Finite Element Model Updating of Laser Stitch Welded Structure

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Abstract. The applications of laser stitch welding are increasing used in assemblies engineering products such as automotive structures due to its efficiency and re-liability in connecting a light weight material. In order to understand the vibration effect of the laser stitch weld towards the assembled structure, it is important to analyse its dynamic behaviour. However, they are relatively difficult to be analyse numerically as the laser stitch welded joints are found to be complex and have many uncertainties. This paper presents the investigation of finite element model for laser stitch welded structure. The reconciliation method of finite element model updating is used to improve the dynamic behaviour of the initial finite element model as close to experimental data. In this work, the finite element model of the laser stitch welded is developed by employing area contact model (ACM2) connector. Meanwhile, the experiment dynamic behaviour is obtained using an impact hammer and roving accelerometer with free-free boundary conditions. Later, the finite element model updating method is carried out in order to reduce the discrepancies of initial predicted models based on the experiment data. Based on the result, it was found that the ACM2 connector can be used to represent as laser stitch welds accurately by updating the most sensitive selected parameters.

Keywords: Laser Stitch Weld, Dynamic Behaviour, Experiment Modal Analysis, Finite Element Analysis, Model Updating.

1. Introduction

In automotive industries, a typical car body-in-white (BIW) is usually consists of thousands of small parts which are made from thin steel sheets and they are connected together by numerous types of joints. However, in order to fulfil the need of producing a light weight car structure and to improve the quality, the application of laser stitch welding has become more preferable.

The used of laser stitch weld joints that used in car BIW are not only form connections between thin steel sheets but also provide significant contribution to the stability and the rigidity of car [1]. Therefore, an accurate finite element (FE) model must be developed in order to predict dynamic behaviour of structure meanwhile experimental work is required as to determine the level of accuracy of the FE model.

Computerized analysis package such as FE analysis is found to be more beneficial to predict the dynamic behaviour of the structure. However, it is difficult and cumbersome to model the laser stitch...
weld joint itself. It is particularly be-cause of the local effects that occur due to welding process are realized to be complex to be included in the FE model and also influenced by many uncertain parameters such as geometry irregularities, heat affected zone and residual stress [2], [3]. Previous studies reported that there are few types of element connectors that are widely used to represent laser welded joints such as Rigid Body Element (RBE2), Area Contact Model (ACM2) and spot weld element such as CWELD format [4]. There are several works that related to the application of CQUAD4, CHEXA, RBE2, CWELD and ACM2 format for welded joints [5], [6]. Kuppuswamy et al. studied modelling techniques for laser welded joints with the accuracy of model were depended on the like sheet thickness, static and dynamic strength of the joint [7]. Ha et al. proposed a guideline for accurate finite element modelling of laser welded region for the crash analysis of vehicles [8].

In prediction stage, it is found that the initial FE models of structures are not always in good agreement with the measured counterparts. This is due to the in-valid assumptions made through the models. Usually, the invalid assumptions in structural dynamics cases are related to the material properties, joints and boundary conditions [9]. For instance, study showed that the prediction models of welded structure made from thin steel sheets that influential by initial stress can be successfully improve using model updating method [10]. Furthermore, other research study showed that, selecting the right updating parameters were really crucial in order to guarantee the reliability of FE models [11], [12]. Therefore, it is important to improve the initial FE models systematically using model updating approach as close as experiment data.

This paper is concerned with the development of the FE modelling with ACM2 connector is used as laser stitch welded joints. Further, this paper also discussed about the procedure of model updating of the dynamic behaviour of a laser stitch welded structure.

2. Finite Element Modelling of Laser Stitch Welded Structure

Finite element (FE) analysis is a numerical method that involve with discretizing of continuous system into small elements (discrete). There are lot of software packages for modelling structural dynamic models and the choices are highly depends on researcher preference. In this work, the structure is designed as hat-plate structure connected by laser stitch welds (as shown in Figure 1) in order to replicate the substructure of typical car BIW.

![Figure 1. FE model of laser stitch welded structure.](image)

The hat-plate structures were discretizing into a CQUAD4 shell elements with 13090 elements and 13348 nodes. Meanwhile, the modelling of the laser stitch welds in the hat-plate structure was prepared using ACM2 connector since it has capability to represent as laser stitch welds.

The natural frequencies and mode shapes of finite element model of hat-plate structure were predicted using normal mode analysis by solving the Eq. (1).

\[(K - \omega^2 M)\phi\]  

(1)
where, $K$ and $M$ are the stiffness and mass matrices respectively, while $\omega$ and $\phi$ represent natural frequency and eigenvector respectively. In the normal mode analysis, the frequency of interest was set starting from 0 to 700 Hz meanwhile the nominal material values of mild steel were used as follow; Young’s modulus: 210 GPa, Poisson’s ratio: 0.30, density: 7900 kg/mm$^3$.

3. Experimental Modal Analysis of Laser Stitch Welded Structure

Experimental modal analysis is a technique to define the dynamic behaviour of the structure from a vibration testing, in terms of natural frequencies, mode shapes and damping ratios [13]. The result from the experimental data will be compared with finite element (FE) model to identify the correlation between its results. If the results from the test structures are shown a good agreement with predicted model, and then FE model can be used in further analysis with higher degrees of confidence.

In this paper, dynamic behaviour of the test structure was obtained using impact hammer and roving accelerometers under free-free boundary condition as presented in Figure 2. An impact hammer was used to excite the structure with one fixed reference accelerometer as shown in Figure 3 and Figure 4. Furthermore, to replicate the free-free boundary condition, four sets of nylon strings and springs were used to hang the structure from the clamps. Meanwhile The frequency bandwidth of interest of the test structure was 0 Hz to 700 Hz. Finally, LMS SCADAS system was used to interpret the load and signal produced by test structure.

Figure 2. Experimental setup of the laser stitch welded structure.

Figure 3. Impact hammer in experiment.
Model Updating of the Laser Stitch Welded Structure

Model updating is an approach to improve the correlation of finite element (FE) models and the test structure by correcting the invalid assumptions of the model to an acceptable level of accuracy [14]. This is carried out by tuning some uncertain model parameters systematically. However, it is difficult to select the right parameters that sensitive to the change of modal properties. Therefore, selection of the most influential parameters was performed using sensitivity analysis.

In order to perform model updating, the NASTRAN optimization code (SOL 200) is used in which it allows the objective function (J) to be minimized by adjusting the eigenvalues of the initial FE model until the objective function is converged. The objective function can be expressed as

$$ J = \sum_{i=1}^{n} W_i \left( \frac{\lambda_{i}^{\text{FE}}}{\lambda_{i}^{\text{EXP}}} - 1 \right)^2 $$

where, \( \lambda_{i}^{\text{EXP}} \) is the \( i \)-th experimental eigenvalue and \( \lambda_{i}^{\text{FE}} \) is the \( i \)-th predicted eigenvalue from the FE model and \( n \) is the number of eigenvalues involved in the updating procedure. In this process, the selected parameters are systematically updated until the minimum errors between FE and experiment results are achieved. However, it is important to pair the mode shapes of FE and experiment correctly as the equation (2) are only calculated the eigenvalue of FE and experiment from the same modes.

Results and Discussion

In this study, the dynamic behaviour of laser stitch welded structures which are natural frequencies and mode shape were obtained numerically and experimentally. Results obtained were showed in Table 1. The experimental natural frequencies and mode shapes were used for the comparison with the initial FE counterparts. It can be seen that in Table 1, the total error of the first six modes which is 28.59 percent (Column III) and the average MAC value is above 0.68 (Column VI). Furthermore, the comparison also reveals that the largest error is in the 4th and 5th mode with 6.68 and 6.63 percent (Column III). These results suggest that it is obligatory to applied FE model updating method to the initial FE model in order to reduce it discrepancies against experimental result.

In order to identify the sensitivity parameters of the initial FE model, several parameters such as Young’s modulus, Poisson’s ratio, and density of the structure were investigated in sensitivity analysis. It was found that by analysing the global material properties of the structure alone were not enough to improve the initial result because welded structure like laser stitch welded structure were always tending to experience localized error consequences from the welding process. Therefore, it is necessary to include parameters such as material properties of laser stitch welds and heat affected zone (HAZ), and residual stress regions.

Table 1 shows (Column VI) the discrepancies between the experimental and the updated natural frequencies of the laser stitch welded structure. It can be seen that the discrepancies of the first six modes were reduced from 28.59 to 6.35 percent. Meanwhile, Table 2 shows the sensitivity analysis results of
the structure. In this analysis, the parameters such as Young’s modulus hat (Ehat), Young’s modulus plate (Eplate) and residual stress hat (RShat) were allowed to vary in a range of material nominal values. This is because to guarantee the physical meaning of updated parameters. However, due to the high uncertainties level, the parameters such as Young’s modulus laser stitch welds (Eweld), Young’s modulus HAZ on hat (EHAZh) and Young’s modulus HAZ on plate (EHAZp) were allowed to have large variation but in reasonable amount in order to justify the rigidity of the weld [15].

In this work, it was found that, it is important to include the local parameters such as laser stitch welds, HAZ and residual stress in FE model updating of laser stitch welded structure. It is essential to accurately identify the source of error that may affects the dynamic behaviour of the finite element model.

**Table 1.** Comparison between experiment, FE and updated natural frequencies of laser stitch welded structure

| Mode | Experiment I (Hz) | Initial FE II (Hz) | Error III (% | MAC IV | Updated FE V (Hz) | Error VI (% | MAC VII |
|------|------------------|--------------------|--------------|--------|-------------------|--------------|--------|
| 1    | 521.52           | 503.51             | 3.45         | 0.95   | 521.77            | 0.05         | 0.98   |
| 2    | 591.17           | 569.27             | 3.70         | 0.94   | 590.22            | 0.16         | 0.98   |
| 3    | 595.44           | 571.93             | 3.95         | 0.90   | 598.84            | 0.57         | 0.97   |
| 4    | 674.67           | 629.59             | 6.68         | 0.81   | 657.69            | 2.52         | 0.85   |
| 5    | 694.64           | 636.39             | 6.63         | 0.76   | 664.49            | 2.51         | 0.77   |
| 6    | 726.47           | 665.67             | 4.17         | 0.68   | 690.84            | 0.55         | 0.69   |
| **Total Error** | **28.59**         |                    | **6.35**     |        |                   |              |        |

**Table 2.** Updated parameters of the laser stitch welded structure

| No  | Parameters                      | Initial value | Updated value | Percentage Different |
|-----|---------------------------------|---------------|---------------|----------------------|
| 1   | Young’s modulus Hat (Ehat)      | 210 GPa       | 200 GPa       | 4.76 %               |
| 2   | Residual Stress Hat (RShat)     | 1.0           | 1.16          | 16 %                 |
| 3   | Young’s modulus Plate (Eplate)  | 210 GPa       | 220 GPa       | 4.76 %               |
| 4   | Young’s modulus LSW (Eweld)     | 320 GPa       | 335 GPa       | 4.68 %               |
| 5   | Young’s modulus HAZ on Hat (EHAZh) | 270 GPa | 283 GPa | 4.81 %               |
| 6   | Young’s modulus HAZ on Plate (EHAZp) | 270 GPa | 268 GPa | 0.74 %               |

6. Conclusions

This work was conducted to investigate the dynamic behaviour of the laser stitch welded structure numerically by using ACM2 element connector as laser stitch weld connectors. The comparison of results reveals that ACM2 element connector can be used to represent as laser stitch welds. However, in order to improve the initial model, it is essential to apply the FE model updating method in light of the experimental results. The approach indicates that the right selection of updating parameters is important in reducing the errors in the finite element models. In addition, the inclusion of local parameters such as laser stitch welds, HAZ and residual stress as updating parameters has led to improvement towards the FE model.

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