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METHOD OF FATIGUE LIFE PREDICTION FOR SPOT WELDED STRUCTURE

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ABSTRACT−The nominal structural stress calculation method proposed by Radaj has included some problems as follows: (a) How the value of the diameter D is decided in the method; (b) It is not possible to estimate nominal structural stress of the spot welded joints with the balanced sheet in-plane load that no general loads are obtained by FE shell analysis. In this paper, the new method for calculating nominal structural stress was proposed to solve above-mentioned problems. The proposed method calculates the nominal structural stress through the circular plate theory in theory of elasticity. This theoretical analysis uses not only general loads but also nodal displacements around spot welding provided by FE shell analysis as boundary condition. Fatigue test data of various spot-welded joints could be arranged in a narrow bandwidth on S-N chart using the nominal structural stresses calculated by proposed method. The fatigue life prediction method using the proposed method for calculating nominal structural stress is useful for the prior evaluation technique that can predict the fatigue life of spot welding by CAE.

KEY WORDS : Fatigue, Multi-axial load, Fatigue life prediction, Spot welded structures, Nominal structural stress

1. INTRODUCTION

The nominal structural stress is one of the key parameters for predicting the fatigue life of spot welding. Analyzing a refined FE model made with very fine elements is necessary to obtain the nominal structural stress with good accuracy. However, the automobile body structure is analyzed by using a rough FE shell model in general.

Radaj (1990) proposed the method for estimating fatigue strength in the spot welding by using nominal structural stress, which is calculated by using the general loads to the nugget obtained by the FE shell analysis of the spot welded structure. However, this method includes some problems as follows. (a) How the value of the diameter D is decided in the method? (b) It is not possible to estimate nominal structural stress of the spot welded joints with the balanced sheet in-plane load that no general loads are gotten by FE shell analysis (Gao *et al.*, 2001).

In this paper, we proposed a new method that can accurately obtain nominal structural stress of the spot welding to solve above-mentioned problems. The proposed method calculates the nominal structural stress through the circular plate theory in theory of elasticity. This theoretical analysis uses not only general loads but also nodal displacement around spot welding provided by FE shell analysis as boundary condition. This means that the proposed method calculates the nominal structural stress considering deformation condition around the spot welding in actual spot-welded structure. The values of nodal displacements around the spot welding depend on how to divide the mesh. Then, the analysis accuracy of nominal structural stress calculated by proposed method was verified by changing FE analysis model in and around the spot welding. The proposed method was applied to the simple spot-welded joint models and the actual structural model (For instance, spot-welded T shape joint structure), and the usefulness of the proposed method was confirmed.

2. METHOD OF FATIGUE LIFE ESTIMATION FOR SPOT WELDED STRUCTURES BY USING CAE

Figure 1 shows the flow chart of the fatigue life estimation method for a spot-welded structure by using the proposed method.

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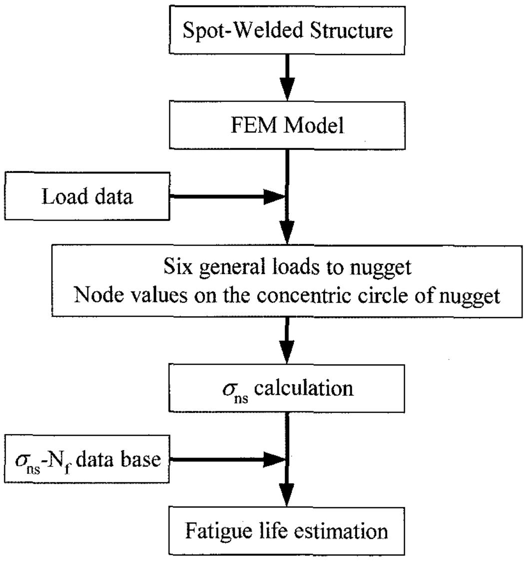


Figure 1. Flow chart of fatigue life estimation of spot-welded structures.

(1) The FE shell model is made for the spot-welded structure, and the finite element analysis is performed.
(2) The general load of the target nugget for the fatigue life estimation in the spot-welded structure and the displacement of the node on the concentric circle, which centers on the nugget, are obtained.
(3) Nominal structural stress σ_{ns} is calculated by the method that is based on the theory described in Chapter 3–4.
(4) The fatigue life is estimated from the σ_{ns}-N_f curve with test specimen under the multi-axial loads.

The key point of our proposed theory is to use the deformation of sheet around the nugget as a displacement boundary condition. This point is greatly different from the theory by D. Radaj.

3. STRESS ANALYSIS AROUND NUGGET

3.1. General Load

In general, the following six components of general loads act on the nugget as shown in Figure 2.

1. Cross tension F_z
2. Bending moments M_x, M_y
3. Shearing forces F_x, F_y
4. Twisting moment M_z

Nominal Structural Stress can be analyzed for general loads F_z, M_x, M_y as a plate bending problem and for general loads F_x, F_y, M_z as a plane stress problem.

3.2. Theoretical Solution for Nominal Structural Stress to Cross Tension and Bending Moment

As shown in Figure 2, the bending problem of a circular plate with cross tension F_z and bending moments M_x, M_y is considered. For the boundary condition on the circumference of the circular plate, the deformation of the sheet around the nugget in the spot-welded structure is adopted. Cylindrical coordinates $r\theta z$ are set, with the origin at the center of the nugget.

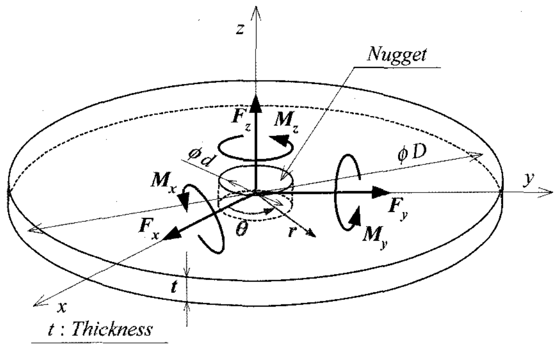


Figure 2. Loads acting on nugget.

The governing equation in the elasticity theory of a bending problem of a circular plate is given as:

$$\Delta\Delta w = 0 \tag{1}$$

$$\Delta = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2}$$

In general, the deflection function that satisfies the above equation is given as:

$$w = w_0 + w_1 + \sum_{n=2}^{\infty} w_n \tag{2}$$

$$= f_0(r) + f_1(r)cos\theta + \sum_{n=2}^{\infty} f_n(r)cos\, n\theta$$

$$f_0(r) = A_0 + B_0r^2 + C_0\ln r + D_0r^2\ln r$$

$$f_1(r) = A_1r + B_1r^3 + C_1r^{-1} + D_1r\ln r$$

$$f_n(r) = A_nr^n + B_nr^{-n} + C_nr^{n+2} + D_nr^{-n+2}$$

$$g_1(r) = A_1'r^n + B_1'r^{-n} + C_1'r^{-1} + D_n'r\ln r$$

$$g_n(r) = A_n'r^n + B_n'r^{-n} + C_n'r^{n+2} + D_n'r^{-n+2}$$

Where the unknown values of coefficients A_n to D_n' are determined by a boundary condition. At the nugget edge ($r = d/2$), the boundary condition is:

$$w_{r=d/2} = w_c + (d/2)(-\theta_{yc}\cos\theta + \theta_{xc}\sin\theta)$$

$$\left(\frac{\partial w}{\partial r}\right)_{r=d/2} = -\theta_{yc}\cos\theta + \theta_{xc}\sin\theta \tag{3}$$

Where w_c, θ_{xc}, and θ_{yc} are unknown coefficients that are determined by a condition described later. The circumferential distributions of the deflection w and its inclination at $\partial w/\partial r$ the nugget edge are expressed as

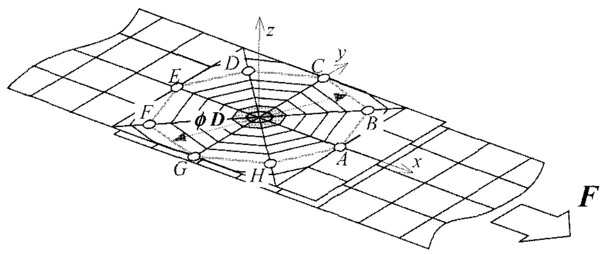


Figure 3. Example of FE shell model of spot-welded joint.

above because the nugget is assumed to be a rigid body.

On the circumference of the circular plate ($r = D/2$):

$$w_{r=D/2} = \frac{1}{2}\alpha_{w0} + \sum_{n=1}^{\infty}\alpha_{wn}\cos n\theta + \sum_{n=1}^{\infty}\beta_{wn}\sin n\theta$$

$$\left(\frac{\partial w}{\partial r}\right)_{r=D/2} = \frac{1}{2}\alpha_{ws0} + \sum_{n=1}^{\infty}\alpha_{wsn}\cos n\theta + \sum_{n=1}^{\infty}\beta_{wsn}\sin n\theta \quad (4)$$

The right-hand side of Equation (4) indicates the deformation around the nugget at the fatigue life estimation position in the spot-welded structure.

The method of obtaining the right-hand side of Equation (4) is explained as follows.

<1> A shell model is created as shown in Figure 3. The general section is divided into elements in a rough grid form. A Finite element analysis is performed to obtain the out-of-plane displacement w and the rotational displacement $\theta_r = \partial w/\partial r$ of the eight nodes, located at the eight vertices of the octagon inscribing the square shown in Figure 3.

<2> These discrete values are interpolated with the tertiary periodic spline interpolation function to obtain the circumferential distributions of the out-of-plane displacement w and rotational displacement θ_r. If the interpolation functions consist of nine sample points, q_i, the spline interpolation function of displacement w is:

$$w(\theta)_{r=D/2} = \sum_{i=-2}^{\infty} a_i B_{i,4}(\theta) + \sum_{i=-2}^{-1} a_i B_{i+8,4}(\theta) + a_5 B_{-3,4}(\theta) \quad (5)$$

Where, is a tertiary B spline obtained by the following recurrent equation:

$$B_{i,4}(\theta) = \frac{\theta - q_i}{q_{i+1} - q_i}B_{i,3}(\theta) + \frac{q_{i+4} - \theta}{q_{i+4} - q_{i+1}}B_{i+1,3}(\theta)$$

$$B_{i,1} = 1(q_i \le \theta \le q_{i+1}),\ 0(\theta < q_i,\ \theta \ge q_{i+1}) \quad (6)$$

In the Equation (5), the coefficient is determined so that $w(\theta)_{r=D/2}$ is equal to the value of the sample point at $\theta = q_i$. The rotational displacement $\theta(\theta)_{r=D/2}$ is also expressed as a spline interpolation function in the same way.

<3> These interpolation formulas are expressed by Fourier series and given as displacement boundary conditions on the circumference of the circular plate, like the right-hand side of Equation (4). The coefficient of the Fourier series in the Equation (4) is calculated as follows:

$$\alpha_{wn} = \frac{1}{\pi}\int_0^{2\pi} w(\theta)_{r=D/2}\cos n\theta$$

$$\alpha_{wsn} = \frac{1}{\pi}\int_0^{2\pi} \theta_r(\theta)_{r=D/2}\cos n\theta$$

$$\beta_{wn} = \frac{1}{\pi}\int_0^{2\pi} w(\theta)_{r=D/2}\sin n\theta$$

$$\beta_{wsn} = \frac{1}{\pi}\int_0^{2\pi} \theta_r(\theta)_{r=D/2}\sin n\theta \quad (7)$$

When the boundary conditions are used, all of the unknown values of the constants in the Equation (2) are determined.

If the equilibrium of the internal and external forces in the z-axis direction and the equilibriums of moments of forces about the x-axis and y-axis are considered for the nugget of the circular plate in Figure 2, constants w_c, θ_{xc}, and θ_{yc} in the Equation (3) can be expressed as cross tension F_z and bending moments M_x and M_y acting on the nugget.

$$-\int_0^{2\pi} Q_r\left(\frac{d}{2}\right)d\theta = F_z$$

$$-\int_0^{2\pi}(M_{r\theta}\cos\theta - M_r\sin\theta)\left(\frac{d}{2}\right)d\theta - \int_0^{2\pi} Q_r\left(\frac{d}{2}\right)^2\sin\theta d\theta = M_x$$

$$-\int_0^{2\pi}(M_{r\theta}\sin\theta + M_r\cos\theta)\left(\frac{d}{2}\right)d\theta + \int_0^{2\pi} Q_r\left(\frac{d}{2}\right)^2\cos\theta d\theta = M_y \quad (8)$$

Where Q_r, M_r and $M_{r\theta}$ are cross sectional force and cross section moments respectively.

Therefore, once the general loads of the nugget at the target position and the node displacements on the circumference of diameter D from the position have been obtained by FE shell analysis on the spot-welded structure, all unknown coefficients of Equation (2) are determined.

3.3. Theoretical Solution for Nominal Structural Stress to Shearing Force and Twisting Moment

As shown in Figure 2, the plane stress problem of a circular plate with shearing forces F_x, F_y and twist moment M_z is considered. The governing equation in the elasticity theory of a plane stress problem of a circular plate is given as:

$$\Delta\Delta\phi = 0$$

$$\Delta = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2} \quad (9)$$

In general, the stress function that satisfies the above equation is given as:

$$\phi = a_0\log r + b_0 r^2 + \frac{a_1}{2} r\theta\sin\theta - \frac{c_1}{2} r\theta\cos\theta$$
$$+ (b_1 r^3 + a_1' r^{-1} + b_1' r\log r)\cos\theta$$
$$+ (d_1 r^3 + c_1' r^{-1} + d_1' r\log r)\sin\theta$$
$$+ \sum_{n=2}^{\infty} (a_n r^n + b_n' r^{n+2} + a_n' r^{-n} + b_n' r^{-n+2})\cos n\theta$$
$$+ \sum_{n=2}^{\infty} (c_n r^n + d_n' r^{n+2} + c_n' r^{-n} + d_n' r^{-n+2})\sin n\theta \quad (10)$$

Where the unknown values of coefficients a_0 to d'_n are determined by a boundary condition.

The stress component are expressed as follows by using the stress function f:

$$\sigma_r = \frac{1}{r}\frac{\partial\phi}{\partial r} + \frac{1}{r^2}\frac{\partial\phi}{\partial\theta^2},\ \sigma_\theta = \frac{\partial^2\phi}{\partial\theta^2},\ \tau_{r\theta} = -\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial\phi}{\partial\theta}\right) \quad (11)$$

Using the stress-strain relation and the strain-displacement relation in 2-dimensional elasticity theory of isotropic homogeneous material and the Equation (11), displacements u and v are obtained.

At the nugget edge ($r=d/2$), the boundary condition is:

$$\begin{aligned} u_{r=d/2} &= u_{xc}\cos\theta + u_{yc}\sin\theta \\ v_{r=d/2} &= -u_{xc}\sin\theta + u_{yc}\cos\theta + \theta_c b \end{aligned} \quad (12)$$

u_{xc}, u_{yc}, and θ_c in the Equation (12) are the displacements of the nugget center. The displacement distributions on nugget edge are expressed as the Equation (12) because the nugget is assumed to be a rigid body. u_{xc}, u_{yc} and θ_c are determined by the general load described later.

On the circumference of the circular plate ($r=D/2$):

$$u_{r=D/2} = \frac{1}{2}\alpha_{Ou0} + \sum_{n=1}^{\infty}\alpha_{Oun}\cos n\theta + \sum_{n=1}^{\infty}\beta_{Oun}\sin n\theta$$
$$v_{r=D/2} = \sum_{n=1}^{\infty}\alpha_{Ow}\sin n\theta + \frac{1}{2}\beta_{Ow}\cos n\theta \quad (13)$$

The right-hand side of Equation (13) indicates the in-plane deformation around the target nugget for the fatigue life estimation in the spot-welded structure. The method for obtaining the right-hand side of the Equation (13) is similar to the bending described in 3.2 section.

By considering the equilibrium of internal and external forces which act on the nugget, the following equations is given.

$$F_x + \int_0^{2\pi} (\sigma_r\cos\theta - \tau_{r\theta}\sin\theta) b d\theta = 0$$
$$F_y + \int_0^{2\pi} (\sigma_r\sin\theta - \tau_{r\theta}\cos\theta) b d\theta = 0 \quad (14)$$
$$M + \int_0^{2\pi} b\tau_{r\theta} b d\theta = 0$$

Therefore, the displacements u_{xc}, u_{yc}, and rotation θ_c of Equation (12) can be shown with general loads F_x, F_y, and M_z.

4. NOMINAL STRUCTURAL STRESS UNDER MULTI-AXIAL LOADS

When the cross tension, the bending moment, the shearing force and the twisting moment act simultaneously on the nugget, as shown in Figure 1, the maximum principal stress at the nugget edge, expressed by the following equation, is assumed to be an nominal structural stress under multi-axial loads. This nominal structural stress is used as a fatigue strength parameter to predict the fatigue life of the spot-welded structure (Nakahara *et al.*, 2000a; Takahashi *et al.*, 2000; Nakahara *et al.*, 2000b; Gao *et al.*, 2001; Sawamura *et al.*, 2002).

$$\sigma_{p1}, \sigma_{p2} = \frac{(\sigma_{rsum} + \sigma_{\theta sum}) \pm \sqrt{(\sigma_{rsum} - \sigma_{\theta sum})^2 + 4\tau_{r\theta sum}^2}}{2} \quad (15)$$

Where, σ_{rsum}, $\sigma_{\theta sum}$, $\tau_{r\theta sum}$ are the superposed analytical results caused by each general load.

The proposed method is applicable to an actual spot-welded structure without bewilderment to decision of the outside diameter D of the circular plate. And, it is possible to estimate nominal structural stress of the spot-welded joints with no general loads to the nugget by FEM. In addition, the accuracy of the nominal structural stress can be enhanced because the sheet deformation around the nugget in the spot-welded structure is given as a boundary condition to calculate the nominal structural stress.

An analytical program based on this theory is easy to create and install in a CAE system.

5. APPLICATION TO LP MODEL

Figure 4 shows the LP model used to verify the solution accuracy of the nominal structural stress calculated by

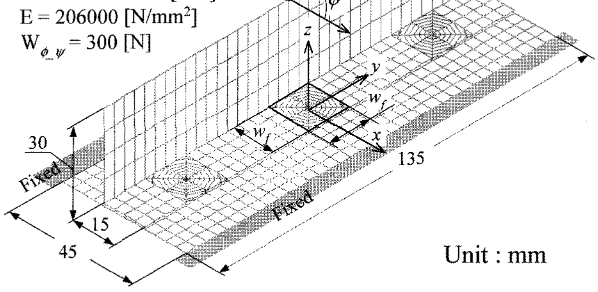
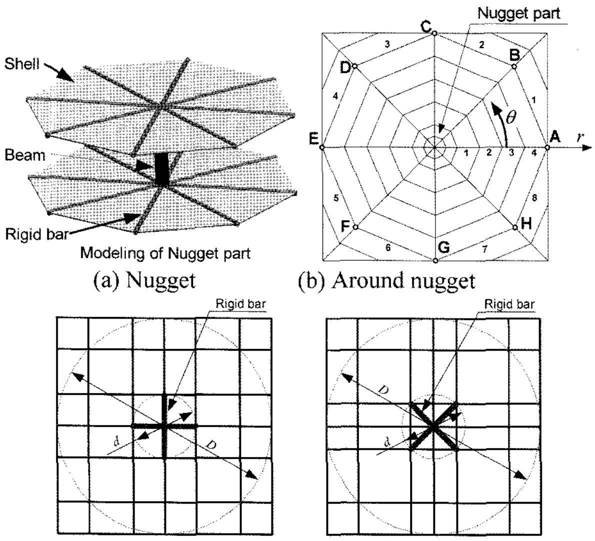


Figure 4. LP model $N_r04N_\theta08$ with number of division $(N_r, N_\theta) = (4, 8)$.



(a) Nugget (b) Around nugget

(c) Circumscribing model (d) Inscribing model

Figure 5. FE models in and around spot welding.

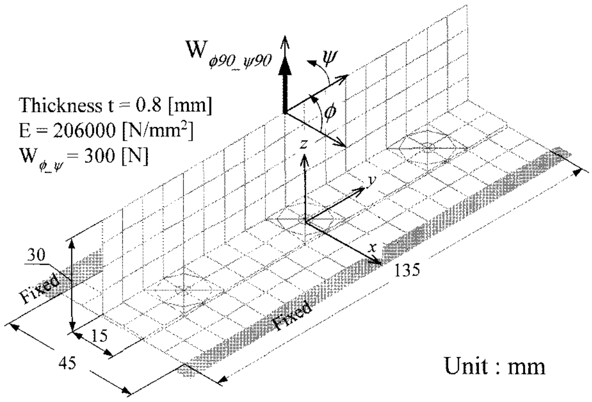
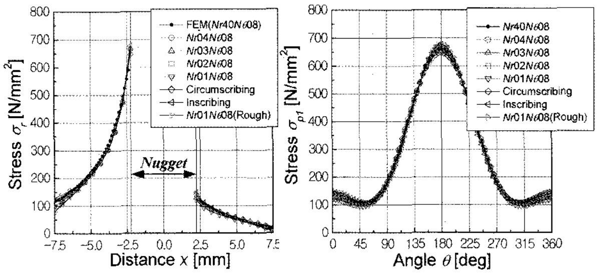


Figure 6. LP model made in rough mesh division.



(a) Normal stress σ_r on x-axis (b) Principal stress σ_{p1} around nugget

Figure 7. Stress distributions of various LP models.

proposed method. The LP model consists of L shape plate and flat plate. L shape plate is overlapped on flat plate and both plates are attached by spot welding at the three points. A FE model in and around the spot welding in LP model is shown in Figure 5.

A square having the flange width w_f as one side is drawn around the nugget. The square inside is divided in detail into the elements. The general section except for vicinity of the spot welding is divided roughly by rectangular elements. The number of elements in the radial direction around the nugget is designated by N_r, and the number of elements in the circumferential direction around the nugget is designated by N_θ. In Figure 5(b), the number of octagons in the nugget is two, and one in the outside of nugget is four. Four radial lines, which pass through the vertices of the six octagons, are created. The eight rigid bar elements are added in the radial direction along the sides of the shell elements in the nugget as shown in Figure 5(a). A beam element which rigidity is equivalent to the nugget is used to join the upper and lower plates at the center of the nugget. Moreover, the other FE models of the spot welding were created as follows. One model is made as the square, which is circumscribed about the circle of the nugget as shown in Figure 5(c), and another model is made as the square, which is inscribed in the nugget as shown in Figure 5(d).

A couple of vicinity of flat plate was assumed to be fixed, and the top edge of L shape plate was loaded with $W_{\phi 90\_\psi 90}$ = 300[N]. The model divided in detail, which is called $N_r40N_\theta08$ was used to obtain the exact solution of the nominal structural stress. This exact solution means the standard solution used to confirm the solution of the nominal structural stress obtained by proposed method.

Table 1. Nominal structural stresses of various division LP models.

Model	Number of element		Nominal structural stress σ_{ns} [N/mm²]	Error [%]
	N_r	N_Θ		
$N_r04N_\theta08$	4	8	676.78	−0.251
$N_r03N_\theta08$	3	8	678.63	0.022
$N_r02N_\theta08$	2	8	675.57	−0.429
$N_r01N_\theta08$	1	8	672.64	−0.861
Circumscribing	–	–	659.05	−2.864
Inscribing	–	–	690.50	1.772
$N_r01N_\theta08$(Rough)	1	8	678.06	-0.062
$N_r40N_\theta08$	40	8	678.48	–

Figure 7(a) shows stress σ_r distribution on x-axis (q=0) through a center of nugget, and Figure 7(b) shows the principal stress σ_p distribution in circumferential direction on the nugget edge. Table 1 shows the analytical results of nominal structural stress of various LP models.

The stress distributions of any models can be obtained

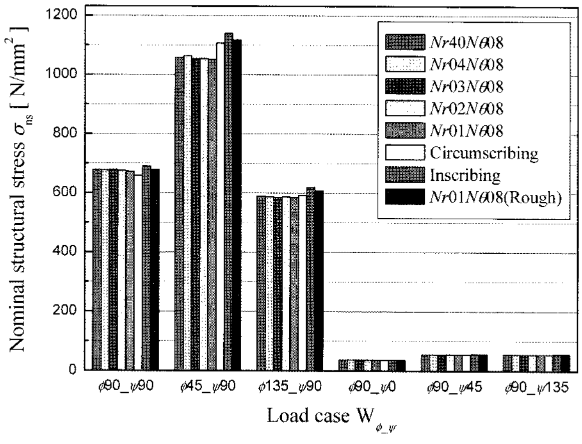


Figure 8. Nominal structural stress of LP model with various directions of load.

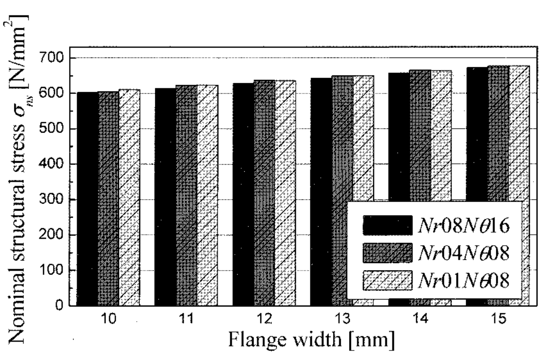


Figure 9. Transition of nominal structural stress by change in the flange width of LP model.

in good agreement with the one of the refined mesh model ($N_r40N_\theta08$). Moreover, the values of nominal structural stress can be obtained within 3% or less error in comparison with the value of refined model $N_r40N_\theta08$.

In the same way, the nominal structural stress was examined by using the roughest-mesh divided model $N_r01N_\theta08$ (Rough) as shown in Figure 6. The nominal structural stress was obtained with good accuracy by this model.

Thus, the proposed method can obtain the solution with good accuracy, even if the model is the rough mesh divided model.

The direction of the load (ϕ and ψ) was changed, and the result of the calculated nominal structural stress was shown in Figure 8. The nominal structural stresses calculated under various loading conditions were accurately obtained in comparison with the nominal structural stress calculated by using the refined model $N_r40N_\theta08$.

6. APPLICATION TO LP MODEL WITH NARROW FLANGE WIDTH

In an automobile body structure, there are spot welded joints with narrower flange width. The proposed method was applied to LP model with narrow flange width.

The flange width of the LP model shown in Figure 4 was changed, and the nominal structural stress was calculated by the proposed method. The load $W_{\phi 90\_\psi 90}$ = 300[N] acted on the top of L shape plate, and the flange width was changed 10 to 15[mm] (2.2 to 3.3 times of d=4.5 mm).

The results of the nominal structural stress are shown in Figure 9. The nominal structural stresses obtained by using the roughest-mesh divided model $N_r01N_\theta08$ were in good agreement with the nominal structural stresses obtained by using the refined model $N_r08N_\theta16$.

7. APPLICATION TO BRACKET MODEL

In the method proposed by D. Radaj, it is not possible to estimate nominal structural stress of the spot welded joints with the balanced sheet in-plane load that no general loads are gotten by FE shell analysis. For example, consider the spot-welded joint made by overlapping large and small two sheets and spot-welding them at the center as shown in Figure 10. This spot-welded joint is called the bracket model. The D. Radaj's method only using the general loads cannot obtain the accurate value of the nominal structural stress for the bracket model, because the value of all general load of

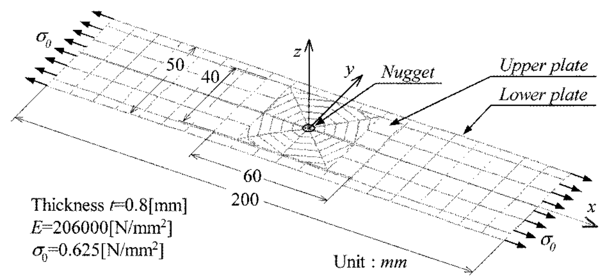


Figure 10. FE shell model for the spot-welded joints with bracket.

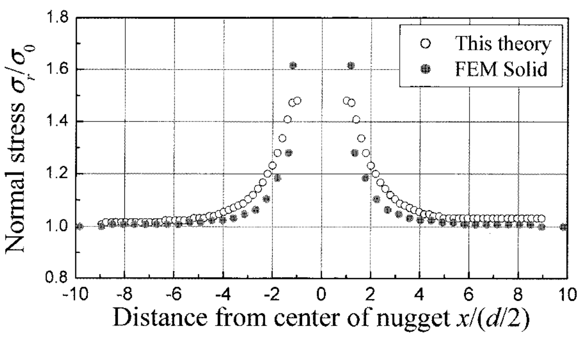


Figure 11. Stress distribution of the bracket model as the spot-welded joint with the balanced sheet in-plane load.

the bracket model obtained by FE shell analysis is zero.

The theory described in section 3.2 uses not only general loads but also nodal displacements around spot welding provided by FE shell analysis as boundary condition. As a result, the proposed method can calculate the nominal structural stress of the bracket model with no general loads. Figure 11 shows the stress distribution on x-axis through a center of nugget by using proposed method.

The proposed method could solve the problem (b) described in introduction.

8. EXAMINATION WITH ACTUAL STRUCTURAL MODEL

The proposed method is applied to T shape joint structure as shown in Figure 12. The various FE models of the spot welding in T shape joint structure were made as well as ones of the LP model described in Chapter 5. As shown

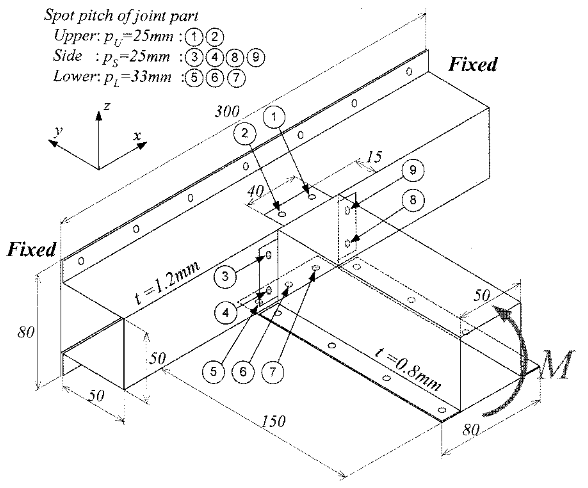


Figure 12. Spot-welded T shape joint structure.

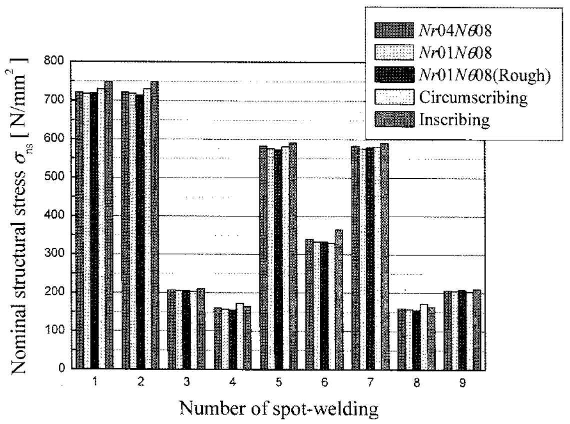


Figure 13. Nominal structural stress of spot welding within the joint part of T shape joint structure.

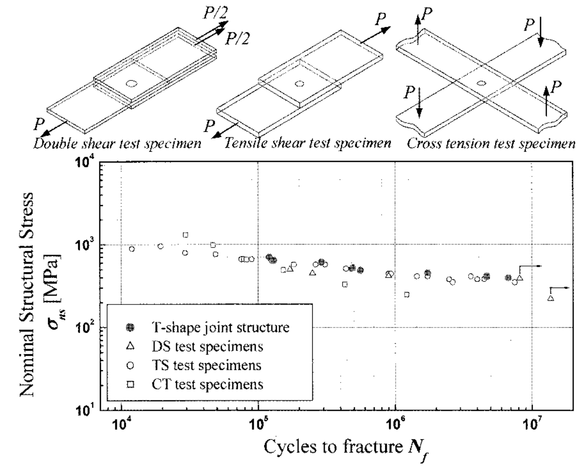


Figure 14. Arrangement of fatigue test data of DS, TS, CT and T shape joint(Nakahara *et al.*, 2000a; Takahashi *et al.*, 2000; Nakahara *et al.*, 2000b; Sawamura *et al.*, 2002).

in Figure 13, the nominal structural stress was obtained with good accuracy for any models in and around the spot welding.

9. ARRANGEMENT OF FATIGUE TEST DATA

The nominal structural stresses of the various test specimens such as DS, TS, and CT and T shape joint structure were calculated by the proposed method, and the fatigue test data was arranged using these stresses. Figure 14 shows the result of the rearrangement of fatigue data. The fatigue test data is arranged in a narrow bandwidth on S-N chart. Thus, the fatigue life prediction method using the proposed method for calculating nominal structural stress is useful for the prior evaluation technique that can predict the fatigue life of spot welding by CAE.

10. CONCLUSIONS

The new method of calculating nominal structural stress for spot-welded structures was proposed to solve some problems in the current calculation method. The main results are as follows.

(1) The proposed method uses not only general loads but also nodal displacements around spot welding provided by FE shell analysis as boundary condition. Therefore, the proposed method can estimate the nominal structural stress of the spot welded joints with the balanced sheet in-plane load that no general loads are gotten by FE shell analysis.

(2) Analytical accuracy of displacement of the node around the spot welding used as a boundary condition in the

proposed method depends on how to divide the mesh around the spot welding. By changing FE analysis model in and around the spot welding, the analytical accuracy of the nominal structural stress calculated was examined. The nominal structural stress could be obtained at the good accuracy, even if the FE analysis model is divided considerably roughly into the elements.

(3) Fatigue test data in test specimens with different loading type such as DS, TS and CT and T shape joint structure could be arranged in a narrow bandwidth on S-N chart using the nominal structural stresses by proposed method.

(4) The fatigue life prediction method using the proposed method is useful for the prior evaluation technique that can predict the fatigue life of spot welding by using CAE.

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