Mechanical Systems and Signal Processing 24 (2010) 1172–1190

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/jnlabr/ymssp

Robust design of spot welds in automotive structures: A decision-making methodology

M. Ouisse *, S. Cogan

FEMTO-ST Institute, Applied Mechanics - UMR CNRS 6174, 24, chemin de l'épitaphe, 25000 Besancon, France

ARTICLE INFO

Article history:
Received 24 November 2008
Received in revised form
11 September 2009
Accepted 16 September 2009
Available online 22 September 2009

Keywords:
Spot welds
Finite elements
Robust optimization
Discrete variables

ABSTRACT

Automotive structures include thousands of spot welds whose design must allow the assembled vehicle to satisfy a wide variety of performance constraints including static, dynamic and crash criteria. The objective of a standard optimization strategy is to reduce the number of spot welds as much as possible while satisfying all the design objectives. However, a classical optimization of the spot weld distribution using an exhaustive search approach is simply not feasible due to the very high order of the design space and the subsequently prohibitive calculation costs. Moreover, even if this calculation could be done, the result would not necessarily be very informative with respect to the design robustness to manufacturing uncertainties (location of welds and defective welds) and to the degradation of spot welds due to fatigue effects over the lifetime of the vehicle. In this paper, a decision-making methodology is presented which allows some aspects of the robustness issues to be integrated into the spot weld design process. The starting point is a given distribution of spot welds on the structure, which is based on both engineering know-how and preliminary critical numerical results, in particular criteria such as crash behavior. An over-populated spot weld distribution is then built in order to satisfy the remaining design criteria, such as static torsion angle and modal behavior. Then, an efficient optimization procedure based on energy considerations is used to eliminate redundant spot welds while preserving as far as possible the nominal structural behavior. The resulting sub-optimal solution is then used to provide a decision indicator for defining effective quality control procedures (e.g. visual post-assembly inspection of a small number of critical spot welds) as well as designing redundancy into critical zones. The final part of the paper is related to comparing the robustness of competing designs. Some decision-making indicators are presented to help the analyst to plan robust resistance spot welds designs along with quality controls in order to insure a specified level of structural performance. All examples are presented on a full body-in-white structure (one million dofs and thousands 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 complex manufacturing process, which includes thermo-mechanical effects that

* Corresponding author. Tel.: +33 3 81 66 60 46.
E-mail address: morvan.ouisse@univ-fcomte.fr (M. Ouisse).
URL: http://www.femto-st.fr (M. Ouisse).

0888-3270/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ymssp.2009.09.012

modify the local nature of materials. Nevertheless, being able to build representative models of spot welds is necessary since it has been demonstrated that they can have a strong influence on the dynamic response of the structure [1]. The models that describe the behavior of RSW can indeed be very complicated. For structural dynamic analysis, 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. Some detailed information can be found in Ref. [2] and in the review [3]. One of the main difficulties of the topic is to be able to estimate the fatigue impact on a given structure comprising spot welds. Many studies have been performed over the years, the Refs. [4,5] can be cited as good starting points for the interested reader. The specific models used to represent RSW and the specific methodology for evaluating design robustness are not the focus of the present article. Our objective is to propose a general methodology that can be applied with any RSW model and any approach for the evaluating robustness.

The first objective of the study presented in this paper is to develop a decision-making methodology to support engineers in designing the RSW distribution while taking into account several criteria and objectives. For example, specific static, dynamic and crash constraints must be satisfied while maintaining the number of spot welds as low as possible in order to reduce the manufacturing costs. The second objective is related to the robustness of the final design to manufacturing uncertainties (location of welds and defective welds) and to degradation of spot welds due to fatigue effects over the lifetime of the vehicle.

Some methodologies related to the first objective have been reported in previous works, for example, [6,7] present some optimization procedures related to spot weld design, even if the applications are only based on small structures. Of course, the challenge in this case is to attain the design objectives with as few RSW as possible. The full robust optimization of the spot weld design, in terms of number and position, is not feasible on large structures such as those in the automotive industry, because of the large number of discrete variables to deal with inducing a very high calculation cost [8]. In Section 3, a specific methodology will be presented as an alternative to these classical optimization procedures. Starting from an over-populated RSW structure, a large set of RSW will be removed at each iteration of the algorithm based on energy considerations until the variation of the design objectives exceed a given threshold. This procedure leads to one or several sub-optimal designs whose calculation costs are much smaller than that required by a classical optimization methodology.

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 simply break over time. Several techniques for robustness analysis are presented in Ref. [9] to evaluate the effect of missing spot welds on the global behavior of a body-in-white structure. This kind of analysis, which is also used in this paper, has a very high calculation cost, hence the objective of the last part of the 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. Description and analysis of the reference finite element model

2.1. Reference model

The examples illustrated in this article are based on the Peugeot-Citroën C4 BIW finite elements model. The MSC/NASTRAN model is shown in Fig. 1. It has approximately 1,000,000 dofs and includes 2643 RSW. The simplified modeling of the spot welds will be discussed in the next section. A modal analysis up to 75 Hz takes about 20 min on a Linux-based computer, Bi-Xeon 2.5 GHz.

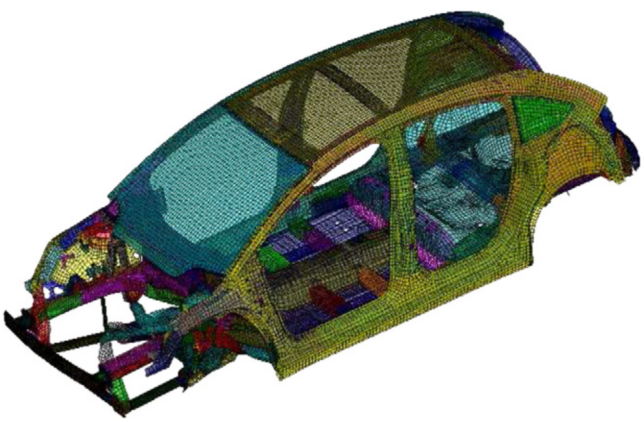

Fig. 1. Finite element model of the PSA Peugeot-Citroën C4 car.

The initial design of the RSW distribution is made by engineers, based on knowledge of earlier designs, in order to satisfy a set of design constraints, such as static torsion angle, crash behavior or modal analysis. The results presented in this article are only based on elastodynamic design constraints, but the methodology is able to take into account other behaviors as well. In the present case, the design objectives will be related to three global modes (two torsion modes and one bending mode, as shown in Fig. 2 and in Appendix B), whose eigenfrequencies should not decrease by more than 3% of the initial value when spot welds are removed. This threshold is chosen arbitrarily, any other value could be used depending on the context of the study. A MAC (modal assurance criteria) value over 70% is used as a matching criterion for these modes, which means that only matched modes can be efficiently considered: some very local modes can appear depending on the local distribution of spot welds, and these cannot be followed by the algorithm during the removal of spot welds since the matching criterion is not verified. Some complementary constraints can be used to avoid the appearance of these local modes, such as a backstep to cancel a spot weld suppression in an area with high strain energy for a given local mode. This adaptive approach is not considered in this work. Some local modes can nevertheless be considered, providing that they are matched with those of the reference structure.

2.2. Resistance spot weld modeling

In this study, each of the resistance spot weld is described with the simplified model shown in Fig. 3: the shell elements of the two structural parts are linked to two master nodes 101 and 102 with multi-point constraint equations, while the two master nodes are linked together with CBUSH elements (springs along the six spatial directions).

The spot weld model is assumed here to be effective for estimating the global dynamic characteristics of the structure for the target behaviors of interest. It is clear that the results of the optimization process will depend on the choice of the spot weld modeling. In the present case, the finite element model has been validated by engineers from PSA-Peugeot Citroën who provided the model.

2.3. Robustness analysis of the reference model

The initial design is not necessarily very robust to the types of uncertainties which are considered here. For example, manufacturing problems can produce defective spot welds and some others can break during the lifetime of the vehicle. All changes in the model that will be considered in the following are related to missing RSW.

2.3.1. Manufacturing uncertainties

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. 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, and since we are dealing with discrete variables (existence or not of the spot welds), almost no alternative to Monte Carlo is available, such as a Latin Hypercube Sampling strategy for continuous variables. The main question is related to the percentage of spot welds which have some chance of being defective. No convenient information being available, a robustness-versus-defectiveness plot can be used to evaluate the evolution of the robustness when the percentage of defective spot welds increases. 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, 200 samples have been chosen, which means that for each considered percentage of failure, 200 numerical modal analyses are performed (leading to a total of 800 calculations) in which the corresponding percentage of RSW is removed randomly from the structure.

The left part of Fig. 4 shows the results of the robustness for the first three elastic modes. In these figures, the reference eigenfrequency is plotted (red vertical line with circle marker at 0%), then the mean eigenfrequency shift for the 200 samples at each percentage of failure *Alpha* (green line with + marker) and finally the largest eigenfrequency shift which has been evaluated among all available results (blue line with × marker). We can note 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 defects since the mean of eigenfrequency shifts for 8% of weakening RSW is less than 1.1% for the three first modes. In a particular case, a 3.5% variation of the first eigenfrequency can be observed. This

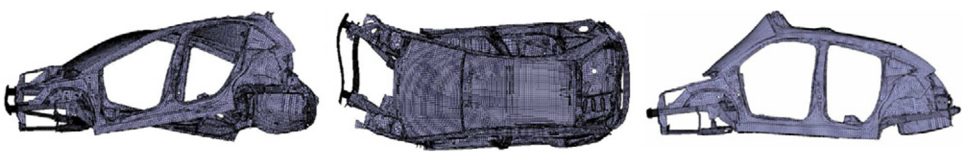

Fig. 2. Shapes of the modes of interest.

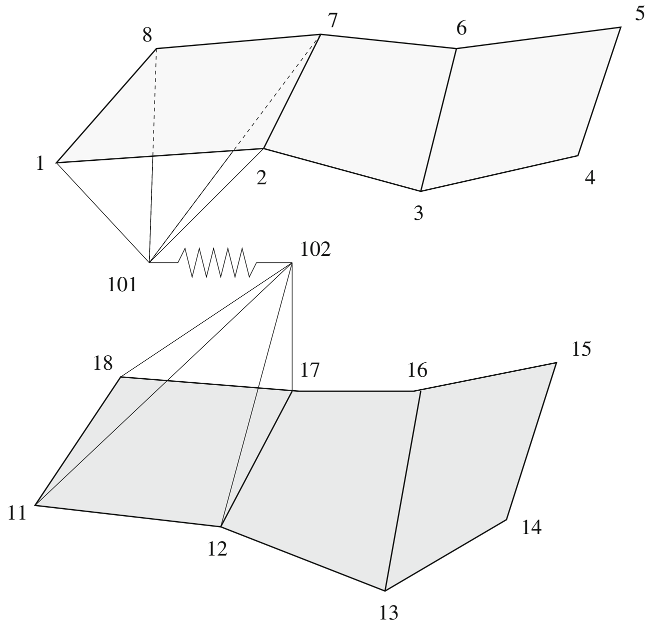

Fig. 3. FE model of a RSW.

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.

This robustness analysis does not involve any theoretical difficulty, but one could be interested in making a Monte Carlo simulation with a smaller number of samples to reduce calculation time. The right part of Fig. 4 shows the results obtained with a limited number of samples for the robustness analysis (only 50 samples for each uncertainty level). 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, comparison with results obtained using 200 samples show that qualitative information can be gleaned. In the following, 50 samples will be used for each uncertainty level for robustness studies in order to reduce the calculation time, since the objective of the work is not to obtain precise results about robustness but rather to propose alternative approaches to reduce calculation time to obtain a robust optimized configuration.

2.3.2. *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, which has been considered in Ref. [9], is to evaluate the robustness of the structure to spot weld fatigue failure considering an energy-based statistical distribution e_i for broken RSW:

$$e_i = \sqrt{\frac{E_i}{E}} \quad \text{with } E = \sum_{i=1}^{n} E_i, \tag{1}$$

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 in Fig. 5. 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 defects. A shift over 5% 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.

Another way to obtain a first estimation for the probability of failure of a given spot weld is to use a statistical distribution which is proportional to the total force in each RSW based on a static configuration which is assumed to induce stresses which are close to operating conditions.

All these analyses provide information on the dynamic behavior of the initial body-in-white (BIW) and its initial RSW distribution as well as the impact of missing spot welds.

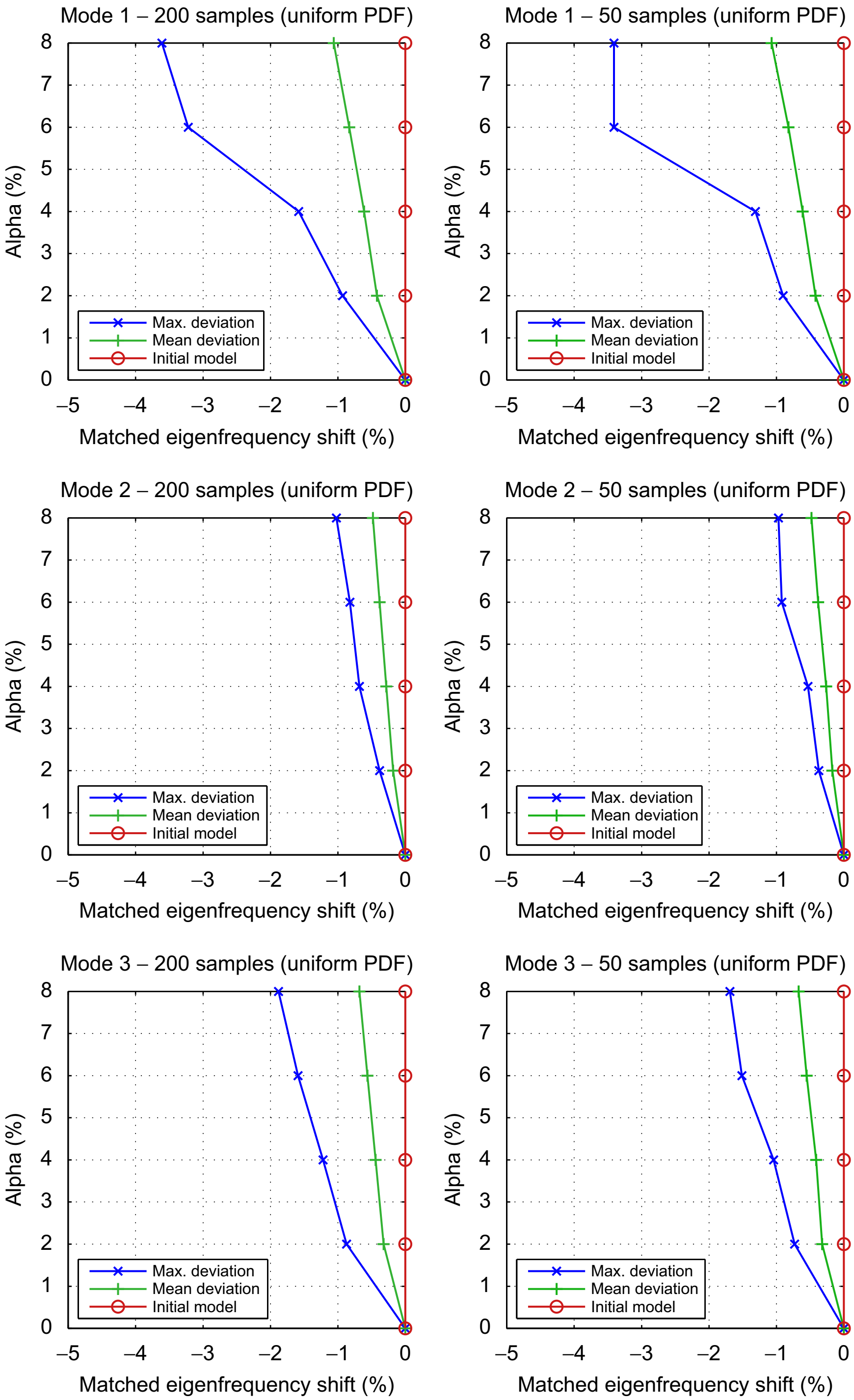

Fig. 4. Robustness results for the first three elastic modes, using a uniform statistical distribution, for 200 samples (left column) and 50 samples (right column). The curves indicate the minimum, maximum and mean value of eigenfrequency shift, compared with the reference configuration.

3. Optimization of the resistance spot weld distribution

Thanks to the growth of computer calculation power, the optimization of a full BIW can be investigated. The analysis which is proposed here deals with spot weld optimization both in terms of number and position. The objective is to detect, among a large number of resistance spot welds, which of them can be removed while preserving certain characteristic behaviors of the structure. In the present case, this means removing as many RSW as possible while insuring that the first

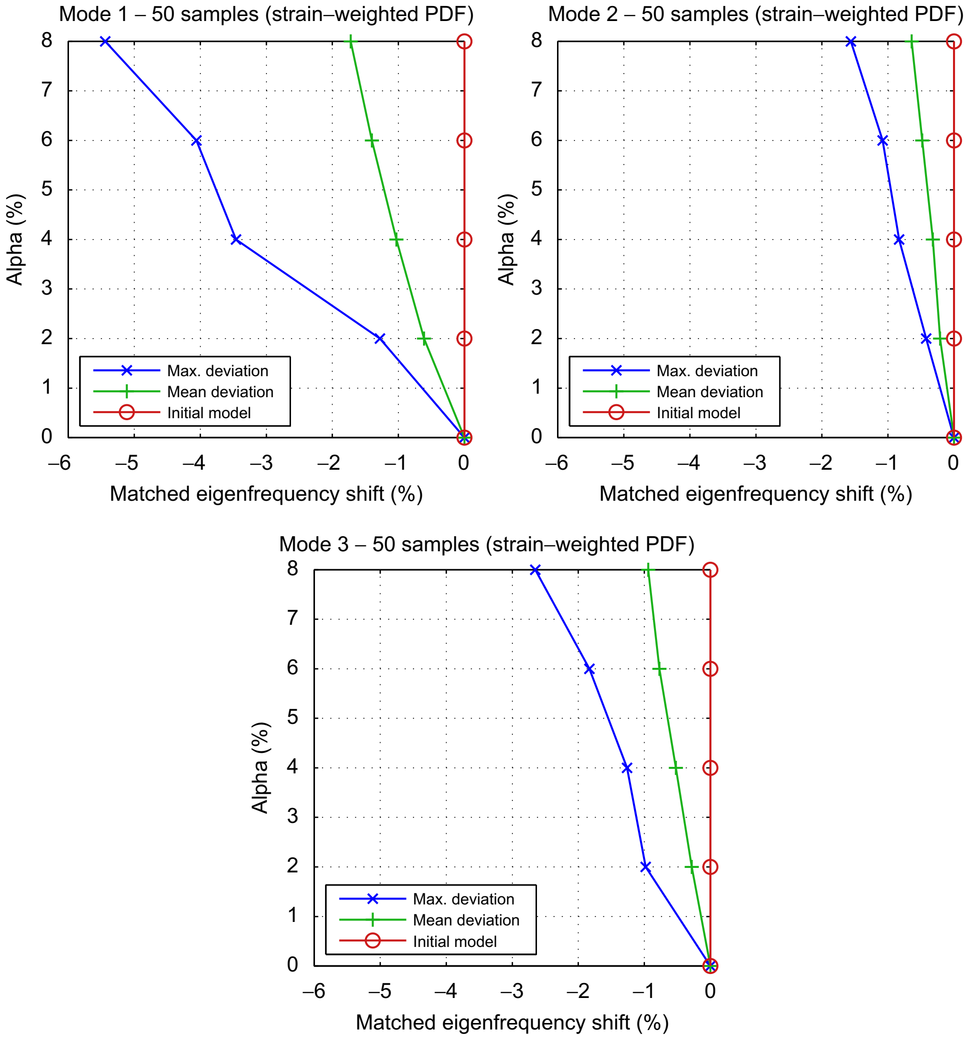

Fig. 5. Robustness results to fatigue for the first three flexible modes, using strain-weighted statistical distribution, for 50 samples. Curves are the minimum, maximum and mean value of eigenfrequency shift, compared with the reference configuration.

three elastic eigenfrequencies do not vary more than 3% from their original values. Of course, this should be done with an efficient optimization procedure in order to reduce the calculation costs as much as possible. We propose an efficient approach based on energy criteria which allows a large number of RSW to be eliminated at each optimization step.

Let us consider the typical behavior of a given feature of the model versus the number of eliminated RSW. This feature could typically be the eigenfrequency shift of a mode of the modified structure (with missing RSW) which has been matched to a homologous target mode of the nominal model. If the original structure includes a large number of RSW, removing them based on a minimum energy criterion and considering the value of this feature versus the number of eliminated spot welds leads to the typical behavior illustrated in Fig. 6.

Earlier formulations of the optimization algorithm were based on the removal of one RSW at a time. Unfortunately, this kind of approach obviously results in a very high calculation cost, in particular due to the large number of variables and to the fact that they are discrete. The calculation cost can be reduced, in particular at the beginning of the procedure when the cost function is almost insensitive to spot weld removal. The basic idea here is to find a method that allows one to reach the end of this insensitive zone in a small number of iterations, using a criterion that would indicate the insensitive spot welds. Ideally, the number of spot welds to be removed at a given iteration would be a function of their energy distributions.

3.1. Description of the optimization methodology

In this part, the optimization algorithm is presented which allows to reduce the number of RSW while verifying a given set of constraints.

3.1.1. General strategy

The general optimization strategy is presented in Fig. 7. Each step of the procedure will be detailed in the following paragraphs.

The initial design, which has been arbitrarily defined, is not necessarily very robust to the types of uncertainties which are considered here. In order to be able to define a more robust starting configuration, the first step of the proposed approach is to create a reinforced spot weld design of the structure. Concretely speaking, the number of spot welds is multiplied by two to define an over-populated structure. In what follows, it is assumed that this reinforced design satisfies all design constraints and, although it is in no way an optimal design in terms of the number of RSW, it has a maximum and satisfactory level of robustness.

The initial design has 2643 RSW distributed along 382 structural interfaces between parts of the BIW, as shown in Fig. 8. Fig. 9 shows a partial comparison of both the initial and reinforced configurations, the reinforced one including 4106 RSW. The optimization process will concern only 3417 which are candidates for removal since, for industrial reasons, some RSW are not allowed to be removed. The percentages that will be shown will be related to the 3417 spot welds. Removing 43% of them will then imply that the final number of spot welds is lower than for the initial configuration.

After the model preparation (reinforcement of the structure, characterization of each RSW by its membership to a given identified interface to which is associated an ordered list of spot weld), a modal (and/or static) Nastran analysis is performed to evaluate the target model features. In this step, a correlation analysis is required in order to identify the modes of interest, based on the modal assurance criteria (MAC). Eigenvectors are considered to be matched if the corresponding MAC is above 0.7. Then, an evaluation of threshold criterion is performed in order to determine if the iterative process has to be stopped or not. The next step is to evaluate the sensitivity of each RSW with respect to the cost function based on the target features, using one of the three criteria that will be described in the next section.

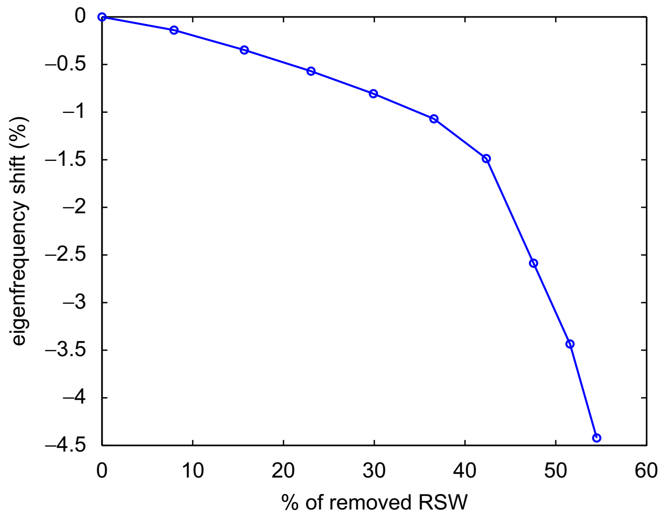

Fig. 6. Typical evolution of eigenfrequency versus % of eliminated RSW.

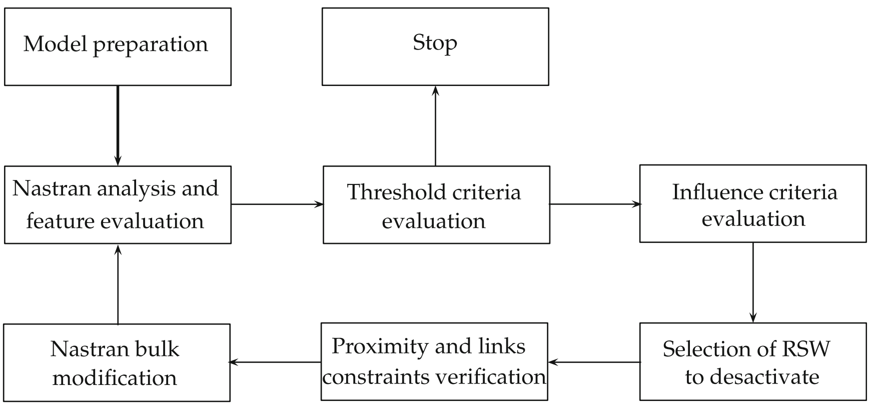

Fig. 7. Optimization procedure.

This evaluation allows us to detect the candidate RSW that are likely to be removed from the structure. Then, before removing the spot welds of the model, two topological constraints must be satisfied: a proximity constraint and a minimal interface constraint.

The proximity constraint is illustrated in Fig. 10, for which the value of the constraint is 7, this value being chosen for visual understanding. In this case, two candidate RSW in a given interface (and at a given iteration) must be separated by six remaining ones. A proximity constraint of one will authorize two consecutive spot welds to be removed at a given

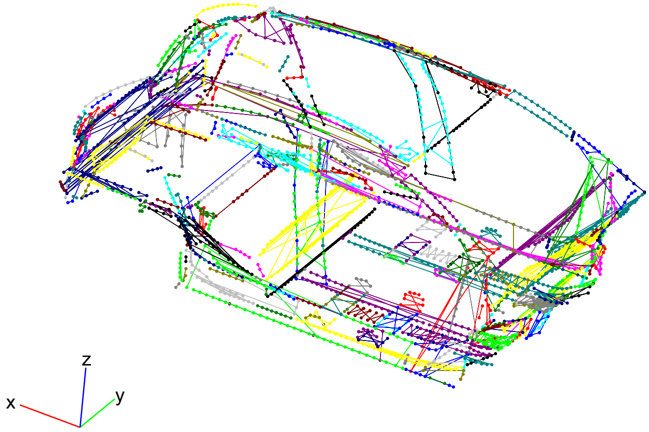

Fig. 8. Initial distribution of spot welds.

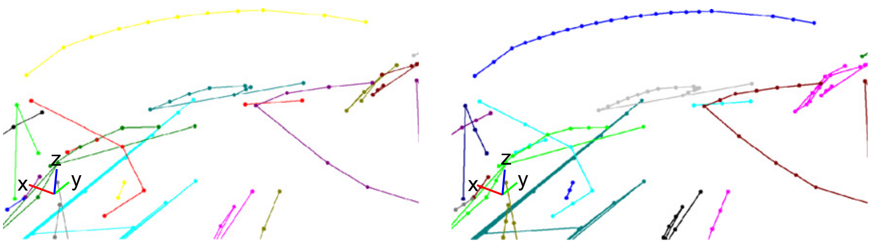

Fig. 9. Partial view of initial (left) and reinforced (right) distribution of spot welds.

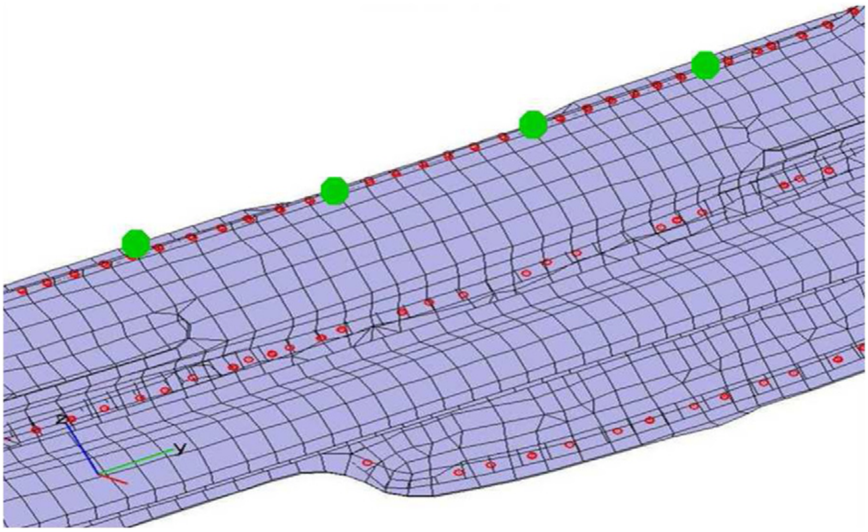

Fig. 10. Candidate RSW for proximity constraint equal to 7.

iteration. This constraint is closely linked to the ability or failure of the procedure to take into account coupling between the effects of removed RSW at a given iteration.

The interface constraint consists in verifying the integrity of interfaces: each interface comprises a given number of RSW at the beginning of the procedure, and while the algorithm can reduce the number of spot welds for this interface, it is not authorized to remove all the interface RSW. In the present study, the RSW at the two ends of the interface are systematically preserved. The Nastran command file is thus modified by removing RSW which have been selected and which verify the constraints. Finally, the optimization loop goes back to the analysis to re-evaluate the current state of the target features. It can be mentioned that approximate methods like reanalysis are generally not very efficient at this step because the number of removed RSW at a given iteration may be too large to obtain reasonable results.

The procedure which is presented here has two specificities compared to the earlier formulations of this optimization problem. The first one is that the number of RSW which can be removed at a given iteration is unknown, that is to say, as many RSW as possible will be removed such that their total contribution to the structural energy is lower than a threshold value. The second specificity is that the proposed criteria are unable to take into account coupling between parameters and it simply provides information about the influence of a given RSW on the features one at a time. The use of the proximity constraints allows this limitation to be circumvented.

3.2. Energy-based ranking of candidate spot welds

In the optimization procedure described above, the critical point is the choice of the influence criteria for each spot weld. Three categories of criteria have been studied:

- Criteria based on interface forces: These criteria are the least expensive to evaluate but there is no simple link between these forces and the evolution of the model features used here. All coupling effects are included in the criteria.
- Criteria based on energies: These criteria are relatively inexpensive to evaluate and there exists simple relationships between values of criteria and eigenvalue shifts. However, coupling effects are not taken into account.
- Criteria based on a posteriori evaluation: These criteria are quite expensive to evaluate but give the exact influence of each parameter. This is considered to be the reference calculation.

In this paper we will focus on the energy criteria. Three of them have been implemented in AESOP, the MATLAB-based optimization and model updating development platform of the FEMTO-ST Institute, and they will be described in this section.

3.2.1. Criterion 1: elastic energy in RSW

The first imaginable criterion is undoubtedly the most physical of all those described in this paper: it is the elastic energy of each spot weld. The element elastic energy considered here can have several expressions, corresponding to the contribution of a given element to the total elastic energy:

- Modal analysis (eigenshape y_v, eigenvalue λ_v):

$$E_i^1 = \frac{y_v^T K^{e,i} y_v}{\lambda_v}. \tag{2}$$

- Static analysis (static response x):

$$E_i^1 = \frac{x^T K^{e,i} x}{x^T K x}. \tag{3}$$

- FRF analysis (frequency response y):

$$E_i^1 = \frac{y^T K^{e,i} y}{y^T K y}. \tag{4}$$

In these expressions, $K^{e,i}$ is the element stiffness matrix of RSW number i, and K is the stiffness matrix of the full model. The normalization operation is done using the total energy of the structure. In this paper we will focus on the first expression, corresponding to a modal analysis. This criterion is very closely linked to eigenvalues shifts, yielding a good performance when the features of the problem take into account only eigenvalues variations and not eigenshapes modifications. Using this first criterion, all spot welds are sorted using their elastic energy E_i^1, in ascending order, and the candidate RSW to elimination will be selected using the following relationship:

$$\text{Select RSW 1 to } n \text{ such that } \sum_{i=1}^{n} E_i^1 < \tau \propto \Delta\lambda, \tag{5}$$

in which τ is an arbitrary tolerance.

3.2.2. Criterion 2: elastic energy in RSW and adjacent shell elements

In some cases, in particular when the stiffness of a given RSW is higher than that of the adjacent shell elements, the above criteria does not capture the correct behavior of the structure, since the elastic energy of the considered spot weld can be very small while the surrounding shell elements have a large elastic energy, implying that removing this RSW will yield a significant change in the considered feature. This is why the second considered criterion will be the same as the previous one, completed by the elastic energy of surrounding shell elements:

$$E_i^2 = E_i^1 + \frac{\sum E_i^{shell}}{\sum V_i^{shell}} V^{sh\ tot}, \tag{6}$$

in which E_i^{shell} is the elastic energy of shell elements surrounding spot weld i, V_i^{shell} the total volume of surrounding shell elements, and $V^{sh\ tot}$ the total volume of shell elements surrounding all considered RSW. This normalization is necessary to avoid artificial variations of the indicator due to element size. Using this second criterion, all spot welds are sorted based on their elastic energy E_i^2, in ascending order, and the candidate RSW for elimination will be selected using the following relationship:

$$\text{Select RSW 1 to } n \text{ such that} \sum_{i=1}^{n} E_i^2 < \tau \propto \Delta\lambda. \tag{7}$$

3.2.3. Criterion 3: hypersensitivity indicator

The third considered criterion is based on work presented in Refs. [10,11], which has been called a "hypersensitivity indicator". For the problem presented here, two stiffness matrices can be defined: K is the stiffness matrix in nominal case (with all RSW), and $\tilde{K}$ is the stiffness matrix corresponding to the structure with some removed RSW. In the present case, no change appears in mass matrix when RSW are removed. The indicator is based on the residual modal force:

$$F_v = (\tilde{K} - K)y_v, \tag{8}$$

which is then transformed into a residual modal displacement:

$$R_v = \tilde{K}^{-1} F_v. \tag{9}$$

Finally, this displacement is used to evaluate a kinetic energy in order to have global information and to link it to variations in the eigenvectors ($\tilde{M}$ is the mass matrix of the modified structure):

$$H_v = R_v^T \tilde{M} R_v. \tag{10}$$

It has been shown in Ref. [11] that this value is closely related to the shifts in the features, based on a modal decomposition of initial shape y_v on the modal basis of modified structure (with removed RSW) $\tilde{y}_v$:

$$y_v = \sum_{\sigma=1}^{N} \alpha_v^\sigma \tilde{y}_v, \tag{11}$$

in which N is the number of considered modes in the decomposition. The α_v^σ factors are the projections of y_v on the modal basis $\tilde{y}_v$, which can be seen as a measure of the difference between the two considered bases: if the structural modifications are small, $\alpha_v^\sigma \approx \delta_{v\sigma}$ in which δ is the Kronecker symbol. Then, H_v can be expressed as

$$H_v = \alpha_v^{v2} \left(\frac{\tilde{\lambda}_v - \lambda_v}{\tilde{\lambda}_v} \right)^2 + \sum_{\sigma \neq v} \left(1 - \frac{\lambda_v}{\tilde{\lambda}_\sigma} \right)^2, \tag{12}$$

in which $\tilde{\lambda}_v$ is the v- th eigenvalue of the modified structure (see Appendix A for details).

This indicator provides a single value for the structure, and then it is decomposed into element contributions to the total energy, and also includes a normalization to avoid artificial variations of indicator due to element size, thus yielding criterion 3 (i is the RSW number):

$$E_i^3 = \frac{R_v^T K^{i,e} R_v}{\sum V_i^{shell}} V^{sh\ tot}. \tag{13}$$

Using this third criterion, all spot welds are sorted using their residual energy E_i^3, in ascending order, and the candidate RSW for elimination will be selected using the following relationship:

$$\text{Select RSW 1 to } n \text{ such that } \sum_{i=1}^{n} E_i^3 < \tau \propto \Delta\lambda^2. \tag{14}$$

The calculation cost for the estimation of criteria 3 is higher than the one required for the first two, but the objective is to obtain a lower global calculation cost thanks to a larger selection of RSW to eliminate at each iteration. The difficulty here is to determine the value of tolerance which should be used in this case: it is on the order of $\Delta\lambda^2$ only when changes in deflection shapes are small.

3.3. *Results of the optimization procedure*

The three criteria have been tested and compared in terms of efficiency. The results are presented by showing the matched eigenfrequency relative error on the three modes of interest, the reference being the initial structure. This eigenfrequency shift is given versus the number of removed RSW during the optimization, which means that the reference number of RSW corresponds to the reinforced configuration (3417 spot welds).

3.3.1. *Criterion 1: elastic energy in RSW*

The results of the analysis using the first criterion are illustrated in Fig. 11. In this case, a proximity constraint of 3, with a threshold value of 0.02 has been used. The value of the proximity constraint is chosen such as the effects of any potentially removed spot weld on energy distribution are not coupled, at least in a local way. It can be seen that 11 iterations are required to reach the maximum eigenfrequency shift of 3%, allowing to eliminate 67% of the RSW. It is seen in this particular example that while the eigenfrequency shift is positive, the changes are quite low, and many RSW can be removed at a given iteration. When the shift becomes negative, the changes are larger, and less spot welds are eliminated at each iteration.

3.3.2. *Criterion 2: elastic energy in RSW and adjacent shell elements*

Results of the analysis using the second criterion are illustrated in Fig. 12. In this case, a proximity constraint of 3 and a threshold value of 0.02 has been used (same parameters as in case 1). One can observe that a given threshold value corresponds to a lower frequency shift, since the energy includes not only the RSW but also the adjacent shell elements, which means that a smaller number of RSW are selected at a given iteration. This results in a higher calculation cost, since the total number of iterations is higher than in the previous case. The final result, that was expected to be better than the

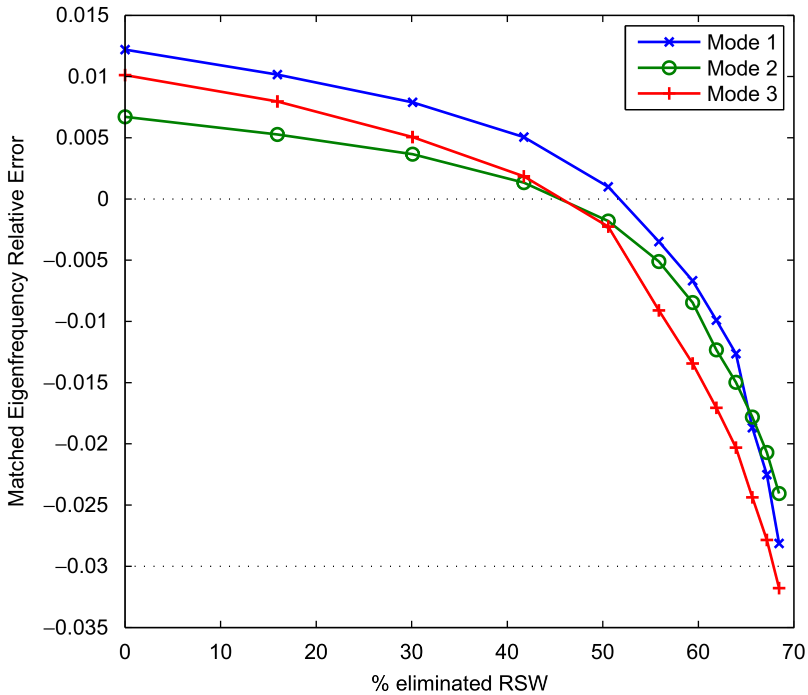

Fig. 11. Results of optimization procedure for criterion 1: eigenfrequency shift (reference = initial structure) versus number of removed RSW (reference = reinforced structure).

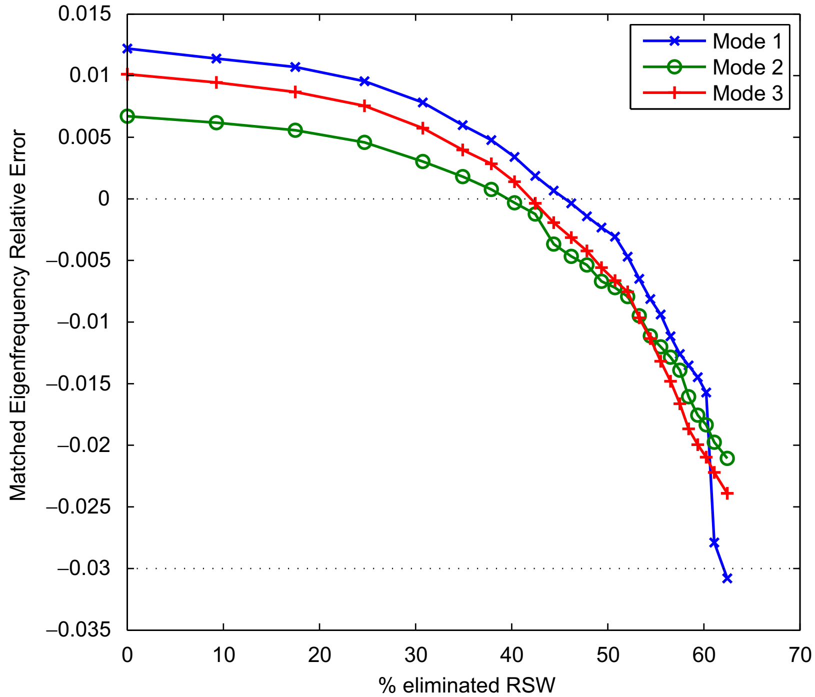

Fig. 12. Results of optimization procedure for criterion 2 (threshold value = 2%): eigenfrequency shift (reference = initial structure) versus number of removed RSW (reference = reinforced structure).

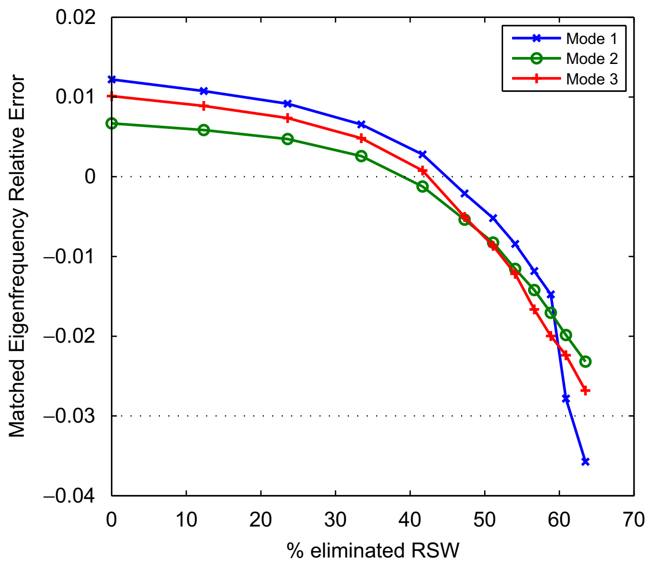

Fig. 13. Results of optimization procedure for criterion 2 (threshold value = 4.5%): eigenfrequency shift (reference = initial structure) versus number of removed RSW (reference = reinforced structure).

previous one, is unfortunately not so good, since the frequency of mode 1 goes down with a high 1.2% shift between iterations 22 and 23. This is clearly explained by the ranking of RSW, which is made using criterion 2. This is of course not an exact ranking, but it requires a low calculation cost. Techniques to avoid this kind of situation are clear: the first alternative is to use a better ranking of RSW, for this another criterion is proposed in what follows. Otherwise, another approach would be to propose an adaptive algorithm that should be able to detect large changes and reinforce the structure at this point, before removing the next ones. This will be considered in our future work.

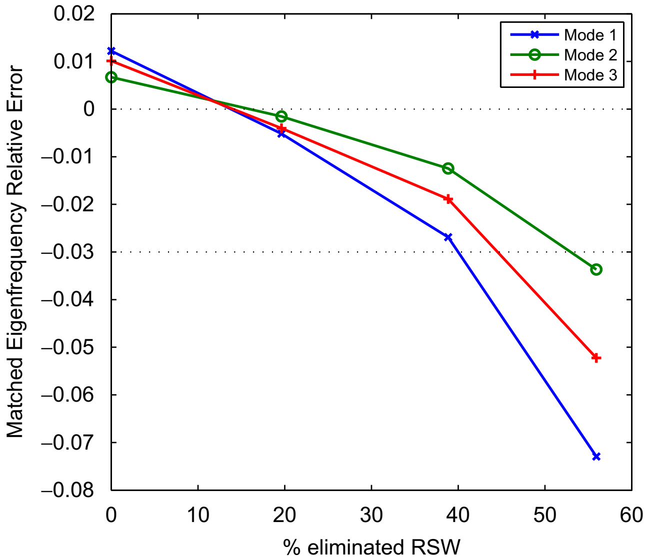

Fig. 14. Results of optimization procedure for criterion 3.

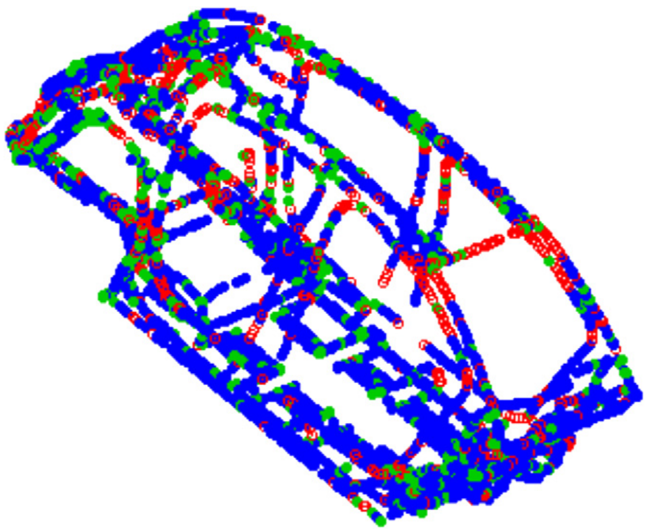

Fig. 15. Results of optimization: removed RSW (blue), kept RSW (red), end of links (green). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The final results correspond to removing of 62% of RSW while keeping the matched eigenfrequency shifts below 3%.

We note that this configuration can be achieved much more quickly using a higher threshold value. Fig. 13 shows the same configuration using a 4.5% value for the threshold. We observe exactly the same behavior as the one of Fig. 12 with only 11 iterations instead of 24 in the previous case.

3.3.3. Criterion 3: hypersensitivity indicator

The results of the analysis using the third criterion are illustrated in Fig. 14. In this case, a proximity constraint of 2 and a threshold value of 0.01 has been used. In order to be competitive compared to the other runs, this indicator would be required to remove many more RSW than the two first indicators at a given iteration, since the required calculation cost is higher, due to the static resolution of the problem (Eq. (9)), which are required several times at each iteration (4 times in this example). This is the reason why a lower threshold value is required, and also a lower proximity constraint, since the indicator is supposed to be more effective for localization compared with the energy-based indicators. The thresholds have been chosen to yield a total optimization time which is equivalent to the ones required with approaches presented above. In this case, the threshold is reached at the fourth iteration, for which 56% of RSW have been removed. The results are not as good as the ones obtained using the first two indicators, mainly because of the high number of RSW that have been removed at each iteration in order to be competitive with simpler methods, in terms of calculation time. This kind of criteria is clearly not useful to localize the less sensitive RSW.

3.3.4. Conclusion

Three energy criteria for the suboptimal design of RSW in large automotive structures have been presented. All of them are based on the elastic energy of spot welds and if they are used in parallel with a proximity constraint, they allow to select hundreds of RSW for elimination at a given iteration. Gains in calculation time with respect to a weld-by-weld elimination approach are thus very large. The third criterion is based on the modal residual force, and requires a higher calculation cost, without improvement in the results. The hypersensitivity approach thus does not seem to provide any real advantages in this case. This approach was designed for localization of the most sensitive parts of a given structure, and has been tested here concerning the localization of the least sensitive RSW. In this case, the higher calculation cost is not associated with a better ranking of RSW, and the simple approaches are clearly much efficient for this purpose.

A typical final result of the optimization procedure is shown in Fig. 15, in which the spot welds are shown with color markers: the blue markers are the removed welds while the red markers indicate the welds that should remain in the model. Finally, the green markers indicate the welds at the end points of each lineal interface and were not candidates for elimination.

Depending on the choice of the energy indicator and the thresholds during the optimization process, several sub-optimal configurations can then be found. The choice of a RSW distribution among the available solutions should not be only based on the lowest RSW number criteria, since the best configuration may not be the most robust. A compromise between RSW number and robustness should be found. This is the topic of the next section.

4. Robustness of the resistance spot weld distribution

4.1. Classical robustness analysis

A classical robustness analysis [12] seems to be a natural way to rank the suboptimal configurations which have been found, or simply to evaluate the robustness of a given spot weld distribution. However, in practice, the computational burden renders its application impracticable. An alternative approach is proposed to manage the robustness of a given configuration.

4.2. Alternative approach for robustness management

There is a fundamental difference between manufacturing defects and fatigue failure. In the case of 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 to insure that they are not defective. Then, while these RSW will remain in the model, the remaining welds 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 most sensitive RSW. Although a criteria such as hypersensitivity [11] could then be used to localize more accurately the most sensitive spot welds, in this paper a simpler indicator is used which is 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 analysis 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:

$$\text{Include interface } i \text{ in analysis if } E_i^L > \tau \sum_{i=1}^{n} E_i^L. \tag{15}$$

   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.

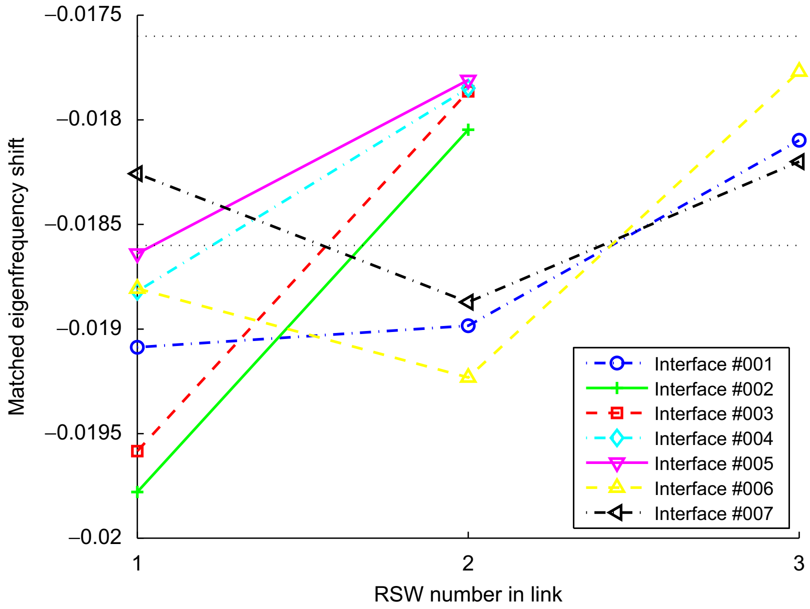

Fig. 16. Improving the robustness: definition of the checklist by interface.

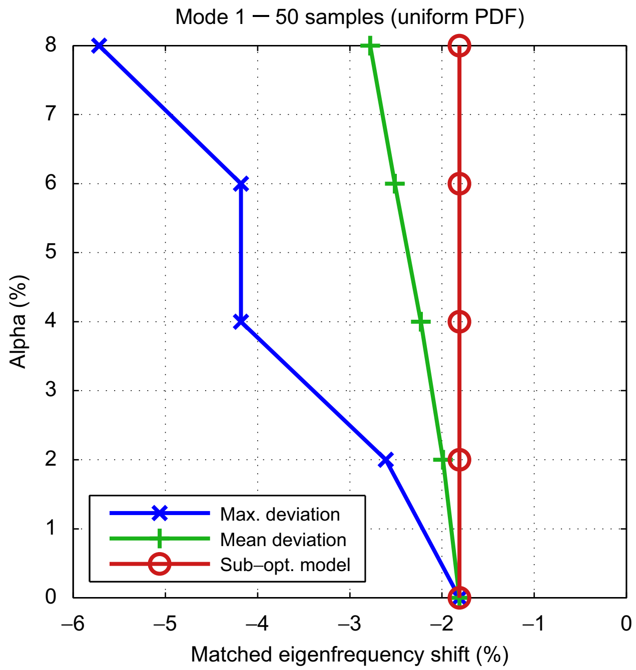

Fig. 17. Final robustness analysis.

(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 reintroduced in the model, and the next spot weld is analyzed, until the eigenfrequency shift is lower than the required limit or if the variation of eigenfrequency shift is below a given threshold.

A typical result of this procedure is illustrated in Fig. 16, where a total of seven interfaces are presented as an example. We observe that in this situation, some interfaces have required an analysis with the removing of 3 RSW, while only two were necessary for some other interfaces before reaching the 1% limit shift chosen as a stop criteria (the upper dotted line indicates the frequency shift after the optimization, and the lower one is the stop limit, 1% below). In this calculation, 27 interfaces have been studied, and a total of 10 spot welds have been identified for quality control, among which the first point studied is in interface 2, whose suppression yields a 0.25% shift of the first eigenfrequency of interest.

Once again, the key point of this analysis is the indicator used for the sorting of interfaces and spot welds. This is the current investigation point in this research. In the future paper, we will focus on the evaluation of the effect of other indicators.

The final result of the proposed methodology can be considered as a suboptimal configuration which verifies all the desired constraints, with a significant reduction of the number of spot welds. In order to evaluate the robustness of that final configuration, a robustness analysis can be performed. In the present case, the analysis has been done using only 50 samples to evaluate the dispersion on the mean value. We can see in Fig. 17 that the robustness of the first mode is almost the same as that of the initial configuration (see Fig. 4): the nominal value of the frequency exhibits a 1.75% shift, but the maximum deviation of the mean frequency shift (compared with the nominal value) is lower than 1%, which is below the 1.1% frequency shift observed for mode 1 of initial configuration.

5. 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 to existing sampling-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 providing an estimation of the cost of the predicted improvement.

Acknowledgments

The authors would like to thank PSA Peugeot-Citroën for their generous support in this study and for providing the finite element model of the body-in-white.

Appendix A. Link between hypersensitivity index and eigenfrequency shifts

Eigenvalues shifts are denoted $\Delta\lambda^\nu = \tilde{\lambda}^\nu - \lambda^\nu$. Notations with ˜ sign are related to the modified structure. Residual (9) can be expressed as

$$R_\nu = y_\nu - \lambda_\nu \tilde{K}^{-1}\tilde{M} y_\nu = y_\nu - \sum_\sigma \alpha_\sigma^\nu \frac{\lambda_\nu}{\tilde{\lambda}_\sigma}\tilde{y}_\sigma \tag{16}$$

or

$$R_\nu = \sum_\sigma \alpha_\sigma^\nu \left(1 - \frac{\lambda_\nu}{\tilde{\lambda}_\sigma}\right)\tilde{y}_\sigma. \tag{17}$$

The kinetic energy of this residual is then

$$H_\nu = R_\nu^T \tilde{M} R_\nu = \left(\sum_\sigma \alpha_\sigma^\nu \left(1 - \frac{\lambda_\nu}{\tilde{\lambda}_\sigma}\right)\tilde{y}_\sigma\right)^T \tilde{M}\left(\sum_\kappa \alpha_\kappa^\nu \left(1 - \frac{\lambda_\nu}{\tilde{\lambda}_\kappa}\right)\tilde{y}_\kappa\right), \tag{18}$$

which can be simplified if the modes are mass-normalized as $\tilde{y}_\sigma^T \tilde{M}\tilde{y}_\kappa = \delta_{\sigma\kappa}$ where $\delta_{\sigma\kappa}$ is the Kronecker symbol:

$$H_\nu = \sum_\sigma \left(\alpha_\sigma^\nu \left(1 - \frac{\lambda_\nu}{\tilde{\lambda}_\sigma}\right)\right)^2. \tag{19}$$

This leads to the expression of indicator (12):

$$H_\nu = (\alpha_\nu^\nu)^2 \left(\frac{\Delta\lambda^\nu}{\tilde{\lambda}_\nu}\right)^2 + \sum_{\sigma\neq\nu} (\alpha_\sigma^\nu)^2 \left(1 - \frac{\lambda_\nu}{\tilde{\lambda}_\sigma}\right)^2. \tag{20}$$

Appendix B. Deflection shapes of the modes of interest

Figs. 18–20 exhibit the three modal shapes of the modes of interest in the study. The color is related to the element strain energy.

Appendix C. Analysis of convergence

Fig. 21 shows the convergence of both mean and maximum values of matched eigenfrequency shifts, for the three modes of interest. The curves have been obtained on the reference structure, using only the 4% level of removed RSW for each sample. Starting from one single sample, a new sample is added, and the features (mean and maximum values of matched eigenfrequencies shifts) are evaluated. This operation is repeated to obtain a set based on 580 samples. One can clearly see in Fig. 21 that even after 580 samples, the exact convergence is not achieved yet. Nevertheless, the value of the mean frequency does not evolve significantly, and some informative conclusions can be obtained with a much lower number of samples. Based on this observation, 200 samples give quite precise information, while the 50 samples used in this paper can be considered as sufficient for indicating the global tendencies. It is clear that concerning the maximum

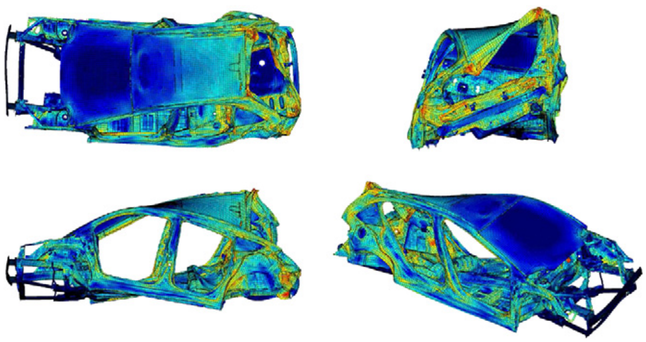

Fig. 18. First mode of interest.

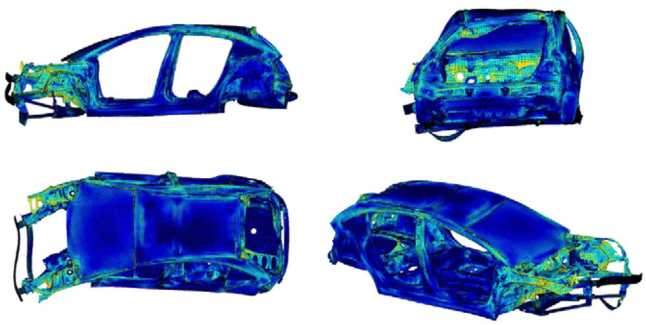

Fig. 19. Second mode of interest.

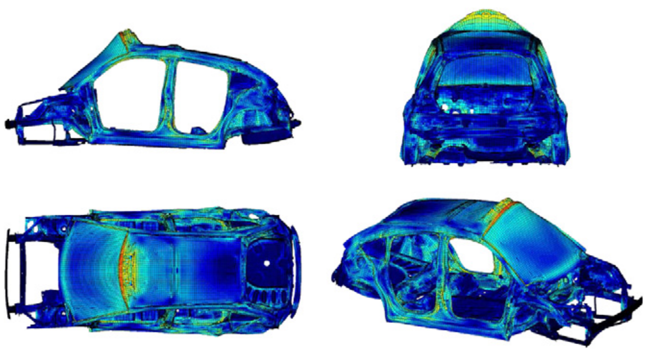

Fig. 20. Third mode of interest.

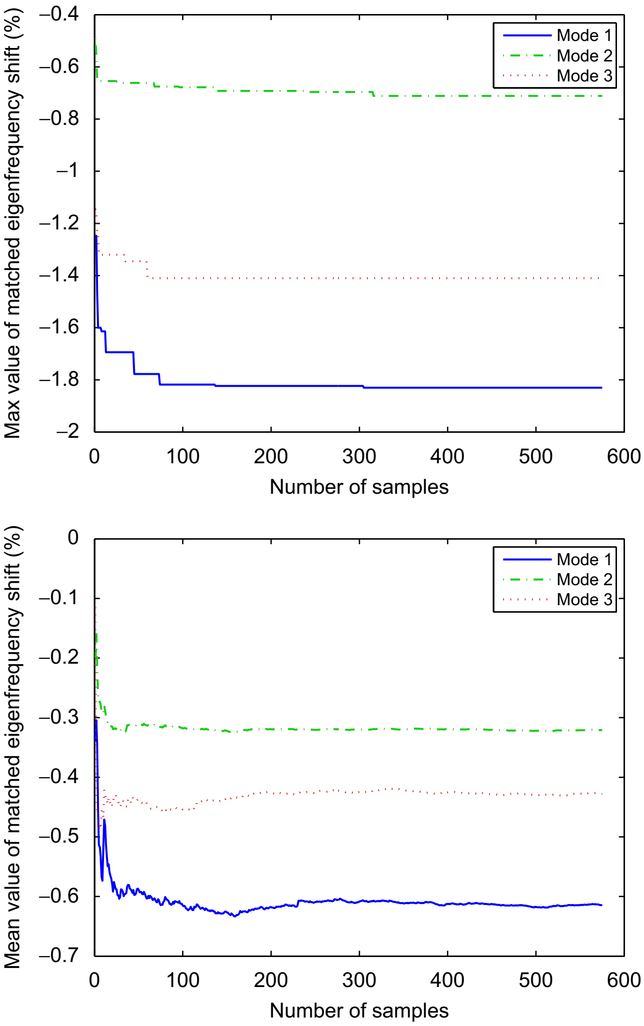

Fig. 21. Convergence of matched eigenfrequency error: mean and maximum values.

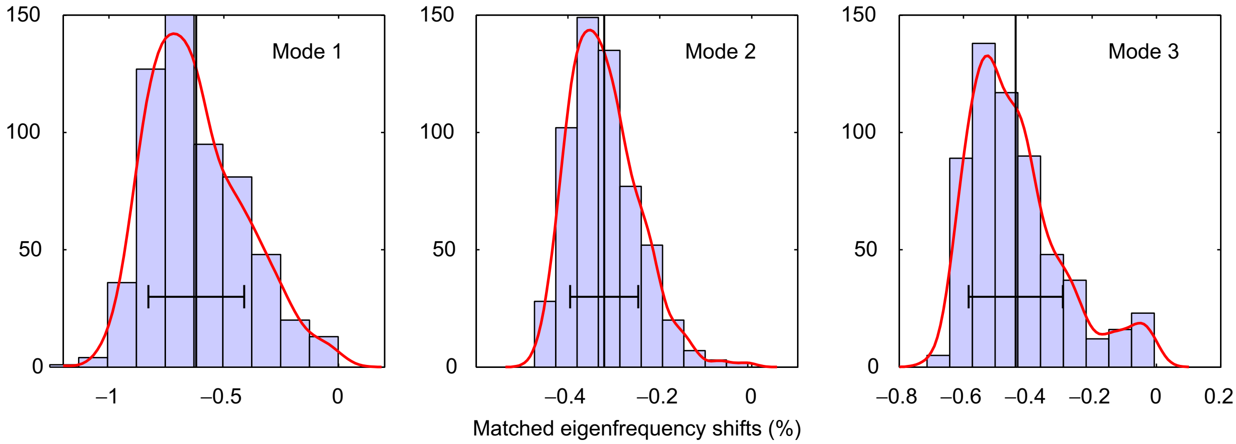

Fig. 22. Histograms and approximate distribution of the matched eigenfrequency shifts for the three modes of interest (580 samples, 4% removed spot welds). The vertical line indicates the mean value while the horizontal mark corresponds to $\pm$ standard deviation.

value, this is a more difficult task and with testing all of the configurations, we can never be sure we have reached the global maximum value. Fig. 21 shows that, despite this fact, the maximum value does not evolve so much after about 100 samples.

This indicates that some pertinent information can be obtained using only a reduced number of samples, even if the full convergence is not reached.

Fig. 22 shows the histograms and approximated distribution of matched eigenfrequency shifts for the three modes of interest. The approximated distribution is normalized using the area of the histogram, and it has been evaluated using a windowed normal kernel function [13]. The figure also shows the mean value and the standard deviation of each frequency of interest.

References

[1] G. Wang, M. Barke, Fatigue cracking and its influence on dynamic response characteristics of spot welded specimens, Experimental Mechanics 44 (5) (2004) 512–521.

[2] P. Salvini, F. Vivio, V. Vullo, A spot weld finite element for structural modelling, International Journal of Fatigue 22 (8) (2000) 645–656 10.1016/S0142-1123(00)00044-X.

[3] M. Palmonella, M.I. Friswell, J.E. Mottershead, A.W. Lees, Finite element models of spot welds in structural dynamics: review and updating, Computers & Structures 83 (8–9) (2005) 648–661 10.1016/j.compstruc.2004.11.003.

[4] N. Pan, S. Sheppard, Spot welds fatigue life prediction with cyclic strain range, International Journal of Fatigue 24 (5) (2002) 519–528 10.1016/S0142-1123(01)00157-8.

[5] W. Fricke, Fatigue analysis of welded joints: state of development, Marine Structures 16 (3) (2003) 185–200 10.1016/S0951-8339(02)00075-8.

[6] Y. Zhang, D. Taylor, Optimization of spot-welded structures, Finite Elements in Analysis and Design 37 (12) (2001) 1013–1022 10.1016/S0168-874X(01)00046-4.

[7] S.-W. Chae, K.-Y. Kwon, T.-S. Lee, An optimal design system for spot welding locations, Finite Elements in Analysis and Design 38 (3) (2002) 277–294 10.1016/S0168-874X(01)00064-6.

[8] M.-W. Huang, J.S. Arora, Optimal design with discrete variables: some numerical experiments, International Journal for Numerical Methods in Engineering 40 (1) (1997) 165–188.

[9] S. Donders, M. Brughmans, L. Hermans, C. Liefooghe, H.V. der Auweraer, W. Desmet, The robustness of dynamic vehicle performance to spot weld failures, Finite Elements in Analysis and Design 42 (8–9) (2006) 670–682 10.1016/j.finel.2005.10.012.

[10] M. Ouisse, J.L. Guyader, An energy residual method for detection of the causes of vibration hypersensitivity, Journal of Sound and Vibration 260 (1) (2003) 83–100 10.1016/S0022-460X(02)00901-X.

[11] M. Ouisse, J.L. Guyader, Localization of structural zones producing hypersensitive behavior: finite element approach, Computer Methods in Applied Mechanics and Engineering 192 (44–46) (2003) 5001–5020 10.1016/S0045-7825(03)00462-6.

[12] G.I. Schuëller, Computational stochastic mechanics—recent advances, Computers & Structures 79 (22–25) (2001) 2225–2234 10.1016/S0045-7949(01)00078-5.

[13] A. Bowman, A. Azzalini, Applied Smoothing Techniques for Data Analysis, Oxford University Press, Oxford, 1997.