Identification of Damaged Spot Welds in a Complicated Joined Structure

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Abstract. In automotive engineering, spot welds on assembled structures such as Body in White (BiW) have a significant effect on the vehicles’ dynamic characteristics. Understandably, imperfections in the spot welds will cause variations in the dynamic properties such as natural frequencies and mode shapes of the structure. In this paper, a complicated welded structure which is a simplified Natural Gas Vehicle (NGV) platform is investigated. The structure fabricated from thin metal sheets consists of ten components. They are jointed together by a number of scattered spot welds. NASTRAN Solution 200 based on sensitivity analysis is used to identify the most sensitive parameters to natural frequencies. The numerical model of the undamaged structure is initially updated in order to minimise the discrepancies between the measured and numerical data using NASTRAN optimisation code. The initial updated model serves as a benchmark for the subsequent structural damage identification. The numerical data of the benchmark model is then compared with the measured data obtained from the damaged structure. The same updating procedure is applied to the benchmark model in order to bring the numerical data as close as possible to the measured data of the damaged structure. The disparity in certain parameter values from the parameter values used in the benchmark model shows a fault or damage in the location of a particular joint, depending on the severity of this disparity. The challenge in this work is to localise damaged area and quantify the damage of the complicated structure with multiple spot welds in the presence of uncertainty in the location and material properties of the welds.

1. Introduction

The automotive industry is fast changing, and vehicles are being made using new technologies to further improve the dynamic performance in terms of noise, vibration and harshness (NVH), at the same time in enhancing the style and functions of vehicles. Complex automotive structures such as Body in White (BiW) are made from a combination of thin metal sheets in different sizes and are joined by thousands of spot welds. The integrity and dynamic characteristic of the structure highly depend on these joints [1]. The defective and even absent spot welds produced during assembly and under extreme operational
conditions could degrade integrity of the structure and alter the dynamic characteristics of the vehicles [2]. Early detection of the presence of damage is very important so that necessary action can be taken to prevent further problems in the structures. There are a wide range of damage identification methods that have been widely used to detect damage on structures [3 - 5]. Visual examination has been commonly used because it is simple to perform for obvious structural damage. However, it is unreliable when the structure becomes complicated given the limited capability of conventional visual inspection. The vibration-based damage identification method has been used in oil industry from early 1970s [6]. Since the development of modern sensing techniques, data acquisition systems and advancement of computing power it can easily be adopted to deal with large and complex structures such as bridges, rail and highways [7- 9]. The purpose of the damage identification is to provide information on the existence, location, and magnitude of damage in structures [10]. Experimental modal analysis (EMA) coupled with finite element analysis (FEA) is used to model and to detect damage in structures [11- 13]. Nominal parameter values are used in the initial FE model. Some of these parameters are chosen in updating the initial FE model. Finite element model updating method has been successfully used to identify structural damage in various applications [14]. The updating parameters updating are carefully selected so that they are the most sensitive parameters. In this paper, damage identification is based on values of measured frequencies, though modes are also examined. The process of model updating is divided into two steps; firstly the FE model of a complicated structure joined by a number of spot welds is developed and updated based on the experimental data obtained from the undamaged structure in order to establish a benchmark FE model. In the second step, the benchmark FE model is updated to the modal test data of the damaged structure in order to identify the damage.

2. Description of Structure

The benchmark structure is developed based on a simplified model of gas compartment that is commonly used in Natural Gas Vehicles (NGV). The completed structure of the NGV compartment consists of ten components and they are fabricated by cold roll thin sheet metal with thickness of 1.2 mm to form a structure with the dimension of 734mm long and 410mm wide as shown in Figure 1.

![Figure 1. Simplified NGV compartment](image1.png)

![Figure 2. Location of Spot welds.](image2.png)

Modal testing was carried out on each of individual components and then they were firstly updated individually to reduce the error between the numerical models and physical components before they were assembled together by a number of resistance spot welds. Then damage was introduced (that could
happen on the structure during production or service) by removing three spot welds on the support plate as shown in Figure 2.

3. Experimental Modal Analysis

The experimental modal analysis (EMA) was performed on the benchmark and damaged structures. The changes in the natural frequencies obtained from the test are an indication of the presence of damaged. The dynamic measurement of the complete assembled structure was obtained under the fixed boundary condition as shown in Figure 3 and an impact hammer was used to excite the structure. As the structure was complex and fabricated by thin metal sheets which have a high tendency to flip when it is excited by an impact hammer, roving accelerometers method is used in the test. The locations of the excitation point and the measurement point were determined based on the mode shapes calculated from the finite-element results and they are distributed over the whole structure in order to minimise the mass loading issue to the structure and to avoid nodes. The frequency range of interest is from 0 to 160 Hz and five accelerometers (Kistler 8728A) were used to measure the dynamic response of 88 degrees of freedom of the structure that cover 140 degrees of freedom through a master-slave relationship. One of the accelerometers was fixed at the excitation point while other accelerometers were roved around to each point shown in Figure 3 and the response for each run was extracted using LMS PolyMAX curve fitting procedure.

![Figure 3. Experimental set-up of the complete structure](image)

4. Experimental Results

The identification on the structure was carried out by comparing the difference in the natural frequencies and visual inspection of the mode shapes obtained from EMA of undamaged and damaged structures. The measured natural frequencies of undamaged and damaged structures are shown in Table 1 and one mode of the undamaged structure and its counterpart of the damaged structure are given in Figure 4.
Even though natural frequencies can be measured more accurately than mode shapes [15, 16] natural frequencies alone may not be able to distinguish the presence of damage in a structure [17]. Therefore, it is advisable to examine mode shapes. However, modes themselves were not used in the updating in this work. The experimental results of the undamaged and damaged structures will be discussed in the next sections.

**Table 1.** Experimental natural frequencies of the undamaged and damaged structures.

| Mode | Undamaged [Hz] | Damaged [Hz] | Error [%] |
|------|----------------|--------------|-----------|
| 1    | 26.40          | 24.66        | 6.59      |
| 2    | 28.44          | 26.94        | 5.28      |
| 3    | 34.70          | 34.21        | 1.44      |
| 4    | 43.50          | 41.86        | 3.52      |
| 5    | 45.04          | 42.80        | 4.97      |

**Figure 4.** Comparison of EMA mode shapes between undamaged and damaged structures

5. **FE Model**

Since the structure used in this study was complicated, modelling the structure was challenging. The FE model was developed from computer aided drawings to produce the FE model of the structure which consisted of ten components assembled together by seventy two spot welds. The following nominal
parameter values were used: thickness of 1.2 mm, Young’s modulus, $E_w = 210$ GPa, Poisson’s ratio, $v = 0.3$, density of components, $\rho = 7850$ kgm$^{-3}$.

![Image of assemble structure](image1)

**Figure 5.** FE model of assemble structure

[![Image of spot welds](image2)](image2)

**Figure 6.** Location of Spot welds.

The structure was represented by 37,000 shell elements (CQUAD4) available in NASTRAN [18] to model the benchmark and damaged structures as shown in Figure 5. In addition, 72 CWELD elements are used to model seventy two spot welds as shown in Figure 6. The numerical and experimental data are given in Table 2.

**Table 2.** Experimental natural frequencies of the benchmark structure and the FE frequencies

| Mode | Experiment [Hz] | FE Model [Hz] | Error [%] |
|------|-----------------|---------------|-----------|
| 1    | 26.40           | 25.60         | 3.03      |
| 2    | 28.44           | 28.39         | 0.17      |
| 3    | 34.70           | 33.97         | 2.10      |
| 4    | 43.50           | 43.33         | 0.38      |
| 5    | 45.04           | 45.03         | 0.02      |

6. Model Updating of Benchmark Model

Model updating can be defined as a systematic way of adjusting the parameters of the theoretical model of the physical structure to bring the theoretical results of the model as close as possible to the experimental results. In this work the parameters related to the spot welds are updated by assuming the error is mainly contributed from the modelling of the spot weld joints. Only the first five frequencies were selected for updating and the number of updating parameters must be kept to a minimum in order to avoid the ill-condition problem during updating process [19]. Prior to the model updating process, sensitivity analysis was carried out to ensure only the most sensitive parameters are chosen [19, 20].

The eigenvalue problem of a structure can be expressed as
\[ [K] \{\phi\}_i = \lambda_i [M] \{\phi\}_i, \quad (1) \]

where \( \{\phi\}_i \) are the \( i \)th mode and \( \lambda_i \) is the corresponding eigenvalue; \([M]\) and \([K]\) are the mass and stiffness matrices respectively.

By differentiating each term with respect to the design parameter, \( P \), the sensitivity is

\[ \frac{\partial \lambda_i}{\partial P} = \{\phi\}_i^T (\frac{\partial [K]}{\partial P} - \lambda_i \frac{\partial [M]}{\partial P}) \{\phi\}_i \quad (2) \]

From the sensitivity analysis four parameters were selected in the updating process, namely, Young’s modulus of the spot weld and the patch (E), and shear modulus of the spot weld and patch (G). Firstly model updating was performed on the benchmark FE model in order to reduce the errors between the frequencies of the physical structure and the numerical model. The updated results are shown in Table 3 and the changes in material properties between the initial and updated benchmark models are shown in Figure 7. The results in Table 4 show that some errors were reduced while other actually increased. This indicates the difficulties in updating this complicated structure.

**Table 3.** Changes in parameters due to updating (FE benchmark)

| Parameters                        | Initial value | Updated value | Change [%] |
|-----------------------------------|---------------|---------------|------------|
| Weld Young’s Modulus, \( E_w \) [GPa] | 210           | 220           | 5.00       |
| Weld Shear Modulus, \( G_w \) [GPa]  | 80.8          | 82.4          | 2.00       |
| Patch Young’s Modulus, \( E_p \) [GPa] | 210           | 441           | 110.00     |
| Patch Shear Modulus, \( G_p \) [GPa]  | 80.8          | 170           | 110.00     |

**Table 4.** Comparison between experimental and updated FE results of the benchmark structure

| Mode | Experiment [Hz] | Updated FE [Hz] | Error [%] |
|------|-----------------|-----------------|-----------|
| 1    | 26.40           | 25.71           | 2.61      |
| 2    | 28.44           | 28.45           | 0.04      |
| 3    | 34.70           | 33.98           | 2.07      |
| 4    | 43.50           | 43.75           | 0.58      |
| 5    | 45.04           | 45.24           | 0.44      |
7. FE model updating for damage detection and results

Initially the spot welds were classified into four groups namely group A, B, C and D. Each group consisted of four spot welds for identification in the next updating process for damage detection purposes. Based on the mode shapes of the undamaged and damaged structure on Figure 4, it was realised that Group B was a suspect and the same values of material properties previously obtained from the benchmark model were used as initial values for the damaged region in the updating process. The benchmark model then was updated to the natural frequencies of the damaged structure and the results are given in Table 5. The Young’s modulus of the patch and spot welds and shear modulus of the patch and spot welds as updating parameters were allowed to vary from 1% to 100% due to potentially big reduction in the material properties of damaged spot welds [21]. The changes in the material properties between the (updated) benchmark model and the updated model of the damaged structure are shown in Table 6 and Figure 8.

Table 5. Comparison between experimental and updated FE results of the damaged structure

| Mode | Experiment [Hz] | Updated FE [Hz] | Error [%] |
|------|----------------|----------------|----------|
| 1    | 24.66          | 25.22          | 2.28     |
| 2    | 26.94          | 27.74          | 2.97     |
| 3    | 34.21          | 33.74          | 1.37     |
| 4    | 41.86          | 41.26          | 1.44     |
| 5    | 42.80          | 42.76          | 0.09     |

Table 6. Changes in parameters due to updating (damaged structure)

| Parameters                  | Initial value | Updated value | Change [%] |
|-----------------------------|---------------|---------------|------------|
| Weld Young’s Modulus, $E_w$ [GPa] | 220           | 10            | (-95.45)   |
| Weld Shear Modulus, $G_w$ [GPa]    | 82.4          | 4             | (-95.15)   |
| Patch Young’s Modulus, $E_p$ [GPa] | 441           | 8             | (-98.19)   |
| Patch Shear Modulus, $G_p$ [GPa]  | 170           | 4.25          | (-97.50)   |
**Figure 7.** Changes of parameters between initial and updated of FE benchmark model

**Figure 8.** Changes of parameters between benchmark and updated of FE damaged model
8. Conclusions

The first five frequencies of a complicated structure of Natural Gas Vehicle platform were investigated experimentally and numerically. In the preparation for the FE benchmark model, the results of the initial FE model obtained from NASTRAN SOL 103 were firstly compared with the experimental data. The errors in the initial FE model were reduced by means of model updating based on NASTRAN SOL 200.

The five natural frequencies dropped when damage was introduced into the test model. The FE benchmark model was used to identify the damage on the test model by updating it against the experimental frequencies of the damaged structure. Mode shapes were examined to locate the potential damaged region of the structure, but otherwise not used in the updating process.

The identification of damage via the FE benchmark model could be improved by including mode shapes in the objective function. This is not considered in this study.

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