Robust optimization and quality control in spot welded structures

Q. I. Bhatti and M. Ouisse and S. Cogan

Abstract The performance characteristics (i.e., static, dynamic, crash, etc.) of a spot welded structure are strongly influenced by the number and the locations of the resistance spot welds. The design problem requires the number and locations of spot welds to be optimized so as to obtain reasonable trade-offs between manufacturing costs and structural performances. An optimization procedure is proposed which iteratively adds and removes spot welds in order to correct for approximations made in the iterative process. Moreover, a robustness indicator is formulated that allows to analyze the impact of the number of defective or broken spot welds on the system performance. This indicator provides a useful decision making tool for deciding both how many spot welds should be inspected following assembly as well as pointing to a small number of critical spot welds that should be reinforced. The proposed methodology will be illustrated on a full body-in-white structure.

1 Introduction

Resistance spot welding is one of the main manufacturing techniques for sheet metal structures and the automotive industry, for example, uses thousands of resistance spot welds (abbreviated RSW or spot weld) to assemble the body-in-white (BIW) for vehicles. Meanwhile, global competition pushes the automotive industry to re-

Q. I. Bhatti
FEMTO-ST Applied Mechanics, University of Franche-Comté, 24, rue de l'épitaphe, 25000 Besançon - France, e-mail: qamar.bhatti@femto-st.fr

M. Ouisse
FEMTO-ST Applied Mechanics, University of Franche-Comté, 24, rue de l'épitaphe, 25000 Besançon - France, e-mail: morvan.ouisse@univ-fcomte.fr

S. Cogan
FEMTO-ST Applied Mechanics, University of Franche-Comté, 24, rue de l'épitaphe, 25000 Besançon - France, e-mail: scott.cogan@univ-fcomte.fr

T. Proulx (ed.), *Linking Models and Experiments, Volume 2*, Conference Proceedings of the Society for Experimental Mechanics Series 5, 297
DOI 10.1007/978-1-4419-9305-2_21,

duce manufacturing cost and spot welds represent a significant contribution to the overall cost of the vehicle. Therefore, it is a worthwhile task to reduce the number of RSWs on the vehicle without compromising the performances. Due to mass production, even a small reduction in their number could lead to substantial reduction in the cost. However, the number and spatial distribution of spot welds has a significant impact on the structural performance criteria that must be taken into account by an analyst including the static, dynamic, and crash behaviors.

Currently, the numbers of spot welds and their locations are largely based on the designer's technical know-how and experience. However, this proves to be a daunting task for even the most experienced designers and problem has not been fully addressed by the research community. Some authors have examined the issue of improving the performance criteria by optimally relocating a fixed number of spot welds in the structure [2, 4, 5, 12, 13]. However, attempting to solve the optimization problem based on a fixed number of spot welds, where one is interested in finding the best locations, can pose two problems. First, this number may be too small and the solution may not be feasible even for the best distribution. Secondly, *a priori* defined number of RSWs may be too large and the overall production cost will be high due to the presence of redundant spot welds. This suggests that not only the locations but also the number of RSWs should be included in the optimization procedure as a variable to be determined. Thus, the aim should be to minimize the number of RSWs and find the best distribution of the existing number of RSWs simultaneously, so as to ensure an acceptable level of performance as dealt in [6–11].

Although simulation time for large and complex structures has been reduced over the years, the iterative nature of the discrete optimization problem still requires careful attention to calculation costs. Hence, in order to optimize the number of spot welds on the structures containing thousands of RSWs in a reasonable time, a simple decision making indicator is needed which can predict the contribution of the individual RSW towards the performance criteria. This indicator will not only be helpful to find the locations of the most influential RSWs but will also serve to indicate the redundant RSWs whose contributions towards the performance criteria are negligible. Bearing this in mind, we propose an optimization procedure which uses the elastic strain energy based indicator to remove the redundant spot welds and simultaneously, adds the new spot welds in the proximity of the most influential RSWs.

Another aspect of this study concerns the impact of uncertainty in the form of missing or defective RSWs on the structural performances. Indeed, when a BIW leaves the assembly line it is not unusual to find a small percentage of spot welds missing. Moreover, fatigue effects through the lifetime of the vehicle can lead to the breakage of spot welds. The important question to address here is just how many RSWs can be defective without compromising the specified performance criteria. In [3, 8], authors have used Monte Carlo (MC) simulations to study this problem under the assumption that each spot weld has equal chance of being defective or missing.

However, large number of analyses required for a meaningful MC simulation renders its use impractical. Hence, we propose a simple and less costly approach based on the impact of the most influential spot welds on the modal behavior. The objective is to plot a robustness curve showing the evolution of eigenfrequencies when progressively more influential spot welds are defective or missing. This robustness curve also serves as a useful decision making tool for deciding both how many spot welds should be inspected following assembly as well as pointing to a small number of critical spot welds that should be reinforced.

This presentation is organized as follows. In next section, optimization procedure is presented along with a brief description of decision making indicator for modal behavior. FE models are presented followed by optimization results. In sec 3 the issues related to robustness and quality control of a small percentage of influential spot welds are presented and finally, the conclusions of the study are drawn in the last section.

2 Spot weld optimization

2.1 Description of optimization procedure

A flowchart of the proposed optimization procedure is shown in the fig 1. The procedure will remove the redundant spot welds from the structure and simultaneously, will add the spot welds at the sensitive locations to the proximity of the most influential RSWs. This implies that either software has capability to create new spot welds when and where needed, or that a pool of candidate spot welds is already available in the numerical model which can be activated when needed. A decision making indicator presented later on will be used to rank the existing spot welds signifying their contribution to the performance criteria of interest.

2.2 Decision making indicator

The decision making indicators are the tools implemented in the spot welding optimization procedure to select the spot welds which are redundant and should be removed or those which are critical and should be reinforced. The indicators are used to correlate the contribution of individual spot welds to the target behavior and ideally should be easily calculated and lead to unambiguous choices. Two categories of indicators can be envisaged, namely *a priori* and *a posteriori*. The former are indicators which forecast in advance the influence of spot welds without removing them from the structure while the latter require the explicit removal of the spot welds from the structure. In practice, *a posteriori* indicators are very costly to evalu-

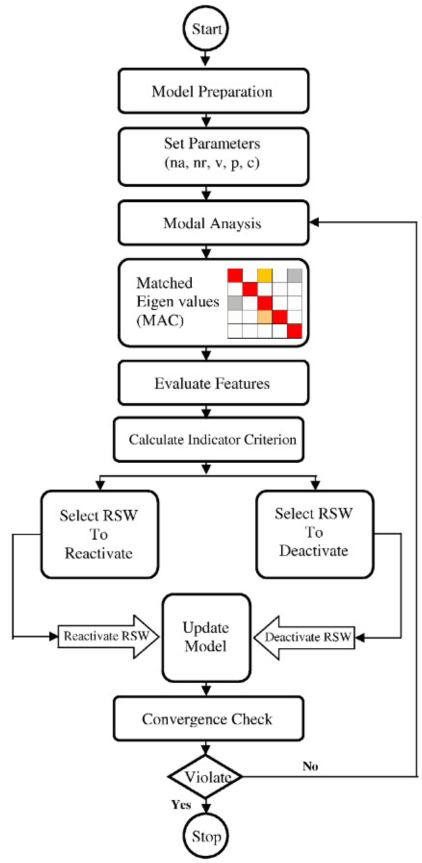


Fig. 1 Flowchart of the optimization procedure

ate since they require a large number of full model analyses while *a priori* indicators are generally far more efficient in terms of computational time.

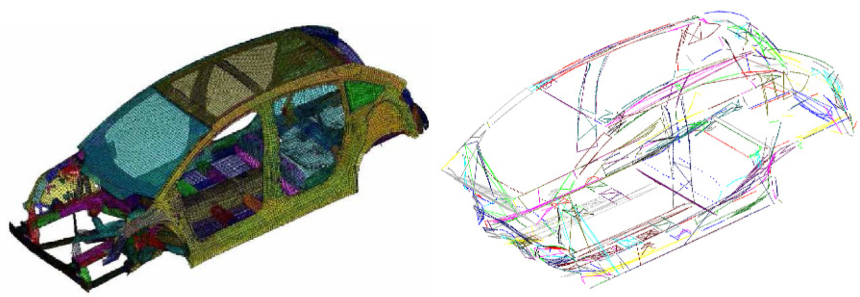
Elastic strain energy of the elements is assumed to be very closely linked with the eigenfrequency shift, thus we decide to use *a priori* indicator based on elastic strain energy in spot weld and its adjacent shell elements. Additionally, the energy is normalized by the volume of the adjacent shell elements in order to remove the effect of their varying sizes. The indicator value for *ith* spot weld for mode *k* can be expressed as:

$$I_{i,k} = U_k^T K^{e,i} U_k + U_k^T K^{sh,i} U_k \frac{V_m^{sh,i}}{V_{tot}^{sh,i}}, \tag{1}$$

where $K^{e,i}$ is the stiffness matrix of *ith* RSW, $K^{sh,i}$ is the stiffness matrix of shell elements adjacent to *ith* RSW, U_k is the eigenvector k while $V_m^{sh,i}$ and $V_{tot}^{sh,i}$ are respectively the mean volume and the total volume of shell elements adjacent to ith RSW.

2.3 Finite element model

The procedure is applied to a full body-in-white of a car. MSC.Nastran [1] FE model having approximately 1,000,000 dofs is meshed with 119498 CQUAD4 and 3459 CTRIA3 shell elements, 793 CHEXA solid elements and 14092 CLEAS1 spring elements as shown in fig 2(a). The subparts are assembled along 382 interfaces containing a total of 2612 active spot welds represented by CBUSH type FE spot weld model [8]. Initial spatial spot welds distribution and interfaces are shown in fig 2. The number of RSWs and eigenfrequencies of this design will be taken as references to calculate the relative shifts in frequencies and the increase or decrease in the number of RSWs.



(a) (b)

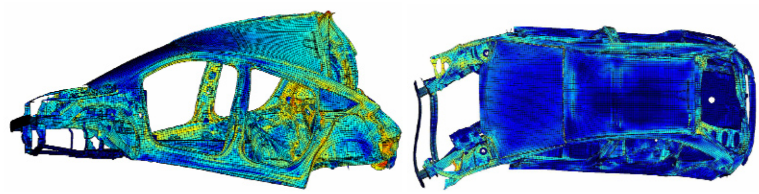
Fig. 2 Body-in-white (**a**) finite element model (**b**) interface definitions (total interfaces: 382, total RSWs: 2612)

The optimization procedure requires new spot welds to be added in the structure, thus we created a pool of 1494 (57% of the original model) candidate RSWs uniformly along the different interfaces that can be added as required. Note that the RSWs removed during the optimization process will be placed in the pool of the candidate RSWs and will thus can be reactivated again if necessary.

2.4 Illustration

In this study, the objective is to minimize the number of spot welds while keeping the eigenfrequencies of the first torsion and bending modes higher than to those of the nominal design.

The first torsion and bending modes of the nominal design are shown in fig 3. MSC.Nastran is used to perform the modal analysis up to 65 Hz and takes almost 20 minutes on a Windows XP professional based computer having processor speed of 3.0 GHz with 2.0 GB RAM.



(a) (b)

Fig. 3 Modes shapes (**a**) torsion mode. (**a**) bending mode

Figure 4 shows the evolution of both eigenfrequencies during the optimization process. The procedure efficiently removed more than 14% of the total RSWs in only 6 iterations while both eigenfrequencies of the final design are better than those of the nominal design: 0.61% higher for mode 1 and 0.1% higher for mode 2. Note that the eigenfrequencies continue to improve despite of the fact that the total number of RSWs is decreasing. This is due to the addition of RSWs at the critical interfaces having higher influence. The final distribution of RSWs is shown in fig 5.

The proposed procedure is also designed to improve the robustness of the structure against defective or missing spot welds. This objective is achieved implicitly by sharing the loads of critical spot welds by adding the new spot welds at sensitive locations to their proximity. As a result, their indicator values will decrease, reflecting that if missing will produce less variations in the eigenfrequencies. To visualize this for the current illustration, we plotted the indicator values of first 270 spot welds of highest values for the nominal as well as the optimized designs in fig 6. Decreases in the indicator values of individual spot welds as well as in the mean values can clearly be observed. This means that optimized design is certainly now more robust against missing of spot welds and we will verify this fact in *a posteriori* robustness analysis in the next section.

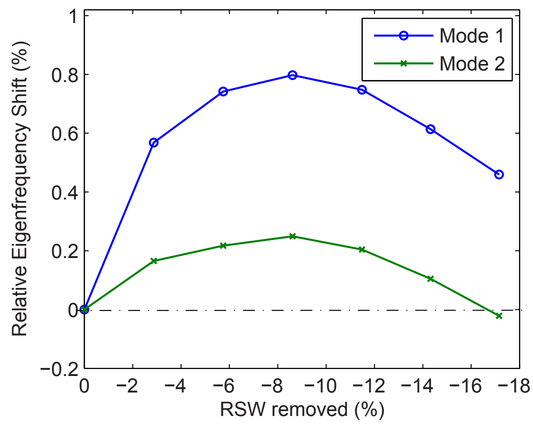


Fig. 4 Evolution of targeted eigenfrequencies during the optimization process

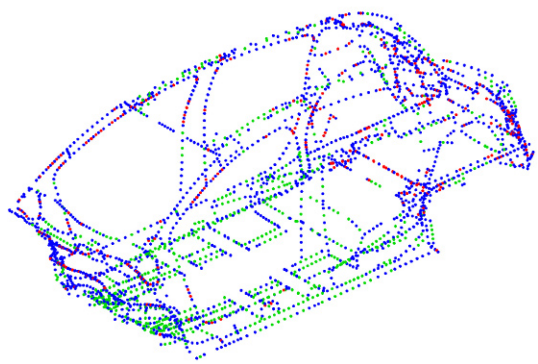


Fig. 5 Final distribution of the RSWs (blue: retained, green: removed, red: added)

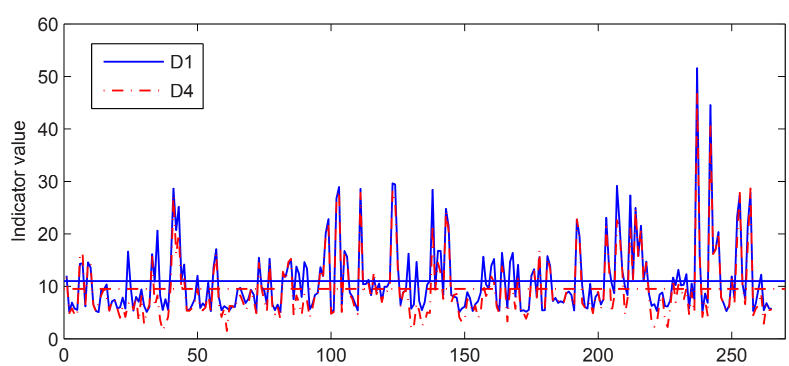


Fig. 6 Indicator values of first 270 spot welds of higher values (horizontal lines represent the mean values for these spot welds)

3 A posteriori robustness analysis and quality control methodology

In this work, we quantify the robustness as the worst case scenario among all possible design configurations due to uncertainty in term of defective or missing spot welds. The structure will be considered more robust which have low worst case variation due to missing of a specific number of spot welds. Alternatively, the structure is to be considered more robust which can afford to loose higher number of spot welds without compromising a specified critical performance limit.

As discussed earlier, while a MC simulation is potentially a straightforward way to quantity the robustness of a spot welded structure to defective or missing spot welds, large number of analyses required, renders its use impractical in the present context. Hence, we propose a simple and less costly approach based on an examination of the impact of the most influential spot welds on the performance criteria of interest. It has already been shown that the spot welds with higher indicator values have relatively stronger influence on the eigenfrequencies than the spot welds with lower indicator values [3, 8]. Therefore, they will be used to define a worst-case degradation curve as a function of an increasing number of missing of the most influential spot welds.

The goal is to draw the robustness curve showing the sensitivity of performance when the most influential spot welds are defective or missing. This robustness curve allows the impact of the number of defective or missing spot welds on the system performance to be analyzed in order to define a set of critical spot welds that should be quality controlled or reinforced. This curve also serves as a useful tool for deciding how many spot welds should be inspected following assembly while taking into account total number of RSWs and specific robustness level.

3.1 Procedure to obtain the robustness curve

The proposed procedure to obtain the robustness curve can briefly be described as follows:

1. all existing spot welds are ranked according to decreasing value of the indicator criteria,
2. a predefined number of spot welds of higher ranks are selected for removal,
3. an analysis is performed to evaluate the impact of removed spot welds on the modal behavior,
4. the indicator criteria is calculated for the remaining spot welds,
5. stop, if stopping criteria is met, otherwise, go to the first step.

3.2 Illustration

We applied the procedure on the nominal (2612 spot welds) and optimized (2238 spot welds) designs in order to quantify the robustness and analyze their relative behavior as a function of increasing number of missing of the most influential spot welds. The robustness curves were obtained due to missing of up to 100 spot welds by removing 10 spot welds of highest indicator values in each iteration. The number of RSWs removed in each iteration may be increased or decreased considering the trade-off between the total number of spot welds to be checked and the time required by one numerical analysis.

The robustness curves obtained for both modes are shown in fig 7 for both designs. The eigenfrequencies of the nominal design were taken as references to calculate the relative eigenfrequency shifts. The curves illustrate that optimized design is relatively less sensitive to the missing of spot welds despite of the fact that it contains 14% less number of spot welds. In other words, it can afford to loose more number of most influential spot welds before violating a specified level of degradation in the eigenfrequencies: for example to observe a 6.0% relative eigenfrequency shift for mode 1, optimized design can loose up to 100 most influential spot welds while nominal design requires only 40 spot welds. This gain in robustness is achieved in the optimization process by adding the spot welds on the sensitive regions in the proximity of critical spot welds. In turn, impact of the critical spot welds decreased, reflected by the decreases in indicator values of these critical spot welds as observed in fig 6.

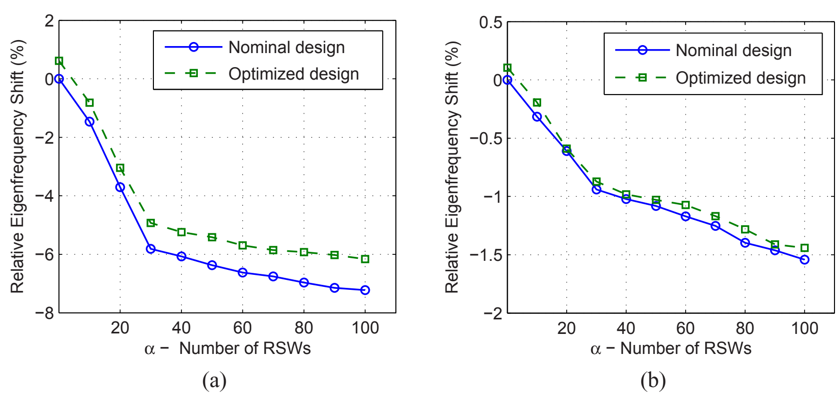


Fig. 7 Robustness curves for two modes (**a**) mode 1 (**b**) mode 2

However, note that most of the degradations in the eigenfrequencies are due to only the first 30 RSWs for both designs. This implies that these are the most critical RSWs and need special attention of the designer. This is a valuable feedback and designer can use this auxiliary information in various ways such as:

- design of a small number of critical spot welds can be modified to improve their performance characteristics,
- subparts joined by the critical spot welds can be redesigned to absorb their adverse impact,
- most critical spot welds may be quality controlled to ensure their effective presence.

3.3 Effect of quality control on robustness

As noted that after optimization, there still remains few spot welds if missing can cause large variations in the performance criteria. Hence, to take an advantage of the information obtained by robustness curves, we propose a quality control of limited number of spot welds in order to guarantee the robustness of the population of identical structures within acceptance level due to missing of remaining uncontrolled spot welds.

Let us assume that first 20 spot welds identified while obtaining the robustness curves for optimized design are quality controlled and thus effectively present on the structure. The procedure was applied again to obtain the robustness curves for the remaining uncontrolled spot welds. New robustness curves along with the initial curves without quality control of spot welds are shown in fig 8 for both modes. See the remarkable improvement in robustness as up to 3 times lower worst case variations are observed now for mode 1 up to missing of 100 most influential spot welds.

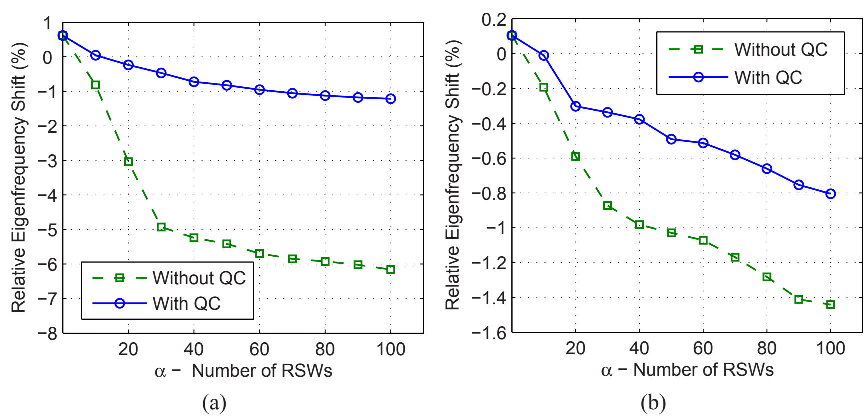


Fig. 8 Robustness curves for two modes after quality control of 20 RSWs (**a**) mode 1. (**b**) mode 2

To further very the methodology, we performed the MC simulations with strain-weighted selection scheme [8] without and with quality control of 20 spot welds for optimized design. 75 samples with 100 missing spot welds have been used for each simulation. Their scatter clouds are shown in fig 9 along with worst case variations obtained by our proposed procedure for missing of the same number of spot welds.

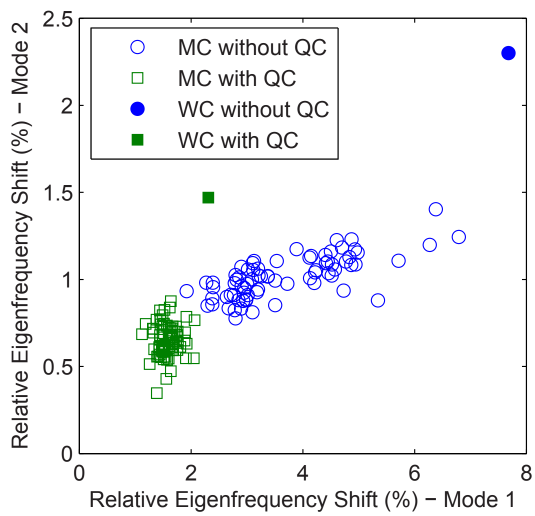


Fig. 9 Scatter clouds of MC simulations along with worst case variations

Results confirm firstly, effectiveness of quality control methodology to guarantee the impact of failure in the remaining uncontrolled spot welds within acceptable level: spread of eigenfrequencies shifts are much smaller for quality controlled spot welds formulation, secondly, procedure proposed to obtain robustness curve is efficient as well as accurate: 10 analyses required to find the worst case variations while 75 analyses for MC simulations are unable to find the worst case variations of the same degree.

Nevertheless, the important question lies in finding an acceptable compromise between robustness and the cost of controlling additional spot welds following assembly or the cost of reinforcing critical spot welds to avoid failure during the lifetime of the vehicle.

To answer this question, the behavior of missing of uncontrolled spot welds on the eigenfrequency is analyzed as a function of the number of quality controlled spot welds for optimized design up to relative eigenfrequency shift of 1.0% for mode 1. Maximum 40 spot welds are considered for quality control. Curves in fig 10 show that the design is becoming less sensitive to missing spot welds as the number of quality controlled spot welds increases. These curves show that there is no gain in robustness in case of controlling 10 spot welds but the robustness increases rapidly above this number.

In conclusion, an analyst can use this approach to select the design taking into account trade-offs between the total number of spot welds, the impact of missing spot welds, and the number of quality controlled spot welds to ensure a specific level of satisfaction.

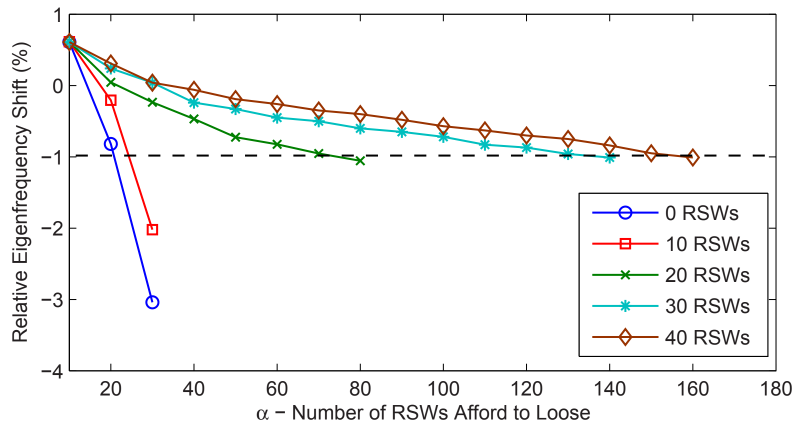


Fig. 10 Effect of increased number of quality controlled RSWs

4 Conclusions

An optimization procedure is presented which iteratively adds and removes spot welds to find the optimal distribution as well as the number of spot welds needed to improve the performance characteristics of interest. Meanwhile, the structural performances can be undermined by the presence of defective or missing spot welds due to manufacturing defects or fatigue. A simple approach is formulated to analyze the impact of the number of defective or missing spot welds on the system performance with the goal of replacing the more cost intensive sampling based approaches found in the literature. This approach can not only provide a measure of robustness but also could serve as a useful tool to provide insight into the most influential spot welds as well as for deciding how many spot welds should be inspected following assembly. The analyst can then ensure a specific level of robustness either by quality controlling or redesigning of these small number of spot welds.

Acknowledgements

The authors would like to thank PSA Peugeot-Citroën for providing the finite element model of the body-in-white.

References

[1] MSC.Nastran, version 2004 edn. MSC (2004)
[2] Chae, S.W., Kwon, K.Y., Lee, T.S.: An optimal design system for spot welding locations. Finite Elements in Analysis and Design **38**(3), 277 – 294 (2002)
[3] Donders, S., Brughmans, M., Hermans, L., Liefooghe, C., der Auweraer, H.V., Desmet, W.: The robustness of dynamic vehicle performance to spot weld failures. Finite Elements in Analysis and Design **42**(8-9), 670 – 682 (2006)
[4] Eom, J.S., Ju, B.H., Choi, N., Park, J.M., Lee, B.C., Byun, H.B.: Optimization on the spot welded configuration of vehicle components considering the structural performance. Key Engineering Materials **362-328**, 957–962 (2006)
[5] Ertas, A.H., Sonmez, F.O.: Optimization of spot-weld joints. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science **223**(3), 545–555 (2009)
[6] Hasegawa, H., Sasaki, H., Uehara, H., Kawamo, K.: Optimization of spot-weld positions for vehicle design by using hybrid meta-heuristics. International journal of vehicle design **43**(1-4), 151–172 (2007)
[7] Liao, Y.G.: Optimal design of weld pattern in sheet metal assembly based on a genetic algorithm. The International Journal of Advanced Manufacturing Technology **26**(5), 512 – 516 (2005)
[8] Ouisse, M., Cogan, S.: Robust design of spot welds in automotive structures: A decision-making methodology. Mechanical Systems and Signal Processing **24**(4), 1172 – 1190 (2010)
[9] Puchner, K., Dannbauer, H., Meise, M.: Spot weld optimization regarding stiffness and fatigue using standard software. SAE 2006 World Congress and Exhibition, Detroit, MI, USA (2006)
[10] Wang, L., Levia, J.P., Basu, P.K.: Design optimization of automobile welds. International journal of vehicle design **31**(4), 377–391 (2003)
[11] Xiang, Y., Wang, Q., Fan, Z., Fang, H.: Optimal crashworthiness design of a spot-welded thin-walled hat section. Finite Elements in Analysis and Design **42**(10), 846 – 855 (2006)
[12] Yamaguchi, A., Wakana, G., Obayashi, K., Okabe, T., Muller-Bechtel, M.: Spot-weld layout optimization for body stiffness by topology optimization. SAE International technical paper no. 2008-01-0878 (2008)
[13] Zhang, Y., Taylor, D.: Optimization of spot-welded structures. Finite Elements in Analysis and Design **37**(12), 1013 – 1022 (2001)