Modal testing and finite element model updating of laser spot welds

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Abstract. Spot welds are used extensively in automotive engineering. One of the latest manufacturing techniques for producing spot welds is Laser Welding. Finite element (FE) modelling of laser welds for dynamic analysis is a research issue because of the complexity and uncertainty of the welds and thus formed structures. In this work, FE model of the welds is developed by employing CWELD element in NASTRAN and its feasibility for representing laser spot welds is investigated. The FE model is updated based on the measured modal data of hat-plate structures and cast as a structural minimisation problem by the application of NASTRAN codes.

1. Introduction

A typical vehicle body-in-white (BIW) is made of metal sheets, which are connected together by thousands of spot welds that are usually manufactured by Resistance Spot Welding (RSW). However, due to strong interest in the use of advanced and lightweight materials (e.g., aluminium alloy, which is very problematic if welded using the conventional RSW) for BIW applications in recent years, the use of Laser Welding for producing spot welds is receiving increased consideration.

The welds in vehicle structures not only provide connections between sheets of metals but also significantly contribute to the vehicle’s dynamic characteristics. Due to this fact, precise theoretical tools must be developed to predict their behaviour in order to make the most of the weld joints in automotive applications. While experimental work could offer the required physical understanding concerning the behaviour of the joints, predictive tasks such as design, analysis and evaluation of welded structures are frequently accomplished by computational methods.

Even though computational methods are widely used in predicting the behaviour of welds on a car structure, modelling the weld itself is complicated. This is mainly because of the existence of many local effects (such as geometrical irregularities, material inhomogeneity and defects in the welds) that are not taken into account by FE modelling [1]. Many studies related to FE modelling of laser welding focus mainly on simulating the welding process itself [2, 3]. There are also works being done on fatigue estimation of laser welds [4]. However, to the authors’ best knowledge, there is no work on modelling the dynamic behaviour of structures with laser welds.

In this paper, a general connection element called CWELD in MSC.NASTRAN™ [5] is used to represent the weld joints. This element establishes the prospect to generate weld joints that are independent of the mesh, which allows a huge reduction in computational effort and model development time. CWELD is commonly employed to represent the construction of spot welds that is
generally produced by RSW. It is uncertain whether the element can well represent spot welds made by other processes, especially Laser Welding as the construction of the joint is very different from the conventional RSW. It is therefore the aim of this paper to investigate the feasibility of utilising CWELD for representing spot welds made by Laser Welding.

This paper also explains the procedures to correlate FE models regarding the test measurements. The FE models are updated accordingly to minimise the discrepancies between the analytical and experimental results, and the feasibility of CWELD is evaluated.

2. Description of hat-plate structure
The hat-plate structure is designed to represent common structures used in the construction of a car BIW. It consists of a flat plate and a formed hat-like shell (or ‘top-hat’) joined together by spot welds at the flanges, as shown in Figure 1. The spot welds, which are produced by Laser Welding, are 5 mm in diameter and 60 mm apart. The length of the structure is 564 mm and the width is 110 mm. The plates are made of cold rolled mild steel sheet metal with the thickness of 1.5 mm. A set of nine identical pairs of the structures are built, each having the same nominal dimensions. In order to reduce manufacturing variability, a general procedure as outlined by Mottershead et al. [6] is followed.

3. Initial FE modelling, modal testing and manual tuning on separate components
Development of the FE models of the components involves four stages [7]: (1) initial FE modelling, (2) modal testing, (3) manual tuning, and (4) model updating. This section describes the development of the initial FE model for the components as well as their modal tests. Then, the manual model tuning is discussed. Model updating is described in Section 4.

3.1. Initial FE modelling
The FE models of the top-hat and flat plate are developed using MSC-NASTRAN shell element (CQUAD4) [8], as depicted in Figure 2. The flat plate’s FE model consists of a total of 300 elements and 350 nodes; the top-hat’s FE model consists of 8648 elements and 8883 nodes. Nominal values for the material properties (Young’s modulus and density) of mild steel are used for both models.

The first five natural frequencies are tabulated in Tables 1 and 2. These FE results are validated in the next section by comparing with the experimental modal data.

Figure 1: The hat-plate structure

Figure 2: The FE models of (a) the flat plate (b) the top-hat
3.2. Modal testing

Modal testing based on frequency response function (FRF) measurements was carried out to verify the modes of vibration obtained in the initial FE model. Modal testing with free-free boundary condition was conducted on each specimen from both sets of components. The flat plates were tested using one hammer point and two measurement points, while the top-hats were tested using one hammer point and five measurement points. The flat plates were tested in the range of 15 to 300 Hz and the top-hats were tested in the range of 50 to 1000 Hz.

The vibration responses from both tests were measured using 12-channels LMS data acquisition system. Natural frequencies and mode shapes were extracted from the measured FRF by using a PolyMAX [9] curve-fitting procedure from LMS Test.Lab [10] system. The average experimental natural frequencies from the tests are given in Tables 1 and 2. As can be seen from the tables, the computed natural frequencies deviate significantly from the experimental values. This indicates that the initial FE model is not good enough and needs to be tuned and updated.

3.3. FE manual tuning

All modes identified experimentally have their counterparts in the initial FE models. The experimental natural frequencies for the bending modes of the flat plate (i.e., modes 1, 2 and 4) are overestimated, with the biggest frequency error of approximately 4.5%. The frequency errors for the top-hat are also poor, with the highest being about 5.4%.

In order to improve the results, FE manual tuning is carried out. The thickness of all nine flat plates are measured at different places and a mean value of 1.4489 mm is used in the manual tuning procedure for both components. Furthermore, a closer inspection on the top-hats reveals that the fold radii are approximately 4 mm, which is 1 mm smaller than the specified radii. The radii corrections are incorporated in the top-hat manual tuning.

When the changes are incorporated in the FE models, the correlations are improved considerably, especially on the flat plate. It is also found that the tuned FE model of the flat plate improves the bending modes but degrades the torsion modes (error of approximately 3.8%). For the top-hat, the error of the three lowest modes is increased (with the minimum value being approximately 6.2%) but the other modes are improved significantly. Due to the big errors, updating has to be carried out in order to improve the results. The frequency errors for the manually-tuned models are presented in Tables 1 and 2.

4. Updating of the models

The updating procedure is performed with the aim to further improve the FE models by minimising the differences between the analytical and experimental models. Therefore, it is cast as a structural optimisation problem [11-13] and the optimisation algorithm of the FE code NASTRAN is used to perform the updating.

**Table 1: Correlation of frequencies \( \phi \) between experimental, initial and manually-tuned FE model for the flat plate**

| Mode | I Experiment (Hz) | II Initial FE model (Hz) | III Error (%) \( = |(II - I)/I| \) | IV Manually-tuned (Hz) | V Error (%) \( = |(IV - I)/I| \) |
|------|------------------|-------------------------|--------------------------------|------------------------|------------------------|
| 1    | 24.20            | 25.14                   | 3.89                           | 24.28                  | 0.34                   |
| 2    | 67.10            | 69.84                   | 4.09                           | 67.46                  | 0.54                   |
| 3    | 78.07            | 77.77                   | 0.39                           | 75.13                  | 3.77                   |
| 4    | 132.24           | 138.26                  | 4.55                           | 133.55                 | 0.99                   |
| 5    | 159.54           | 159.49                  | 0.03                           | 154.07                 | 3.43                   |
Table 2: Correlation between experimental, initial and manually-tuned FE model for the top-hat

| Mode | Experiment (Hz) | Initial FE model (Hz) | Error (%) | Manually-tuned (Hz) | Error (%) |
|------|----------------|-----------------------|-----------|---------------------|-----------|
| 1    | 70.04          | 70.79                 | 1.07      | 67.85               | 3.13      |
| 2    | 272.72         | 258.12                | 5.35      | 255.91              | 6.16      |
| 3    | 286.67         | 275.68                | 3.83      | 272.86              | 4.82      |
| 4    | 333.58         | 348.05                | 4.34      | 336.47              | 0.87      |
| 5    | 394.76         | 411.91                | 4.34      | 388.06              | 1.70      |

4.1. Parameter sensitivities
Selecting the updating parameters \(\theta\) is a vital step in model updating [7, 11, 14]. The number of parameters should be kept to a minimum to avoid problems due to ill-conditioning [7, 11]. Having done a sensitivity analysis, two parameters are selected for the flat plate and four parameters are chosen for the top-hat, as tabulated in Table 3. The parameters are normalised in the form of \(\delta\theta / \theta_0\). So, the sensitivities become \((\delta \omega / \delta \theta) \theta_0\), where \(\delta\) denotes a small increment.

Table 3: Normalised sensitivities associated to initial values of updating parameters \(\theta_0\)

| Component | Parameter                  | Natural frequencies |
|-----------|----------------------------|---------------------|
| Flat plate| Young’s modulus, \(E_p\)    | \(\omega_1\) 33.39  |
|           | Density, \(\rho_p\)        | \(\omega_2\) -33.38 |
| Top-hat   | Fold thickness, \(t_1\)     | \(\omega_3\) 25.55  |
|           | Flange thickness, \(t_2\)   | \(\omega_4\) -46.24 |
|           | Sidewall thickness, \(t_3\) | \(\omega_5\) 34.46  |
|           | Top thickness, \(t_4\)      | \(\omega_6\) 63.20  |

4.2. Target response selection
Target responses should be selected among those measured. With confidence in the quality of the experimental data, all measured natural frequencies of the flat plate and the top-hat are targeted in the updating process.

4.3. Updating and its results
NASTRAN optimisation algorithm permits the specification of objective function to be minimised in the updating procedure, as follows [15]

\[
J = \sum_{i=1}^{n} \left( \frac{\omega_i}{\omega_{i}^{exp}} - 1 \right)^2
\]  

where \(\omega_i\) is the \(i\)th computed natural frequency, \(\omega_{i}^{exp}\) is the \(i\)th experimental natural frequency and \(n\) is the number of measured frequencies.

Tables 4 and 5 show the updating results for the flat plate and the top-hat, while Table 6 shows the change in the updating parameters from the initial values. The parameters for the flat plate are allowed to change from 85 to 110% of the initial values, while the change of the top-hat’s parameters is from 85 to 120% of their initial values. The updating process for the flat plate converges after two iterations and the top-hat reaches convergence after seven iterations.

The updated results of the flat plate, although reasonable, are not as good as expected. This is probably due to the variations of the material properties along the length of the plate, which is not incorporated in the updating procedure. The top-hat’s updating results, however, are improved significantly. The updated FE models of both components are used in modelling the complete welded...
structure. By ignoring the uncertainties due to manufacturing when welding the complete samples, the modelling uncertainties from the complete model will merely be due to the weld modelling.

Table 4: Flat plate updating - experimental and updated FE model

| Mode | I Experiment (Hz) | II Updated FE model (Hz) | VI Error (%) = |(II – I)/I|
|------|------------------|--------------------------|----------------|
| 1    | 24.20            | 24.53                    | 1.37           |
| 2    | 67.10            | 68.16                    | 1.58           |
| 3    | 78.07            | 75.91                    | 2.77           |
| 4    | 132.24           | 134.93                   | 2.03           |
| 5    | 159.54           | 155.66                   | 2.43           |

Table 5: Top-hat updating - experimental and updated FE model

| Mode | I Experiment (Hz) | II Updated FE model (Hz) | III Error (%) = |(II – I)/I|
|------|------------------|--------------------------|----------------|
| 1    | 70.04            | 70.03                    | 0.01           |
| 2    | 272.72           | 272.45                   | 0.10           |
| 3    | 286.67           | 287.09                   | 0.15           |
| 4    | 333.58           | 333.55                   | 0.01           |
| 5    | 394.76           | 394.57                   | 0.05           |

Table 6: Parameter changes due to updating

| Component | Parameter          | I Initial value | II Updated value | Changes (%) =|(II – I)/I|
|-----------|--------------------|-----------------|------------------|----------------|
| Flat plate| Young’s modulus, $E_p$ (GPa) | 210             | 212              | 1.03           |
|           | Density, $\rho_p$ (kg/m$^3$) | 7860            | 7779             | 1.03           |
| Top-hat  | Fold thickness, $t_1$ (mm)  | 1.4489          | 1.4062           | 2.95           |
|           | Flange thickness, $t_2$ (mm) | 1.4489          | 1.5580           | 7.53           |
|           | Sidewall thickness, $t_3$ (mm) | 1.4489          | 1.2370           | 14.63          |
|           | Top thickness, $t_4$ (mm)  | 1.4489          | 1.6254           | 12.18          |

5. FE modelling of the complete structure

Using the updated FE models of the flat plate and the top-hat, the FE modelling for the complete welded hat-plate is carried out.

5.1. Representation of CWELD

CWELD (Fig. 3) is developed using a 2-noded special shear flexible beam type element [16] with 12 degrees of freedom (six for each node) and each node is connected to its corresponding patch. In modelling the welded hat-plate, 20 CWELD elements are employed to represent the 20 spot welds. The initial values for the material properties and the diameter of the CWELD elements are defined, with the diameter being 5 mm and the material properties are assumed to be the same as the bulk material’s nominal values. The potential of CWELD for updating is investigated and briefly described in Section 7.
5.2. Initial FE results
The initial FE results are tabulated in Table 7 (Column II) and the mode shapes are given in Figure 4. These FE results are validated by comparing with the experimental findings, which is explained in the next section.

6. Modal tests on the welded structures
Free-free hammer tests with three hammer points and seven measurement points were performed on the welded structures. As in the previous tests, the vibration response (in the range of 400 to 1000 Hz) was measured using the 12-channels LMS system and extracted using the PolyMAX curve-fitting procedure. The average measured natural frequencies for the samples are shown in Table 7 (Column I).

All the five modes identified experimentally have their counterparts in the initial FE model. Both experimental and numerical findings are compared and the modes are found to be very well correlated. However, the natural frequencies of all the experimental modes are significantly underestimated by the numerical model, with the frequency errors being about 10% and more. The big errors show the critical need for updating to be carried out.

7. Model updating of the complete model
Following the findings explained in the previous section, it is very important for the initial model of the hat-plate to be updated. Several parameters are investigated for updating but only three of them are selected for the procedure, as explained in the following section.

7.1. Parameters sensitivities
Several parameters from the spot weld and the patch of the welds (such as the diameter, thicknesses, Young’s moduli, densities and Poisson’s ratios) are investigated by carrying out the sensitivity analysis. The patch parameters are included because it is found that the weld parameters alone cannot successfully improve the results of the initial model. Of all the possible parameters, the weld diameter \( d_w \) and the Young’s moduli of the weld and patch \( E_w \) and \( E_{ patch } \) are found to be sensitive enough to be selected for the updating process. It is also found that the natural frequencies of the welded structure are all more sensitive to \( d_w \) than \( E_w \) and \( E_{ patch } \), as shown in Table 8.
7.2. Model updating process
Updating is carried out on the basis of the first five measured frequencies from the welded samples, and is completed after three iterations. The natural frequencies of the updated model are presented in Table 7 (Column IV), while the initial and final values of the parameters are shown in Table 9. The values of the weld parameters (i.e., \( d_w \) and \( E_w \)) are constrained to within a reasonable range. However, the Young’s modulus of the patch is allowed to have a very big variation due to uncertainties from the patch properties. The initial value of \( E_{patch} \) is made very high to justify for the rigidity of the patch in comparison to the adjacent bulk materials. From the updating procedure, it is found that all the natural frequencies are improved significantly, although the error from the first frequency is not as small as the others.

| Mode (Experiment) | I | Experiment (Hz) | II | Initial FE model (Hz) | III | Error (%) = | IV | Updated FE model (Hz) | V | Error (%) = |
|-------------------|---|-----------------|----|-----------------------|----|---------------|----|-----------------------|---|---------------|
| 1                 |   | 508.12          | 459.20 | 9.63 | 492.39 | 3.10 |
| 2                 |   | 553.69          | 472.96 | 14.58 | 552.73 | 0.17 |
| 3                 |   | 575.39          | 505.31 | 12.18 | 577.72 | 0.40 |
| 4                 |   | 627.45          | 526.55 | 16.08 | 636.18 | 1.39 |
| 5                 |   | 643.66          | 532.36 | 17.29 | 640.11 | 0.55 |

| Parameter                  | Natural frequency for corresponding mode | \( \omega_1 \) | \( \omega_2 \) | \( \omega_3 \) | \( \omega_4 \) | \( \omega_5 \) |
|----------------------------|------------------------------------------|------|------|------|------|------|
| Weld diameter, \( d_w \)  |                                          | 4.26 | 6.35 | 160.77 | 148.86 | 168.09 |
| Weld Young’s modulus, \( E_w \) |                                      | 1.19 | 1.60 | 4.21 | 3.73 | 4.23 |
| Patch Young’s modulus, \( E_{patch} \) |                                   | 1.54 | 2.26 | 5.33 | 4.88 | 5.59 |

| Parameter                  | I Initial value | II Updated value | Changes (%) = |(II – I)/I|
|----------------------------|----------------|-----------------|----------------|
| Diameter, \( d \) (mm)    | 5              | 5.4             | 8.00           |
| Young’s modulus of Weld, \( E_w \) (GPa) | 210          | 220             | 4.50           |
| Young’s modulus of Patch, \( E_{patch} \) (GPa) | 10000       | 17235           | 72.35          |

8. Conclusions
At the beginning of this study, it was uncertain whether CWELD element was capable of representing laser spot welds of the hat-plate structure and leading to reasonably accurate values of natural frequencies. Numerical results show that the initial frequencies were very low in comparison with the experimental ones when CWELD is used and CWELD parameters alone cannot improve the results of the initial model even after updating. Further investigation reveals that when a patch parameter is
included in the updating the results improve significantly and combined with this patch CWELD is capable of producing very good results when the right parameters are updated.

The FE model updating procedure is cast as an optimisation problem and handled by the structural optimisation module of NASTRAN. This allows the power of NASTRAN to be exploited and would facilitate application of the method presented in this paper. It is expected that this method can be used for prediction of modal properties and damage assessment of structures with laser spot welds.

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