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Design optimization of spot welded structures to attain maximum strength

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Abstract. This study presents design optimization of spot welded structures to attain maximum strength by using the Nelder-Mead (Simplex) method. It is the main idea of the algorithm that the simulation run is executed several times to satisfy predefined convergence criteria and every run uses the starting points of the previous configurations. The material and size of the sheet plates are the pre-assigned parameters which do not change in the optimization cycle. Locations of the spot welds, on the other hand, are chosen to be design variables. In order to calculate the objective function, which is the maximum equivalent stress, ANSYS, general purpose finite element analysis software, is used. To obtain global optimum locations of spot welds a methodology is proposed by modifying the Nelder-Mead (Simplex) method. The procedure is applied to a number of representative problems to demonstrate the validity and effectiveness of the proposed method. It is shown that it is possible to obtain the global optimum values without stacking local minimum ones by using proposed methodology.

Keywords: optimal design; spot weld; Finite Element Analysis (FEA); modified Nelder-Mead (Simplex) method; mechanical strength

1. Introduction

Resistance spot welding (RSW) is accepted as the primary joining method especially for automotive and railroad structures because of its advantages such as their simplicity, economical, and reliability. Another important reason is the adaptation of the resistance spot welding (RSW) to automation in a mass production environment.

Spot welds are especially crucial to the automotive industry. According to studies, a coach or bus body contain hundreds, even thousands spot welds (Ertas *et al*. 2009). In the view of such information it can be said that the dominating joining technique in the vehicle assembly process is resistance spot welding (RSW).

Because spot welds are widely used in almost all kind of industries, there are many works related to the effects of the design parameters on spot welded structures in the literature. For example, the effects of spot weld diameter (Ertas and Sonmez 2011, Zhou *et al*. 1999, Kang *et al*. 2000, Gean *et al*. 1999, Di Fant-Jaeckels and Galtier 2000, Zhang 1997, Davidson and Imhof 1983, Thornton *et al*. 1996), number of spot welds, positions and layouts (Ertas and Sonmez 2011,

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Mundo *et al*. 2009, Soderberg *et al*. 2012, Jie 2010, Perez *et al*. 2013, Fang *et al*. 2014, D'lppolito *et al*. 2009, Pakalapati *et al*. 2011, Gean *et al*. 1999, Di Fant-Jaeckels and Galtier 2000, Adib *et al*. 2004, Matsoukas *et al*. 1984, Pook 1975), metal sheet thickness (Zhou *et al*. 1999, Di Fant-Jaeckels and Galtier 2000, Zhang 1997, Matsoukas *et al*. 1984, Pan and Sheppard 2002, Pollard 1982, Bae *et al*. 2003), metal sheet width (Zhou *et al*. 1999, Zhang 1997, Davidson and Imhof 1983, Bae *et al*. 2003), joint type (Kang *et al*. 2000, Gean *et al*. 1999, Zhang 1997, Davidson and Imhof 1983, Thornton *et al*. 1996, Pan and Sheppard 2002, Pollard 1982, Bae *et al*. 2003, Wonseok *et al*. 2004, Rathbun *et al*. 2003), material (Grujicic *et al*. 2009, Gean *et al*. 1999, Di Fant-Jaeckels and Galtier 2000, Thornton *et al*. 1996, Pollard 1982, Rathbun *et al*. 2003, Linder and Malender 1998, Newman and Dowling 1998, Xu and Deng 2000) were investigated both experimentally and numerically. These studies show that failure mechanism of a spot-welded structure is closely related to the stress values -especially at the peripheries of the spots-, spot weld diameters, and metal sheet thicknesses. Hence design and optimization of spot welds under typical loading conditions have been drawing attention of researchers. Understanding the mechanical behavior of spot-welds as well as plates is important in structural integrity assessment (Ertas and Sonmez 2009).

The primary factors which determine the performance of spot welded structures are location and number of spot welds (Ertas and Sonmez 2011, Lee *et al*. 2004). Optimization of the number and location of the spot welds used under different loading conditions is a major economic consideration. For example, a small reduction of the number of spot welds, through their efficient and optimal usage, can mean a great saving in production costs (Ertas and Sonmez 2011, Zhang and Taylor 2001).

Studies on optimization usually involve numerical work. It is important to note that while experimental studies provide the necessary physical insight about the behavior of spot-welded joints, predictive tasks such as design, analysis, and evaluation of spot-welded structures are often carried out by computational methods. In addition, optimization of the spot weld joints via experimental studies is not practicable because of economical reasons. Hence the design optimization method should rely on numerical tools (Ertas and Sonmez 2009, 2011).

In the literature, there are lots of optimization techniques, grouped as nonlinear, linear, geometric, dynamic, integer, and stochastic. In this study, a linear type of optimization technique which is The Nelder-Mead (Simplex) algorithm is used. The Nelder-Mead (Simplex) algorithm is a popular search method for multidimensional unconstrained optimization. This method does not require the functions to be differentiable or continuous which makes the algorithm favorite in different engineering problems in industry (Rao 1996). However, the developed program may stuck into a local minimum point rather than the globally minimum one because of both the program's feature and also the structural problem considered, that is structural optimization problems may contain many locally minimum configurations. Hence, the solution may change depending on the starting points. To eliminate this problem and to obtain the globally minimum configuration, the algorithm has been modified via using a general loop and employed many times starting from previous different configurations for every problem just make sure that the solutions are general optima.

2. Problem statement

In the present study, the geometry (Fig. 1) (l = 300 mm, w = 300 mm, t = 1 mm), material of the metal sheets, material and size of the spot welds (d = 4 mm), and loading conditions (in plane loads: through "x" direction, through "y" direction, through both "x" and "y" directions) are assumed as predetermined. The locations ("x_i" and "y_i") of spot welds are selected as design variables.

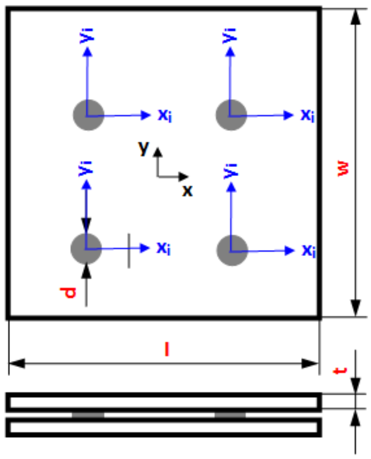

Fig. 1 Geometry of square plate with four spot weld joints and design variables (top and side views)

In this modified algorithm, the program has created different starting points by itself automatically via a second loop. Then the analysis were repeated using the so called starting points until to obtain the globally or near globally optimum configuration. The considered problem with the boundaries has also been repeated using different number of spot welds (2 spots, 3 spots, and 4 spots) to investigate the effect of spot weld number to the strength of the structure considered. The material properties and other details belong to structure can be found in the following reference (Ertas and Sonmez 2009).

In the present problem, the objective is to minimize the maximum equivalent (von-Misses) stress value, $S_{\max}$, and accordingly increase fatigue life of the structure.

$$\text{minimize } S_{\max} \tag{1}$$

When the objective is considered, side constraints have to be considered to design a proper structure. According to industrial organizations like American Welding Society (AWS), in spot welded structures the design should conform to the standards related to weld-to-weld spacing and weld-to-edge distance. For instance, the distance between an edge and the center of a spot weld should be greater than one spot weld diameter, d. Accordingly, the constraint equations are given as

$$\begin{gathered} -[(l/2)-d] \le x_i \le [(l/2)-d] \\ \& \\ [x_i - x_{i+1}] \ge 5*t \end{gathered} \tag{2}$$

$$\begin{gathered} -[(w/2)-d] \le y_i \le [(w/2)-d] \\ \& \\ [y_i - y_{i+1}] \ge 5*t \end{gathered} \tag{3}$$

where “l” and “w” represent the side lengths of the square plate as seen in Fig. 1. Besides, the distance between the centers of the spot welds should be greater than twice the spot weld diameter as recommended by the industry. Then

$$s_{ij} \geq 2d \tag{4}$$

where s_{ij} is the distance between spot welds i and j.

3. Methodology

3.1 General solution procedure

To integrate the design optimization procedure, a code utilizing the built-in parametric language of commercially available finite element analysis software, ANSYS, was developed by (Ertas and Sonmez 2009). However, the so called algorithm can be used for limited number of design variables. Additionally to make sure that the global or near global optimal values are obtained different starting points are used by the user which are both time consuming and boring process for the users. In this study, however, the previous algorithm has been improved, hence it can be used to find globally or nearly globally optimum values for complex problems, that is having much more variables, defining just one starting point for the program.

Because the locations of spot welds are selected as design variables, they are changed iteratively during the optimization process. For searching process, Nelder-Mead (Simplex) method (Haftka and Gurdal 1992, Vasiliev and Gurdal 1999, Ertas and Sonmez 2011) is used. The objective function, i.e., maximum equivalent (von-Misses) stress, is recalculated whenever the design is changed. The resulting von-Misses stresses developed in each element are sorted, and then the largest value is obtained. The iterations terminate when the convergence criterion is met. Otherwise, the algorithm resumes finding new values for the positions of the spot welds.

3.2 Search algorithm

The sequential simplex method was first proposed by Spendley, Hext, and Himsworth (Spendley *et al*. 1962). Then the method was improved by Nelder and Mead (Nelder and Mead 1965). Because of this sequential simplex method is also known as Nelder-Mead method.

The search algorithm can be summarized as follow: it begins with a regular geometric figure called the simplex requiring N+1 initial sets (vertices) of the design variables in an N-dimensional space, N being the number of the design variables. These vertices can be defined by the origin and by points along each of the N coordinate directions (Ertas and Sonmez 2009, 2011). The following equations are suggested for the calculation of the positions of the vertices of a regular simplex of size “a” in the N-dimensional design space (Haftka and Gurdal 1992).

$$x_i = x_0 + pe_j + \sum_{\substack{k=1 \\ k \neq j}}^{N} qe_k \qquad j = 1, 2, \ldots\ldots, N, \tag{5}$$

where

$$p = \frac{a}{N\sqrt{2}}\left(\sqrt{N+1} + N - 1\right) \quad \text{and} \quad q = \frac{a}{N\sqrt{2}}\left(\sqrt{N+1} - 1\right)$$

where e_k is the unit base vector along the kth coordinate direction, and x_0 is the initial base point. Once the simplex is defined, the objective function is evaluated at each of the N+1 vertices, x_0, x_1, x_2,......, x_N. Let x_l and x_h denote the vertices where the objective function assumes its minimum and maximum values, respectively, and x_s the vertex where it assumes the second highest value. The simplex method discards the highest value and replaces it by a point where objective function has a lower value doing of the following operations, namely "reflection", "contraction", and "expansion". The reflection operation crates a new point x_r along the line joining x_h to the centroid $\bar{x}$ of the remaining point defined as

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i, \qquad i \neq h, \tag{6}$$

The vertex at the end of the reflection operation is calculated by

$$x_r = \bar{x} + (\bar{x} - x_h), \tag{7}$$

If the value of the objective function at this new point satisfies the condition, that is $f_l < f_r \leq f_s$, where $f_l = f(x_l)$ then x_h is replaced by x_r and the process is repeated with this new simplex value. If, on the other hand, the value of the function at the end of the reflection is less than the lowest value of the function, then there is a possibility that it can be further decreased the function by going further along the same direction. It is searched an improved point x_e by the expansion technique using the relation

$$x_e = \bar{x} + 2(x_r - \bar{x}), \tag{8}$$

If the value for this function is smaller than the value at the end of the reflection step, then x_h is replaced by x_e and the process is repeated with the new simplex value. However, if the expansion leads to a function value equal to or larger than the function value of reflection point, then it is formed the new simplex by replacing x_h by x_r and continued.

Finally, if the process of the reflection operation leads to a point x_r such that the function value of reflection is smaller than function value of maximum value, it is performed contraction without any replacement using

$$x_c = \bar{x} + 0.5(x_h - \bar{x}), \tag{9}$$

If the function value of this point is greater than the function value for maximum value, then all the points are replaced by a new set of points

$$x_i = x_i + 0.5(x_l - x_i), \qquad i = 0,1,2,........, N, \tag{10}$$

and the program restart the process with this new simplex. The operation in the last equation causes the distance between the points of the old simplex and the point with the lowest function value to be halved and is therefore referred to as the "shrinkage" operation. Detailed information can be found in (Haftka and Gurdal 1992).

In addition, it should be noted that the plate lengths naturally define the algorithm constraints.

If the configuration returns a logical value, that is if they locate inside the plates region, then the configuration is feasible; if not then the close-loop system is unstable and hence the configuration is infeasible. Infeasible solutions are excluded by penalizing them with very large objective function defined previously.

For the problems considered, the number of initial locations varies depending on the design variables which is the weak side of the algorithm. In other words, it sometimes can go in circles around a minimum and get stuck into local optimum. In order to eliminate the so called problem the algorithm has been modified adding a general loop (Loop 2 in Fig. 2) to consider all possible initial locations.

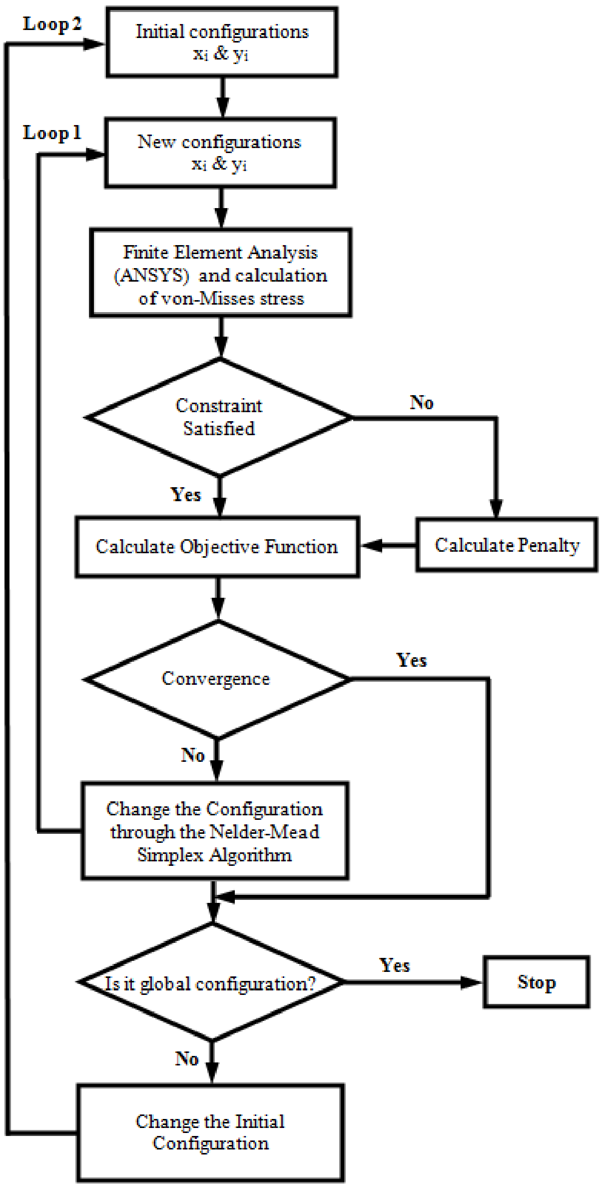

Fig. 2 Flow chart in the design process of the optimization with ANSYS

For the subsequent case, instead of running the program many times starting from previous configurations, the following formula is used to obtain global results

$$x = rand * (x_U - x_L) + x_L \tag{11}$$

where x_L and x_U represent lower and upper bound of the design variables, respectively. "*rand*", on the other hand, represents random number and its value varies between "0" and "1".

Accordingly, it can be said that even if Nelder-Mead is accepted as local optimization method, with this improvement it can be used as a general optimization method. In other words, contrary to the previous study (Ertas and Sonmez 2009, 2011) the proposed algorithm can be safely used to find global optima for all kind of problems having much more design variables. Fig. 2 shows flow chart of the proposed program.

3.3 Finite element analysis

The boundary conditions in the Finite Element Analysis (FEA) model of square plate with four spot weld joints, shown in Fig. 3, can be summarized as follow: displacements and rotations in all degrees of freedom of the upper plate are fixed at left end and uniformly distributed in-plane load (only axial, only transverse and both axial and transverse loading cases) is applied to the right end of the lower plate. As for loading, 3000 N force is uniformly applied both in the "*x*" and/or "*y*" direction(s) on the right surface of the lower plate.

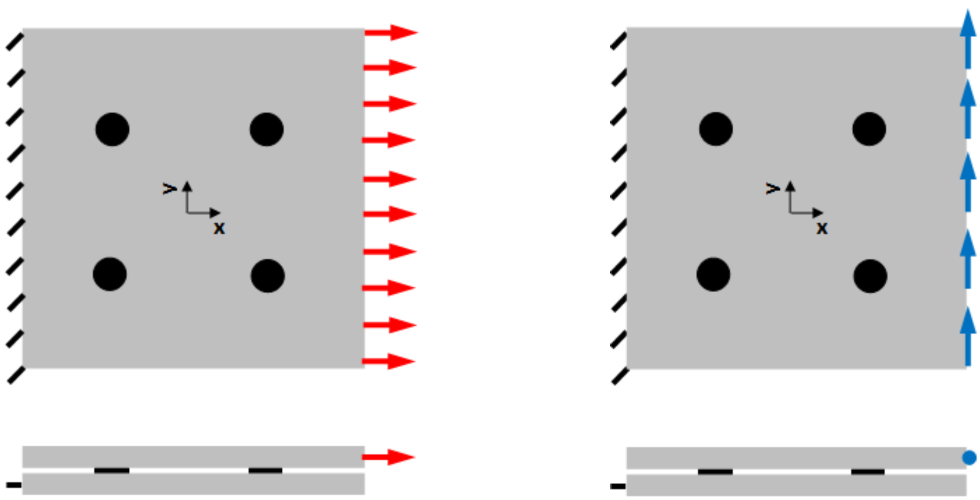

Fig. 3 Boundary conditions of the FEA model for only axial, only transverse and both axial and transverse loading cases

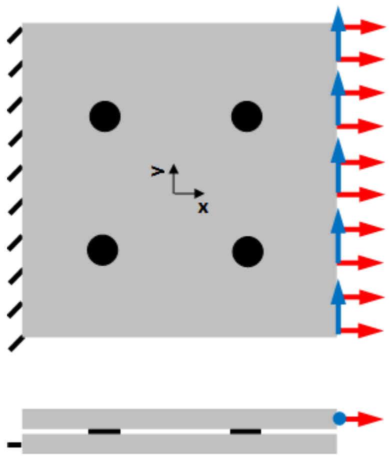

Fig. 3 Continued

In order to perform structural analysis and to determine the stress state developed in the structure, a nonlinear analysis was carried out using a commercial FEA software, ANSYS. The base metal and spot weld nugget were modeled using 3D 10-node tetrahedral solid elements, (SOLID92), and a two-node beam element, (BEAM 188), respectively. Contact elements were defined on the interfaces between the plates. Due to high stress concentrations in the vicinities of the spot welds, much smaller elements in comparison to that of the base metal were used within and around them. In order to obtain an appropriate mesh structure that may enable accurate calculation of the stress state, a convergence analysis was carried out for the element size. Convergence was obtained for 0.002 mm element size. The size of the elements used within and around the spot-weld nugget was chosen to be much smaller than 0.002 mm element size. Because high stress concentration occurs in the vicinities of the spot welds, much smaller elements were used within and around the spot-welds in comparison to that of the base metal. As the positions of the spot welds change during the optimization process, the model is re-meshed and refinement is introduced at the new positions of the welds. The number of elements ranges approximately between 80,000 and 120,000 depending on the number of spot welds in the joint.

4. Results and discussions

In the present study, spot welded structures having different number of spot weld joints (e.g., two, three and four-spot weld joints) and subjected to different in-plane loadings were considered. Optimization results for all plate structures considered are tabulated in Tables 1-9. These tables also include the converged step number of Loop 1 and the last few results of Loop 2. Figs. 5-7 show von-Misses (equivalent) stress (MPa) distribution on the upper sheet's inner surfaces of 2, 3 and 4-spot welded structures, respectively.

Firstly, a two-spot welded joint subjected to different in-plane loadings were considered and accordingly optimized in which spot weld locations ("x_i" and "y_i") were chosen as design variables (Fig. 4). Fig. 4 also shows the location of the reference axis.

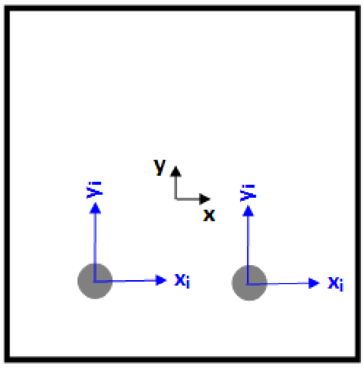

Fig. 4 Geometry of square plate with two spot weld joints and design variables

Tables 1-3 list the last few cases for loop 2 together the converged step number and also corresponding optimization results for loop 1 for different in-plane loads- that is for just axial loading, just transverse loading, and both axial and transverse loading, respectively.

As seen from the Tables 1-3, presenting the results obtained, higher stress values for the plate structure joint by two spots occurred for the case of combining axial and transverse loadings and lower stress values occurred for the just axial loading conditions as it was expected. While the maximum reduction in the stress values during optimization routine are more pronounced for the cases combining axial and transverse loadings (i.e., from 343.89 MPa to 291.23 MPa), this difference is low for the remaining two loading conditions. These are the cases for the plate structure joint by three and four spots (Tables 4-9).

Table 1 Optimization results for the plate structure joint by two spots and subjected to just axial loading

Case No in Loop 2	Converged Step No in Loop 1	x_1 (mm)	y_1 (mm)	x_2 (mm)	y_2 (mm)	S_{max} (MPa)
71	58	12.44	54.18	18.89	-46.45	201.89
72	76	38.45	-50.26	32.18	56.93	201.10
73	62	24.33	91.92	42.72	-71.76	200.41
74	77	18.89	-83.31	50.11	47.92	200.12
75 (converged)	39	-56.64	66.56	-71.53	-90.03	197.82

Table 2 Optimization results for the plate structure joint by two spots and subjected to just transverse loading

Case No in Loop 2	Converged Step No in Loop 1	x_1 (mm)	y_1 (mm)	x_2 (mm)	y_2 (mm)	S_{max} (MPa)
79	58	-76.43	98.06	126.18	-100.07	232.32
80	77	86.94	83.91	67.89	-84.12	212.62
81	66	33.49	-103.11	58.39	115.95	211.98
82	58	68.76	-99.65	67.11	84.74	211.62
83 (converged)	58	64.85	92.99	56.95	-101.66	211.11

Table 3 Optimization results for the plate structure joint by two spots and subjected to both axial and transverse loadings

Case No in Loop 2	Converged Step No in Loop 1	x_1 (mm)	y_1 (mm)	x_2 (mm)	y_2 (mm)	S_{max} (MPa)
65	47	-54.08	-103.06	60.85	-38.28	343.89
66	51	96.89	-17.78	-47.75	-115.66	339.75
67	65	-68.66	76.82	111.69	-106.45	297.12
68	61	104.87	-103.65	-10.66	42.73	296.56
69 (converged)	60	38.99	41.16	115.86	-100.15	291.23

Secondly, the three spot welded joint subjected to different in-plane loadings were considered. Tables 4-6 list the corresponding optimization results for this case.

Finally, the four spot welded joint subjected to different in-plane loadings were considered. Tables 7-9 list the corresponding optimization results for this case.

Table 4 Optimization results for the plate structure joint by three spots and subjected to just axial loading

Case No in Loop 2	Converged Step No in Loop 1	x_1 (mm)	y_1 (mm)	x_2 (mm)	y_2 (mm)	x_3 (mm)	y_3 (mm)	S_{max} (MPa)
89	96	-49.17	59.07	-11.24	-25.65	-44.34	14.41	179.89
90	104	-24.75	-22.57	-50.62	109.16	89.18	-64.26	176.35
91	103	-19.45	54.32	-57.03	-44.61	-71.11	-108.91	156.54
92 (converged)	104	-4.94	-30.92	-12.06	-89.95	17.71	70.45	155.21

Table 5 Optimization results for the plate structure joint by three spots and subjected to just transverse loading

Case No in Loop 2	Converged Step No in Loop 1	x_1 (mm)	y_1 (mm)	x_2 (mm)	y_2 (mm)	x_3 (mm)	y_3 (mm)	S_{max} (MPa)
79	138	72.81	-30.02	-33.98	-124.32	-55.26	109.69	189.52
80 (converged)	67	120.21	28.82	-83.86	-101.06	-81.17	120.59	177.14

Table 6 Optimization results for the plate structure joint by three spots and subjected to both axial and transverse loadings

Case No in Loop 2	Converged Step No in Loop 1	x_1 (mm)	y_1 (mm)	x_2 (mm)	y_2 (mm)	x_3 (mm)	y_3 (mm)	S_{max} (MPa)
69	68	81.11	-21.21	-62.86	-60.72	119.46	-5.03	252.25
70	98	15.58	-94.74	-29.16	-11.44	125.23	83.27	251.14
71 (converged)	86	29.02	-5.78	70.56	-103.85	76.49	42.94	247.63

Table 7 Optimization results for the plate structure joint by four spots and subjected to just axial loading

Case No in Loop 2	Converged Step No in Loop 1	x_1 (mm)	y_1 (mm)	x_2 (mm)	y_2 (mm)	x_3 (mm)	y_3 (mm)	x_4 (mm)	y_4 (mm)	S_{max} (MPa)
88	96	83.21	78.62	-47.03	104.79	54.89	-40.91	-30.69	-69.36	183.21
89	93	43.44	44.26	-42.27	42.71	46.43	-49.73	-51.39	-71.03	181.45
90 (converged)	178	21.37	51.89	14.59	132.28	28.67	-102.75	24.11	-26.92	132.56

Table 8 Optimization results for the plate structure joint by four spots and subjected to just transverse loading

Case No in Loop 2	Converged Step No in Loop 1	x_1 (mm)	y_1 (mm)	x_2 (mm)	y_2 (mm)	x_3 (mm)	y_3 (mm)	x_4 (mm)	y_4 (mm)	S_{max} (MPa)
112	118	91.83	84.42	-140.95	107.37	135.77	-43.85	132.74	114.03	164.95
113	133	127.79	92.18	-108.29	-32.15	52.88	-46.79	-120.14	-111.91	159.62
114 (converged)	127	100	94.51	-121.38	-140.39	119.67	-83.66	127.32	-87.26	143.66

Table 9 Optimization results for the plate structure joint by four spots and subjected to both axial and transverse loadings

Case No in Loop 2	Converged Step No in Loop 1	x_1 (mm)	y_1 (mm)	x_2 (mm)	y_2 (mm)	x_3 (mm)	y_3 (mm)	x_4 (mm)	y_4 (mm)	S_{max} (MPa)
99	121	51.97	90.61	-53.43	121.36	21.19	-96.23	-32.37	9.27	256.65
100	91	81.98	-13.58	-56.06	48.74	91.93	-89.97	22.41	-54.12	241.56
101	104	39.61	-34.56	-88.64	-39.09	49.79	99.19	-41.49	-91.05	233.22
102 (converged)	97	98.68	119.68	-94.94	5.98	73.16	-94.55	-51.27	93.24	232.65

It is naturally expected that increasing number of spot welds has an adverse effect on the stress values occurring on the plate structures (In other words, it has a positive effect on the fatigue strength of the plate structures) due to fact that the applied loads are shared by the spot welds. These phenomena can be observed from the Tables 1 to 9. For example, for the case of just axial loading conditions, the maximum converged stress value for the plate structure joint by two spots is 197.82 MPa, it is 155.21 MPa for the plate structure joint by three spots and for the plate structure joint by four spots, this value reduced to 132.56 MPa. To conclude, with increased number of spot welds, the stress values decrease and accordingly fatigue life of the structures increases. However, it shouldn’t be forgotten that increasing spot welds number results in an increase in the manufacturing cost. So, care must be taken into consideration during the design routine.

On the other hand, Figs. 5-7 show equivalent stress distributions (in terms of Pa) over the inner surface of the upper sheets for 2, 3 and 4 spot welded sheets, respectively in the optimum state.

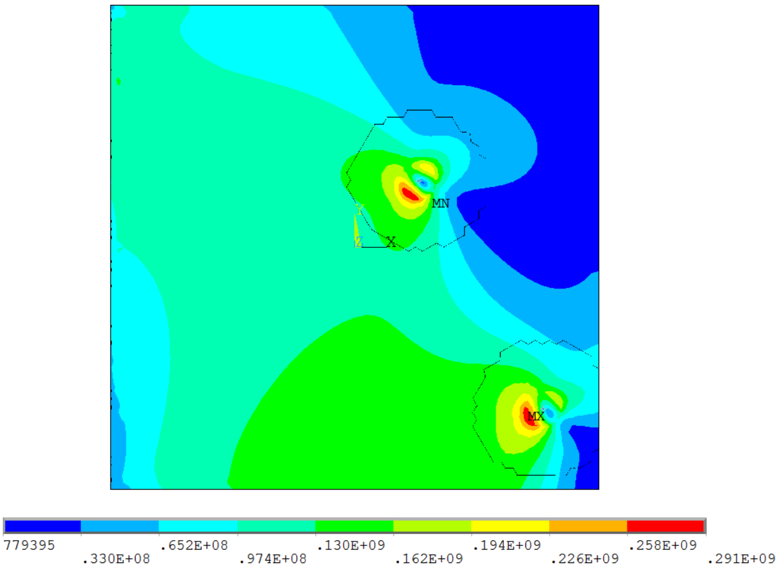

Fig. 5 von-Misses (equivalent) stress (Pa) distribution on the upper sheet's inner surface of 2-spot welded structure (under axial and transverse loading case)

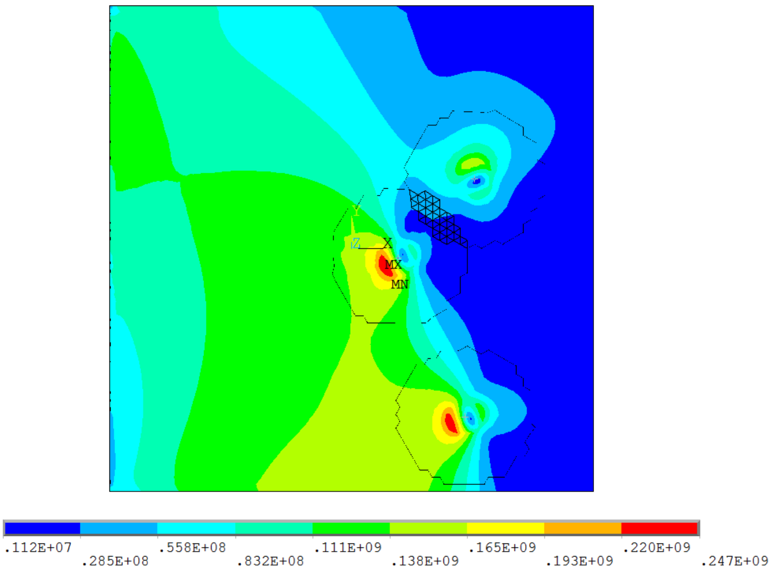

Fig. 6 von-Misses (equivalent) stress (Pa) distribution on the upper sheet's inner surface of 3-spot welded structure (under axial and transverse loading case)

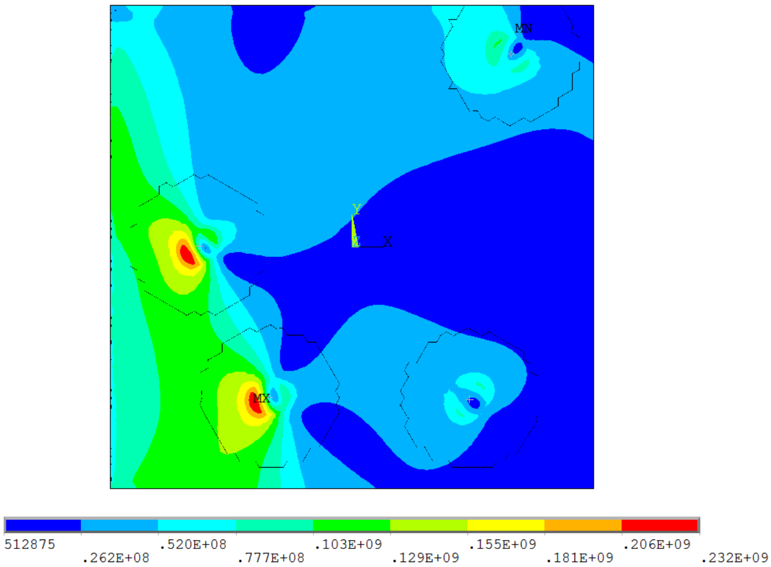

Fig. 7 von-Misses (equivalent) stress (Pa) distribution on the upper sheet's inner surface of 4-spot welded structure (under axial and transverse loading case)

As seen, high stresses develop at regions on the inner surfaces of the sheets close to the peripheries of the spot welds because load transfer in a spot-weld nugget mainly occurs through the material near the boundary of the nugget while the central region of the nugget is mostly stress-free. High stresses develop at a region within the lap zones of the sheets, where contact occurs. The peak stress develops close to the spot weld but not on its periphery. It has been also observed that at the point where peak equivalent stress develops, largest principal stress is tensile.

5. Conclusions

Even if it is an old type of connection technique, resistance spot welding is one of the most widely used joining mechanism especially in automotive industry. Spot welds are considered the weakest parts of a structure because they induce very high stress concentration like other fastening elements. Hence, it can be said that the overall integrity of the spot welded structures depend on the strength of the spot welds. In other words, properly designing a spot weld joint provides reduction in the stress concentration, which in turn, resulted in increments in mechanical strength.

On the other hand, this study is a modified version of the study of (Ertas and Sonmez 2009). A number of enhancements are made to attain maximum strength of the plate structures with different number of spot welded joints by minimizing the maximum equivalent (von Misses) stress along with constraints. One of the most important improvements is that by modifying Nelder-Mead (Simplex) method, globally optimum designs are obtained. Also, more design variables are included to the optimization routine. This proposed procedure has been applied to a number of test problems in order to check how well the results reflect the globally optimum designs. It has been used a local search algorithm to search for the optimum locations of the spot welds resulting in the minimum level of peak equivalent stress. The so called algorithm has been modified via defining a general loop for the starting points and used as a global optimization algorithm. It has been observed that the optimum coordinates and peak stress converged to certain values.

The proposed optimization procedure shows that the globally optimal designs can be obtained easily without stacking local optimal ones via modifying a local search optimization technique which is Nelder-Mead (Simplex) method. This also shows the effectiveness of the proposed procedure.

With increased number of spot welds, the complexity of the optimization problem, as well as the possibility of improvement, increases. As seen from the tables presenting the results obtained, significant improvements in terms of maximum equivalent stress as well as fatigue strengths of structures can be obtained when the number of spot welds is increased. Hence it can be concluded that choosing a high number of spot welds if possible is necessary to obtain the best possible design. However, it shouldn't be forgotten that increasing spot welds number results in an increase in the manufacturing cost. So, care must be taken into consideration during the design routine.

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