A Comparative Study of CWELD and ACM2 Element Connectors on the Dynamic Behaviour of a Laser Spot Welded Hat-Plate Structure under Initial Stress Influence

C Peter¹, M N Abdul Rani¹*, H Hashim¹, M A Yunus¹, M.N Machmud² and M S Mohd Zin¹

¹ Structural Dynamics Analysis and Validation, Faculty of Mechanical Engineering, Universiti Teknologi MARA (UiTM), 40000 Shah Alam, Selangor, Malaysia
² Laboratory of Structural Dynamics, Department of Mechanical and Industrial Engineering, Universitas Syiah Kuala, JL. Syech Abdurrauf No.7 Bandar Aceh 23111, Indonesia.

*Corresponding author: mnarani@salam.uitm.edu.my

Abstract. Analytical modelling of the dynamic behaviour of a laser spot welded structure can be developed using two element connectors which are CWELD and ACM2. In the presence of initial stress in the structure, the performance of these two connectors can be different. In order to properly investigate the dynamic behaviour of the structure, the difference of these two element connectors in representing the laser spot welded in the structure should be evaluated. The finite element method was used to develop the welded structure comprising two structural components. The element connectors were then used to represent the laser spot welds in the structure. Normal modes analysis was performed on the FE model of the welded structure to calculate the modal parameters. Experimental modal analysis was carried out to measure the modal parameters of the physical welded structure. The modal parameters calculated from the two different FE models were evaluated by the experimental counterparts in terms of natural frequencies, mode shapes and MAC value. The accumulated error registered from all 6 modes from the CWELD element connector FE model is 10.59%. Meanwhile, the accumulated error calculated from all 6 modes of the ACM2 element connectors based FE model is 26.67%. It was found that the FE model with CWELD element connectors has shown a good correlation with the physical welded structure. The findings can have an important effect on how analytical modelling of the dynamic behaviour of the welded structure under initial stress can be effectively and accurately carried out.

1. Introduction

Thin metal sheets are found to be widely used in the automotive and aerospace industries because of their light in weight and high structural integrity. For example, a car body in white, comprising a large number of structural components made from thin metal sheets. In practice, the structural components are usually assembled together by joints such as rivets, bolts and welds [1]. In recent years, the use of laser welding for joining the structural components has received much attention in the industries [2]. This is because,
the welded joints do not only provide strong connections between structural components, but they also significantly contribute to the dynamic behaviour of the structures [3].

Laser spot welding offers higher process speed and excellent flexibility for automation [4]. However, laser spot welded joints are found to be complex and have many uncertainties when it comes to analytical modelling [5] due to the presence of local effect in the welded areas (Palmonella et al., 2005). Although a large number of studies on spot welded joints have been carried out, very little work has been found on the attempt to establish a proper procedure for designing and verifying laser spot welded structures via the finite element method [6]. For example, Nurul et. al [7] used CWELD element connectors to represent laser spot welds in the structure under study. In the study, modal based updating was performed on the hat-plate structure to minimise the differences between the measured and FE results. However, the differences were not successfully reduced. Recently, the frequency response function (FRF) based updating was adopted by Syazwan et. al [8] to improve the predicted results of the laser spot welded structure. It was found that the method adopted has led to a strong correlation between the predicted and measured frequency response function, particularly for lower modes. The powerful and successful model updating in improving the predicted results, however, remains to be very challenging and have many fundamental issues to be handled properly. This is because the use of the common updating properties of model and joints in updating the FE models is found to be no longer successful, especially for updating an assembled structure with different types of joints. Therefore, other potential updating properties can be fundamentally explored for a better correlation between the physical test structure and analytical model. One of the most potential updating candidates is initial stress resulting from welding and assembly of structural components.

Initial stress may arise from the way structural components are assembled using welded joints to form an assembled structure, particularly, with a large thin span surface. Initial stress is also connected with residual stress and the fatigue behaviour of a structure, in connection of those two subjects is extremely significant for researchers to learn more about this topic [9]. The attempt to understand the effect of initial stress was discussed by [10] in which the fatigue behaviour between resistance spot welds and laser spot welds of a structure with dissimilar materials was evaluated. The findings of the attempt showed that there were still noticeable errors. This result may be explained by the fact that there is the possibility of the presence of initial stress in the welded structure. Thus, the effects of initial stress on structural dynamics are still completely unknown and required further investigation [11].

This paper presents and discusses finite element modelling of the dynamic behaviour of a laser spot welded structure under initial stress using two different types of element connectors which are CWELD and ACM2 in representing the laser spot welded joints in the physical test hat-plate structure.

2. Description of the Welded Hat-Plate 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, 564mm long and 80mm wide. The structure consists of two components welded together with a total of 20 laser spot welds as shown in Figure 1. The test structure was set up in free-free boundary conditions by suspending the structure using strings and rubber bands as shown in Figure 1. 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 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 analytical analysis of the dynamic behaviour of the welded hat-plate. Specifically, the former was used for normal modes analysis and the latter for model updating. Full details of the methods used in this study are available in [12-18]. Figures 2 and 3 show two different types of the finite element model of the welded hat-plate developed in this study. The finite element models of the hat and plate were developed based on CQUAD4 shell elements with 17673 elements and 18146 nodes. In Figure 2, CWELD element connectors were used to represent the laser spot welds in the test hat-plate structure. Meanwhile, Figure 3 shows the same FE model but ACM2 element connectors were used instead. Beforehand, the actual dimensions of the test structure were measured using a coordinate measuring machine (CMM). The purpose was to reduce the uncertainties in 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, the main area of initial stress which was largely found on the bottom plate of the test welded hat-plate structure was modelled in the FE model by discretising the plate into 56 collectors. In order to investigate the effect of initial stress on the natural frequencies of the welded hat-plate structure, the initial value of initial stress modelling was set to be 1 which is the same setting that was found in [4]. The frequency of interest used in the normal modes analysis was from 0Hz to 1000Hz. Only the first six frequencies and mode shapes were investigated because the confidence level in the modes is greater than the other modes.
Table 1: Model properties of the FE model of the welded hat-plate structure

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

Table 2: Model properties of CWELD and ACM2 element connectors used in the FE model of the welded hat-plate structure

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

3.1 Modal Assurance Criterion

In a brief historical view, Modal Assurance Criteria originated from the necessity for a quality assurance indicator for experimental modal vectors that are predicted from measured frequency response functions. Thus, it leads to the discovery of Modal Assurance Criterion which can be defined as a scalar constant relating the degree of consistency (linearity) between one modal and another reference modal vector [19], as shown in Equation 1, the equation for MAC. This method is widely used to validate the results between experimental modal analysis and finite element analysis because the modal assurance criterion takes on values from zero, representative of no consistent correspondence, to one, representing a consistent correspondence. In this manner, if the modal vectors under consideration accurately display a consistent, linear relationship, the modal assurance criterion should approach unity and the value of the modal scale factor can be considered reasonable [20]. However, unlike the orthogonality calculations, the modal assurance criterion is normalized by the magnitude of the vectors and, thus, is bounded between zero and one. Thus, imaginary value from the experimental modal analysis and finite element analysis can be validated by using this method on top of the degree of the accuracy of natural frequencies and mode shapes.

\[
\text{MAC} = \frac{\phi_a^T \phi_m \phi_a}{\phi_a^T \phi_a \phi_m^T \phi_m} = (\frac{\phi_m^T \phi_a}{\phi_a^T \phi_a})^2
\]

Where:
- \( \phi_a \) = Modal vector for test mode
- \( \phi_m \) = Modal vector for FE mode
- \( \phi_a^T \) = Transpose of test modal vector
- \( \phi_m^T \) = Transpose of FE modal vector
4. Results and Discussion

In this study, the predicted and measured modal parameters, particularly natural frequencies and mode shapes of the welded hat-plate structure were obtained from the finite element method and experimental modal analysis respectively. Two different types of element connectors which are CWELD and ACM2 were used in representing the laser spot welds. The influence of initial stress on the physical welded hat-plate was introduced in the finite element model as described in the section of finite element modelling and analysis. The level of correlation between the predicted and measured results of both CWELD and ACM2 model was evaluated by frequency deviation and MAC value.

Table 3 shows the comparison of natural frequencies obtained from three different sources which are the experimental modal analysis (column II), the finite element model with CWELD (column III) and the finite element model with ACM2 (column V). Therefore, from a direct comparison, particularly, between the model with CWELD element connector (column III) and EMA (column II), in column IV it was found that the largest percentage error has been recorded from the 2nd mode with 2.97%, while the lowest error which is 1.22% has been registered from the 1st mode. The accumulated error registered from all 6 modes is 10.59%. The next comparison of the natural frequencies which are tabulated in column VII, is between the finite element modal with ACM2 element connector (column VI) and EMA (column I). From column VII, it is shown that the largest error which is 6.71%, has been registered from the 2nd mode and the lowest error of 2.97% has been recorded from the 1st mode. Meanwhile, the accumulated error calculated from column VII is 26.67%.

MAC values of corresponding mode shapes (mode pairing) between EMA and FEM were used to quantify the mode shapes calculated from both types of the finite element models. Figure 4 shows MAC analysis on the FE model with CWELD element connectors model and the findings are tabulated in Table 3 (column V). While Figure 5 shows the MAC analysis on the FE model with ACM2 element connectors; the calculated MAC values are tabulated in Table 3 (column VIII). In general, any mode with MAC value more than 0.7 is regarded as a well correlated mode shape while MAC value is less than 0.7 is considered as a poor correlated mode shape. In Table 3, the lowest MAC value has been recorded from the 1st mode of both types of the FE models.

It is worthwhile to note that the comparisons of the MAC values for both types of the FE models reveal that the FE model with CWELD element connectors has recorded the highest MAC values for all 6 mode shapes in comparison with that of the FE model with the ACM2 element connectors. However, there are three modes with MAC values of less than 0.7 recorded from the former. This may be due to the low quality of the calculated mode shapes as a result of the incapability of the FE model to accurately represent the physical laser welded structure, especially the local effects of the laser welding and the presence of initial stress. One way to increase confidence in the quality of the FE model is the use of model updating methods. Previous studies [21-23] revealed that initial stress has a profound impact on structural dynamic behaviour which is crucial to the performance of engineering products.
Table 3: Comparison of the natural frequencies between the EMA, FEA and MAC values of both types of FE models with different element connectors (CWELD and ACM2)

| Modes | EMA (Hz) | CWELD (Hz) | Error % | CWELD MAC (Hz) | Error % | ACM2 MAC (Hz) | Error % |
|-------|----------|------------|---------|----------------|---------|----------------|---------|
| (I)   | (II)     | (III)      | (IV)    | (V)            | (VI)    | (VII)          | (VIII)  |
| 1     | 503.8    | 509.95     | 1.22    | 0.38           | 514.24  | 2.97           | 0.37    |
| 2     | 555.5    | 572        | 2.97    | 0.88           | 592.79  | 6.71           | 0.87    |
| 3     | 572.5    | 586.39     | 2.43    | 0.43           | 594.07  | 3.77           | 0.42    |
| 4     | 634.43   | 640.93     | 1.36    | 0.46           | 664.2   | 5.05           | 0.42    |
| 5     | 643      | 651.03     | 1.25    | 0.88           | 670.37  | 4.26           | 0.88    |
| 6     | 664.9    | 673.93     | 1.36    | 0.71           | 696.91  | 4.81           | 0.66    |
|       | Total error | 10.59      |         |                 | Total error | 26.67          |         |

Figure 4: MAC values of the hat-plate model with CWELD element connectors
5. Conclusions

This study gives an account of a comparative study of modelling and analysing the dynamic characteristics of the laser spot welded hat-plate structure using two different types of element connectors. As mentioned earlier in the introduction, the purpose of this study was to investigate the best candidate of element connectors in representing the dynamic behaviour of the laser spot welded hat-plate structure under initial stress using the finite element method and experimental modal analysis. The results of the investigation show that the FE model with CWELD element connectors has demonstrated the best capability in representing the dynamic behaviour of the laser welded structure under the influence of initial stress. The findings of the study also disclose that the inclusion of initial stress to the FE model has improved the degree of accuracy of the FE model. However, the accuracy of the correlation between the measured and predicted data can be further improved by adopting the modal based updating method.

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