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Calculation of Welding Deformations by Simplified Thermal Elasto-plastic Analysis

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Abstract

Welding deformations injure the beauty of appearance of a structure, decrease its buckling strength and prevent increase of productivity. Welding deformations of real structures are complicated and the accurate prediction of welding deformations has been a difficult problem. This study proposes a method to predict the welding deformations of large structures accurately and practically based on the simplified thermal elasto-plastic analysis method. The proposed method combines the inherent strain theory with the numerical or theoretical analysis method and the experimental results. The weld joint is assumed to be divided into 3 regions such as inherent strain region, material softening region and base metal region. Characteristic material properties are used in structural modeling and analysis for reasonable simplification. Calculated results by this method show good agreement with the experimental results. It was proven that this method gives an accurate and efficient solution for the problem of welding deformation calculation of large structures.

Keywords: inherent strain, large structure, efficient numerical method, simplified thermal elasto-plastic analysis, welding deformation

1 Introduction

Welding deformations are generated by the nonuniform temperature distribution during welding process. After local melting and thermal cycle is completed, plastic strains remain which are the cause of permanent deformation. Welding deformations cause errors during the assembly of a structure and reduce productivity efficiency. Also, welding deformations decrease the strength of the structure and injure outward beauty. If welding deformations are predicted precisely before construction of the structure, various countermeasures can be prepared and problems are reduced.

Many researchers have studied to predict welding deformations precisely. Accumulated research results up to now can be classified into the results by the experimental method, the ones by the analytical methods and the ones by the numerical methods. The experimental method deduces the relation between welding parameters in terms of simple equation(Satoh and Terasaki 1976). However, the relation is normally confined to the specified deformation mode because the number of combinations between the parameters is so large and experimental results are limited by cost and time. The experimental method is only useful in estimation of specified deformation of the simple structure.

The analytical method is based on the classical theory of elasticity and neglects the thermal elasto-plastic process. The analytical method only considers residual plastic strains, which are defined as inherent strains, and assumes all the regions including the inherent strain region remain elastic (Watanabe and Satoh 1961). Calculation of the welding deformation results in the solution of problems of the theory of elasticity (Fujimoto 1971). However, the analytical method has shortcomings such that possible solutions of the theory of elasticity problems are limited and the solution for the large structure is impossible. The region and magnitude of the inherent strain should be given by the experimental results.

Nowadays, numerical methods such as finite element method and boundary element method are popular in almost all engineering fields because simulation of the behavior is possible Ueda and Yamakawa (1973), Masubuchi (1980) and Moshaiov and Vorus (1987). Commercial general purpose software such as ABAQUS (Hibbit, Karlson and Sorensen, 1993) and ANSYS (Swanson Analysis System 1992) based on the finite element method enable simulation of the thermal elasto-plastic process during welding. Specified software SYSWELD (Framasoft+CSI 1995) for welded structures enables more convenient analysis of welding deformations. However, the detailed thermal elasto-plastic analysis using the commercial software requires very much computing time and accuracy is not good. Practical application of the simulation method to calculation of welding deformations for an actual large structure is restricted and almost impossible.

In this study, to calculate the welding deformations of the actual structure, a new method is proposed as a candidate for the solution of the shortcomings of the developed methods mentioned above. It combines the previous experimental, analytical and numerical methods to get the accurate results efficiently enough for practical purpose. Calculated results by using the proposed method show good agreement with the experimental results.

2 Concept of simplified thermal elasto-plastic analysis method

Since welding deformation is produced through complicated nonlinear behavior of the structure during thermal cycle, thermal elasto-plastic analysis allowing for the related factors is needed to calculate welding deformations. However, it is difficult to apply the thermal elasto-plastic analysis method to general structures because computing time is very large and accuracy depends greatly on modeling technique and incremental calculation step. Simplified thermal elasto-plastic analysis method was developed for practical use. It avoids simulating detailed thermal nonlinear process. It assumes thermal process takes place only in the confined region. It also separates thermal process from deformation calculation process and the interaction between the processes is considered by equivalent force and spring constant. Time varying material properties during welding are represented by the specified representative values at one instant.

2.1 Regions of welded joint

The weld joint is assumed to be composed of three parts such as inherent strain region, material softening region and base metal region. The inherent strain region experiences rapid temperature rise and transfer of heat input, where plastic strains remain. Around the inherent strain region, there can be a region where plastic strains are not created but material properties are changed due to heat transferred from the inherent strain region. This region may be defined as material softening region. Except the inherent strain region and the material softening region, the base metal region has the material properties of room temperature and remains elastic. Rapid temperature changes of the inherent strain region are restrained by the material softening region and the base metal region. The material softening region may make little contribution to restraining the inherent strain region because material properties and strength may be negligible in high temperature.

2.2 Calculation of inherent strain

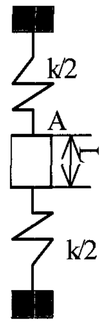


Figure 1: Simplified body and spring model for describing welding process

Figure 1 shows a body and spring model to represent the mechanical process of welding (Seo and Jang 1999). The behavior of the material softening region and the base metal region is represented by the spring. Thermal stress is caused by the difference of temperatures and thermal expansions between the inherent region and the other regions. Plastic strain is calculated by equilibrium condition and stress-strain relation. Plastic strain is concentrated on the inherent strain region. Residual plastic strain after welding is the sum of plastic strains produced during temperature increasing stage and temperature decreasing stage. Resulting plastic strain is given by the following equation.

$$\varepsilon_p = \varepsilon_{p1} \cdot \varepsilon_{p2} = -\left[\alpha\left(T_m - T_0\right) + \frac{\sigma_Y}{E} + \frac{\sigma_Y A}{L}\right] \tag{1}$$

where, $\varepsilon_{p1}, \varepsilon_{p2}, \varepsilon_{p3}$, α and T_m, T_0 are plastic strain, plastic strain at temperature decreasing stage, plastic strain at temperature increasing stage, thermal expansion coefficient, mean temperature and room temperature, respectively. In addition, σ_Y, E, k, A, L are yield stress, Young's modulus, spring constant, area of body and length of body, respectively.

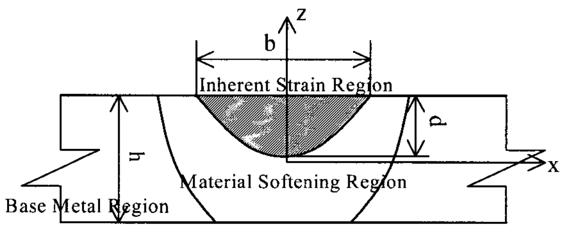
Equation (1) shows that residual inherent strain is determined by mean temperature after welding, material properties and the effect of restraint. During thermal elasto-plastic process, temperature and material properties are changed, but in simplified thermal elasto-plastic analysis, one characteristic value is assumed to represent the whole process for simplification. It is the concept similar with the time average of the material property(Seo and Jang 1999).

3 Equivalent forces of inherent strain

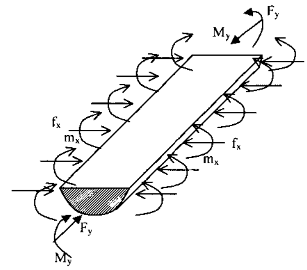
The region where the temperature exceeds the critical temperature becomes the plastic strain region. The critical temperature is defined as the temperature at which material loses the capacity to resist deformation. For the simplicity, the region above the critical temperature is defined as inherent strain region. The shape of the isothermal curve of the critical temperature is near elliptical, which is verified by theory and experiment (Masubuchi 1980). The inherent strain region can be determined by the temperature distribution curves obtained by the heat conduction theory. However, it can also be determined by the following thermal equilibrium relation.

$$\frac{\pi}{4}bd = \frac{fq}{c\rho(T_{\max} - T_0)} \tag{2}$$

where, Q, f, c and ρ are heat input, portion of heat input, specific heat and density, respectively.



(a) Definition of inherent strain region



(b) Forces and moments due to inherent strain

Figure 2: Inherent strain region

Equivalent forces induced by the inherent strain can be divided into the forces and moments acting in the direction normal to the weld line and those acting in the direction parallel to the weld line as shown in Figure 2(b). Normal forces and moments parallel to the weld line per unit length can be calculated by the following equations.

$$f_x = E_{ix}\int_{-h/2}^{h/2}\frac{1}{b}\varsigma_x dz = E_{ix}\left[\alpha T_{c(x)} + \frac{\sigma_{Yx}}{E_{ix}} + \frac{\sigma_{Yx}h}{k_x b}\right]\frac{\pi}{4}d \tag{3}$$

$$m_x = E_{ix}\int_{-h/2}^{h/2}\frac{1}{b}z\varsigma_x dz = E_{ix}\left[\alpha T_{c(x)} + \frac{\sigma_{Yx}}{E_{ix}} + \frac{\sigma_{Yx}h}{k_x b}\right]\frac{\pi}{4}d\frac{h}{5} \tag{4}$$

where, T_c is critical temperature and ς_x is plastic strain times length. Subscript i and x mean inherent strain region and x-direction, respectively.
Forces normal to the weld line and moments parallel to the weld line are affected by

temperature gradient in the plate thickness direction because shrinkage normal to the weld line is dependent on the temperature distribution in the plate thickness direction. Forces parallel to the weld line and moments normal to the weld line can be calculated by the following equations.

$$F_y = E_{iy} \int_{-h/2}^{h/2} \varepsilon_{P(y)} dz = E_{iy} \left[\alpha T_{c(y)} + \frac{\sigma_{Ty}}{E_{iy}} + \frac{\sigma_{Yy} H}{k_y b} \right] \frac{\pi}{4} bd \tag{5}$$

$$M_y = E_{iy} \int_{-h/2}^{h/2} z \varepsilon_{P(y)} dz = E_{iy} \left[\alpha T_{c(y)} + \frac{\sigma_{Yy}}{E_{iy}} + \frac{\sigma_{Yy} h}{k_y b} \right] \frac{\pi}{4} bd \frac{h}{5} \tag{6}$$

where, subscript y means y-direction.

4 Calculation procedure

A procedure to predict welding deformations combining the simplified thermal elasto-plastic analysis method with the finite element method can be summarized as shown in Figure 3.

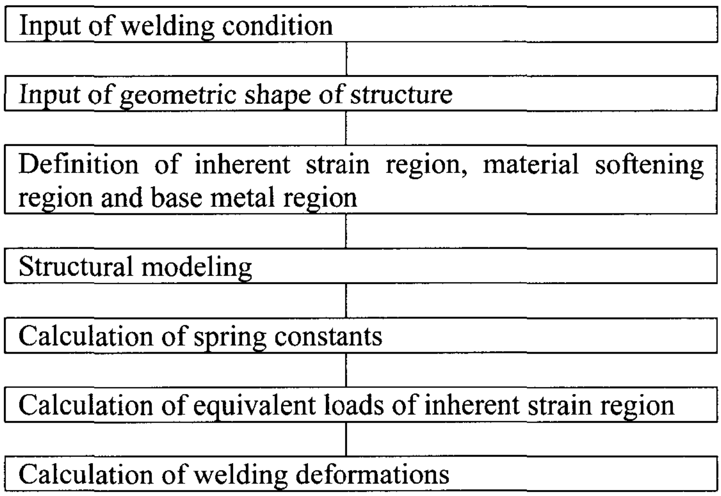


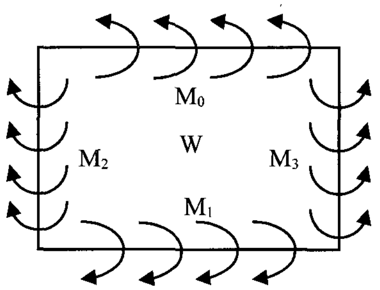
Figure 3: A procedure to calculate welding deformation

The inherent strain region is given by equation (2). As the material properties of the three regions are different, different material constants are used in structural modeling. The spring constants are calculated by structural analysis. Since the magnitude of the inherent strain depends on the restraining effect as well as temperature distribution, the previous analysis result is used to determine the magnitude. Equivalent loads are calculated by using equations (3), (4), (5) and (6), which are the integrated values of the inherent strain. Final deformations are calculated by the structural analysis for the calculated equivalent loading case.

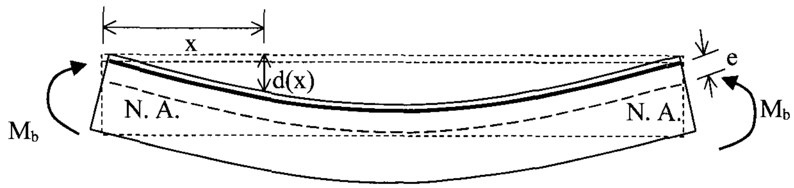
5 Calculation of welding deformations of stiffened plate

As an example to apply the proposed method, stiffened plate common in ship structure is taken. The out-of-plane deformation is calculated by the proposed method combined with the theoretical method. For theoretical analysis, the stiffened plate is divided into rectangular plates and stiffeners with effective plating. A simply supported rectangular plate under edge moments is shown in Figure 4. Since within linear elastic limit, principle of superposition can be applied to the plate, the deformations of the plate under 4 edge moments are the sum of the deformation under each edge moment. In Figure 4(a), material softening region is considered as simply supported boundary.

The deformation of the plate shown in Figure 4 can be calculated by the analytic solution based on the plate bending theory as follows(Timoshenko and Woinowsky 1970).



(a) Simply supported plate under 4 edge moments



(b) Stiffener under edge moments

Figure 4: Equivalent moments of weld stiffened plate

$$w_0 = -\frac{a^2}{4\pi^2 D}\sum_{m=1,3,5,\cdots}^{\infty}\frac{E_{m0}\sin\frac{m\pi x}{a}}{m^2}\left[\begin{array}{l}\frac{1}{\cosh\delta_m}\left(\delta_m\tanh\delta_m\cosh\frac{m\pi y}{a}-\frac{m\pi y}{a}\sinh\frac{m\pi y}{a}\right)\\+\frac{1}{\sinh\delta_m}\left(\delta_m\coth\alpha_m\sinh\frac{m\pi h}{a}-\frac{m\pi y}{a}\cosh\frac{m\pi y}{a}\right)\end{array}\right] \quad (7)$$

where, a, D and s are length of plate, plate bending rigidity and breadth of plate, respectively. Also, $\delta_m = m\pi s/2a$.

The deformation of the stiffener subjected to internal eccentric bending moment can be calculated by simple beam theory as follows.

$$d(x) = \frac{M_b L_s}{2EI}\left(1-\frac{x}{L_s'}\right)x \quad (8)$$

where, Ls and I are length of stiffener and second moment of stiffener including effective plating.
Since the stiffeners are also deformed, the deformations of the stiffeners are superimposed to the whole out-of-plane deformation of the panels.

5.1 Estimation of equivalent moments

Edge moments of stiffeners and plate due to the inherent strain are estimated by equations (9) and (10), respectively

$$M_i = \frac{f_p Q h}{b} \quad (9)$$

where, fp, h and Mi are correction factor, plate thickness and edge bending moment per unit length, respectively. fp can be given by equations (2) and (4).

$$M_b = f_s \frac{E\alpha}{c\rho} Q e \quad (10)$$

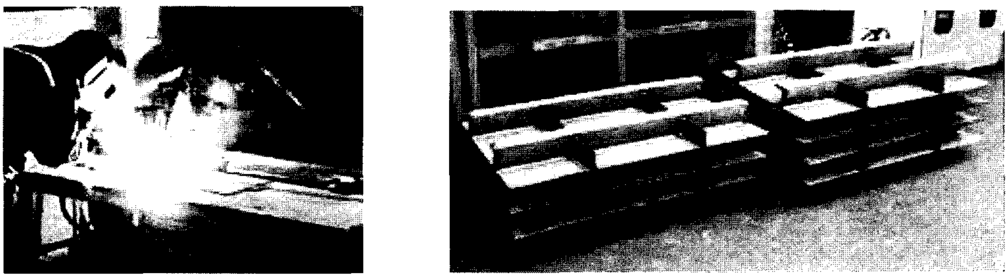
where, f_s and e are correction factor and distance between neutral axis and weld line.

Resulting bending moment for the restrained panel can be calculated by using the bending moment for free panel based on equations (1), (2), (4) and (9) (Seo and Noh 2003). The moment is expressed by the following equation.

$$M_r = \left(0.5 + \frac{1}{2 + \frac{\beta}{s}} \right) M_i \quad (11)$$

where, β is constant for restraining effect. It is considered by the stress to produce unit angular change in the joint and given by 180 cm in the stiffened plate (Watanabe and Satoh 1961).

To verify the proposed method, automatic CO2 welding is done on the test specimen as shown in Figure 5 and deformations are measured.

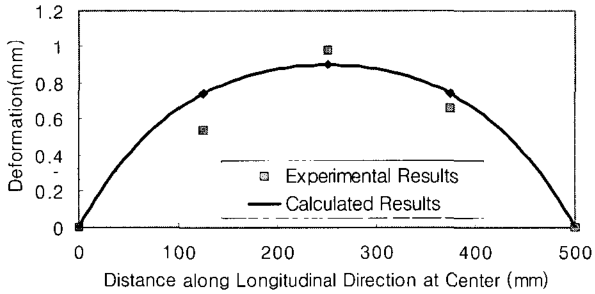


(a) Automatic CO2 welding (b) Test specimens

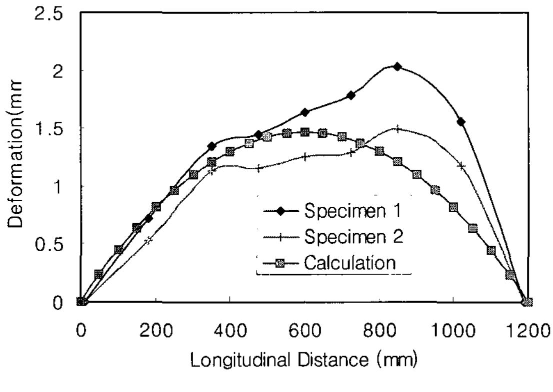
Figure 5: Automatic CO2 welding and test specimen

The typical welding conditions for the typical specimen are such that welding current, voltage and speed are 107 A, 29 V and 424 mm/sec, respectively. Leg length of fillet joint is 4.5 mm.

The edge bending moment for the free panel is calculated by equation (9) and the modified bending moment for restrained panel is calculated by equation (11). Final deformation of panels are calculated by equation (7). The calculated results of a panel of 800 mm×1200mm×8mm are presented in Figure 6, and compared with the experimental results.



(a) Deformation of typical panel along longitudinal direction at center



(b) Deformation of stiffener

Figure 6: Calculated welding deformation

6 Calculation of welding deformation with finite element method

When the simplified thermal elasto-plastic analysis method is combined with the finite element analysis method, it can be more powerfully used in practical problems. Since only linear elastic analysis is required, solution can be obtained rapidly. Calculation procedure is the same with Figure 3. Structural modeling is done following the conventional method, but different material properties should be used for the three regions. The elements corresponding to the inherent strain region and the material softening region are modeled as orthotropic material. Young's modulus in the y direction is much smaller than that in the x direction (Seo and Jang 1999). To calculate the magnitude of inherent, unit loads are applied at the boundary of the inherent strain region and deformations are calculated by finite element analysis. The spring constant at the boundary between the inherent strain region and the other regions can be obtained by applying unit loads to the boundary of the base metal region and calculating influence coefficients of the structure. Influence coefficient is defined as the deformation of loading point subjected to unit load. Since spring constant is load per deformation, it is related with the influence coefficient. When the unit force is applied on the surface of the plate, it exerts force and moment. The deformation at the surface is the sum of the translational deformation due to force and the translational deformation due to moment. The spring constant of joint surface is the inverse of the deformation at the surface and is given by equation (12).

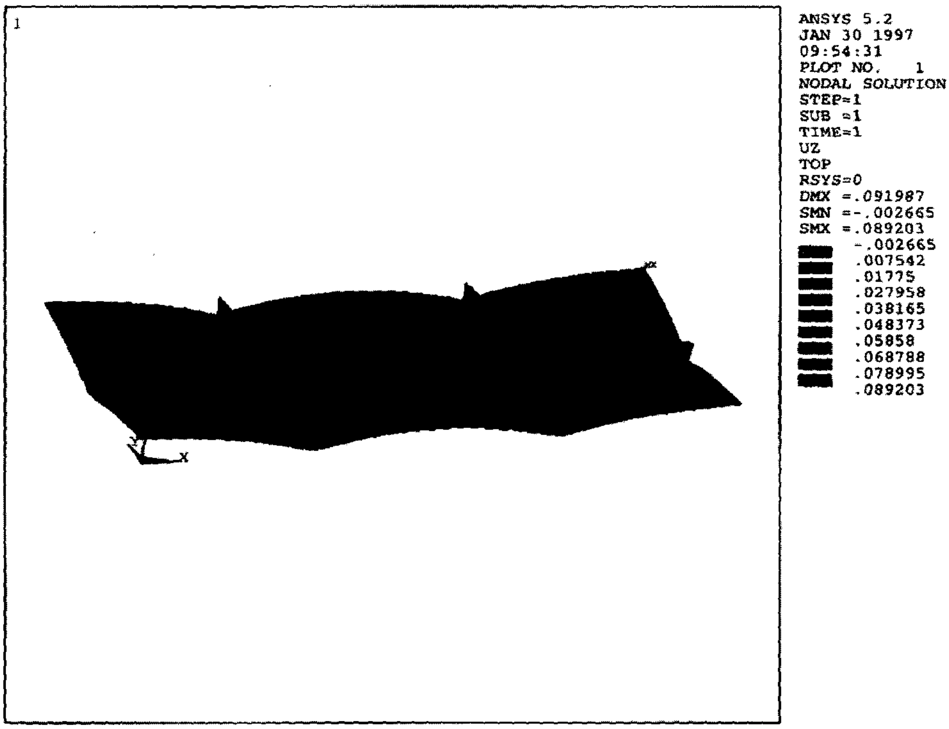


Figure 7: Deformed shape of the stiffened plate structure

$$k_x = \frac{1}{e_1 + \frac{h^2}{4} e_2} \qquad (12)$$

where, k_x is the spring constant, e_1 is the translational influence coefficient of joint and e_2 is the rotational influence coefficient.

After equivalent loads are calculated, final deformations can be calculated by combining the results for the unit loading cases without performing full finite element analysis based on the principle of superposition. Calculated deformation for a stiffened plate structure following the above procedure is shown in Figure 7.

7 Conclusions

In this study, to calculate welding deformations of a large structure, a simplified thermal elasto-plastic analysis method was proposed. The proposed method is based on the inherent strain theory, but overcomes the limitations of the inherent strain theory by combining with the numerical or theoretical analysis method and the experimental results. The proposed method has strong points such as accurate result and efficient solution. Calculated results by this method showed good agreement with the experimental results. It was proven that this method gives a useful tool for calculation of welding deformations of the large structure.

References

Framasoft+CSI 1995. SYSWELD Technical Description. Paris, La Defense.

Fujimoto, T. 1971. Residual stresses in rectangular plates with slit-type butt welded joint. J. of the Japanese Welding Society, **40**, **5**, 459-473.

Hibbit, Karlsson and Sorensen Inc. 1993. ABAQUS User's Manual. Farmington Hills, Michigan.

Jang, C.D. and S.I. Seo. 1995. A simplified method to estimate longitudinal deformations of built-up beams due to welding and heating. J. of Ship Research, **39**, **2**, 176-183.

Masubuchi, K. 1980. Analysis of Welded Structures. Pergamon Press, 148-188.

Moshaiov, A. and W.S. Vorus. 1987. The mechanics of the frame bending process: theory and applications. J. of Ship Research, **31**, **4**, 269-281.

Satoh, K. and T. Terasaki. 1976. Effect of welding conditions on welding deformations in welded structural materials. J. of the Japanese Welding Society, **45**, **4**, 302-308.

Seo, S.I. and C.D. Jang. 1999. A study on the prediction of deformations of welded ship structures. J. of Ship Production, **15**, **2**, 73-81.

Seo, S.I. and J.G. Noh. 2003. Development of a system for prediction and visualization of welding deformation of stiffened plates. J. of Ship Production, **19**, **2**, 84-90.

Swanson Analysis System Inc. 1992. ANSYS User's Manual. Houston, Pennsylvania.

Timoshenko, S.P. and S. Woinowsky-Krieger. 1970. Theory of Plates and Shells. McGraw-Hill, 180-185.

Ueda, Y. and T. Yamakawa. 1973. Analysis of thermal elasto-plastic behavior of metals during welding by finite element analysis method. J. of the Japanese Welding Society, **42**, **6**, 567-577.

Watanabe, M. and S. Satoh. 1961. Effect of welding conditions on the shrinkage distortion in welded structural materials. Welding J., **40**, 377s-384s.