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FE Model Updating for Damage Detection – Application to a Welded Structure

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Abstract. Finite Element (FE) model updating is initially developed to update numerical models of structures to match their experimentally measured modal properties (i.e., natural frequencies and modes). In FE model updating, uncertain physical parameters of a structure are modified so that the discrepancies between the numerically estimated and experimentally measured modal properties are minimized. The process of updating is employed not only in parameter identification; it can also be developed for structural damage identification.

In this work, a welded structure that is intended to represent a common configuration used in automotive body construction is investigated. It is known that presence of any damage in the welds of such a structure could affect its dynamic behavior. So, in theory modal test data can allow damage to be assessed accurately. As a typical automotive body contains thousands of welds, the effects of damage in the welds could be influential.

The FE model updating process using experimental data is presented. It is carried out using NASTRAN optimization code. The procedure aims to adjust the uncertain properties of the FE model (from the weld joints) by minimizing the differences between the measured modal properties and the corresponding numerical predictions. The initial parameter values used in the numerical model are the nominal values. The procedure brings the numerical results of the structure as close as possible to the experimental ones, according to an objective function, therefore altering some of the FE model parameters of the structure. It may be concluded that when the identified values of certain parameters deviates from the nominal values to certain extent, there is a fault or damage at that particular joint.

Introduction

Damage identification of structures and mechanical systems has been developed in the last few decades, mainly for health monitoring purposes [1]. Early detection of damage will enable necessary actions to be taken, which in turn will avoid further problems. Visual inspection has been the most commonly used method in observing structural damage. However, as structures become more complicated, the efficiency of the conventional visual inspection is reduced.

Extensive research activity in damage identification has been driven by public demands and technological advancements (e.g., computing power, sensor technology). Consequently, various methods have been developed to detect damage at early stages [1-7]. One of the most frequently used methods is finite element model updating [8-18], which has been applied successfully in many fields. In FE model updating, the values of updating parameters are modified so that the difference between the numerical and experimental modal properties is minimized. However, performing the task with ease and consistency is proven challenging [7, 10, 17]. One of the difficulties is the non-uniqueness of the updating solution [7, 17].

Existence of structural damage leads to alteration of vibration modes. This is due to the fact that modal properties (frequencies and mode shapes) are dependent on the physical properties of a structure. Because of this, the location and severity of damage can be predicted by monitoring the structural modal properties before and after the damage. Therefore, an adequate FE model that can reveal changes in the modal properties of a structure should be used.

This paper describes the FE model updating technique applied to damage detection of a spot-welded structure. In this work, the procedure of updating for damage identification is carried out in two stages. Firstly, an FE model of a benchmark structure is developed and updated (stage 1) to its experimental data. Identified parameters from the updating procedure are used in modeling the ‘damaged’ structure. The ‘damaged’ FE model is then updated (stage 2) to its experimental counterpart to reproduce the measured modal properties of the ‘damaged’ structure. In this work, damage identification is carried out on the basis of modal frequencies only. Moreover, only deviations in size and material properties of the welds and surrounding areas are investigated.

The experimental setup and results are explained in the following section. Then, the FE models of the benchmark and ‘damaged’ structures are described and a brief explanation of the FE model updating method is included.

Experimental Model

Description of Structure. Two cases are considered in this work: 1) the benchmark structure, and 2) the ‘damaged’ structure. Each structure, as illustrated in Fig. 1, is 564 mm long and 110 mm wide, and welded along the flanges by means of 20 spot welds that are produced by Laser Welding. A general procedure as outlined by Mottershead et al. [19] is followed to minimize the manufacturing variability from the structures.

For the benchmark structure, a good-quality hat-plate is produced and tested. The modal data (i.e., natural frequencies) determined from the test is used as point of reference for damage evaluation. A structure with biggest variations from the benchmark is identified and classified as problematic, therefore is scrutinized in damage assessment.

After visual inspections on the ‘damaged’ structure, the spot welds are grouped into three groups (Table 1): 1) ‘normal’ welds, 2) ‘oversized’ welds, and 3) ‘undersized’ welds. The ‘oversized’ and ‘undersized’ welds are considered as anomalies. These discrepancies in size are incorporated in the FE model of the ‘damaged’ structure, as described in the following sections.

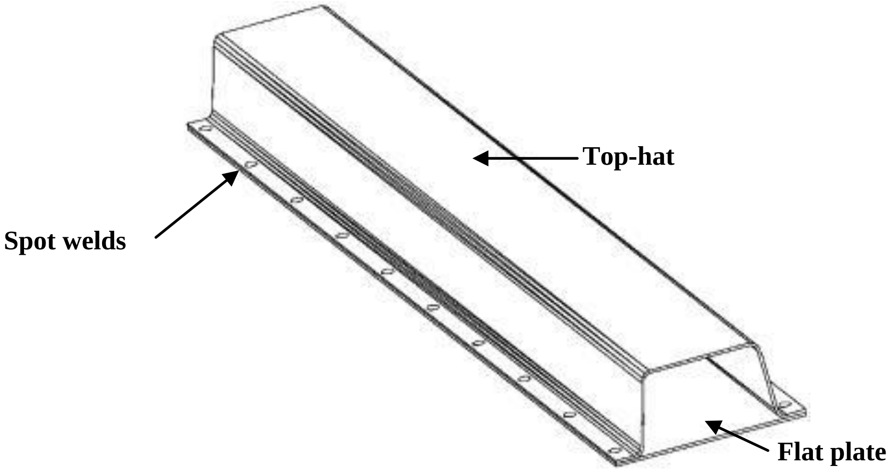

Fig. 1. The hat-plate structure

Table 1: List of normal and problematic spot welds

Group	Number of welds	Spot weld ID* (see Fig. 2)
Oversized	8	1, 11-14, 17-19
Normal	7	2-4, 10, 15-16, 20
Undersized	5	5-9

Modal testing procedure. Modal tests were performed on both structures. The structures were hung by springs and strings to achieve a free-free boundary condition and were tested in the frequency range of 500 to 1000 Hz. An impact hammer was used to excite the structures at two different points and the response was measured by seven accelerometers, as depicted in Fig. 3. Five accelerometers were positioned on the top-hats, and one each on the flat plates and the side of the top-hats.

Experimental results. The experimental results of the benchmark and 'damaged' structures are presented in Table 2. Both sets of results are compared to see the significance of damage in terms of the natural frequencies. The deviations of the frequencies from the benchmark data are very small, especially for modes 2, 4 and 5. This is because frequencies alone often may not be sensitive enough to significantly distinguish damage in a structure [1]. Therefore, it is advisable to include more structural information, such as mode shapes, in damage detection, which is not studied in this work.

The experimental results are also used to validate the FE models of both benchmark and 'damaged' structures, which is presented in the next sections.

Numerical model

Initial FE models. The FE models of the benchmark and 'damaged' structures (shown in Fig. 2) are composed of approximately 8500 shell elements (CQUAD4) and the welds are modeled using 20 connector elements (CWELD), both available in NASTRAN [20]. The problem could also be modeled in a more detailed approach, such as using solid elements and a finer mesh, but that will result in highly expensive computational effort. The FE models do not incorporate the accelerometers used in the experiments as they are considerably lighter (approximately two grams each) than the structure under investigation.

For the flat plates and the top-hats, nominal values are used for the thickness (1.5 mm) and the material properties ($E_w = 210$ GPa, $\nu = 0.3$ and $\rho = 7860$ kgm^{-3}). For the spot welds, the initial value of the diameter is 5 mm and the values for the material properties are the same as the bulk material. The patch area surrounding each weld is made rigid by giving it a Young's modulus that is one order higher (i.e., $E_p =$ 2100 GPa) than the bulk material. The numerical and experimental results are compared in Table 3.

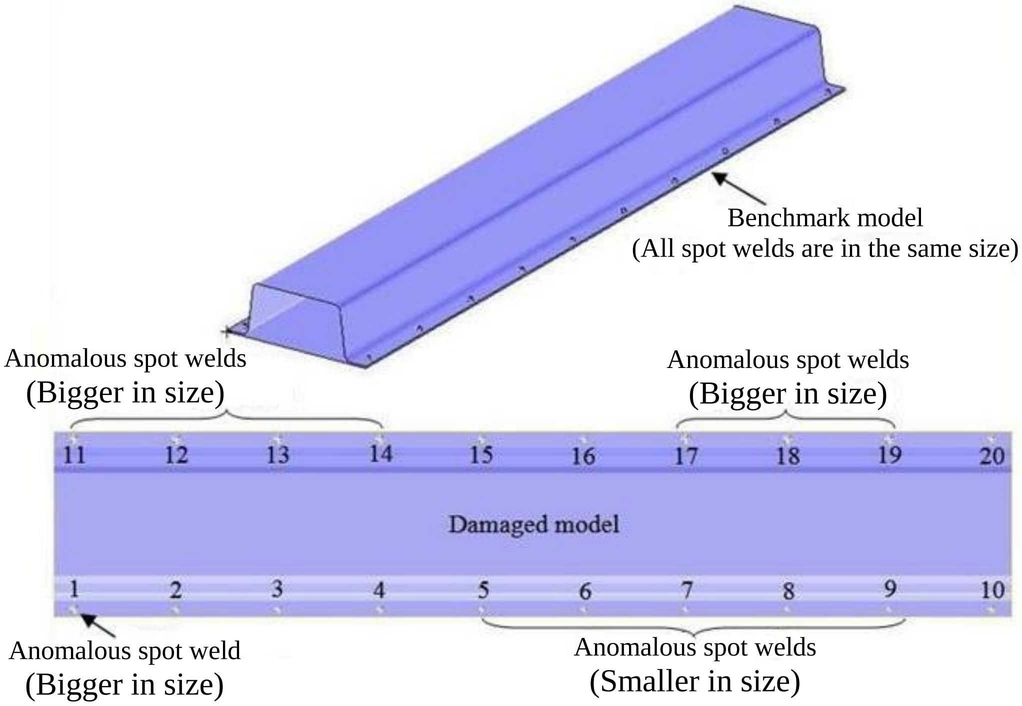

Fig. 2. FE models of benchmark and 'damaged' hat-plates

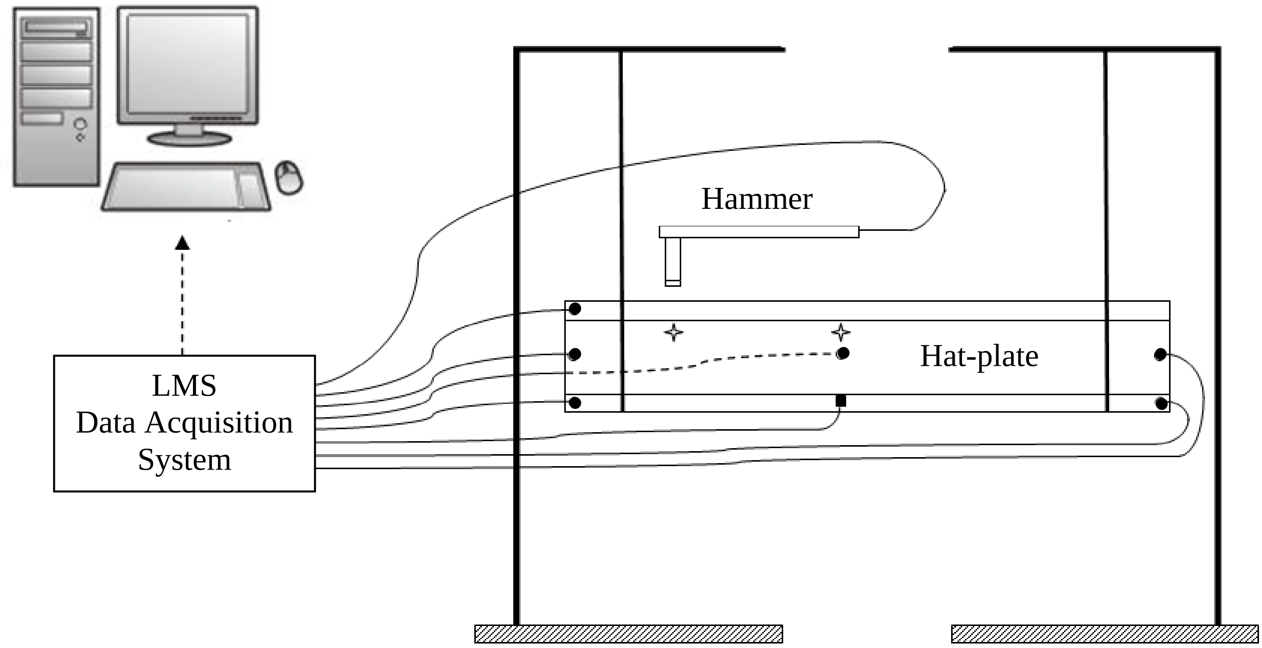

Fig. 3. Experimental set-up for the hat-plates (benchmark and ‘damaged’)

Table 2: Experimental natural frequencies for the benchmark and damaged hat-plates

Mode	Benchmark [Hz]	Damaged [Hz]	Error [%]
1	513.95	507.04	1.34
2	550.46	550.40	0.01
3	578.69	572.83	1.01
4	624.86	625.47	0.10
5	639.07	643.49	0.69

Model updating of the benchmark model

Model updating procedure. Generally, the aim of model updating procedure is to minimize the discrepancy between the experimental and the analytical modal data. In this work, only the first five frequencies are chosen for updating. This is mainly because the higher modes cannot be measured as accurately.

Parameters selection. The number of updating parameters should be kept to the minimum to avoid ill-conditioning problem in updating procedure. Therefore, sensitivity analysis is carried out prior to selecting the updating parameters to ensure that only sensitive parameters are chosen for model updating. From the sensitivity study, two updating parameters are chosen: 1) weld diameter (d), and 2) Young’s modulus of the welds (E_w). From past experience [21], the two parameters alone could not bring the numerical results near to their experimental counterparts. Therefore, the Young’s modulus of the patch (E_p) is also included for updating, as shown in Table 4.

Identification of benchmark welds. Model updating procedure is carried out on the benchmark FE model to identify the diameter and material properties of the welds and the surrounding patch area. The updated results are tabulated in Table 3 and the errors between the initial and updated benchmark models are shown in Fig. 4. From the figure, it can be seen that the error for mode 1 in the updated model is bigger than the error from the initial model, while the errors for the rest of the modes are significantly reduced. The updating procedure is concluded as successful; therefore the updated parameters for the benchmark (as in Table 4) are used further in modeling the ‘damaged’ FE model.

Table 3: Comparison of experimental and initial FE results of the benchmark structure

Mode	Experimental [Hz]	Initial FE [Hz]	Error [%]	Updated FE [Hz]	Error [%]
1	513.95	509.79	0.81	503.62	2.01
2	550.46	581.56	5.65	558.24	1.41
3	578.69	584.91	1.08	575.82	0.50
4	624.86	653.84	4.64	626.56	0.27
5	639.07	657.43	2.87	632.69	1.00

Table 4: Changes in parameters due to updating - benchmark

Parameter	Initial value	Updated value	Change [%]
Weld diameter, *d* [mm]	5	4.57	8.52
Weld Young's modulus, E_w [GPa]	210	206	2.10
Patch Young's modulus, E_p [GPa]	2100	1849	11.95

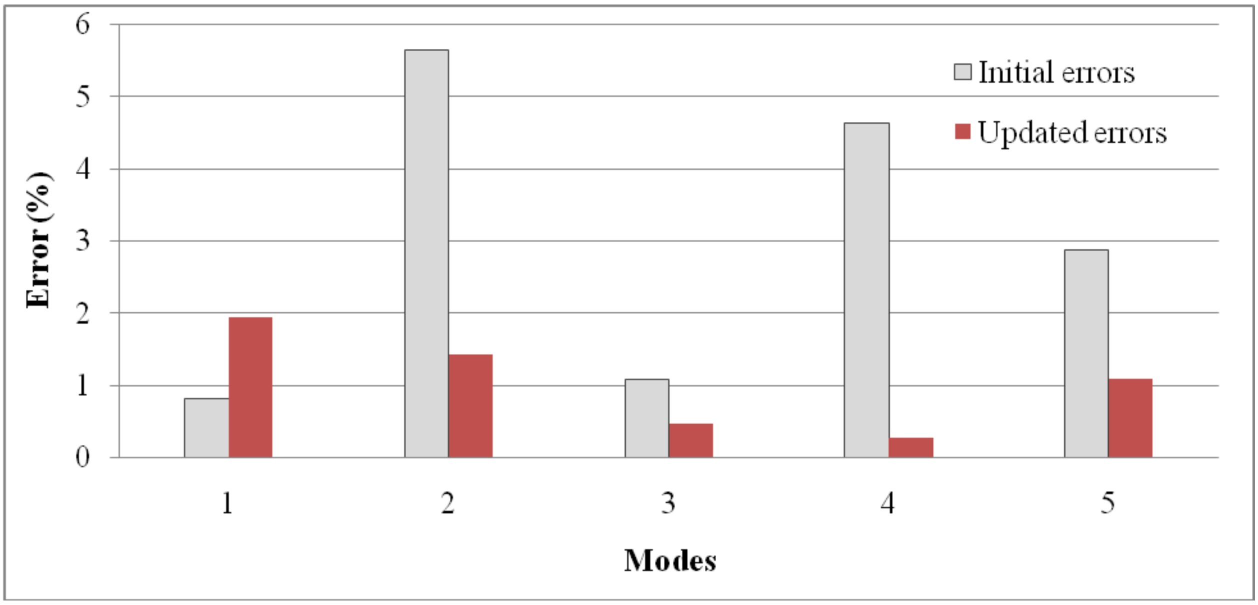

Fig. 4. Comparison between initial and updated frequency errors of benchmark model to experimental data

FE model updating for damage detection

Damage detection procedure. As explained in the earlier section, the spot welds are grouped into three groups for damage detection purposes. The 'normal' spot welds are represented using the identified parameters ($d = 4.57$ mm, $E_w = 206$ GPa) from the first stage of updating. The same value of Young's modulus is also used as the initial value for the 'damaged' welds. The initial 'damaged' model is analyzed and the natural frequencies are determined and then compared with the corresponding experimental results, as tabulated in Table 5.

From the table, the errors for the initial model are already quite small. This is due to the success in predicting the updating parameters for the benchmark model, which are then employed in the 'damaged' model. However, the 'damaged' model is still being updated to their corresponding experimental data in order to estimate the parameter values for the 'damaged' welds.

Parameters selection. The diameters and the Young's moduli of the two 'damaged' spot weld groups are chosen for updating, as given in Table 6. Parameter d_b is allowed to change from 90% to 130% of the initial value, while parameter d_s is permitted to vary from 50% to 110% of its initial value. The changes are set to those limits to allow for physical justifications to be made. However, both Young’s moduli parameters, E_b and E_s, are varied from 1% to 200% of their initial values. These parameters are allowed to have the big variations because of major uncertainties in the ‘damaged’ welds material properties.

Identification of ‘damaged’ welds. The updated results for damage detection are tabulated in Table 5. The frequency errors for the initial and updated models to the experimental data are given in Fig. 5, while Fig. 6 shows the convergence of the updating parameters. By updating the initial FE model to the experimental data, the overall error improves by approximately 10% from the initial errors. From Fig. 5, it can be seen that the updating procedure improves the results for modes 2, 3 and 4. However, the result for mode 5 is slightly depreciated, while mode 1 remains about the same.

The diameter of the ‘oversized’ welds (d_b) is increased by 30% from the initial value and its Young’s modulus (E_b) is 15% higher than the ‘normal’ welds. On the other hand, the updated values for the ‘undersized’ welds parameters (i.e., d_s and E_b) are reduced from their initial values by approximately 25% and 7%, respectively. If the updated values are believed to reflect the reality, both sets of welds may be classified as anomalies and hence support the findings from earlier visual inspections made to detect physical inconsistencies in the welds.

Table 5: Comparison of experimental and FE results of the ‘damaged’ structure

Mode	Experimental [Hz]	Initial FE [Hz]	Error [%]	Updated FE [Hz]	Error [%]
1	507.04	503.79	0.64	503.56	0.69
2	550.40	558.60	1.49	555.85	0.99
3	572.83	576.01	0.56	575.04	0.39
4	625.47	627.25	0.29	624.13	0.21
5	643.49	633.28	1.59	631.89	1.80

Table 6: Changes in parameters due to updating - ‘damaged’

Parameter	Initial value	Updated value	Change [%]
‘Oversized’ weld diameter, d_b [mm]	5.0	6.5	30.00
‘Oversized’ weld Young’s modulus, E_b [GPa]	206	238	15.41
‘Undersized’ weld diameter, d_s [mm]	4.5	3.4	24.82
‘Undersized’ weld Young’s modulus, E_s [GPa]	206	191	7.11

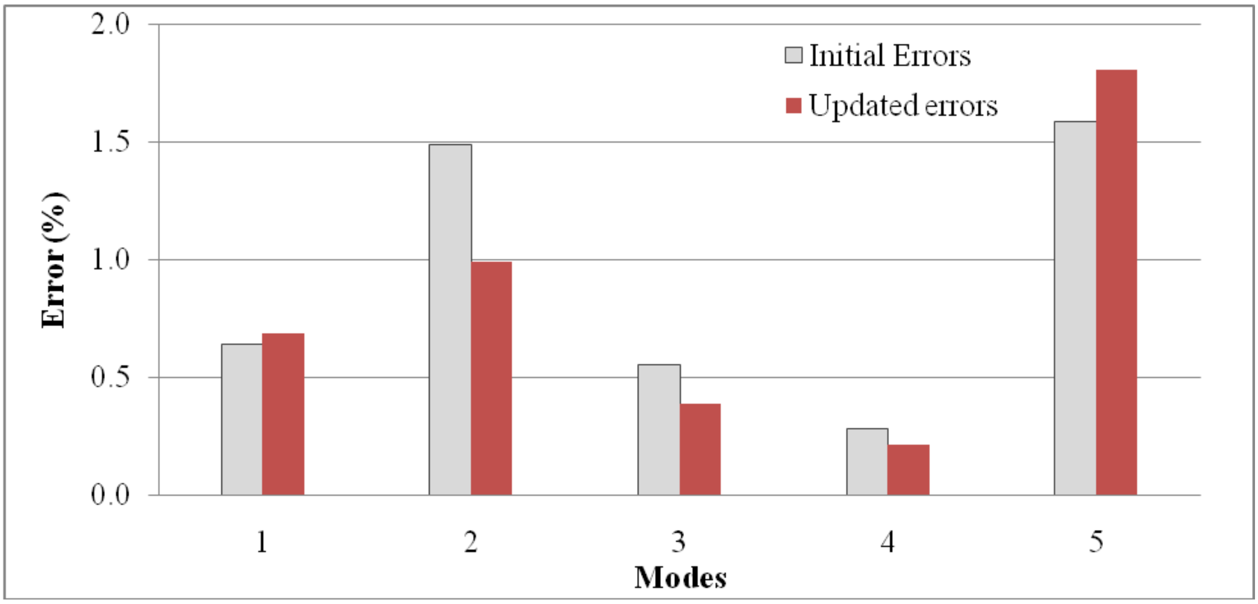

Fig. 5. Comparison between initial and updated frequency errors for ‘damaged’ model

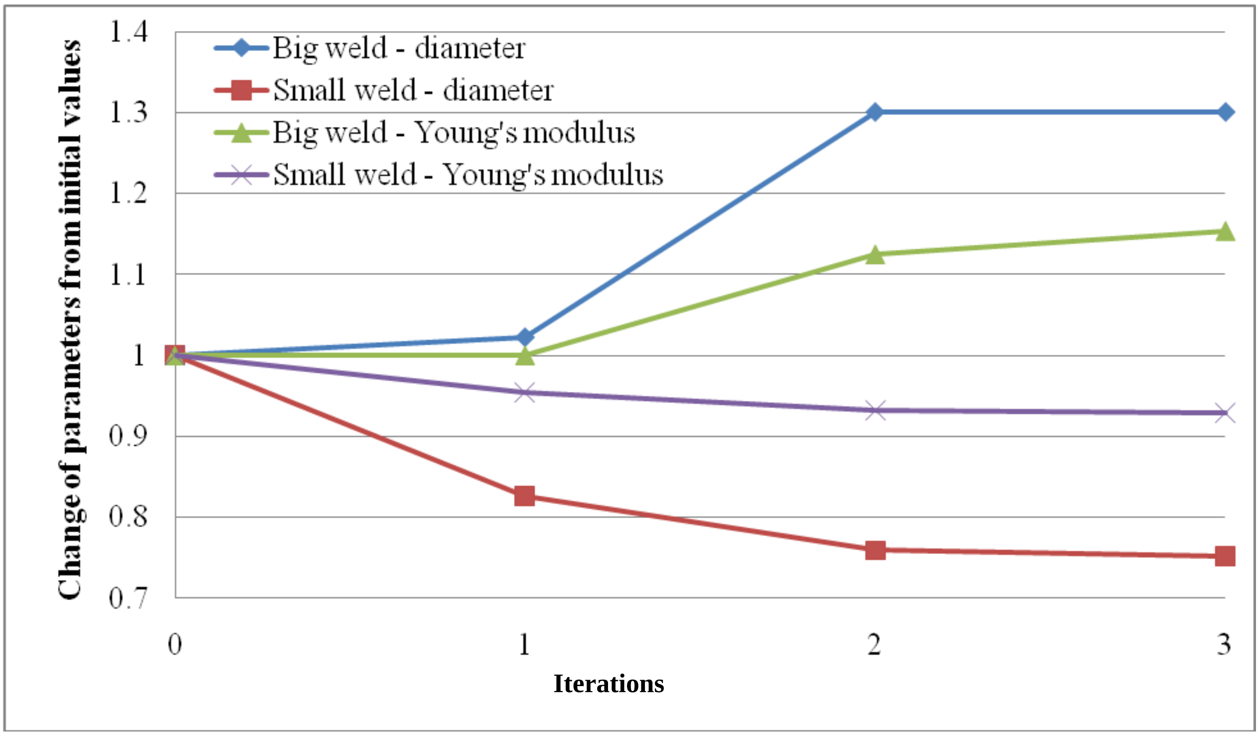

Fig. 6. Convergence of updating parameters

Summary

FE model updating procedure for damage detection based on the correlation of experimental modal data (i.e., natural frequencies) to data from FE is presented. The updating procedure is regarded as parameter identification, which aims to improve the numerical prediction to be as closely as possible to the measured counterpart. The method is applied to a structure that is welded by 20 laser spot welds.

Four parameters are chosen for updating the initial model of the ‘damaged’ structure based on the first five measured natural frequencies. The locations of ‘damaged’ spot welds are determined from visual inspections and the defect is incorporated into the ‘damaged’ FE model. Model updating procedure is carried out as a structural optimization problem using SOL 200 in NASTRAN for predicting the extent of the damage.

The initial FE model for the ‘damaged’ specimen shows excellent correlation with the experimental findings. This is because most of the uncertainties (especially for the patch properties) are successfully identified when updating the benchmark model. Furthermore, the natural frequencies for the updated ‘damaged’ model are found to correspond very well with the experimental data. In addition, the updated ‘damaged’ parameters are found to be reasonable and in agreement with the findings from the visual inspections.

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Damage Assessment of Structures VIII

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