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Towards a robust optimization of spot weld design in automotive structures

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Abstract

The design of a resistance spot weld distribution for an automobile body-in-white has a strong impact not only on the global system performance but also on the robustness of this performance with respect to uncertainties due to assembly defects and fatigue failures. A quantitative methodology is presented that provides decision-making indicators that allow the analyst to insure a given level of system performance at the cost of performing a quality control of a limited number of welds coming off the assembly line as well as reinforcing a set of critical welds in order to improve the robustness to fatigue failure. In contrast with existing sample-based robustness analyses, the proposed methodology gives visibility to the compromise between improved robustness and higher assembly and quality control costs. In other words, this methodology provides a tool to guide the analyst in the next step to improving robustness while giving an estimation to the cost of the predicted improvement. All examples are presented on a full BIW structure (1,000,000 dofs and 6,500 spot welds).

1 Introduction

In the automotive industry, resistance spot welds (RSW) are widely used to join components. Understanding their mechanical behavior is difficult due to the manufacturing process, which includes many thermal effects that modify the local nature of materials. The models that describe the behavior of RSW can indeed be very complicated. For structural dynamic analyses, relatively simple models are generally used in the automobile industry since it is the global effect of spot welds on mode shapes and eigenfrequencies, which is of interest and not their local behavior. A review of commonly used models is given in reference [1]. Two aspects are then of first importance. The first one deals with the design of the structure: how to design the structure and its RSW (number and location on each interface) in order to attain a given objective? The initial distribution of spot welds on the structure is generally defined by engineers based on engineering know-how, before performing intensive calculations in the several critical domains (static, crash and dynamic behaviors) in order to obtain a reference configuration. This design is not optimized, but it generally verifies all the required design criteria. An optimization procedure is then performed to obtain another configuration, which ideally leads to a significant reduction in the number of RSW while verifying all the constraints. The main difficulty of this optimization process is undoubtedly the very large dimension of the design space.

A number of RSW studies have been reported in previous work, for example, [2] is a very complete description of the influence of spot weld failure on structural dynamics, and [3] represents a first step of the work presented here. Of course, the challenge in this case is to attain the design objectives with as few RSW as possible. The second aspect is related to the differences between the original design of the structure and its

current state. The manufacturing process is one of the main causes of these differences, since at the end of the assembly line, some RSW are found to be defective due to robotic or process problems and the large number of RSW makes it impossible to verify each of them individually. Moreover, the structure also evolves as a result of fatigue and some RSW may simple break over time. The objective of this paper is to develop decision-making indicators to help the analyst to plan robust RSW designs along with quality controls in order to insure a specified level of structural performance.

2 Optimization of RSW distribution

2.1 Description of the structure

The examples illustrated in this article are based on the Peugeot-Citroen C4 body-in-white (BIW) finite element model. This MSC/NASTRAN model has approximately 1,000,000 dofs, and 5,000 RSW which are modeled with CBUSH elements. A modal analysis up to 75 Hz takes about 20 minutes on a Linux-based computer, Bi-Xeon 2.5 GHz.

The first flexible mode of the BIW is shown in figure 1, and all examples in this paper will deal with this particular mode as well as the following 2 global elastic modes. Hence, two torsion modes and one bending mode are taken into consideration.

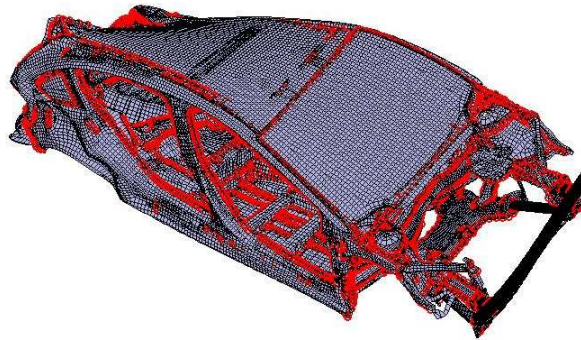


Figure 1: First elastic mode of the BIW

2.2 Optimization Methodology

2.2.1 Generalities

The optimization procedure implemented in this paper is based on a method which is fully described in reference [3], and can be summarized in the following steps:

1. An initial design of the structure is developed based on knowledge rules with a largely over-populated distribution of RSW. We assume that this reinforced design satisfies required constraints, for example, static, crash and dynamic behaviors.
2. An iterative calculation is performed in order to remove as many RSW as possible based on energy considerations as well as some specific heuristic rules to avoid technical problems [3].
3. The final configuration represents a sub-optimal design solution. A post-processing analysis can be performed in order to compare the results with earlier designs and to detect the interfaces which have been either reinforced, weakened or left unchanged.

The energy criterion which has been used in this optimization is related to the local strain energy of each RSW:

$$E_i^\nu = \frac{y_\nu^T K_i^e y_\nu}{\lambda_\nu} + \frac{y_\nu^T K_i^{sh} y_\nu}{\lambda_\nu} \frac{V_{tot}^{sh}}{V_i^{sh}} \quad (1)$$

In this equation:

- K_i^e is the element stiffness matrix of RSW number i
- y_ν is the modal shape of mode ν
- λ_ν is the squared eigenvalue
- K_i^{sh} is the stiffness matrix of surrounding shells of RSW number i
- V_i^{sh} is the volume of surrounding shells of RSW number i
- V_{tot}^{sh} is the total volume of all surrounding shells of RSW

The first term in equation 1 is related to the modal strain energy of a given RSW, while the second one is associated to surrounding shell elements. It has been found in previous studies that this indicator is quite efficient for this kind of optimization.

At a given iteration, all spot welds are sorted by decreasing energy, and the candidate RSW for elimination are selected using the following relationship:

$$\text{Select RSW } 1 \text{ to } n \text{ such as } \sum_{i=1}^n E_i^\nu < \text{tol} \propto \Delta\lambda \quad (2)$$

Of course the final configuration is rarely optimal but rather a sub-optimal solution which satisfies the defined performance criteria. As the optimization advances or as a result of user-defined modifications, several sub-optimal configurations can be found. The objective of a robustness analysis is to compare these configurations, all of which are assumed to satisfy the design requirements, with respect to their robustness to defective RSW.

2.2.2 Results of the optimization

Running the optimization procedure on the C4 model leads to a configuration which is used as a starting point for the robustness analysis. The reinforcement of 382 interfaces on the original vehicle induces 4106 spot welds to optimize. After 4 iterations, 1469 of them have been suppressed. The optimized model has the same global behavior as the original structure, with a maximum of 5 percent shift of eigenfrequencies for the first 3 flexible modes. The evolution of the shifts versus the percentage of removed RSW is shown of figure 2.

The final configuration is illustrated on figure 3, on which the interfaces status is shown: one can observe which RSW can be removed without large influence on the global dynamic behavior. Among the criteria which have been used during optimization process, one of them is related to the extremities of the interfaces: these RSW must remain in the model and cannot be removed during the optimization process, in order to be sure that all interfaces still exist. Full details about used criteria are given in reference [3].

3 Robustness analysis

3.1 Classical approach to manufacturing defects

One source of RSW uncertainty is the result of defective assembly processes. The statistical distribution of these uncertainties is considered to be uniform, hence each RSW has the same chance of being defective.

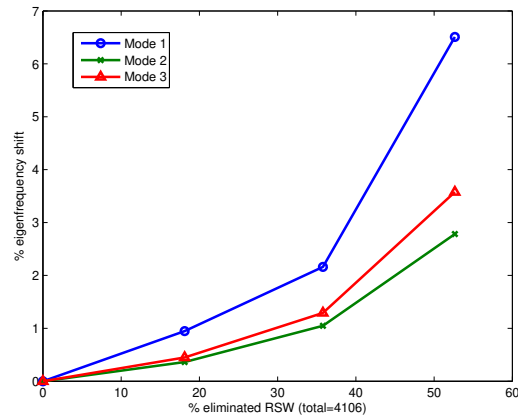


Figure 2: Optimization results, evolution of eigenfrequency shifts for the 3 first flexible modes

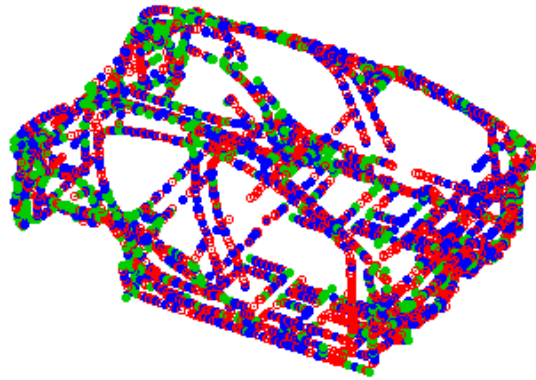


Figure 3: Optimization results, 3D interfaces status (blue: eliminated RSW, green: end of lines, red: kept RSW)

Theoretically, it is then quite simple to evaluate the robustness of the system performance to manufacturing problems using a Monte-Carlo simulation. However, this approach requires a very large number of analyses given the size of the design space. An illustration is given here for several degrees of failure (typically 2, 4, 6 and 8% of defective RSW) in order to study the impact of increasing failure levels on the eigenfrequencies shifts. In the present case, 25 samples have been chosen, which means that for each considered percentage of failure, 25 numerical modal analyses are performed (leading to a total of 100 calculations) in which the corresponding percentage of RSW is removed randomly from the structure. This relatively low number of samples, in comparison to the large number of RSW, means that the results will not be very precise since the Monte-Carlo simulation is not fully converged. However, qualitative information can nevertheless be gleaned. More precise results can be obtained using more samples, but this is not the objective of the present paper.

The left part of the figure 4 shows the results of the robustness for the 3 first elastic modes. In these pictures, the reference eigenfrequency is shown (vertical line at 100%), then the mean of eigenfrequency shift for the 25 samples at each percentage of failure α (dotted line) and finally the maximum eigenfrequency shift which has been evaluated among all available results. One can observe that the first mode is the most sensitive one, and that the shifts obtained are quite small using this uniform statistical distribution. In this sense, the structure is quite robust to manufacturing effects since the mean of eigenfrequency shifts for 8% of weakening RSW is less than 1% for the three first modes. In a particular case, a 3% variation of the first

eigenfrequency can be observed. This situation will be discussed in the next section, since it is possible to perform a quality control to check a small percentage of the RSW at the end of the assembly line. .

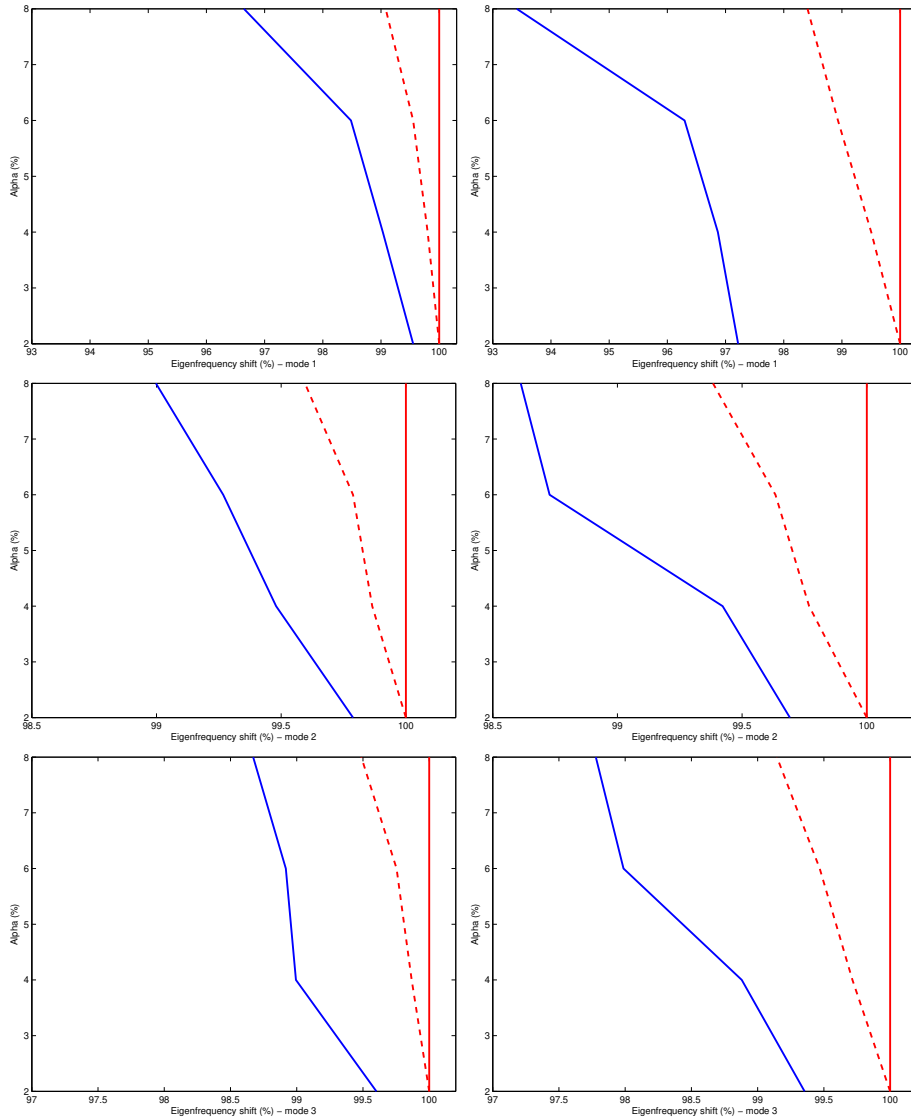


Figure 4: Robustness results: comparison of robustness for the first 3 flexible modes, using uniform (left) or strain energy weighted (right) statistical distribution. The continuous line is the maximum eigenfrequency shift, the discontinuous one is the mean of eigenfrequency shift.

3.2 Classical approach to fatigue failure

The second problem that must be addressed in studying the influence of RSW's on structural dynamics is related to their fatigue resistance. A simplified approach to evaluate the robustness of the structure to RSW fatigue failure is to consider an energy-based statistical distribution e_i of broken RSW:

$$e_i = \sqrt{\frac{E_i}{E}} \quad \text{with} \quad E = \sum_{i=1}^n E_i \quad (3)$$

where E_i is the maximal strain energy of the RSW number i for all considered modes. Using this distribution, the most loaded RSW are more likely to be removed from the numerical model. The robustness analysis is

then a first model of the fatigue effects. The same kind of analysis as the one which has been described for manufacturing effects above has been performed here. The results are presented on the right part of figure 4. We can observe that changes are larger than in the previous case, as is to be expected, since the most energetic RSW are those which are a priori along the main load transmission paths and their absence will have a greater impact on the studied dynamic behavior. Once again, we note that the first torsional mode is the one which is the most influenced by the RSW breakage. A shift over 6% of the corresponding eigenfrequency has been obtained for 8% of removed RSW, which can occur when several high energy welds are removed at the same time. This situation is very unlikely when the statistical distribution of missing RSW is assumed to be uniform.

3.3 Alternative approach to manufacturing defects

There is a fundamental difference between manufacturing defects and fatigue failure. In the case of the manufacturing defects, it is generally possible to perform a control on some of the spot welds. Of course, the control of all of them would be too costly, but verifying 10 or 20 spot welds at the end of the assembly line is quite reasonable. Clearly, this type of quality control would be more difficult to implement during the lifetime of the vehicle. Hence, in this section the topic is related only to manufacturing defects.

We would like the optimized RSW design to be robust to defective and unchecked RSW. The optimized BIW will be analyzed in order to determine a set of RSW which have to be checked at the end of the assembly line in order insure that they are not missing. Then, while these RSW will remain in the model, the remaining ones will be supposed to be defective in a random way. This investigation will lead to a robustness curve representing the compromise between sensitivity to RSW defects and number of controlled welds.

The objective is then to find the more sensitive RSW. Although a criteria such as hypersensitivity [3] could be then used to localize more accurately the most sensitive spot welds, in this paper a simpler indicator is used which is simple based on the element strain modal energy. A spot weld with a high strain energy is assumed to be more influential than one with low strain energy for the considered mode. One advantage of this indicator is that it does not require additional analyses since the modal energies have already been calculated during the optimization process.

Hence, the procedure for determining which RSW should be checked coming off the assembly line is defined as follows:

1. Sorting of interfaces by decreasing modal energy. Definition of the interfaces that should be included in the analysis according to the following criterion:

$$\text{Include interface \#}i \text{ in analysis if } E_i^L > \tau \sum_{i=1}^n E_i^L \quad (4)$$

where E_i^L is the strain energy of all RSW belonging to interface i , and τ is a tolerance allowing one to study only the most energetic interfaces.

2. For each interface that has to be studied in detail:
 - (a) Classify RSW of the interface by decreasing energy.
 - (b) Remove the most energetic RSW 1 from the model and compute eigensolutions of interest.
 - (c) If the eigenfrequency shift is over a fixed limit, the spot weld is included in the list of RSW to be checked. Otherwise the analysis of the interface is over.
 - (d) Once a spot of the interface has to be checked, it is assumed to be effectively present in the structure, and the following RSW of the interface to be analyzed one by one in the order given by the decreasing strain energy. The considered RSW is then removed from the model, and the modal analysis is performed once again, until the eigenfrequency shift is lower than the required limit or if the variation of eigenfrequency shift is below another threshold.

The result than one can obtain with this procedure is illustrated on figure 5, where a total of 7 interfaces are presented corresponding to the interfaces in which 3 spots have been studied. We can observe that in this situation, a maximum of 1 RSW for each interface has to be checked, since the eigenfrequency shift is very low when the first spot weld is effectively present. In this calculation, 27 interfaces have been studied, and a total of 10 spot welds have been identified for quality control. This method is undoubtedly effective in this case since the suppression of one of the RSW leads to a shift of 2% of the torsion frequency, which means that this point is very sensitive and should be carefully checked,

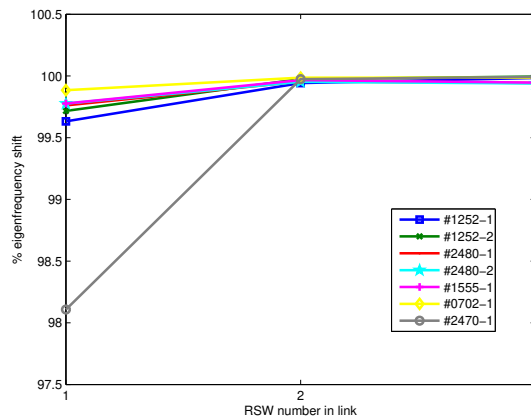


Figure 5: Improving the robustness: definition of the checklist by interface

The keypoint of this analysis is the indicator used for the sorting of interfaces and spot welds. No tests have been done yet to try to evaluate the effect of other indicators.

3.4 Alternative approach for fatigue failure

The fatigue effects are more difficult to check, since it is not possible to verify if the important RSW are still intact on the real structure. Nevertheless, an alternative approach for robustness can be proposed in analogy with the analysis described above for manufacturing defects. However, instead of a check list, a list of RSW to be reinforced is created. All welds which are considered to be too sensitive must be locally reinforced by addition of RSW's in the surrounding area. Moreover, the local reinforcement of the RSW distribution will have a very positive effect on the fatigue resistance, since the energy that pass through the considered spot weld will decrease due to the added spot welds.

4 Conclusion

The design of a resistance spot weld distribution for an automobile body-in-white has a strong impact not only on the global system performance but also on the robustness of this performance with respect to uncertainties due to assembly defects and fatigue failures. A quantitative methodology is presented that provides decision-making indicators that allow the analyst to insure a given level of system performance at the cost of performing a quality control of a limited number of welds coming off the assembly line as well as reinforcing a set of critical welds in order to improve the robustness to fatigue failure. In contrast with existing sample-based robustness analyses, the proposed methodology gives visibility to the compromise between improved robustness and higher assembly and quality control costs. In other words, this methodology provides a tool to guide the analyst in the next step to improving robustness while giving an estimation to the cost of the predicted improvement.

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