A SPOT-WELD FATIGUE ANALYSIS MODULE IN THE MSC/FATIGUE ENVIRONMENT

by

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ABSTRACT

A software system has been developed in the MSC/FATIGUE [1] environment which permits fatigue life predictions to be made for automotive spot-welds joining two steel sheets. The method uses bar element forces to calculate the "structural stresses" in each spot-weld nugget and the adjacent sheets using the methodology described by Rupp, Störzel and Grubisic [2]. The system described here extends this general method to support the use of dynamic stresses derived from road load data, using either a quasi-static or transient approach to stress history determination. The method is geometry independent and suitable for application to large models (because it does not require local mesh refinement). The system provides a convenient way for users of MSC/PATRAN [3], MSC/NASTRAN [4] and MSC/FATIGUE to predict the location and life of fatigue sensitive spot-welds.

INTRODUCTION

A key feature of the modern durability design process is the use of computer-based finite element methods to predict durability at an early stage in the design cycle. This process is driven by the need for designs with low weight, low cost of manufacture, short development cycles and good durability. Calculations based on fatigue life and realistic loading histories permit structures and components to be optimised for durability without the need for the expensive and time-consuming testing of a series of prototypes. Design analysis based on fatigue life calculations results in designs that are less conservative (i.e. better optimised) than those based on traditional criteria such as maximum load or stress for a series of standard load cases.

Resistance spot welds are very commonly used in the automotive industry in the fabrication of all manner of components and structures, and the durability of such structures is very often controlled by the strength of the spot welds. The cost of tooling up for a single weld spot as part of an automated manufacturing process is around \$30000, and this can more than double if a weld spot has to be added during production to remedy a problem [2]. These costs may be minimised if the life of spot welds can be predicted at an early stage in the design process, though the reduction in development time and improvement in quality is likely to be more significant.

Smith and Cooper [5] addressed the problem of life prediction of shear spot welds using a fracture mechanics approach. They noted that a spot weld could be "....considered to be a circular solid surrounded by a deep circumferential crack, which when loaded in a combination of Mode I and Mode II, would grow a branch crack in the direction of maximum local Mode I". They showed that good predictions of life could be made on the basis of calculated crack growth rates, and used their calculations to generate some simple design curves. The method was based on detailed finite element modelling of simple spot-welded lap-joints loaded in shear. This method would need further development in order to cover all the possible weld configurations used in automotive structures and to deal with the variable amplitude out-of-phase loadings to which they are subject. The results of this might be a simple design code for spot-welds along the lines of BS 7608 [6] with families of load-life curves for different classes of spot-weld. In practical FE models of automotive structures there is no scope for such detailed modelling of individual spot welds.

In fact, load is a rather poor parameter for correlating the fatigue strength of spot-welds under different loading conditions. Radaj [7] and Sheppard [8,9] note that durability of spot welds of a variety of configurations and loadings can be better understood through numerical analysis of the local stresses at the weld spot edge on the inside of the plate - the structural stresses around the weld.

Rupp, Störzel and Grubisic [2] describe the calculation of these structural stresses, and also carry out fatigue life predictions based on maximum and minimum stresses and a load spectrum. The software described in this paper is closely based on the work of Rupp et al, but combines their method for structural stress calculation with the methods of stress scaling and superposition and access to transient FE results normally used in MSC/FATIGUE [10]. The current paper describes the software developed and its use is illustrated with a simple example.

FATIGUE ANALYSIS OF SPOT WELDS

General description

The method requires spot welds to be modelled as stiff beam elements in MSC/NASTRAN. The forces transmitted through these beam elements are used to calculate the structural (nominal) stresses in the weld nugget and the adjoining sheet metal at intervals around the perimeter of the nugget. These stresses can then be used to make fatigue life predictions on the spot weld using a S-N (total life) method.

The software system consists of some modified versions of existing MSC/FATIGUE modules and a new spot-weld fatigue analyser called SPOTW. The system is outlined in Figure 1.

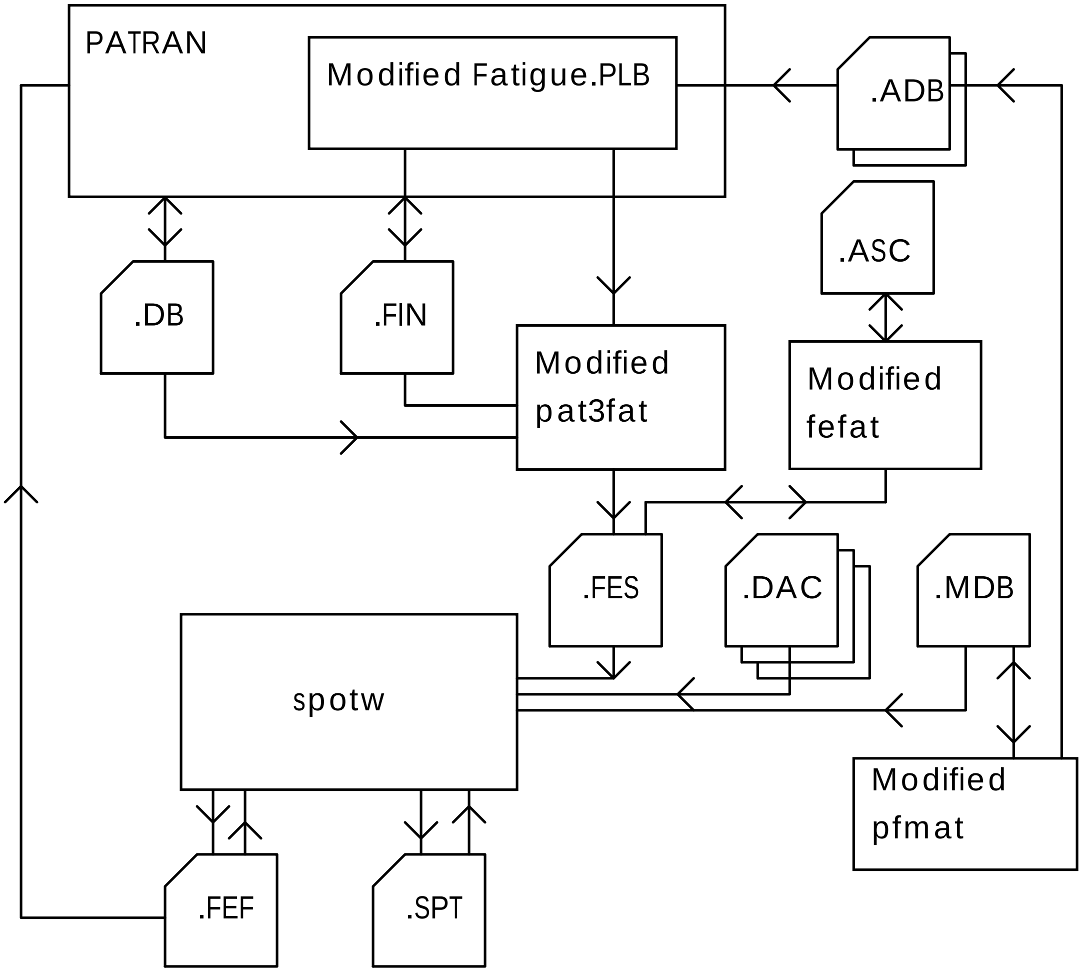

Figure 1: Spot weld fatigue analysis system

The system currently only supports fatigue calculations on spot welds joining 2 sheets. In the FE model, the spot-welds should be represented by stiff beam elements joining the mid-planes of the 2 sheets of shell elements, and perpendicular to both. The length of the spot weld and the sheet separation should therefore be half the sum of the sheet thicknesses. There is no need for any refinement of the mesh around the spot-welds. The only requirement for the shell elements used to model the sheets is that they transmit the correct loads to the bar elements. In fact it seems that best results are achieved when the dimensions of the shell elements are quite large - more than twice the diameter of the weld nuggets.

The system is used in a similar manner to MSC/FATIGUE. A job-file is created by means of a set of forms. This job-file includes information about weld spot diameters, sheet thicknesses, and fatigue property sets. The job-file is read by a translator which extracts all the relevant information from the MSC/PATRAN database and writes an intermediate file. The spot-weld analyser then uses the information in the intermediate file, any required loading histories and fatigue properties and makes life predictions for each spot weld. The results are written to two output files, one of which is readable by MSC/PATRAN.

The steps in the fatigue calculation are now described in more detail.

Structural stress calculation

A typical spot-weld is illustrated in Figure 2. The shaded part is the spot weld "nugget". In a finite element analysis, the weld is modelled in MSC/NASTRAN as a stiff beam element joining the mid-plane of 2 sheets. The length of the beam element will be $0.5(s_1 + s_2)$ where s_1 and s_2 are the thicknesses of sheets 1 and 2 respectively. Point 3 is on the axis of the weld nugget and at the interface of the 2 sheets, i.e. $0.5\,s_1$ from Point 1. All forces and moments are taken to be in the MSC/FATIGUE beam element co-ordinate system illustrated. This is taken to be a Cartesian system with the Z axis going from Point 1 to Point 2. This is different both from the arrangement used by Rupp et al [2] and that used in MSC/NASTRAN [4], but a little simpler.

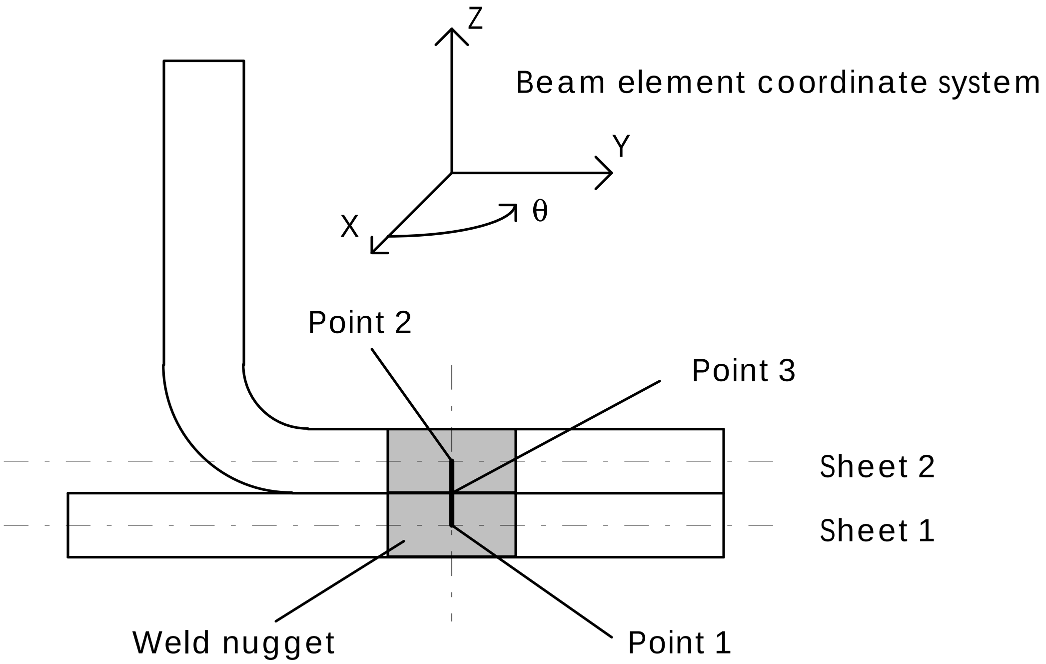

Figure 2: Schematic of typical spot weld.

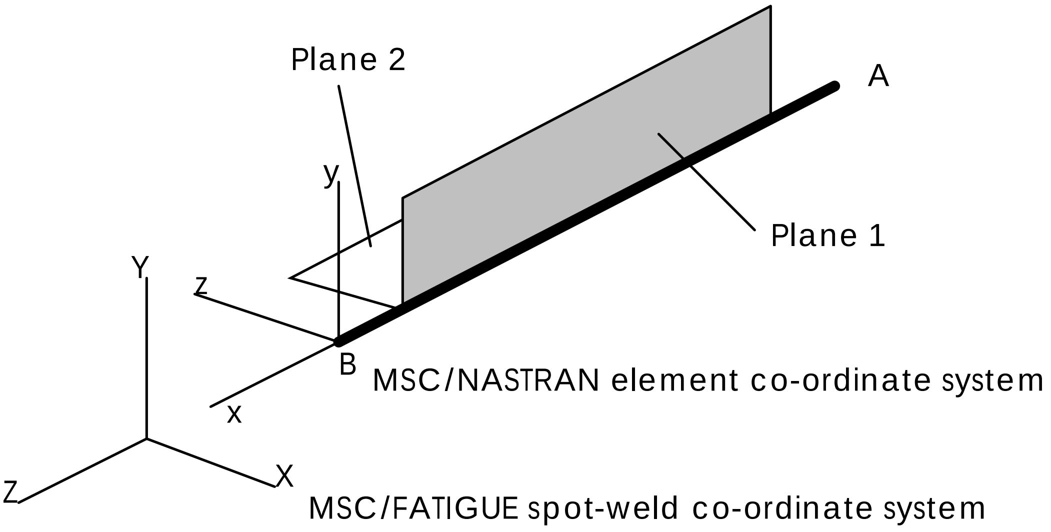

Figure 3: Relationship of MSC/FATIGUE spot weld co-ordinate system to MSC/NASTRAN.

The translator extracts forces and moments $F_{x,y,z}$ and $M_{x,y,z}$, in the MSC/FATIGUE co-ordinate system, and in the conventional right-handed sense, from the results in the database, for each of the three specified points. These forces and moments (except M_z) are used to calculate nominal stresses (structural stresses) on the inner surface of sheet 1 and sheet 2, and in the weld nugget at the interface of the two sheets, at intervals around the circumference of the spot weld ($\theta = 0^o$ to 360^o by increments of 10^o). The forces and moments at points 1 and 2 are those applied *by* the spot welds *on* the sheets, and the forces and moments at point 3 will be those applied *by* the upper section (between point 3 and point 2) *on* the lower section (between point 1 and point 3).

The stresses are calculated as follows:

Point 1

The equivalent stress on the inner surface of the sheet as a function of angle θ around the circumference of the spot weld is:

$$\sigma_{v1} = -\sigma_{max}(F_{x1})\cos\theta - \sigma_{max}(F_{y1})\sin\theta + \sigma(F_{z1}) + \sigma_{max}(M_{x1})\sin\theta - \sigma_{max}(M_{y1})\cos\theta \qquad (1)$$

where:

$$\sigma_{max}(F_{x1}) = \frac{F_{x1}}{\pi d s_1} \qquad (2)$$

$$\sigma_{max}(F_{y1}) = \frac{F_{y1}}{\pi d s_1} \qquad (3)$$

$$\sigma(F_{z1}) = K_1\left(\frac{1.744F_{z1}}{s_1^{\,2}}\right) \quad \text{for} \quad F_{z1} > 0 \qquad (4)$$

$$\sigma(F_{z1}) = 0 \quad \text{for} \quad F_{z1} \le 0 \tag{5}$$

so that only the tensile component of the axial force in the nugget contributes to damage, and:

$$\sigma_{\max}(M_{x1}) = K_1\left(\frac{1.872 M_{x1}}{d{s_1}^2}\right) \tag{6}$$

$$\sigma_{\max}(M_{y1}) = K_1\left(\frac{1.872 M_{y1}}{d{s_1}^2}\right) \tag{7}$$

Note that $K_1 = 0.6\sqrt{s_1}$ and d is the diameter of the weld nugget, dimensions in mm. Forces are in N and moments in Nmm.

Point 2

The equivalent stress on the inner surface of the sheet as a function of angle θ around the circumference of the spot weld is:

$$\sigma_{v2} = -\sigma_{\max}(F_{x2})\cos\theta - \sigma_{\max}(F_{y2})\sin\theta - \sigma(F_{z2}) - \sigma_{\max}(M_{x2})\sin\theta + \sigma_{\max}(M_{y2})\cos\theta \tag{8}$$

where:

$$\sigma_{\max}(F_{x2}) = \frac{F_{x2}}{\pi d s_2} \tag{9}$$

$$\sigma_{\max}(F_{y2}) = \frac{F_{y2}}{\pi d s_2} \tag{10}$$

$$\sigma(F_{z2}) = K_2\left(\frac{1.744 F_{z2}}{{s_2}^2}\right) \quad \text{for} \quad F_{z2} < 0 \tag{11}$$

$$\sigma(F_{z2}) = 0 \quad \text{for} \quad F_{z2} \ge 0 \tag{12}$$

so that only the tensile component of the axial force in the nugget contributes to damage, and:

$$\sigma_{\max}(M_{x2}) = K_2\left(\frac{1.872 M_{x2}}{d{s_2}^2}\right) \tag{13}$$

$$\sigma_{\max}(M_{y2}) = K_2\left(\frac{1.872 M_{y2}}{d{s_2}^2}\right) \tag{14}$$

Note that $K_2 = 0.6\sqrt{s_2}$ and d is the diameter of the weld nugget, dimensions in mm. Forces are in N and moments in Nmm.

Point 3

From the forces calculated for point 3, nominal stresses are calculated at intervals around the circumference of the weld nugget, say at 10 degree intervals. The method of Rupp et al then suggests that the direct stress be calculated on multiple planes at 10 degree intervals, i.e. use a stress-based critical plane method. This would mean $36 \times 18 = 648$ calculations for each weld nugget. This is very computationally intensive, especially in view of the fact that spot welds do not usually fail by cracking through the nugget. For this reason, two faster approaches were considered: to ignore the possibility of nugget failure altogether, and to use the absolute maximum principal stress as the damage parameter, as used in MSC/FATIGUE (only 36 calculations). This is calculated as follows:

$$\tau = \tau_{max}(F_{x3})\sin^2\theta + \tau_{max}(F_{y3})\cos^2\theta \tag{15}$$

$$\sigma = \sigma(F_{z3}) + \sigma_{max}(M_{x3})\sin\theta - \sigma_{max}(M_{y3})\cos\theta \tag{16}$$

where:

$$\tau_{max}(F_{x3}) = \frac{16F_{x3}}{3\pi d^2} \tag{17}$$

$$\tau_{max}(F_{y3}) = \frac{16F_{y3}}{3\pi d^2} \tag{18}$$

$$\sigma(F_{z3}) = \frac{4F_{z3}}{\pi d^2} \quad \text{when} \quad F_{z3} > 0 \tag{19}$$

$$\sigma(F_{z3}) = 0 \quad \text{when} \quad F_{z3} \leq 0 \tag{20}$$

$$\sigma_{max}(M_{x3}) = \frac{32M_{x3}}{\pi d^3} \tag{21}$$

From the shear and direct stresses on the nugget, the in-plane principal stresses can be calculated from:

$$\sigma_{1,3} = \frac{\sigma}{2} \pm \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2} \tag{22}$$

The principal stress with the greatest magnitude is taken as the damage parameter.

Material properties

The system requires an S-N curve for each metal sheet and for the weld nugget at load ratio R=0, plus a mean stress sensitivity factor and a standard error parameter. The formulation of the S-N curve is as follows:

$$\Delta S = SRI1(N_f)^{b_1} \tag{23}$$

for $N_f < N_{c1}$ the transition life. For $N_f > N_{c1}$ a second slope b_2 is used. It is possible to correct each cycle with amplitude S and mean stress S_m to calculate an equivalent stress amplitude S_0 at R=0:

$$S_0 = \frac{S + MS_m}{M + 1} \tag{24}$$

Rupp et al [2] describe generic S-N curves for sheet steel and weld nuggets. There is quite a wide scatter band, which is partly a reflection of the fact that this data represents spot-welds in a variety of steels, including mild and high strength. Better predictions may be possible if S-N data specific to the materials being used is available.

Damage Calculation

Damage calculations are carried out at 10 degree intervals around the spot weld in both sheets and in the weld nugget. There are therefore 108 fatigue calculations per spot-weld. At each calculation point the effective stress history is calculated either directly from the force and moment results from a transient FE analysis, or by scaling and superimposing the results of a number of static load cases according to the quasi-static method [10]. The stress history is then rainflow cycle counted to form a range-mean histogram. Rainflow cycles are converted to equivalent stress amplitude for R=0, then damage is calculated and summed using Miner's rule. The results are written to two files: a MSC/PATRAN 2.5 .els file containing summary results for postprocessing in MSC/PATRAN, and a more detailed file for post-processing by SPOTW.

The method for life prediction of spot-welds described here is somewhat computationally intensive. Computation time is roughly proportional to the number of data points in the load histories. Substantial reductions in computation time can therefore be achieved by judicious filtering of the loading inputs.

SIMPLE EXAMPLE

The following example is intended as an illustration of the method and not as a validation. The component is a laboratory test specimen made from a mild steel V-1147 with two rows of five spot welds. The test piece is illustrated in Figure 4. The specimen is loaded in tension so that the spot welds are subject to shear loadings. A series of constant amplitude tests were carried out with a load ratio (minimum to maximum load) of 0.1.

The finite element model is illustrated in Figures 5(a) and 5(b), including the loads and boundary conditions. Note that this is a half model due to the plane of symmetry. The model consists of two sheets of shell elements joined by five bar elements representing the spot weld nuggets. The bars are stiff and have a length equal to half the sum of the sheet thicknesses.

The spot weld fatigue analysis system was used to predict load-life curves for these test specimens. The calculation was based on the S-N curves for spot welds in Reference [2] derived for spot welds in St1403 with thicknesses from 0.66 mm to 2.5 mm and spot weld nugget diameters from 3.5 mm to 6.5 mm.

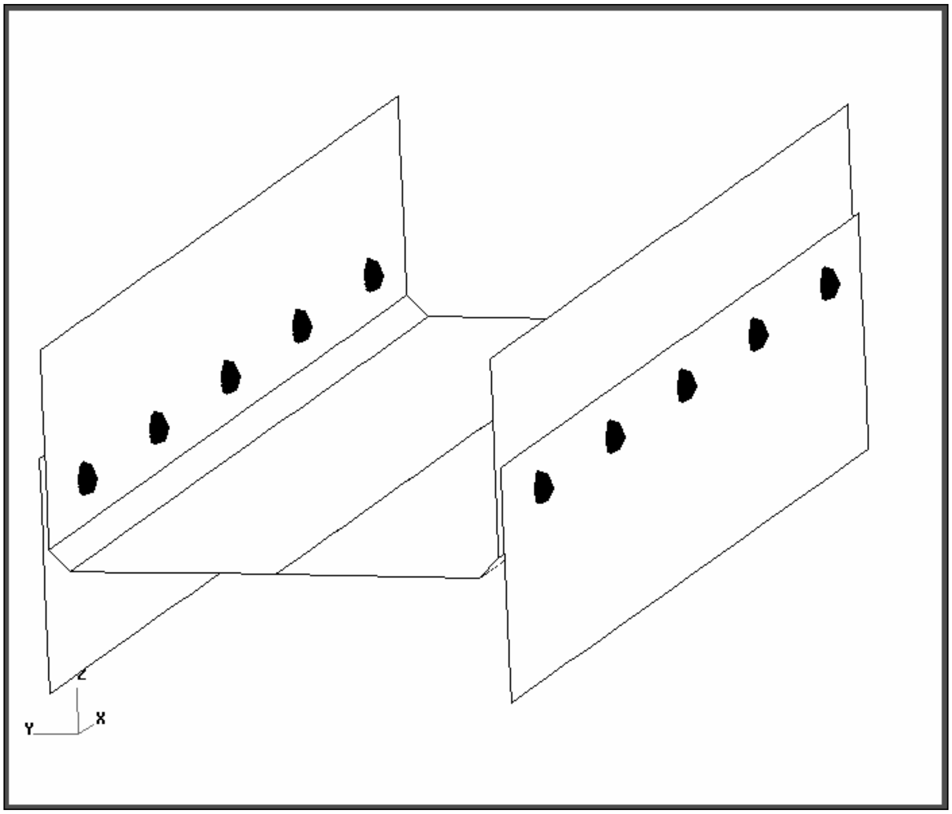

Figure 4: H-profile spot welded laboratory test piece.

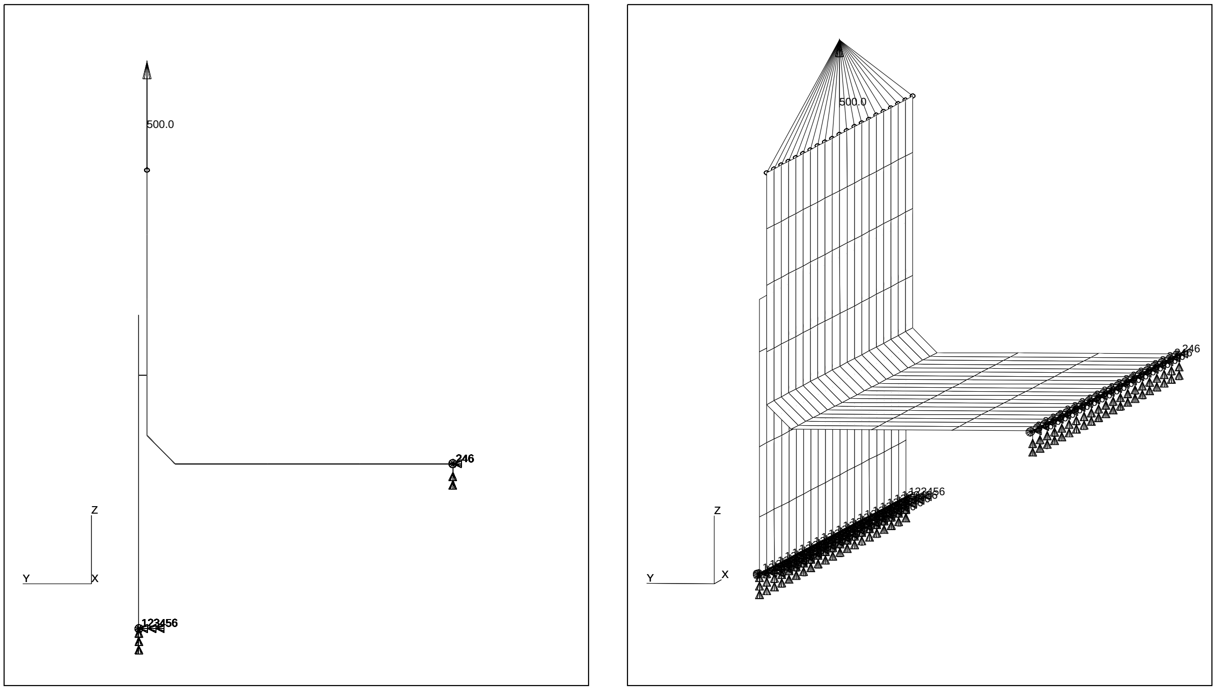

Figure 5: Finite element model of spot welded laboratory test piece.

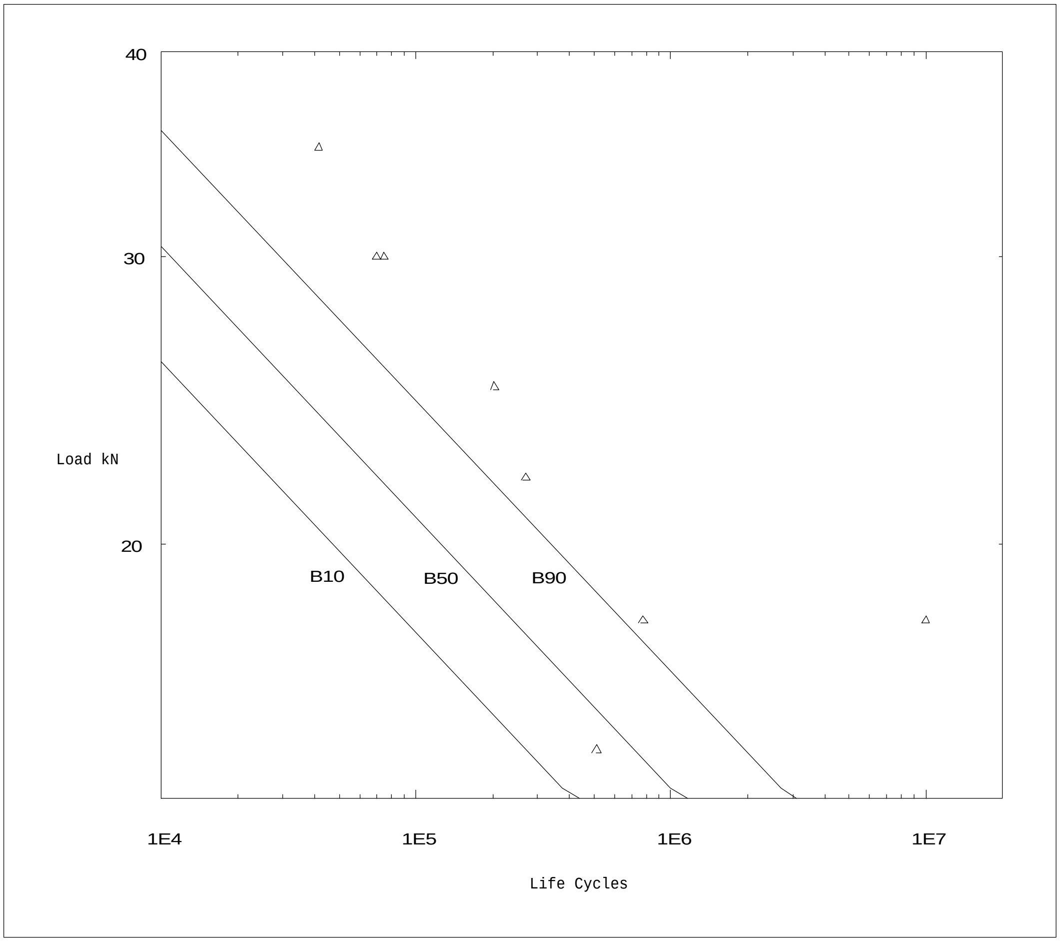

Figure 6: Comparison of test data with scatter band predicted using data from Reference [2].

In Figure 6 the test data are compared with the calculated B10, B50 and B90 lines based on Reference [2].

The spot weld fatigue results can be post-processed in a number of ways:

1. By listing the global results file.

2. By plotting the results in MSC/PATRAN. Insight is particularly good for this, allowing the fatigue life of each spot weld to be clearly visualised in the form of colour coded spheres attached to each beam element.

3. Detailed information may also be obtained about the life, damage, stresses and forces at each calculation point (i.e. 108 sets of results per spot weld).

4. Damage may also be visualised in the form of a polar plot. Figure 7 is a polar plot of log(damage) for the most damaged spot weld after one cycle of 3kN - 30kN - 3kN.

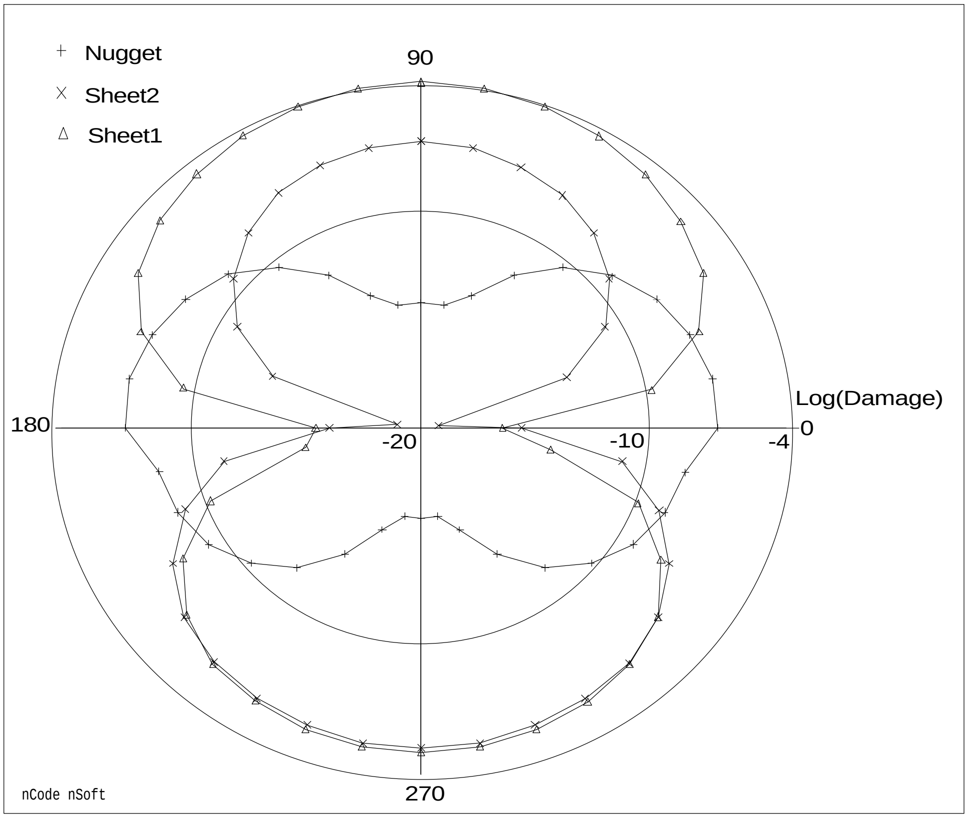

Figure 7: Polar plot of damage in the most damaged spot weld. Maximum load 30kN.

DISCUSSION

There appears to be reasonable correlation between the tests and the analysis, given the assumptions made. Clearly the predicted load-life curve is somewhat conservative compared to the experimental data. There are a number of possible reasons for this:

1. There may be a significant difference between the fatigue strength of spot welds in V-1147 and those in St1403 which were used to build the S-N curves used in the calculation.

2. A better spot welding technique may have been used in the specimens.

3. When the S-N data for shear loadings were processed for Reference [2], it seems that the effect of axial forces in the bar elements was neglected. In practice there is some axial force in shear tests which is quite sensitive to the geometry of the test assembly.

4. The failure criterion used in the test data plotted here was 30% decrease in stiffness. The failure criterion used to derive the basic S-N curve is not known.

Further work is desirable to identify the reasons for the differences between the predicted and experimental lives, and to validate the software system for other test specimens and for real automotive parts. The influence of the parent plate on spot weld durability also needs investigation, and there are some structures in which three sheets of metal are spot welded together. This method does not support such joints at present.

CONCLUSIONS

A software system has been developed for the fatigue life prediction of spot welds. It is based on the work of Rupp, Störzel and Grubisic [2] and supports analyses based on road load data, using either a quasi-static or a transient approach to stress history determination. This system provides a user-friendly way of predicting the location and life of fatigue sensitive spot welds.

This system could be of great benefit to users of MSC/NASTRAN, MSC/PATRAN and MSC/FATIGUE, especially those concerned with the durability of automotive chassis, suspension and body parts.

ACKNOWLEDGEMENTS

This work relied heavily on the programming efforts of Tim Fellows of nCode International Ltd and Mike Mathers of Structured Solutions Inc. It would not have been possible without the support of Alan Caserio of The MacNeal-Schwendler Corporation and Bengt Johannesson of AB Volvo. The contributions made by these people are gratefully acknowledged.

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