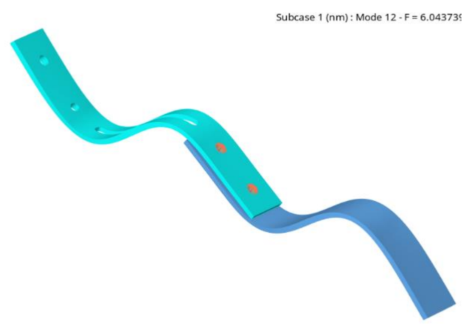
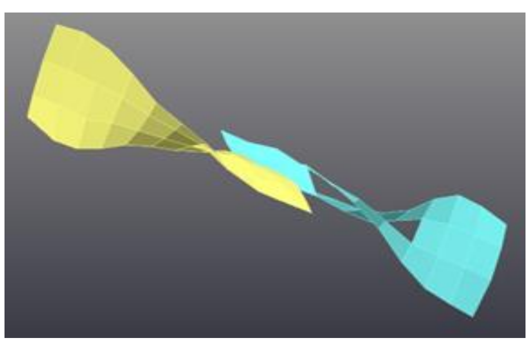
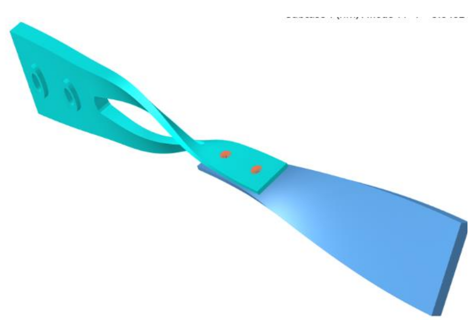
4		
5		
6		
7		

FIGURE 6. Comparison of the mode shapes between FE and Experiment

CONCLUSIONS

This paper demonstrates systematic scheme of improving the uncertainties of the input parameters of the FE model of bolted structure. The dynamics characteristic of the FE model of the bolted structure in terms of natural frequencies and mode shapes are observed and validated with the experiment result. The experimental study has revealed that the local effects from the mating area of the bolted joints such as friction, slip and contact area of washers have contribute to the large discrepancies on the natural frequencies and mode shapes of the predicted model, especially at the higher modes. However, without considering the local effects of the structure in finite element modelling, an accurate model with high accuracy is impossible to be obtained especially for the bolted structure. Therefore, it is very crucial to address these local effects in order to minimise the discrepancies of the initial FE model. In this research the CBEAM and thin layer element (TLE) were used to represent the bolts joins and the mating area of the components. An efficient technique of the modal based updating method are used to enhance the uncertainty of parameters of the bolt joints. The sensitivity analysis and has been successfully applied in this research and it can be seen that, by the error initial finite element model of bolted structure is successfully reduced from 35 percent to 11 percent. Selection of the right candidate of the input parameters has played an important role in producing an accurate prediction of the dynamic behaviour of the bolted structure. Therefore, any error emerges from the assembled FE model can be categorise from bolted modelling. These results emphasize that, the FE model updating schemes used in this study managed to identify optimum values of the bolt stiffness in the particular directions and therefore managed to produce an accurate mathematical model of bolt joints.

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Model Updating of a Bolted Joint Contact Surface Using Thin Layer Element Parameters

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Abstract

The dynamic behaviour prediction scheme of contact surface of bolt joints has found to be extremely difficult to model due the complex behaviour of the structural joints. In this paper, the bolted structure was used with aim to investigate the dynamic behaviour of the bolted structure using practical modelling scheme via finite element modelling and updating method. A simplified FE model of the bolted structure was developed using CBEAM element to represent geometrical shape of the bolt and Thin Layer Element (TLE) was used to represent the contact surface of the bolted structure. Subsequently, the normal mode analysis using NASTRAN103 was used to predict the dynamic behaviour of the FE model. Potential updating parameters of the FE model was analysed by implemented sensitivity analysis formulated in Nastran SOL200. The model updating method is then used to update the initial FE model of the bolted structure based on the experimental modal analysis (EMA) result. The comparison of the results is used in verifying the accuracy of the updated FE model of the bolted joint structure. The result suggested that the CBEAM and TLE can be used efficiently to represent the bolted joints and the contact surface of the bolted joint of the assembled structure.

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