A METHOD OF CALCULATING NOMINAL STRUCTURAL STRESS FOR CHARACTERIZING FATIGUE BEHAVIOR OF SPOT-WELDED JOINTS

N. Tomioka[1], A. Okabe[1]

[1] Department of Mechanical Engineering, College of Science & Technology, Nihon University, 1-8-14, Kanda-surugadai,chiyoda-ku,Tokyo, Japan

ABSTRACT

This paper describes the method of calculating nominal structural stress which is correlated with the fatigue strength of the spot-welded joints. The proposed method is as follows. (a)First of all, the finite element model for spot-welded structure with shell elements of practicable size is made. (b)The data of displacement field around the assessed spot welding is derived from analyzing the finite element model in section (a). (c)The circular region, which is surrounded by concentric circle of a diameter D at the assessed spot welding in finite element model, is replaced by the circular plate with the same dimensions and same material as it and the stress analysis of the circular plate is curried out using plate theory in elasticity. In this analysis, the data of displacement field around the spot welding in section (b) is used as the displacement boundary conditions of the circular plate. The stress analysis results the excellent value of the nominal structural stress. The transferability of spot-welding S-N test data, regardless of sheet thickness and nugget diameter, can be established using the nominal structural stress based parameters.

KEYWORDS

Nominal structural stress, calculation method, spot-welded joints, spot-welding, fatigue behavior, fatigue life prediction, fatigue strength, finite element modeling, plate theory

INTRODUCTION

In developing new model vehicles, CAE has been positively employed recently for estimating in advance various vehicle performances, to shorten the development period as well as to reduce the number of prototypes. Application of CAE has also spread in the filed of the fatigue strength evaluation for vehicle body structures. Vehicle bodies are constructed of thin steel sheets and the sheets are connected by spot-welds. Since there are a lot of spot-welds and they are exposed to a variety of multi-axial loads, some fatigue troubles are often caused. In result, the need for more accurate estimation of fatigue strength, especially in spot-welds, are increasing.

D. Radaj [1] proposed the method for estimating fatigue strength in the spot welds 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 that fatigue crack is generated in causing stress concentration around the nugget edge, even if no general loads affect the nugget.

N. Tomioka and A. Okabe [3-9] proposed the method that can accurately obtain nominal structural stress of the spot welds in order 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 node displacement around spot welds got in FE shell analysis as boundary condition. It is meant that the nominal structural stress is calculated considering deformation condition around the spot welds in actual spot welded structure. In the proposed method, the FE model of the nugget as shown in figure 1 is used. The two octagons are formed by shell elements, and the eight rigid bar elements are added in the radial direction along the sides of the shell elements. A beam element having the nugget-equivalent rigidity is used to join the upper and lower sheets at the center of the nugget. However, it is desirable that the FE model of the nugget is as simple as possible for the applications of the method, because there are several thousand spot-welds in a vehicle body.

In this study, the new method of calculating nominal structural stress for characterizing fatigue behavior of spot-welded joints was proposed in order to simplify the FE model of the nugget and the accuracy of solution of nominal structural stress calculated by the proposed method was investigated.

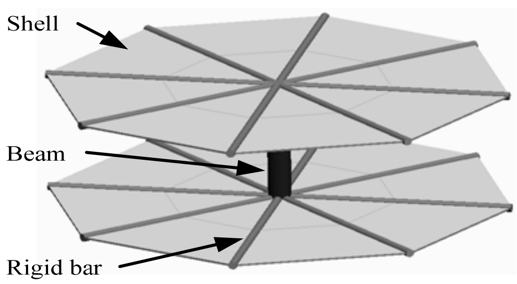


Fig. 1 : Modeling nugget for FEA

A PROPOSED METHOD OF CALCULATING NOMINAL STRUCTURAL STRESS

The flow chart of proposed method of calculating nominal structural stress is shown in figure 2 and explained as follows.

(a)First of all, the finite element model for spot-welded structure with shell elements of practicable size is made.

(b)The data of displacement field around the assessed spot welds is derived from analyzing the finite element model in section (a).

(c)Each circular region on upper and lower sheets, which is surrounded by concentric circle of a diameter D at the assessed spot weld in finite element model, is replaced by the circular plate with the same dimensions and same material as each circular region respectively, and the two circular plates are jointed by one beam having the nugget-equivalent rigidity.

(d)The stress analysis of the circular plates with one beam is curried out using plate theory in elasticity. In this analysis, the data of displacement field around the spot weld in section (b) is used as the displacement boundary conditions of the upper and lower circular plates.

(e)As a result, the excellent value of the nominal structural stress can be calculated.

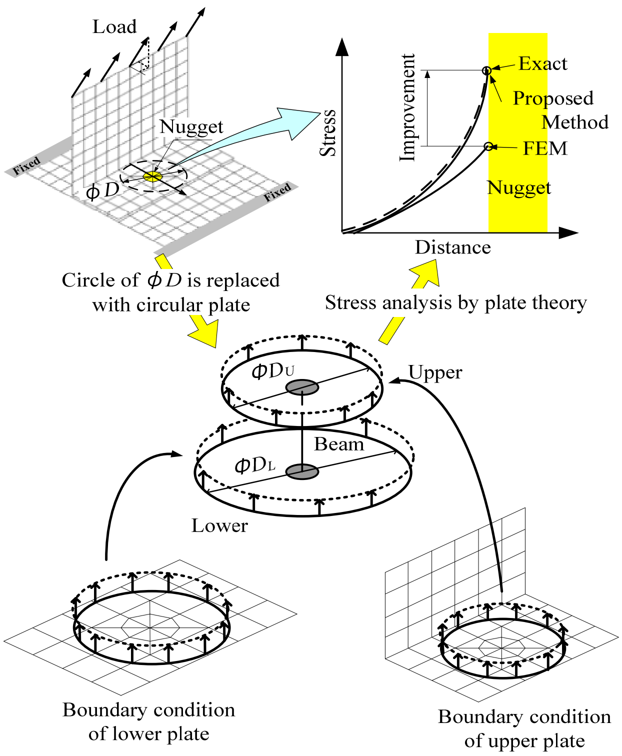


Fig. 2 : Method of calculating nominal structural stress

A STRESS ANALYSIS METHOD OF CIRCULAR PLATE

N. Tomioka and A. Okabe have proposed the method of calculating the nominal structural stress of the spot-weld through the circular plate theory in theory of elasticity. According to the method, the derived stresses and displacements components of plate are the function of general loads and displacements around spot welds as shown in figure 3.

$$\boldsymbol{\sigma}_{ij} = \boldsymbol{F}\left(\boldsymbol{P}_k, \boldsymbol{u}_l\right) \tag{1}$$

$$\boldsymbol{v}_i = \boldsymbol{F}\left(\boldsymbol{P}_k, \boldsymbol{u}_l\right) \tag{2}$$

Where, $\boldsymbol{\sigma}_{ij}$ are stress components, v_i displacement components of plate, $\boldsymbol{P}_k$ general loads, $\boldsymbol{u}_l$ displacement components used as boundary condition.

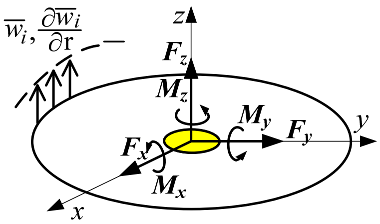


Fig. 3 : Analyzing stresses of circular plate using general loads and displacements boundary conditions

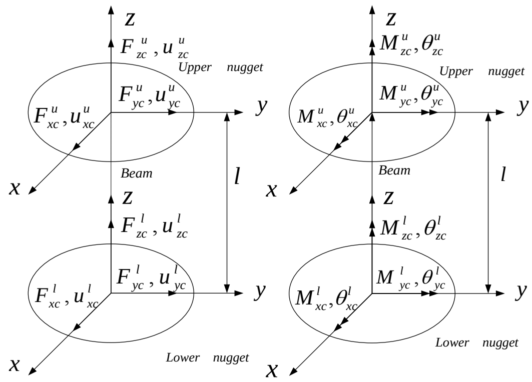


Fig. 4 : Forces and moments of nugget and displacements boundary conditions

In this study, the data resulted from FE analysis of the spot-welded structure is only displacement components, and no general loads are assumed to be obtained. Then, when the only displacements as the boundary conditions are imposed on the two circular plates jointed by one beam as shown in figure 2, the general loads, which act on the nuggets in the upper and lower plates, can be found as follows.

Figure 4 shows the upper and lower nuggets, which are assumed to be rigidity, jointed by one beam at the center of nugget. F_{xc}^u, F_{yc}^u, F_{zc}^u, M_{xc}^u, M_{yc}^u, M_{zc}^u designate general loads of upper nugget, F_{xc}^l, F_{yc}^l, F_{zc}^l, M_{xc}^l, M_{yc}^l, M_{zc}^l general loads of lower nugget, u_{xc}^u, u_{yc}^u, u_{zc}^u, θ_{xc}^u, θ_{yc}^u, θ_{zc}^u displacement components at the center of upper nugget, and u_{xc}^l, u_{yc}^l, u_{zc}^l, θ_{xc}^l, θ_{yc}^l, θ_{zc}^l displacement components at the center of lower nugget. The equilibriums equations of forces and moments, which act on the beam, are:

$$F_{zc}^{u} + F_{zc}^{l} = 0\,, \quad F_{xc}^{u} t^{u} + F_{xc}^{l} t^{l} = 0\,, \quad F_{yc}^{u} t^{u} + F_{yc}^{l} t^{u} = 0$$

$$M_{zc}^{u} t^{u} + M_{zc}^{l} t^{l} = 0\,, \; -M_{xc}^{l} - M_{xc}^{u} + F_{yc}^{u} t^{u} l = 0\,, \; -M_{yc}^{l} - M_{yc}^{u} - F_{xc}^{u} t^{u} l = 0 \quad (4)$$

Where, t^u and t^l designate thickness of upper and lower nuggets respectively, l length of beam. The relationships between the displacements at the nugget centers are:

$$u_{xc}^{u} = u_{xc}^{l} + \theta_{yc}^{l} l - \frac{t^{u} F_{xc}^{u} l^{3}}{3EI} - \frac{M_{yc}^{u} l^{2}}{2EI}\,, \quad u_{yc}^{u} = u_{yc}^{l} + \theta_{xc}^{l} l - \frac{t^{u} F_{yc}^{u} l^{3}}{3EI} - \frac{M_{xc}^{u} l^{2}}{2EI}\,,$$

$$w_{c}^{u} = w_{c}^{l} - \frac{F_{zc}^{u} l}{EA}\,,$$

$$\theta_{xc}^{u} = \theta_{xc}^{l} - \frac{t^{u} F_{yc}^{u} l^{2}}{2EI} - \frac{M_{xc}^{u} l}{EI}\,, \quad \theta_{zc}^{u} = \theta_{zc}^{l} - \frac{M_{zc}^{u} l}{GI_{p}}\,, \quad \theta_{yc}^{u} = \theta_{yc}^{l} - \frac{t^{u} F_{xc}^{u} l^{2}}{2EI} - \frac{M_{yc}^{u} l}{EI} \qquad (5)$$

Where, EA is elongation rigidity of the beam, EI flexural rigidity and GI_p torsion rigidity.

Since each component of displacement at center of the nugget is represented by the liner sum of general loads(7), the twelve components of general loads in equations (4) and (5) can be solved. The resulted general loads are substituted into the equations (1) and (2), and the stresses and displacements of circular plate are obtained.

When the cross tension, the bending moment, and the shearing force and the twisting moment act simultaneously, as shown in figure 3, an nominal structural stress is defined as the maximum principal stress produced at the nugget edge expressed by the following equation (6). The nominal structural stress is used to predict the fatigue strength of spot-weld[2] [3] [4] [5].

$$\sigma_{p1}, \sigma_{p2} = \frac{(\sigma_{rsum} + \sigma_{\theta sum}) \pm \sqrt{(\sigma_{rsum} - \sigma_{\theta sum})^{2} + 4\tau_{r\theta sum}^{2}}}{2} \qquad (6)$$

Where σ_{rsum}, $\sigma_{\theta sum}$, $\tau_{r\theta sum}$ are the sum of stresses components resulted from stress analysis for each general load.

APPLICATION TO A SINGLE SPOT-WELDED JOINTS UNDER TENSILE SHEAR

Figure 6 shows finite element model of single spot-welded joints, which is composed of two same rectangular sheets, under tensile shear. The general section except overlap between two sheets is divided into rectangular shell elements. The finite element model of nugget is two inscribed octagons of circular nugget, which are composed of eight triangle shell elements, as shown in figure 7(a). The eight points A, B, C, D, E, F, G, H designate nodal points of upper sheet and the eight points A', B', C', D', E', F', G', H' designate nodal points of lower sheet. The two octagons are jointed at the center by a common node. The young modulus of shell elements in nugget is 10,000 times as high as one of other part and the rigidity of nugget is higher than one of other. The another finite element model of nugget is inscribed square of circular nugget with the young modulus equal to one of the octagon model as shown in figure 7(b).

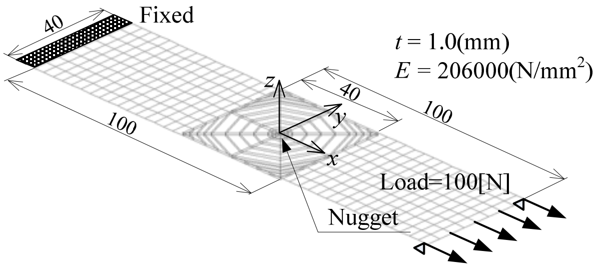
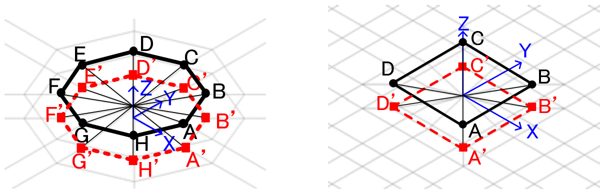


Fig. 6 : FE model of single spot-welded joints under tensile shear (TS)



(a) Octagon (b) Square

Fig. 7 : FE models of nugget

Figure 8 shows the distributions of normal stress σ_r of TS on the x axis. The maximum principal stress produced at the end of nugget is equal to the normal stress σ_r at the same point and is the nominal structural stress of TS. The analytical results of the proposed method were agree well with the detailed finite element analysis results and the excellent nominal structural stress was able to be obtained.

Figures 9 and 10 show the relationships between nominal structural stress of TS and sheet thickness and nugget diameter respectively. The S-N diagrams resulted from the fatigue test of TS are shown in figure 11 and 12. As shown in figure 12, the fatigue data are rearranged in the narrow band using the nominal structural stress based parameter, regardless of sheet thickness.

The fatigue data of TS with different sizes of nugget diameter are also arranged using the nominal structural stress as shown in figure 13. The transferability of spot-welding S-N test data, regardless of sheet thickness and nugget diameter, can be established using the nominal structural stress based parameters.

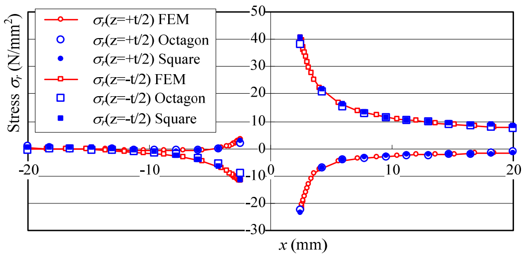


Fig. 8 : Distribution of normal stress σ_r of TS on x axis

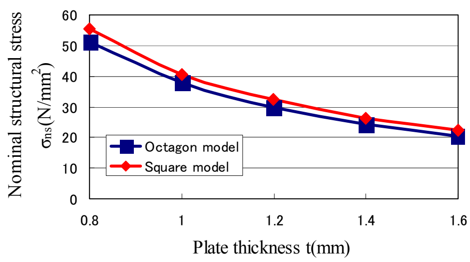


Fig. 9 : Relationships between nominal structural stresses and sheet thickness

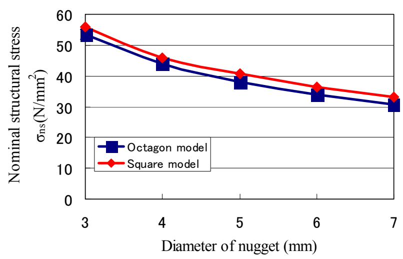


Fig.10: Relationships between nominal structural stresses and diameter of nugget

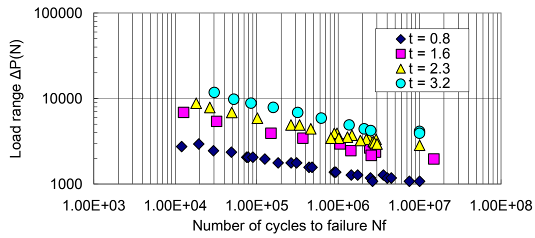


Fig.11: S-N data of TS arranged using load range

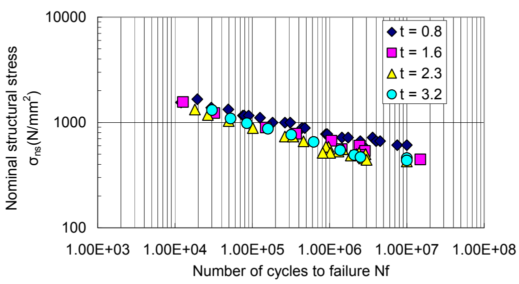


Fig.12: S-N data of TS with different sheet thickness rearranged using nominal structural stress

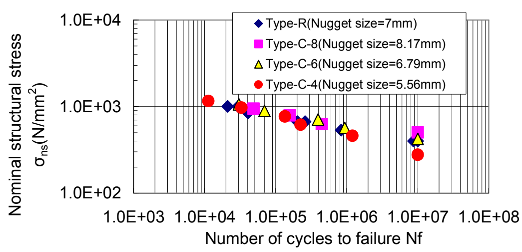


Fig.13: S-N data of TS with different nugget size rearranged using nominal structural stress

CONCLUSIONS

The method of calculating nominal structural stress which is correlated with the fatigue strength of the spot-welded joints was proposed. The main results are as follows.

(1)It is confirmed that the proposed method makes the value of the nominal structural stress of the tensile shear specimen, which is one of the typical spot-welded joints, excellent.

(2) The relationships between the nominal structural stresses and the size of the spot weld and sheet thickness are come out.

(3) The transferability of spot-welding S-N test data, regardless of sheet thickness and nugget diameter, can be established using the nominal structural stress based parameters.

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