

Optimization of spot-weld joints

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Abstract: Integrity of the resistance spot welds determines the overall structural rigidity and integrity of the mechanical system. The main mode of failure for spot-weld joints is fatigue fracture due to fluctuating loads. Resistance spot welds are of great importance to manufacturing industry, considering that it is a commonly used technique for joining thin-sheet components of metals. For example, car and bus bodies may contain thousands of spot welds. Besides economic aspects, spot-welded structures drive the development of optimization in the field of spot welds.

Accordingly, the objective of this study is to develop a procedure to maximize the fatigue life or the load-carrying capacity of spot-weld joints by minimizing the maximum stress. In the optimization procedure, the material and size of the sheet plates are predetermined. On the other hand, the number and locations of the spot welds are chosen as design variables. In order to calculate the objective function, which is the maximum equivalent stress, ANSYS (version 9.0) finite-element analysis software is used. The procedure is applied to a representative problem to demonstrate the effectiveness of the proposed method.

Keywords: optimal design, spot weld, finite-element analysis, Nelder–Mead (Simplex) method, fatigue

1 INTRODUCTION

Spot-weld joints are mostly used to assemble metal sheets, especially in automotive and railroad industries for decades. As, sometimes, there are hundreds and thousands of spot welds in a structure, the design and fabrication of the spot-weld joint affect the quality as well as the safety of the structure. In addition, because fatigue is the most common failure mode for the spot-weld joints under fluctuating loads, understanding their fatigue behaviour and assessment of their fatigue lives are crucial.

In today's world, due to several aspects such as simplicity, economical, and reliability, the resistance spot welding is accepted as the primary joining method especially for automotive and railroad structures because of its advantages such as adaptation to automation in a mass production environment. Also, it is an inexpensive and effective way of joining thin-sheet components of metals. According to studies, a coach or a bus body may contain hundreds

or even thousands of spot welds. In other words, in an automotive body assembly, about 90 per cent of the welds are resistance spot welds [1–7].

Mechanical components usually experience cyclic loading. Naturally, they are liable to fail because of fatigue. In mechanical and structural systems, fatigue is perhaps one of the most important failure modes because it is known that over 80 per cent of observed service failures are mainly due to fatigue [8, 9]. Hence, it can be concluded that the structural rigidity and durability of the spot-welded structures rest on the fatigue strength of spot-weld joints [3, 7, 9, 10].

In general, spot-welded specimens deform through the sheet thickness, resulting from crack growth across the nugget area and then crack propagation through the sheet thickness. The studies examining the effects of the design parameters on spot-welded structures [3, 11–15] show that failure mechanism of a spot-welded structure is closely related to stress values, especially at the peripheries of the spots, spot-weld diameters, and metal sheet thicknesses. Crack growth through the metal sheets, for instance, is encouraged by low load range, thin metal sheet, and large spot-weld diameter. Crack growth across the nugget, in contrast, is favoured by high load ranges, thick metal sheet, and small spot-weld

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diameter [7, 16]. Hence, design and optimization of spot welds under typical loading conditions have been drawing the attention of researchers. Understanding the mechanical behaviour of spot welds as well as plates is important in structural integrity assessment. The primary factors that determine the performance of spot-welded structures are the location and number of spot-weld positions and the quality of the spot welds [17].

Even if tensile shear-type (TS) and modified tensile shear-type metal sheets joined by resistance spot welds are subject to uniaxial in-plane loads, multi-axial stresses occur, especially at the peripheries of the spot welds. Because of this, high stress concentration, and, as a result, non-linear deformation occur around the spot welds. Hence, these high stresses control the failure life of the joint and thus its structure.

Optimization of the number and, of course, location of the spot welds under different loading conditions are major economic considerations. Because spot welds are commonly used in mass production due to their simplicity, a small reduction in the number of spot welds, through their efficient and optimal usage, can mean a great saving in production costs [18].

Studies on optimization usually involve numerical work. It is important to note that although experimental studies provide the necessary physical insight into the behaviour of the spot-weld joints, predictive tasks such as design, analysis, and evaluation of the spot-welded structures are often carried out by computational methods. Spot-weld joints present several challenges to design engineers in terms of mechanical analysis and evaluation. First, depending on the relative size of the spot welds to base-metal thickness and their quality, the spot-weld joints can fail either through the base metal or through the spot-weld nugget (there is some uncertainty involved). Second, because of geometrical complexity of spot-weld joints, effective correlation between the mechanical performance of the joints and loading and geometry is difficult to obtain through experimental 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.

In the literature, there are a few studies related to optimization of spot-weld number and locations [14, 15, 19, 20], regarding stiffness and fatigue behaviour. A topology optimization algorithm was used in references [14], [19] and [21] and the maximum stress intensity factor of spot welds, which is a control parameter for the fatigue life of the structure, was minimized in a spot-welded structure. In reference [22], a design optimization procedure was introduced using a special element to model the spot weld. In reference [14], sheet metals were modelled using shell elements, and spot welds were modelled as bar elements. In reference [18], the spot welds were

modelled using an umbrella (spoke bar) model. The optimization problem of the spot-welded structures was examined using radial (structural) stresses and the umbrella model, finding optimal locations of spot welds. In reference [23], a meta-heuristic method that is an integer optimization method on the discrete type was proposed, and the effectiveness of the method was discussed through optimization of the spot-weld positions.

There are a number of optimization techniques such as non-linear, linear, geometric, dynamic, integer, and stochastic. In this developed program, for the optimization part, a linear program, Nelder–Mead, which is used in different engineering problems in industry [24], is chosen. Because structural optimization problems may contain many local minimum configurations, the developed algorithm, in which a monotonically decreasing value of the objective function is iteratively created, may stick in a local minimum point rather than the global minimum solution depending on the starting point. To eliminate this problem and to obtain the global minimum configuration, the algorithm has been employed many times starting from different configurations for every problem.

2 PROBLEM STATEMENT

The purpose of optimization is to find the best possible solution among the many potential solutions for the given problem in terms of a performance criterion. The objective of the design optimization problem is to generate an optimum design for spot-weld joints in order to maximize their load-carrying capacity.

Any design process requires some design variables through which the part can be defined with the objective of choosing a suitable set of these variables, such that the performance of the corresponding part becomes satisfactory.

The optimization process tries to find the optimum set of design variables such that the corresponding part yields the best performance. In our problem, it is assumed that the geometry (Fig. 1) and material of the metal sheets, material and size of the spot welds, and loading conditions are predetermined. Design variables are then the number and locations of spot welds. Because of the difficulty of varying the number of spot welds in a single optimization run, the number is fixed; however, choosing a different number for different runs is possible. In this article, a common geometry, TS specimen, was considered and optimized for different types of in-plane loading.

The objective of the design optimization problem is to minimize the maximum equivalent stress value, S_{\max} , of the joint

$$\text{minimize } S_{\max} \quad (1)$$

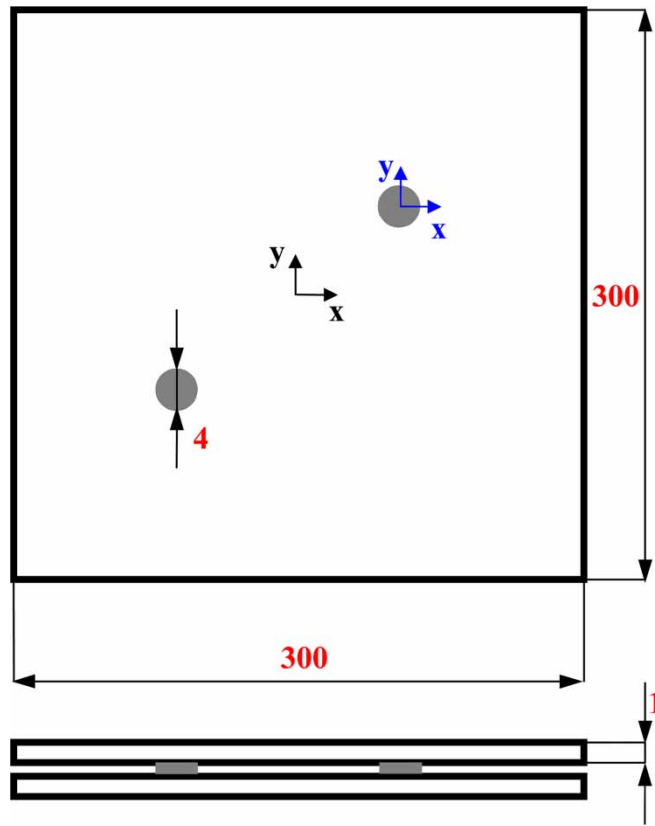


Fig. 1 Geometry of the TS specimen (top and side views)

The design variables are subject to a number of side constraints. The spot welds should be prevented from interfering with each other and getting close to the plate boundaries; this means that the design should conform to the standards related to weld-to-weld spacing and weld-to-edge distance. According to industrial organizations such as American Welding Society, the distance between an edge and the centre of a spot weld should be greater than one spot weld diameter, d . Accordingly, the constraint equations are given as

$$-\left[\left(\frac{l}{2}\right) - d\right] \leq x_i \leq \left[\left(\frac{l}{2}\right) - d\right] \quad (2)$$

$$-\left[\left(\frac{l}{2}\right) - d\right] \leq y_i \leq \left[\left(\frac{l}{2}\right) - d\right] \quad (3)$$

where l is the total length of the square plate; it was pre-determined as 300 mm. Besides, the distance between the centres of the spot welds should be greater than twice the spot-weld diameter as recommended by the industry. Then

$$s_{ij} \leq 2d \quad (4)$$

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

In many cases, joints are under fluctuating loads, and spot welds are then susceptible to fail due to

fatigue fracture. Therefore, their load-carrying capacity is limited by the fatigue failure mode. As fatigue crack initiation is quite susceptible to a stress level, reduction in the maximum stress level considerably increases the fatigue life of the component. Accordingly, the objective function to be minimized is the maximum equivalent stress developed in the structure. Consequently, the locations of the spot welds that will result in the minimal value of Von Mises [25, 26] stress was determined.

There are some limits on the coordinates of spot welds, i.e. constraints on optimization variables. The welds should not get near the edges of the plates, or go outside. In these cases, maximum stress level increases. Because, in such a case, cost function increases, and there is no need to impose constraints on the optimization variables or to calculate a penalty function. The search algorithm already diverts the weld away from the edges.

3 METHODOLOGY

3.1 General solution procedure

In order to integrate the design optimization procedure with a commercially available finite-element analysis (FEA) software (ANSYS 9.0), a code was developed utilizing the built-in parametric language.

Using the available commands, the necessary tasks are achieved, which includes definition of the model (geometry and element types), material properties, and boundary conditions (restraints and forces), solution, and extracting the results.

During the optimization process, the locations of the welded joints are changed iteratively in search of a better objective function. For this purpose, the Nelder–Mead simplex method [27, 28] is used as a search algorithm. The objective function, i.e. maximum equivalent stress, is recalculated whenever the design is changed. The code automatically regenerates mesh data in each analysis step and extracts results for different spot-weld locations. As the welded components have complex shapes, mesh is generated on three-dimensional surfaces. The resulting Von Mises 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 Structural analysis

In the meshing step, ten-node tetrahedral structural solid elements (SOLID92) [29] are used. New meshes are constructed in each iteration taking into account the change in spot-welding locations. The elements around the weld joints are refined to capture the stress state accurately, because in these regions high stresses develop due to stress concentration effects of the joints. In contrast, the mesh density over the rest of the solid body is uniform. This gives uniform quality of meshes throughout the optimization process. Using different levels of refinement, the optimization procedure is repeated in order to observe the differences between different levels of mesh refinements and choose the most suitable one.

In this article, instead of modelling the spot welds as metal sheets, a rigid bar model [30] is used in the analyses. Hence, a rigid bar element (BEAM 188) [29] is used, which directly creates a line representing the spot weld between the metal sheets.

3.3 Search algorithm

As our structural analysis is based on a numerical method, consequently, the stress state cannot be predicted in the closed form; it is difficult to use the search algorithms that require the derivative of the objective function. In this respect, zero-order methods are more suitable; among them are stochastic and deterministic methods. The advantage of stochastic methods such as simulated annealing and genetic algorithms [27, 28] is that they may easily converge to the global minimum and start from any set of values of design parameters. However, they are difficult to

apply and expensive in terms of computational time. Zero-order deterministic methods such as the Nelder–Mead and Powell's methods [27, 28] are much easier to apply, but they do not necessarily converge to the global optimum. A deterministic algorithm should be employed many times starting from different points within the feasible region of design parameters. Then, the lowest value is chosen as the global minimum of the objective function. In this article, the search for optimum design parameters was started using the Nelder–Mead method which requires only the values of the objective function for the given set of design variables. Using this method, the solution domain was proved to be containing a low number of local minima. Therefore, the Nelder–Mead method was found to be a suitable choice; thus, after a number of trials, spot-weld positions resulting in the minimum peak stress can be denoted as the global optimum positions.

The sequential simplex or the Nelder–Mead method was originally proposed by Hext and Himsworth and Spendly. Then, the so-called method was improved by Nelder and Mead, so that the simplex method is also known as the Nelder–Mead method. The search algorithm, shown in Fig. 2, sequential simplex, begins with a regular geometric figure called the simplex requiring $N + 1$ initial sets (vertices) of the design variables in an N -dimensional space, where N is the number of the design variables. These vertices can be defined by the origin and by points along each of the N coordinate directions. 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 [27].

$$x_j = x_0 + pe_j + \sum_{\substack{k=1 \\ k \neq j}}^N qe_k, \quad j = 1, 2, \dots, N,$$

where

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

$$q = \frac{a}{N\sqrt{2}} (\sqrt{N+1} - 1)$$

(5)

where e_k is the unit base vector along the k th coordinate direction and x_0 is the initial base point. For the problem examined in this article, the initial location number was 3 because there were two different design variables, namely x and y coordinates of the second spot weld. Hence, equation (5), for our case, leads to an equilateral triangle of side a . Once the simplex method is defined, the objective function is evaluated at each of the $N + 1$ vertices, $x_0, x_1, x_2, \dots, x_N$. Let x_l and x_h denote the vertices where the objective function assumes its minimum and maximum values, respectively, and x_s is the vertex where

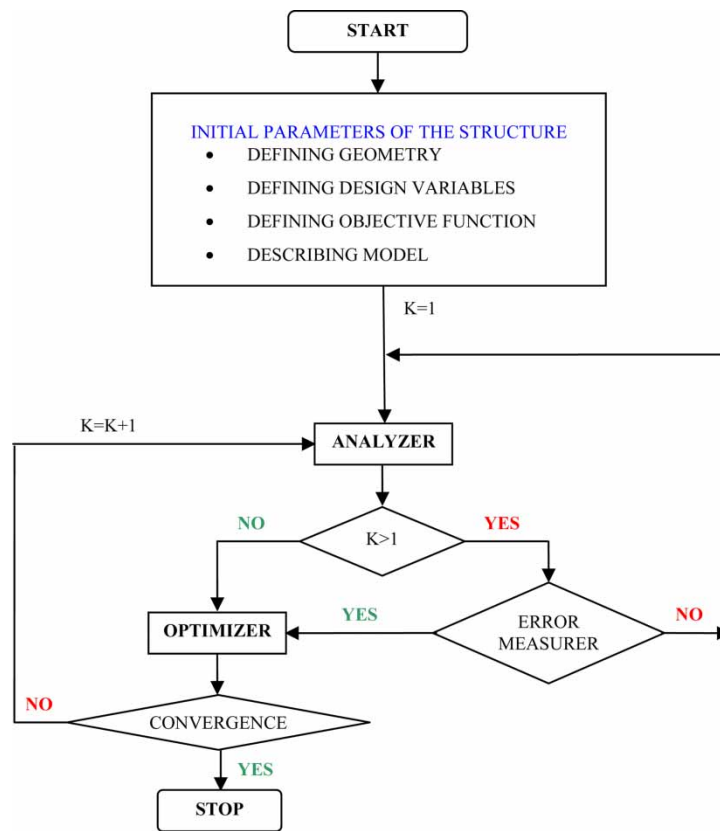


Fig. 2 Flow chart in the design process of optimization with ANSYS

it assumes the second highest value. The simplex method discards the highest value and replaces it by a point where the objective function has a lower value in the following operations, namely ‘reflection’, ‘contraction’, and ‘expansion’. The reflection operation creates a new point x_r along the line joining x_h to the centroid \bar{x} of the remaining point defined as in reference [27]

$$\bar{x} = \frac{1}{N} \sum_{i=1}^N x_i, \quad i \neq h \quad (6)$$

The vertex at the end of the reflection operation is calculated by Haftka and Gurdal [27]

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

If the value of the objective function at this new point satisfies the condition, that is $f_i \setminus f_r \leq f_s$, where $f_i = f(x_i)$, then x_h is replaced by x_r and the process is repeated with this new simplex value. If, in contrast, 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 to the function by going further along the same direction. It is searched as an improved point x_e by the expansion technique using the relation [27]

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

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 greater than the function value of the reflection point, then the new simplex is formed by replacing x_h by x_r and continued [27].

Finally, if the process of the reflection operation leads to a point x_r such that the function value of reflection is smaller than of the maximum, contraction is performed without any replacement using [27]

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

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

$$x_i = x_i + 0.5(x_l - x_i), \quad i = 0, 1, 2, \dots, N \quad (10)$$

and the program restarts 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 [27].

3.4 Finite-element analysis

In order to determine the stress state developed in the structure, a non-linear analysis was carried out using a commercial FEA software, ANSYS. The base metal and spot-weld nugget were modelled using three-dimensional ten-node tetrahedral solid elements, SOLID92 [29], and a two-node beam element, BEAM 188 [29], respectively. Contact elements were defined on the interfaces between the plates. Because high stress concentration occurs in the vicinity of the spot welds, much smaller elements were used within and around the spot welds in comparison with that of the base metal.

The boundary conditions in the FEA model are shown in Figs 3 and 4. In one loading case, displacements and rotations in all degrees of freedom are fixed at one end; the other end is subject to uniformly distributed in-plane load.

4 RESULTS AND DISCUSSIONS

The same problem was also studied by Chao *et al.* [31] using different search algorithms and analysis techniques. The comparison of the results will

indicate the relative strengths of the methods [32]. In the first step, a study performed by Chao *et al.* [31] was repeated using our procedure and the results were compared in Tables 1 and 2. In this comparison, a three spot-welded, 300 mm by 300 mm square plate, shown in Fig. 3, subjected to a 3000 N force which is uniformly applied in both x and y directions on the right surface of the lower sheet was used. The results summarized in Table 1 show good agreement with the previous ones. In Table 2, four different cases were also summarized for the same problem using the proposed optimization procedure.

In the second part, another problem was studied. The optimization procedure is applied to 300 mm by 300 mm square sheets joined by two spot welds; one is fixed and the other is movable. The sheet thickness and the spot-weld nugget diameter are chosen to be 1.0 and 4.0 mm, respectively. The initial space between the metal pieces is assumed to be 0.5 mm.

The spot-welded joint is composed of the nugget and the base metal. The material properties for the base metal and nugget are listed separately in Table 3. In addition, the materials of the sheets are assumed to be homogeneous, isotropic, and linearly elastic; large deformation and nugget indentation are not considered.

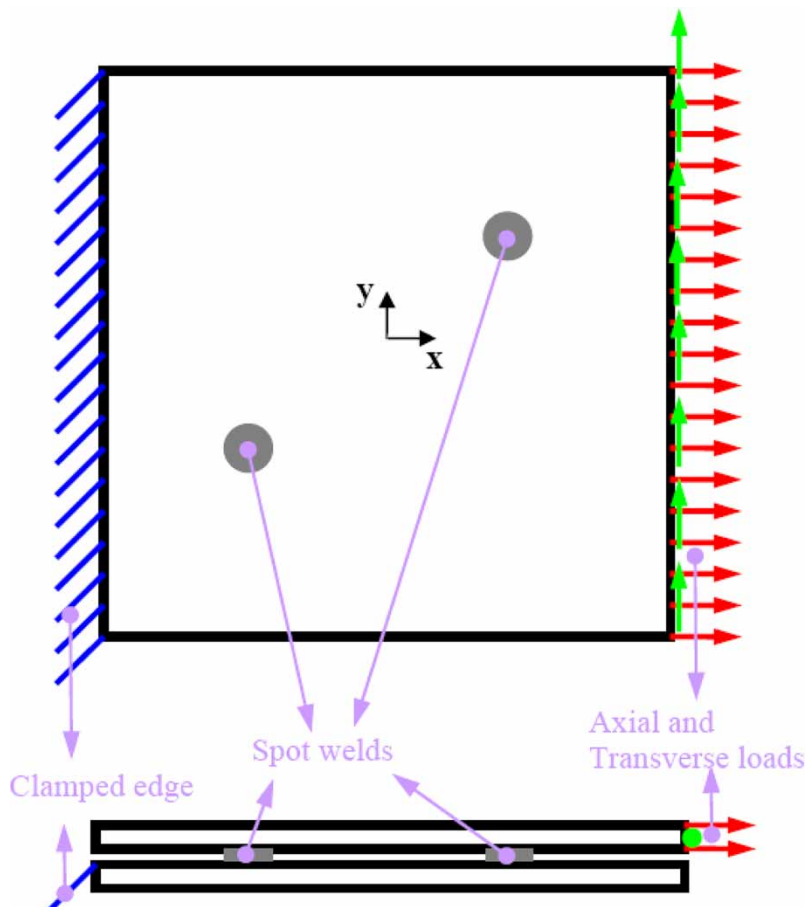


Fig. 3 Boundary conditions of the FEA model for the axial and transverse loading case

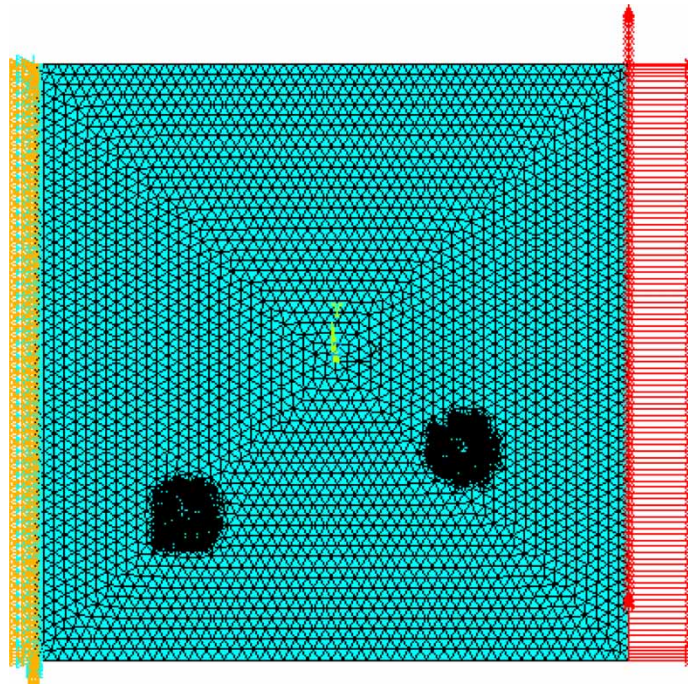


Fig. 4 Finite-element meshes and boundary conditions on the optimized square plate with two spot welds (under axial and transverse loading case)

Table 1 Comparison of the predicted results performed by Chao *et al.* [31] for three spot-welded square plates under both axial and transverse loading of 3000 N

Spot weld no.	Chao <i>et al.</i>		Ertas <i>et al.</i>	
	<i>x</i>	<i>y</i>	<i>x</i>	<i>y</i>
Initial locations (mm)				
1	-50	-50	-50	-50
2	50	-50	50	-50
3	0	50	0	50
Optimized locations (mm)				
1	-50	-86	-55	-89
2	6	-86	4	-87
3	94	18	90	6

As seen in Figs 3 and 4, the left end of one of the metal sheets, the upper sheet, is clamped (i.e. displacements and rotations are set to zero) whereas the other

Table 3 Material properties of base and nugget

	Base material	Nugget
Young's modulus (GPa)	190	200
Poisson's ratio	0.25	0.2

one, the lower sheet, is not restrained. As for loading, a 3000 N force is uniformly applied in the *x* direction and a 3000 N force in the *y* direction on the right surface of the lower sheet.

Figure 4 also shows the finite-element mesh generated over the volume of the structure. The total number of elements in the model is $\approx 90\,000$ and the total number of nodes is $\approx 160\,000$.

Because the region around the spot welds is critical, finer meshes are introduced near to the edges of the spot welds; the dimension of the smallest

Table 2 Optimum positions of the spot welds obtained starting from different locations with only converged mesh densities, L-50 and R-2 (under axial and transverse loading case)

Set no.	First spot		Second spot		Third spot		S_{max}
	<i>x</i>	<i>y</i>	<i>x</i>	<i>y</i>	<i>x</i>	<i>y</i>	
Initial locations of the spots (mm) and resulting maximum peak stresses (MPa)							
1	-100	-100	0	0	-50	0	425
2	-75	-75	-50	-50	50	50	439
3	-50	-75	0	-50	0	50	396
4	-75	-50	-50	0	50	0	412
Optimal locations of the spots (mm) and resulting maximum peak stresses (MPa)							
1	-60	-95	-15	-79	101	8	221
2	-48	-86	1	-89	89	11	232
3	-50	-73	-1	-87	82	15	236
4	-58	-89	5	-84	81	20	229

elements being 0.0005 mm. The extent of the region where elements are refined is two times the spot-weld diameter. Expanding this region has little effect on the stress state. In order to prevent the penetration of the sheets into each other, node-to-node and flexible-flexible contact elements (CONTACT 12) [29] are defined around the spot welds over the inner surfaces. Because of the contact elements, the analysis becomes non-linear.

The afore-mentioned optimization procedure was applied to obtain optimum locations of the spot welds. Initially, the weld at the bottom left region was fixed, and the other was allowed to change its location.

Figures 5 and 6 show equivalent stress distributions (in terms of MPa) over the inner surfaces of the lower and upper sheets, respectively, in the optimum state. High stresses develop at regions on the inner surfaces of the sheets close to the peripheries of the

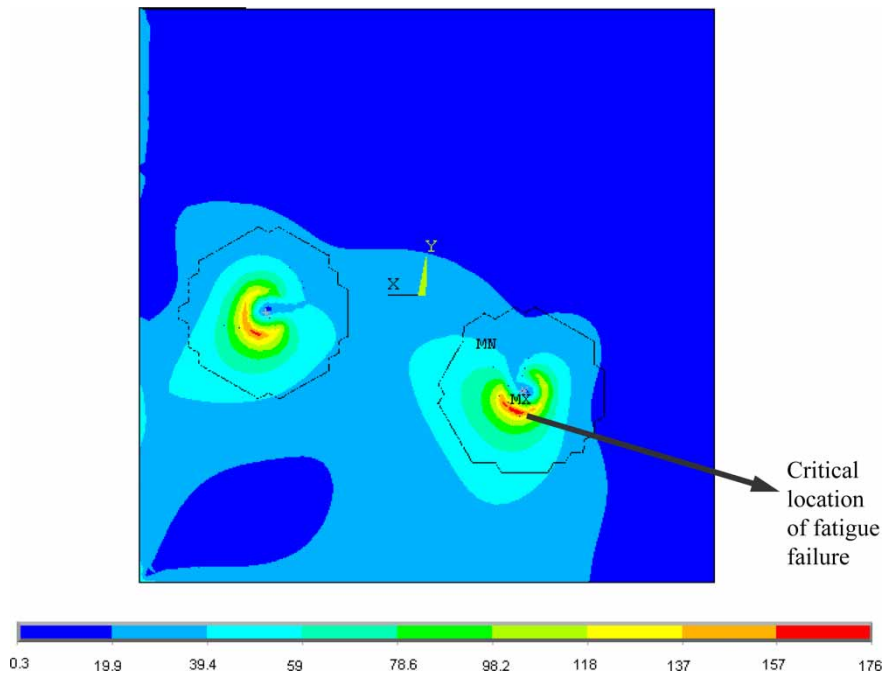


Fig. 5 Von Mises stress (MPa) distribution on the lower sheet's inner surface (under axial and transverse loading cases)

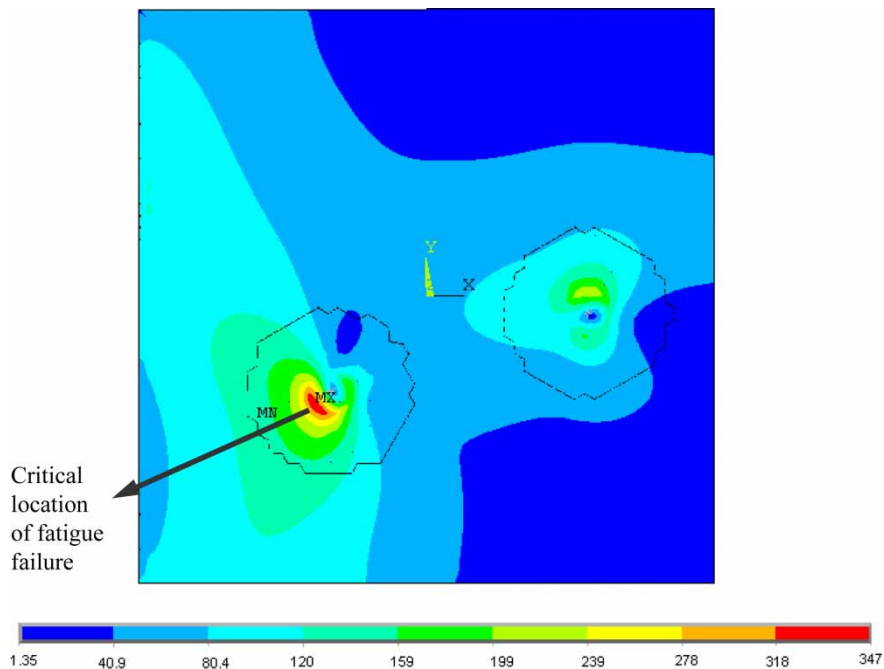


Fig. 6 Von Mises stress (MPa) distribution on the upper sheet's inner surface (under axial and transverse loading cases)

spot welds because load transfer in a spot-weld nugget mainly occurs through the material near the boundary of the nugget, whereas 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. The largest principal stress is tensile at the point where peak equivalent stress develops. It may be concluded that this is the critical location for fatigue failure. This location, shown in Figs 5 and 6, also conforms to the fatigue crack-initiating sites observed in an experimental study [12, 33].

Examining the deformed shape of spot-welded sheets, it can be mentioned that the deformation of lap zones of the spot-welded joint in the middle part is more serious than that at other zones of the specimen. The reason for the phenomena may be as follows. The loads that are applied to the spot-welded specimens are due to the spot welds in the spot-welded joints. Hence, the stresses flow with concentrating to the spot welds in the middle parts of the lap zones, so that high stresses arise there.

As the number of design variables is 2, which are x and y coordinated of the moving spot weld, the Nelder–Mead algorithm [27, 28] requires three sets of design variables; this means three different positions should be chosen for the moving spot weld.

Because a local search algorithm is used, the optimization process is repeated many times starting from different positions for the moving spot weld, so that global optimum solution can be determined.

One should also note that the degree of accuracy in calculating the objective function affects the resulting design.

By using a coarse mesh, one may carry out the optimization process in a very short time; but due to error in the peak stress level, the resulting design may not reflect the global optimum one. If an extremely fine mesh is used, the optimum position can be accurately determined; but computational times may be excessively long. For these reasons, a study is conducted on the accuracy of the results by repeating the optimization process many times starting from different locations with different mesh densities. Table 4 gives the optimum positions of the moving spot weld obtained in some of these runs.

First, it is noted that both optimum coordinates and the resulting peak stresses converge to certain values as finer and finer meshes are used. Secondly, there are many global optima or near global optima. This is better depicted in Figs 5 and 6, in which the optimum locations of the moving spot weld was obtained using the finest mesh (L-50 and R-2). Fifteen of the 18 runs, starting from different positions, ended up with optimum locations around $x = 80$ mm and $y = -10$ mm. The magnitudes of the peak stresses were ~ 343 MPa. Three of these runs stuck to local optima with higher levels of stress, not shown in the figure. Optimum positions obtained from different locations under only axial loading case were summarized in Table 5. In this second case of the problem, the optimum locations calculated

Table 4 Optimum positions obtained starting from different locations with different mesh densities (under axial and transverse loading cases)

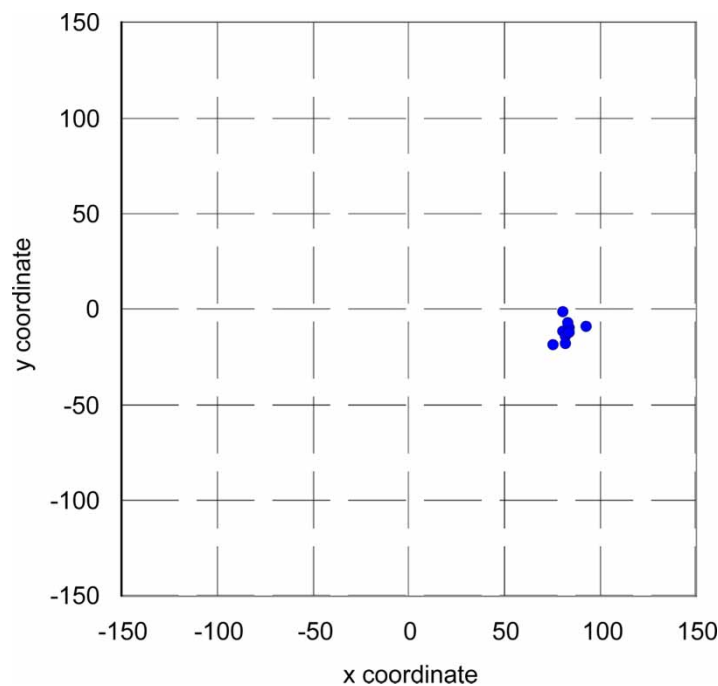
Refinement types and levels	Initial coordinate of the second spot weld (mm)								S_{\max} (MPa)
	First point		Second point		Third point		Optimum coordinates		
	x	y	x	y	x	y	x	y	
L-10 and R-1	0	-80	0	-70	10	-73	14.4	-74.7	156
L-10 and R-1	-75	75	-10	5	6	4	29.6	-14.9	141
L-10 and R-1	30	0	25	0	26	-15	24	-15	142
L-10 and R-2	-75	75	65	-70	75	-65	24	12	138
L-20 and R-1	0	-80	0	-70	10	-73	59	-47	220
L-20 and R-1	-75	75	-10	5	6	4	60.1	-47.8	220
L-20 and R-1	-75	75	65	-70	75	-65	57	-55	220
L-20 and R-1	30	0	25	0	26	-15	62.9	-24.2	219
L-30 and R-1	-75	75	65	-70	75	-65	64.6	-49.6	300
L-30 and R-2	30	0	25	0	26	-15	65.7	-53.1	316
L-30 and R-2	-75	75	-10	5	6	4	65.8	-52.6	316
L-30 and R-3	0	-80	0	-70	10	-73	69.3	-36.0	336
L-40 and R-2	0	-80	0	-70	10	-73	75.8	-15.8	331
L-40 and R-2	-75	75	-10	5	6	4	70.7	-36.9	333
L-40 and R-2	-75	75	65	-70	75	-65	69.8	-14.9	331
L-40 and R-2	30	0	25	0	26	-15	74.9	-11.9	331
L-50 and R-2	0	-80	0	-70	10	-73	84	-9.2	343
L-50 and R-2	-75	75	-10	5	6	4	80.7	-11.2	342
L-50 and R-2	-75	75	65	-70	75	-65	82.3	-6.5	344
L-50 and R-2	30	0	25	0	26	-15	83.6	-6.5	344

L denotes the number of divisions along the lines of the edges affecting overall mesh density; R denotes mesh refinement around the spot welds; and S_{\max} denotes the maximum equivalent stress.

Table 5 Optimum positions obtained starting from different locations with only converged mesh densities, L-50 and R-2 (under only axial loading case)

Refinement types and levels	Initial coordinate of the second spot weld (mm)								S_{\max} (MPa)
	First point		Second point		Third point		Optimum coordinates		
	x	y	x	y	x	y	x	y	
L-50 and R-2	0	-80	0	-70	10	-73	-75.1	75	258
L-50 and R-2	-75	75	-10	5	6	4	-75	75	253
L-50 and R-2	-75	75	65	-70	75	-65	-75.3	75.1	261
L-50 and R-2	30	0	25	0	26	-15	-75	75	254

L denotes the number of divisions along the lines of the edges affecting overall mesh density; R denotes mesh refinement around the spot welds; and S_{\max} denotes the maximum equivalent stress.

**Fig. 7** Near global optimum locations on the plates obtained using the finest mesh (under axial and transverse loading cases)

only for converged mesh density values (L-50 and R-2 cases) occurred around $x = -75$ mm and $y = 75$ mm. The resulting peak stress values were around 255 MPa.

Tables 4 and 5 show the initial starting locations (three points) and optimal locations of the second spot weld and the value of maximum equivalent stress of the structure. Because the number of design variables is two, namely, the x and y locations of the second spot weld, for the Nelder–Mead optimization technique, the number of the starting locations of the second spot weld must be 3. Hence, as indicated in Tables 4 and 5, for every case, three different starting values were defined. Then, the optimization procedure found the optimal location of the spot weld. Additionally, it was added to the corresponding maximum equivalent stress value of the structure, which occur always at the peripheries of the spot welds, as shown in Figs 5 and 6.

5 CONCLUSIONS

In this article, an optimization procedure is proposed to determine the optimum designs of spot-weld joints. A local search algorithm is used to search for the optimum locations of the spot wells, resulting in the minimum level of peak equivalent stress. This procedure is applied to a test problem in order to check how well the results reflect the globally optimum designs. Starting from different points with different mesh densities, the optimization process is repeated and the optimum coordinates and peak stress converging to certain values are observed. As shown in Fig. 7, the converged values for two spot-welded square sheet problems under both axial and transverse loading were ~ 75 and 0 mm, respectively, for x and y locations of the second (movable) spot weld. Also, the results show that the number of local minima is low.

Therefore, using the local search algorithm instead of a global one is appropriate.

The proposed optimization procedure shows that the global optimal designs can be obtained easily without stacking local optimal ones. This also shows the effectiveness of the proposed procedure.

REFERENCES

- 1 **Barkey, M. E., Kang, H., and Lee, Y. L.** Failure modes of single resistance spot welded joints subjected to combined fatigue loading. *Int. J. Mater. Prod. Technol.*, 2001, **16**(6/7), 510–527.
- 2 **Rathburn, R. W., Matlock, D. K., and Speer, J. G.** Fatigue behavior of spot-welded high-strength sheet steels. *Weld. J.*, 2003, **82**(8), 207–218.
- 3 **Chao, Y. J.** Failure mode of spot welds: interfacial versus pullout. *Sci. Technol. Weld. Joint*, 2003, **8**(2), 133–137.
- 4 **Deng, X., Chen, W., and Shi, G.** Three-dimensional finite element analysis of the mechanical behavior of spot welds. *Finite Elem. Anal. Des.*, 2000, **35**, 17–39.
- 5 **Hou, Z., Wang, Y., Li, C., and Chen, C.** An analysis of resistance spot welding. *Weld. J.*, 2006, **85**(3), 36–40.
- 6 **Barkey, M. E., Kang, H., and Lee, Y. L.** Evaluation of multiaxial spot weld fatigue parameters for proportional loading. *Int. J. Fatigue*, 2000, **22**, 691–702.
- 7 **Lee, Y. L. and Lu, M. W.** Fatigue-reliability analysis of resistance spot-welds. In Proceedings of Annual Reliability and Maintainability Symposium, Anaheim, CA, USA, 1994, pp. 178–184.
- 8 **Wirsching, P. H.** Fatigue reliability. Construction Research Communication Limited, 1998, 1365-0556.
- 9 **Di Fant-Jaekels, H. and Galtier, A.** Fatigue life-time prediction model for spot welded structures. La Revue de Metallurgie-CIT, Paris, France, 2000, pp. 83–95.
- 10 **Salvini, P., Scardecchia, E., and Demofonti, G.** A procedure for fatigue life prediction of spot welded joints. *Fatigue Fract. Eng. Mater. Struct.*, 1997, **20**(8), 1117–1128.
- 11 **Ertas, A. H., Yilmaz, Y., and Baykara, C.** Investigation of the effect of the gap values between the overlap portions of the spot-welded pieces on fatigue life. *Proc. IMechE, Part C: J. Mechanical Engineering Science*, 2008, **222**(6), 881–890. DOI: 10.1243/09544062JMES787.
- 12 **Ertas, A. H., Vardar, O., Sonmez, F. O., and Solim, Z.** Measurement and assessment of fatigue life of spot weld joints. *J. Eng. Mater. T. ASME*, in press.
- 13 **Pan, N.** *Fatigue life study of spot welds*. PhD Thesis, Stanford University, 2000.
- 14 **Rui, Y., Yang, R.-J., Chen, C.-J., and Agrawal, H.** Fatigue optimization of spot welds. In Proceedings of the Body Design and Engineering, 1996 International Body Engineering Conference (IBEC'96), Detroit, Michigan, 1–3 October 1996, pp. 68–72.
- 15 **Ertas, A. H. and Sonmez, F. O.** A parametric study on fatigue strength of spot weld joints. *Fatigue Fract. Eng. Mater. Struct.*, 2008, **31**(9), 766–776.
- 16 **Davidson, J. A. and Imhof, E. J. Jr.** A fracture-mechanics and system-stiffness approach to fatigue performance of spot-welded sheet steels. SAE paper 1983-83-0034, 1983.
- 17 **Lee, H., Kim, N., and Lee, T. S.** Overload failure curve and fatigue behavior of spot-welded specimens. *Eng. Fract. Mech.*, 2004, **72**, 1203–1221.
- 18 **Zhang, Y. and Taylor, D.** Optimization of spot welded structures. *Finite Elem. Anal. Des.*, 2001, **37**, 1013–1022.
- 19 **Puchner, K., Dannbauer, H., and Meise, M.** Spot weld optimization regarding stiffness and fatigue using standard software. SAE paper 2006-01-1247, 2006.
- 20 **Ertas, A. H. and Sonmez, F. O.** Optimization of spot weld joints. The 12th International Conference on *Machine design and production* (UMTIK), Istanbul, Turkey, 2006, pp. 883–894.
- 21 **Yang, R. J., Rui, Y., Mohammed, A., and Singh, G.** Spot weld/adhesive pattern optimization. In Proceedings of the 1996 ASME Design Engineering Technical Conference in Engineering, Irvine, CA, 1996, ASME paper 96-DETC/DAC-1478.
- 22 **Wang, L., Leiva, J. P., and Basu, P. K.** Design optimization of automobile welds. *Int. J. Veh. Des.*, 2003, **31**(4), 377–391.
- 23 **Hasegawa, H., Hiroto, S., Hiroyasu, U., and Kawamo, K.** The optimization of spot-weld positions for vehicle design by using hybrid meta-heuristics. *Int. J. Veh. Des.*, 2007, **43**(1–4), 151–172.
- 24 **Rao, S. S.** *Engineering optimization: theory and practice*, 1996 (John Wiley & Sons Inc., Canada).
- 25 **Stephens, R. I., Fatemi, A., Stephens, R. R., and Fuchs, H. O.** *Metal fatigue in engineering*, 2001 (John Wiley & Sons Inc., Canada).
- 26 **Suresh, S.** *Fatigue of materials*, 2004 (Cambridge University Press, Cambridge).
- 27 **Haftka, R. T. and Gurdal, Z.** *Elements of structural optimization*, 1992 (Kluwer Academic Publishers, Dordrecht).
- 28 **Vasiliev, V. V. and Gurdal, Z.** *Optimal design: theory and applications to materials and structures*, 1999 (Technomic Publishing Co. Inc., Lancaster).
- 29 **ANSYS user's manual**, version 9.0, ANSYS Software Inc., 2004.
- 30 **Xu, S. and Deng, X.** An evaluation of simplified finite element models for spot-welded joints. *Finite Elem. Anal. Des.*, 2004, **40**(9–10), 1175–1194.
- 31 **Chao, S. W., Kwon, K. Y., and Lee, T. S.** An optimal design system for spot welding locations. *Finite Elem. Anal. Des.*, 2002, **38**, 277–294.
- 32 **Zuniga, S. T.** *Predicting overload pull-out failure in resistance spot welded joints*. PhD Thesis, Stanford University, 1994.
- 33 **Ertas, A. H.** *Fatigue behavior of spot welds*. MSc Thesis, Bogazici University, 2004.