FINITE ELEMENT MODEL UPDATING OF INTERFACES IN SINGLE-LAP BOLTED JOINTS USING MODAL TEST DATA

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In this study the behaviour of single-lap bolted joint with linear dynamics are investigated and updated using modal test data. Two methods of joint modelling including interface layer element method and combined beam-bar elements using finite element analysis are examined. In interface layer method a thin layer of solid elements with an isotropic material property are used. On the other hand, in present work a combined beam-bar element were used to describe the contact region because of their capability of taking into account the physical characteristics of bolted joint region properly and more accurately. The parameters for both methods are updated using modal test data. These results have been compared and evaluated by the work of the other investigators.

1. Introduction

Joints have a critical role in integrity and dynamic behaviour of structural systems and are the most important source of uncertainty in analytical approaches. Most of engineering structures are complex systems made of parts and members that are connected to each other by mechanical or adhesive joints. Single lap joints are one of the most common structural joints in all engineering disciplines like aerospace, mechanical and civil engineering. Now a day, the finite element method is the most accepted approach to model and analyze the structural systems extensively. To achieve a reliable analytical model in FEM approach, especially, structural models that contain various kinds of joint members, it is important to evaluate the theoretical model experimentally and update it if necessary.

Mackerle\textsuperscript{1} presented a review for finite element analysis of various types of joints under different loading conditions published between 1990 and 2002. Ahmadian et al.\textsuperscript{2} updated parameters of surface-to-surface contact region in a finite element model within the linear behaviour range. Ibrahim and Pettit\textsuperscript{3} presented a review on dynamic problems of bolted joints and other fasteners. Mayer and Gaul\textsuperscript{4} have used segment-to-segment contact elements to define the contact stiffness of fixed joints for FE model updating.

In present research, a linear model called X-Frame element is developed for a single lap joint type connection. In thin layer element model, the stiffness is assumed to be distributed uniformly throughout the contact region of the joint which may leads to inaccurate results for large structures in the outer region of joints. In contrast, in X-frame element model it is possible to use a nearly real stiffness distribution based on physical characteristics of the joint area.
2. Modeling of joint

2.1 Interface element modelling

Interface element models have been used for the lap joint modeling in literature by several investigators. There are two group of such interface elements; zero thickness and thin layer. In the case of zero thickness elements, the compatibility equations contain constant values for normal and shear stiffness's. On the other hand, thin layer models use the same usual elements which are used in classical finite element method with special attention on compatibility relations. In this situation the joint may have quasi-elastically behavior that means there is no slip at the interface region and the applied force would be less than the identified force for friction and therefore the compatibility relations remain linear.

![Figure 1. The interface thin layer](image)

In this modeling procedure the joint region materials are assumed to be isotropic. The general Hook law for thin layer can be written as follow:

\[ \sigma_{ij} = C_{ijkm} \varepsilon_{km} \]  

(1)

Where \( \sigma_{ij} \) and \( \varepsilon_{ij} \) are stress and strain components respectively and \( C_{ijkm} \) are components of matrix coefficient. The choice of parameters is a crucial step in model updating. In present study the matrix of coefficient in equation (1) can be chosen as the updating parameters and so it is possible to model the slip and no-slip conditions in joint region. By no slip condition and isotropic assumptions in the model under consideration it can be concluded that most terms of coefficient matrix \( C_{ijkm} \) must be vanish, except two parameters \( E \) and \( G \) which are related to normal and torsional stiffness in joint region respectively. These two parameters are chosen as updating parameters in present research.

2.2 X-Frame element modelling

The other proposed element model for the interface region of the joint can be composed of two groups of springs including normal \( K_n \) and torsional \( K_s \) springs respectively as illustrated in Fig2.

![Figure 2. Two linear spring model for joint region.](image)
However it should be noted that the torsional springs cannot alone describe correctly the joint region behavior because in such a situation there isn’t any torsional-bending coupling in that region of structure and this may in turn leads to incorrect results. If two points \( i \) and \( j \) in Fig2 are chosen from the upper and lower parts of joint in a specified distance, it is expected that these two points have two displacement components \( u \) and \( v \) in horizontal and vertical directions respectively as shown in Fig3. This is equivalent to a coupling between rotational, lateral and axial displacement components.

![Figure 3. Typical displacement field in joint region](image)

Therefore in order to solve the above mentioned problem in joint modeling, it is proposed that instead of using linear springs in that region, it is convenient to use the combination of bar and beam elements in the form of a single frame-like element. This element is called X-frame element because of having two distinguished modulus of elasticity in normal and shear directions which are \( EA \) and \( EI \) respectively. The X-frame element is illustrated in detail in Fig4. Two elasticity parameters \( EA \) (or \( K_{n} \)) and \( EI \) (or \( K_{s} \)) were chosen as the updating parameters.

![Figure 4. X-Frame element model](image)

The stiffness matrix of X-Frame element in interface region including two nods \( i \) and \( j \) is defined as follow:
A FEM code is developed for structural dynamics analysis of two joining beam members including joint region in MATLAB software. In this method, two joining members were modeled by beam elements and the bolted joint itself was modeled by so called X-Frame elements. In order to describe the real physical characteristics of joint region, it is assumed that normal and shear stiffness’s in the interface region of the joint have a linear distribution along the bolted joint interfaces which has its maximum value at the center point where the bolt is located and decreases with approaching to fastener edges. The normal stiffness is assumed to be linear in the fastener region and the shear stiffness of the joint was investigated in both uniform and linear distribution cases.

3. Experimental set-up of joining structures

3.1 Case study

The experimental model of structural system under consideration consists of two steel beam members which are joined by a bolted joint fastener as illustrated in Fig 5.

![Figure 1. Experimental set-up of structural system](image)

The length of two joining beams is the same which is 350 mm, the width of each beam is 25mm and their thickness is 6mm. The length of joining region is 60 mm where a M8 bolt is fixed in the mid length of fastener as shown in Fig 5. The boundary conditions are free-free condition and the structure was excited by an impact hammer. There mounted two accelerometers in the vicinity of joint in order to measure the response of structure in that region. The frequency response functions for two accelerations are shown in Fig 6.
Figure 6. Frequency response function of the system for point 1.

Figure 7. Frequency response function of the system for point 2.

In Table 1 the first four frequencies of the system under study which are extracted from FRF’s are given. These frequencies were used for finite element model updating of jointed structures to obtain a proper correlation between test results and theoretical model.

<table>
<thead>
<tr>
<th>Mode No.</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>83.1</td>
</tr>
<tr>
<td>2</td>
<td>205.4</td>
</tr>
<tr>
<td>3</td>
<td>385.8</td>
</tr>
<tr>
<td>4</td>
<td>657.4</td>
</tr>
</tbody>
</table>

4. Updating of joint parameters

As stated before, in this research, the first 4 bending frequencies of a two beam structure jointed by a bolted fastener are extracted from the modal test data for a free-free boundary condition.

The updating process is based upon the linear iterative sensitivity analysis with respect to eigenvalues using the following equation:
\[ (\omega_i^a)^2 - (\omega_i^e)^2 = \frac{(\phi_i^a)^T(\Delta K - (\omega_i^e)^2 \Delta M(\phi_i^a))}{(\phi_i^a)^T M(\phi_i^a)} \] (2)

The values of chosen parameters for updating process in the case of X-Frame elements were selected from the following objective function:

\[ \min \sum_{i=1}^{5} W_i (\omega_i^a / \omega_i^e - 1)^2 \] (3)

Where \( \omega_i^a \) and \( \omega_i^e \) are analytical and experimental frequencies respectively and \( W_i \) are the positive weighting coefficients. As it can be seen from Fig 8, the solution is converged after ten iterations. This diagram is for the case in which the normal springs have a linear distribution while the torsional springs have a constant stiffness throughout. It can also be found from this figure that by increasing the element numbers, the stiffness of the joint region converges to lower values.

![Figure 8](image)

**Figure 8.** Updating iterations of normal stiffness (upper) and flexural stiffness (lower).

![Figure 9](image)

**Figure 9.** The objective function convergence process by iterations.
On the other hand, if both normal and torsional springs have a linear distribution along the joint region, the convergent behaviour of torsional stiffness is increased by increasing the element numbers as shown in Fig. 10 which is due to series combination of torsional springs.

![Figure 10. The convergence of flexural stiffness updating by iterations.](image)

Table 2 illustrates the updated frequencies for first 4 bending modes and their percent error in the best case.

<table>
<thead>
<tr>
<th>Mode No.</th>
<th>Measured Frequencies</th>
<th>Updating $K_n$ and $K_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\omega_i$ (Hz)</td>
<td>Error</td>
</tr>
<tr>
<td>1</td>
<td>83.1</td>
<td>85.3, 2.7</td>
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<tr>
<td>2</td>
<td>205.4</td>
<td>198.1, -3.5</td>
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<tr>
<td>3</td>
<td>385.8</td>
<td>386.5, 0.17</td>
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<tr>
<td>4</td>
<td>657.4</td>
<td>657.4009, 0.001</td>
</tr>
</tbody>
</table>

5. Conclusion

A new complex element was proposed for a single lap bolted joint region composed of bar and beam properties which was called X-frame element. This element was employed in such a way that the physical properties of a real bolted joint fastener were modelled. Eventually this FE model was updated using modal test data on an equivalent structural model which excited. The updating results showed a proper correlation between analytical and experimental model.
REFERENCES