Finite Element Modelling and Analysis for Dynamic Investigation of a Laser Spot Welded Hat-Plate Structure under Initial Stress Influence

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Abstract. This paper presents the finite element modelling and analysis of the dynamic behaviour of a laser spot welded structure under the influence of initial stress. Modal based updating with a new scheme was used to improve the finite element model of the structure. Element connectors with CWELD ELPAT format were used to represent the laser spot welded in the structure. The modal parameters of the structure were measured using impact hammer testing and roving accelerometers under free-free boundary conditions. NASTRAN SOL 200 was used in updating the finite element model in light of the experimental results. In this study, it was found that modal updating with the new scheme has successfully matched the finite element model of the welded structure with the experimental model. The achievement demonstrates the accuracy and efficiency of the proposed new scheme.

Keywords: Finite Element Analysis, Model Updating, Experimental Modal Analysis, Initial Stress

1. Introduction

Large and complex engineering structures such as a car body in white, usually consists of a large number of structural components made from thin metal sheets. They are assembled together by thousands of joints which significantly influence the dynamic behaviour of the structure [1].

Laser spot welds are one type of joints and the use of laser spot welds in the automotive and aerospace industries has lately shown a significant increase. This is because laser spot welding is a cost effective and efficient method of assembling structural components. In addition, laser spot welding offers higher process speed and excellent flexibility for automation [2]. However, laser spot welded joints are found to
be complex and have many uncertainties when it comes to analytical modelling [3]. One way to represent laser spot welds in a jointed structure for dynamic analysis is to use the finite element method. For example, Nurul et. al [4], showed that CWELD element connectors were used to represent laser spot welds. In the study, modal updating had been done on the hat-plate structure but there are still noticeable errors. Recently, Syazwan et. al [5], had done a study on frequency response function (FRF) based updating for the laser spot welds on a similar structure. The method had successfully shown a strong correlation between the updated and measured frequency response function. However, although modelling and analyses of the dynamic behaviour of welded structures were demonstrated, the issues of discrepancies between the FE and EMA results have remained to be unsolved. The discovery reveals that the use of the common model properties in updating the FE models are not successful and other potential updating parameters such as initial stress should be looked into.

Initial stress can arise when components are assembled. For a structure with a large surface of low thickness with initial curvature, stiffeners can be intentionally added to remove it and they may also unintentionally remove it. Initial stress is also connected with residual stress, improved understanding of the fatigue behaviour, in connection of those two subjects is extremely important [6]. Previous work [7] has compared the fatigue behaviour between resistance spot welds and laser spot welds of dissimilar materials. Thus, the effects of initial stress on structural dynamics are still completely unknown [8].

When the initial curvature is suppressed after adding of stiffeners, initial stress arises. Initial stress can also arise as a result of fabrication and heat treatment. However, such initial stress is very problematic to estimate by theoretical analysis or to measure, unless the unstressed configuration is first measured in the latter case, which is very infrequent in reality. In addition, the influence of initial curvature and initial stress on the natural frequencies of structures was investigated and was found to be noticeable in [9-12]. Furthermore, work on the effect of initial curvature was carried out in [13]. It was also pointed out in the same paper, that finite element commercial software treats membrane and bending deformation as being independent and this approximation is only practical for structures with a small initial curvature and small deflection. However, as for a moderate initial curvature and a small deflection the interaction between membrane and bending deformations should not be ignored.

This paper presents and discusses the importance of modelling initial stress in the finite element model and the use of initial stress as an updating parameter for enhancing the performance of the finite element model of the laser spot welded hat-plate structure made of thin metal sheets.

2. Description of the Jointed Structure and Experimental Set up
In this study, the structure under investigation is a laser spot welded hat-plate made from steel sheets of a uniform thickness of 1.5mm, 110mm long and 80mm wide. The structure consists of two components welded together as shown in figure 1. Component labelled number 1 is the hat shaped plate and number 2 is the flat plate. There are in total of 20 laser spot welds used in the structure.

The test structure was set up in free-free boundary conditions by suspending the structure using strings and rubber bands as shown in figure 2. The dynamic characteristics of the test structure were obtained using impact testing with two accelerometers. An impact hammer was used to excite the structure with one accelerometer was used as a reference by fixing to the predefined excitation point. The other accelerometer was roved around to measure 60 points throughout the structure. LMS SCADAS system was used to process the input and output responses of the structure under the test.
3. Finite Element Modelling and Analysis
The finite element model of the welded hat-plate structure was developed using HyperMesh software. MSC NASTRAN SOL 103 and SOL 200 were used for the prediction of the dynamic behaviour of the welded structure. The former was used for normal modes analysis and the latter for modal updating. Full details of the methods used in this study are available in [14-16].

Figure 3 shows the finite element model of the welded hat-plate. The finite element models of the hat and plate were developed based on CQUAD4 shell elements with 17673 elements and 18146 nodes. CWELD element connectors were used to represent the laser spot welds in the FE models. The actual dimensions of the test structure were measured using a coordinate measuring machine (CMM). The measurement was carried out for minimizing the uncertainties of the FE model developed. Detailed information on the model properties used in the FE model of the welded hat-plate structure is given in table 1 and table 2. In this study, initial stress exhibited in the test welded hat-plate structure was modelled in the FE model of the welded hat-plate structure. The modelling was carried out by discretizing the plate into 56 collectors mimicking the effect of the exhibited initial stress. The FE model with initial stress is shown in figure 4. By engineering judgement, the initial value of initial stress modelling was set to be 0.5 in the finite element analysis and the frequency of interest used in normal modes analysis was from 0 to
1000 Hz. Only the first six frequencies and mode shapes were investigated because there is high confidence in the modes.

![Figure 3. The finite element model of the welded hat-plate structure.](image)

**Table 1.** Model properties of the FE model of the welded hat plate structure.

| Property name   | Nominal Value |
|-----------------|---------------|
| Young’s Modulus | 210GPa        |
| Poisson’s Ratio | 0.3           |
| Density         | 7500kg/m³     |

**Table 2.** Model properties of CWELD element connectors used in the FE model of the welded hat-plate structure.

| The name of Property | Nominal Value |
|----------------------|---------------|
| Young’s Modulus      | 210GPa        |
| Poisson’s Ratio      | 0.3           |
| Density              | 7500kg/m³     |
| Diameter             | 4.5           |

![Figure 4. Modelling of the initial stress in the plate.](image)
3.1 Modal Updating

Modal updating has been widely used to improve the accuracy of finite element models by correcting the invalid assumptions about the finite element models [17-19]. The improvement is carried out by systematically changing predefined potential updating parameters which have a large influence in improving the accuracy of the finite element models. The NASTRAN optimization code (SOL 200) is used to perform modal updating. Furthermore, the optimization algorithm in equation 1, which is a sensitivity based iterative-based procedure, let the objective function (J) to be minimized by correcting the eigenvalues of the initial finite element model until the objective function is converged. The objective function based on eigenvalues is defined as follows [22]:

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

(1)

Where, \( \lambda_i^{exp} \) is the experimental eigenvalue and \( \lambda_i^{pred} \) is the predicted eigenvalue from the finite element model and \( n \) is the number of eigenvalues used in the updating procedure.

4. Results and Discussion

Previous studies [20-21] revealed that efficient and economical methods of studying the initial stress of the structure were vital to accurately determine dynamic ability which is directly related to the performance of engineering products. Model updating method has been successfully used by researchers [21-23] to accurately determine modal parameters of engineering structures in the light of experimental results which are usually obtained from experimental modal analysis.

In this study, the predicted and measured modal parameters of the test structure were obtained from the finite element method and experimental modal analysis. CQUAD4 shell elements and CWELD element connectors were used in modelling the welded hat-plate structure. The initial stress was introduced in the finite element model and modal updating scheme was then used in updating the initial finite element model of the structure to the test structure.

Table 3 tabulates the natural frequencies obtained from experimental modal analysis (column II), initial finite element modal (column III) and updated finite element model (column V). From the comparison of the natural frequencies, it was found that the errors in terms of percentage recorded in column IV are inconsistent. The largest error is shown in the 2\(^{nd}\) mode with 2.71 percent and the smallest one is 1.02 percent from the 4\(^{th}\) mode. The total error registered from six modes is 9.39 percent. The inconsistency in the errors suggests that the updating parameters (as stated in Tables 1 and 2) used in the updating scheme are not capable of updating the finite element model to the test structure. These findings are in fact consistent with the ones presented and discussed by [4,5,18]. Therefore, other potential updating parameters that can be identified using sensitivity analysis may be useful in updating the finite element model. Initial stress that may result from laser spot welding of the test structure was used as the potential updating parameters in the second attempt to update the finite element. In other words, initial stress with the updating parameters stated in Tables 1 and 2 were used in the attempt. Column V of table 3 presents the natural frequencies calculated from the second attempt which is the updated finite element model.

A compelling accomplishment in terms of percentage individual and total error was recorded in the updated finite element model after each of the six modes calculated from the model was compared with the experimental counterparts. An extraordinary reduction in the total error calculated from the updated model was noted in column VI with 0 percent. Another remarkable achievement recorded from the updated model is the percentage of individual error which is calculated from the direct comparison of each mode between the updated model and experimental modal analysis in which 0 percent was registered for each of the six modes. Meanwhile, figure 5 shows a graph of normalized values of the updating
parameters used in the updated finite element model of the welded hat-plate structure. Fifty-six updating parameters as shown in the figure were used in the updating. It was observed that forty-five cycles were taken to complete the updating process. In other words, the number of the cycles was required to systematically adjust the fifty-six updating parameters in the process of updating the finite element model. However, the number of the cycles could be reduced further if the 13th cycle in which all the updating parameters started converging was taken into consideration. The perturbations in the diameter and Young’s modulus of the spot welds was observed in the 45th cycle. The initial diameter used has dropped from 4.5mm to 4.05mm and the initial Young’s modulus defined has slid from 210GPa to 170GPa. The findings and achievement in this study have revealed that initial stress resulting from spot welding has a large influence on the accuracy of the finite element modelling and analysis of the dynamic behaviour of the laser spot welded hat-plate structure.

![Figure 5. Graph of the normalized values of the updating parameters vs number of cycles.](image)

**Table 3.** Comparison of the natural frequencies between the EMA, initial FEA and updated FE with initial stress.

| Modes | EMA (Hz) | Initial FE (Hz) | Error % | Updated FE with initial stress (Hz) | Error % |
|-------|----------|-----------------|---------|------------------------------------|---------|
| (I)   | (II)     | (III)           | (IV)    | (V)                               | (VI)    |
| 1     | 504.58   | 509.95          | 1.06    | 504.58                            | 0       |
| 2     | 556.89   | 572             | 2.71    | 556.89                            | 0       |
| 3     | 572.33   | 586.39          | 2.46    | 572.33                            | 0       |
| 4     | 634.43   | 640.93          | 1.02    | 634.43                            | 0       |
| 5     | 644.41   | 651.03          | 1.03    | 644.41                            | 0       |
| 6     | 666.54   | 673.93          | 1.11    | 666.54                            | 0       |
|       | Total error | 9.39           |         | Total error                      | 0       |
5. Conclusions

The finite element modelling and analysis of the dynamic behaviour of the laser spot welded hat-plate structure under initial stress influence have been successfully investigated using experimental modal analysis, finite element method and modal based updating. From the investigation it was found that the conventional updating parameters and updating method largely used by researchers to update the finite elements models have appeared to be incapable of attaining the main objective of model updating. On the other hand, the findings from the investigation demonstrate that the proposed new updating scheme including initial stress in updating the finite element model of the structure is able to offer a superior updating capability. The proposed updating scheme has been successfully used to reduce the total error recorded in the initial finite element model of the welded structure. The reduction means that the dynamic behaviour of the initial finite element model has been perfectly matched with the test welded structure. In addition, initial stress has contributed a large of error.

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