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Reduction of residual stress for welded joint using vibrational load

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Abstract. A new reduction method of residual stress in welding joint is proposed where welded metals are shaken during welding. By an experiment using a small shaker, it can be shown that tensile residual stress near the bead is significantly reduced. Since tensile residual stress on the surface degrades fatigue strength for cumulative damage, the proposed method is effective to reduction of residual stress of welded joints. The effectiveness of the proposed method is demonstrated by the response analysis using one mass model with nonlinear springs.

Key words: welding; residual stress; vibration; X-ray diffraction method.

1. Introduction

Welding is widely used for construction of many structures (Zuraski 1993), (Bush 1992). It is well known that residual stress is generated near the bead because of locally given heat. Tensile residual stress on the surface degrades fatigue strength (American Society of Metals 1983) life time, resistance against cracks and fractures initiation (Slovacek and Junek 2003). For reduction of residual stress, some methods are studied and used. Heat treatment is one of the effective methods (Root *et al.* 1997), (Nakacho 2002). This method needs special equipment and is time consuming. Shot peening (Wozney and Crawmer 1968) and hammer peening (Dong *et al.* 1998) are also used. Those methods may be cause of crack. For tubes, methods using pressure loading (Andersson and Josefson 1988) and internal pressure, hot and cold thermal shock (Le 1994) are proposed. Vibrational load was tried to use as external load to reduce residual stress. Some papers were presented (Wozney and Crawmer 1968), (Norton and Rosenthal 1943), (Bouhelier *et al.* 1988), (Gnirss 1988). In those papers, vibrational load applied for relatively long duration, 10 to 20 minute.

Theoretical methods for welded joints are presented. The effects of residual stress on stress intensity factor (Green and Knowles 1994) and fatigue life (Deqing and Weijian 2002) are examined. FEM models are used as analytical methods for welded joints to estimate stress intensity factor (Burst *et al.* 2003), strength for impact load (Yoon *et al.* 2003), fatigue life (Lutes and Sarkani 1996), the effect of weld length (Dong *et al.* 2002) are presented. In analysis of reduction of residual stress using vibrational load is examined based on yield of welded joint by external load (Norton and Rosenthal

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1943), (Bouhelier *et al*. 1988) is discussed. Since residual stress is close to yield force, the effect of shakedown is to be taken into consideration (Jahed and Dubey 1997), (Seshadri 1994). In those papers, the dynamic characteristics of welded joint are not considered.

In this paper, a method is proposed in which vibrational load is used during welding operation. Advantage of this method is that vibrational load is generated by a small shaker. Hence, it is easy to move the shaker. In this method, vibrational load is applied for relatively short duration. This method is expected to be practical.

First, two plates are supported by supporting device. In order to transmit vibrational load, turnbuckles are used. Vibrational load is applied to the specimens during welding. Specimens are welded by manual operation. Residual stresses in the direction of the bead are measured. It is found that tensile residual stress on the bead can be reduced when the proposed method is applied.

Next, in order to improve transmission of vibrational load, arms are connected to shaker instead of turnbuckles. Specimens are welded using automatic CO_2 gas shielded arc welding machine in order to get constant welding condition. Residual stresses are measured for some values of amplitude of excitation. It is found that tensile stress on the bead can be reduced when the proposed method is applied independent of excitation frequency. Residual stress decreases as amplitude of excitation increases.

From these experimental results, it is obvious that tensile residual stress near the bead can be reduced by using vibrational load during welding.

Finally, an analytical method for reduction of residual stress by the proposed method is examined. It is obvious that reduction of residual stress is caused by local plastic deformation because initial residual stress is great and nearly equal to yielding stress. In order to consider shakedown, an analytical model which consists of mass and preloaded springs with elasto-plastic characteristic is used. Reduction of residual stress is evaluated using this model. It is found that reduction rate of residual stress increases as the amplitude of excitation increases. Since it is considered that yielding force of metal immediately after is very low, condition where residual stress tends to yielding force is satisfied. Thus, effectiveness of the proposed method can be shown by the response analysis using the proposed analytical model.

2. Experiment by manual operation

First, effectiveness of a new method for reduction method of residual stress is examined by experiment using welding by manual operation.

2.1. Experimental method

Fig. 1 shows the specimen used in this study. In this experiment, specimen without holes is used. Material of specimen is rolled steel for general use (JIS SS400). Two plates are supported on the supporting devices as shown in Fig. 2 and shaken by a small shaker during welding. Specimens are butt welded by manual operation using arc welding machine. Groove is V-shaped. Diameter of the welding rod is 4 mm. Voltage is 35 V and current is 150 A. Welding is completed through one pass and root opening is 1 mm. Groove angle is 30 degrees. Velocity of welding is about 30 cm/min. Specimens are fixed on the supporting devices as shown in Fig. 3 and shaken at the points 50mm from the weldment. Length between weldment and edge of fixed part is 180 mm. In order to transmit vibrational load from

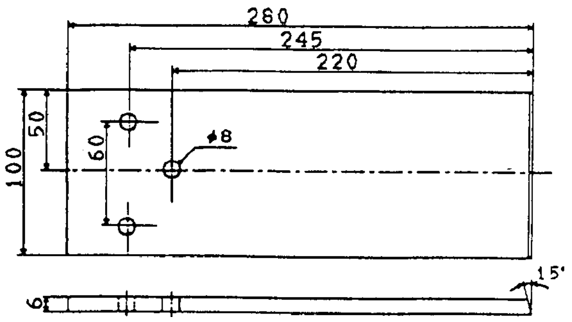

Fig. 1 Shape of specimen (mm)

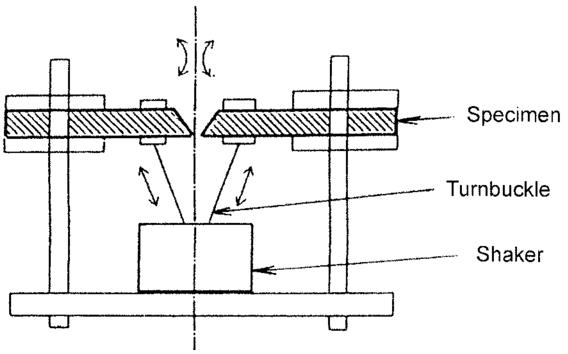

Fig. 2 Experimental set-up

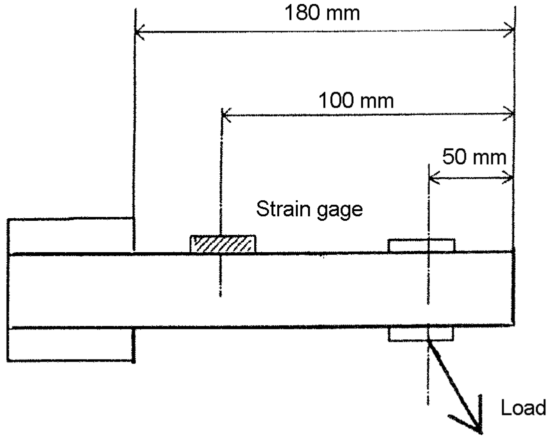

Fig. 3 Set of specimen

the shaker, turnbuckles are connected with driving part of the shaker. Excitation frequency is chosen as 62.5 Hz which is the fundamental natural frequency of specimens installed as shown in Fig. 2. The peak to peak values of displacement amplitude of free edge of the specimens before welding are determined as 0.02 mm, 0.04 mm, 0.06 mm and 0.08 mm. The amplitudes of free edge of the specimens are measured by strain gages adhered at 100 mm from free edge. For comparison, some specimens are welded without vibrational load.

Table 1 Conditions for X-ray stress measurements

Characteristic X-rays	Cr-Kα
Diffraction plane	α-Fe(211)
Filter	Vanadium foil
Stress determination	$\sin^2\psi$ method
Irradiated area	2×4 mm^2
Tube voltage and current	30 kV, 8 mA
Scan condition of 2θ	Step scanning
Divergence angle shift	1.0°
Peak determination	Half value width method

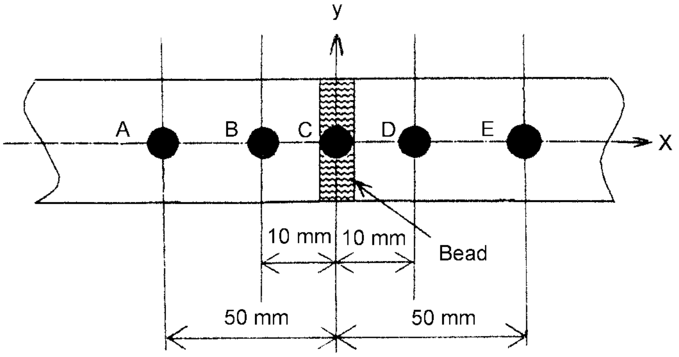

Fig. 4 Measuring points of residual stress

Residual stress is measured by removing the quenched scale chemically and using a paralleled beam X-ray diffractometer with a scintillation counter. The conditions of the X-ray stress measurements are shown in Table 1. Measuring points are shown in Fig. 4, 5 points at the center of the specimens are selected. Stresses in the direction of the bead are measured. Point C is on the bead. Points B and D are 10 mm from the bead. Points A and E are 50 mm from the bead.

2.2. Results of experiment

Fig. 5 shows the results for residual stress of the specimens shaken by 0.04 mm amplitude of excitation. In this figure, 68.3% confidence limits are shown. Tensile residual stresses are measured on and near the bead points B, C and D. Compressive residual stresses are measured at points A and E 50 mm from the bead.

In Fig. 6, results for some values of amplitude of excitation are shown. Symbols ● are the results for specimen without vibrational load. From this figure, on the bead, tensile residual stress is significantly reduced when vibrational load is acting during welding. At points B and D, residual stresses tend to increase. At points A and E, compressive residual stress tends to be tensile.

It is obvious from experiment by manual operation that when the specimens are shaken during welding, residual stress on the bead can be reduced.

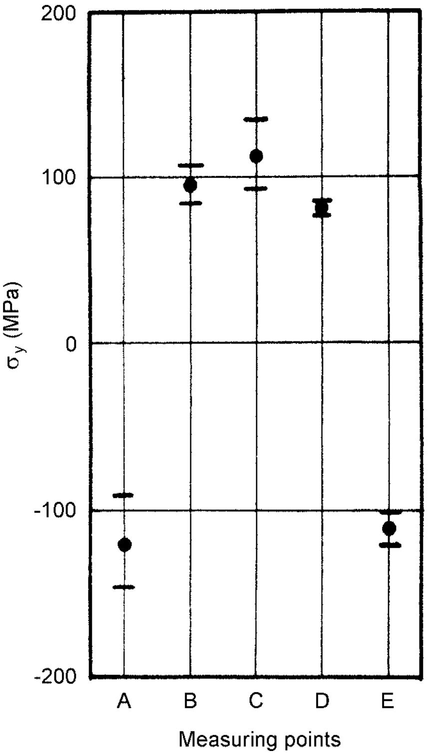

Fig. 5 Residual stress (0.04 mm p-p)

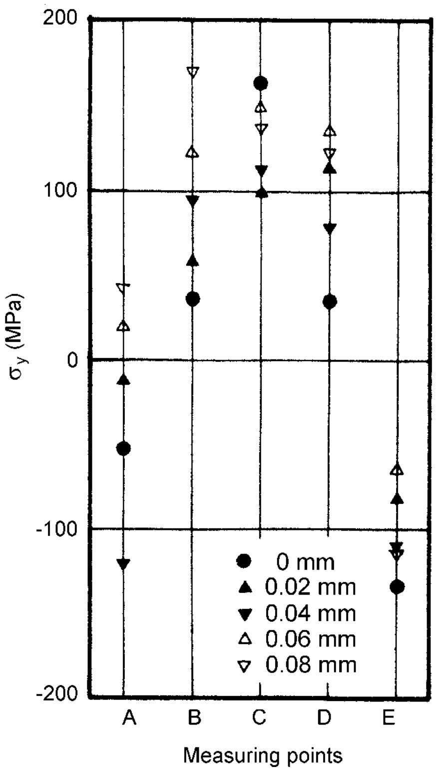

Fig. 6 Residual stress

3. Experiment by automatic welding machine

Next, in order to improve transmission of vibrational load, arms are connected to shaker instead of turnbuckles. Specimens are welded using automatic arc welding machine in order to get constant welding condition.

3.1. Experimental method

In this experiment, specimen shown in Fig. 1 is used. Two plates are supported on the supporting devices by bolts as shown in Fig. 7 and shaken by a small shaker during welding. Specimens are butt welded using automatic CO_2 gas shielded arc welding machine. Groove is V-shaped. Diameter of the wire is 1.2 mm. Voltage is 25 V and current is 200 A. Welding is completed through one pass and root opening is 1 mm. Groove angle is 30 degrees. Velocity of welding is 30 cm/min. Specimens are fixed on the supporting devices as shown in Fig. 8 and shaken at the points 75 mm from the weldment. In order to transmit vibrational load from the shaker effectively, arms are connected with driving part of the shaker using plates of 45 mm width. Excitation frequency is chosen as 60 Hz which is the fundamental natural frequency of specimens installed as shown in Fig. 8. In order to examine reduction effect of residual stress at non-resonance frequency, excitation frequency is also chosen as 100 Hz. The amplitudes of excitation are determined by current indicated at the amplifier of the

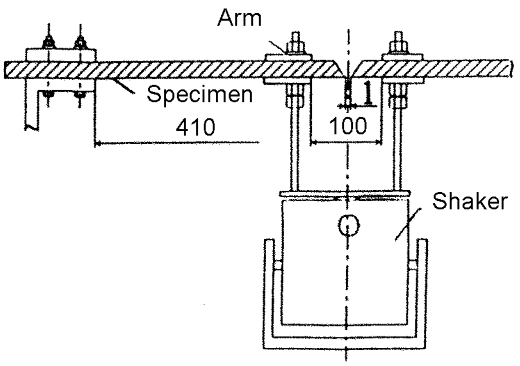

Fig. 7 Improved experimental set-up (mm)

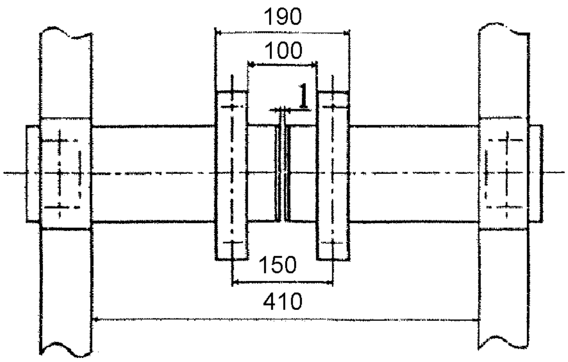

Fig. 8 Improved supporting device (mm)

Table 2 Relation between current and amplitude

Freq.(Hz)	Current (A)	Amplitude Acc.(G)	Amplitude Disp.(mm)
60	0.4	1.3	0.090
	2.0	5.5	0.379
	4.0	9.7	0.669
100	2.0	2.5	0.062
	4.0	5.2	0.129
	5.8	7.4	0.184

shaker. The amplitudes of free edges of the specimens before welding are almost proportional to indicated current. For each current, peak to peak values of acceleration at free edge of the specimen before welding are measured by accelerometer and listed in Table 2. Peak to peak values of displacement are calculated and listed in Table 2. For comparison, some specimens are welded without vibrational load.

Residual stress is measured by the same way as experiment by manual operation. Measuring points are shown as in Fig. 4. Stresses in the direction of the bead are measured.

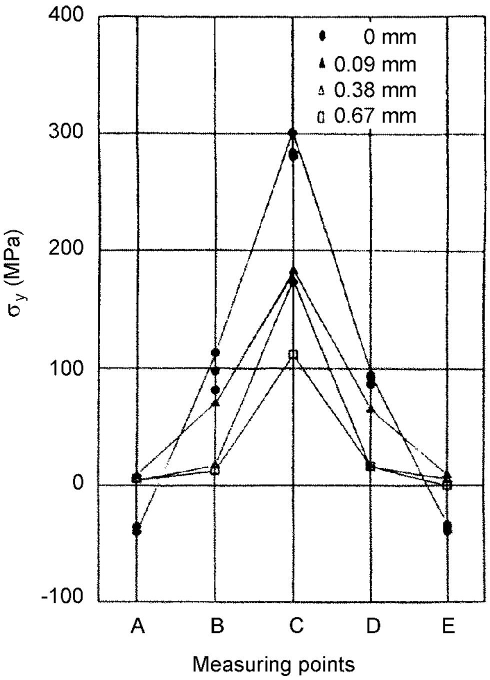

Fig. 9 Residual stress (60 Hz)

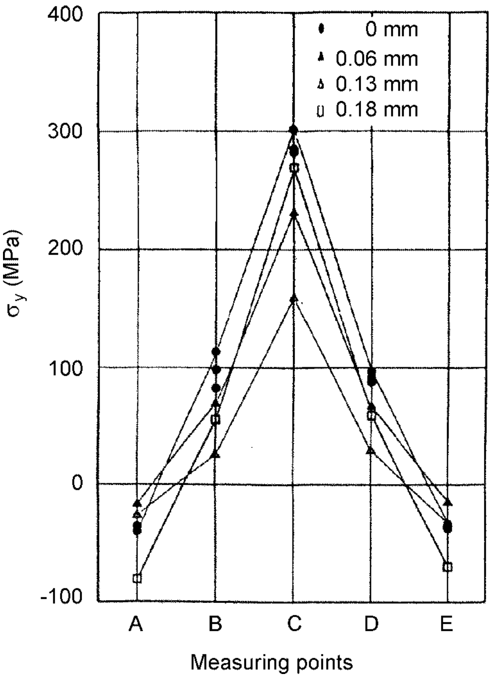

Fig. 10 Residual stress (100 Hz)

3.2. Results of experiment

Fig. 9 shows the results for residual stress of the specimens shaken by 60 Hz vibrational load. Symbols ● are the results for specimen without vibrational load. For this condition, experiments are performed three times. From Fig. 9, on the bead, tensile residual stress is reduced when vibrational load is acting during welding. At points B and D, residual stress is also reduced. At points A and E, compressive residual stress tends to be tensile. Residual stress decreases as the amplitude of excitation increases. Fig. 10 shows the results for the case where the excitation frequency is 100 Hz. Almost the same results as shown in Fig. 9 are obtained. When the amplitude of excitation is large, 5.8 A, the reduction effect is small. It is considered that there are energy loss in joints connected by bolts which are between specimens and plates of experimental set-up in this condition. However, even if the excitation frequency is not equal to the natural frequency of the specimen, the proposed method is also effective. In this case, the amplitude at the free edge of the specimen is small.

Thus, it is obvious that when the specimens are shaken during welding, residual stress near the bead can be reduced.

4. Analytical method

Since welding is joint method by melting base metal and weld metal, large residual stress and deformation are generated by shrinkage of metal during resolidification process. On the other hand, yielding stress of metal immediately after resolidification is generally very low. It is considered that permanent deformation can be generated by very low external load. In this paper, reduction of tensile residual stress on the bead is dealt with.

4.1. Analytical model

As an analytical model, a single-degree-of-freedom system shown in Fig. 11 is used. As shown in Fig. 11(b), the single-degree-of-freedom system is excited on the condition where springs are extended by Z_e from the equilibrium position. In this case, kZ_e is initial residual stress. It is assumed that restoring force-deformation relation of the springs is represented by the perfectly-elasto-plastic model as shown in Fig. 12. Z_r is displacement in which sign of velocity changes from positive to negative vice versa. The amplitude of response is assumed to be small and the spring is yielding only when tensile force is acting. Equation of motion in the elastic range is expressed as;

$$m\ddot{y} - k(y-u-Z_e-Z_p^-) + k(y-u+Z_e-Z_p^+) = 0 \tag{1}$$

where Z_p^+ and Z_p^- are permanent deformation of left spring and right spring, respectively. Equation of motion with respect to relative displacement $z(=y-u)$ can be written as;

$$m\ddot{z} + k(z-Z_e-Z_p^-) + k(z+Z_e-Z_p^+) = -m\ddot{u} \tag{2}$$

When left spring yields, that is, $z+Z_e-Z_p^+>Z_y$ and $\dot{z}>0$, equation of motion is given as;

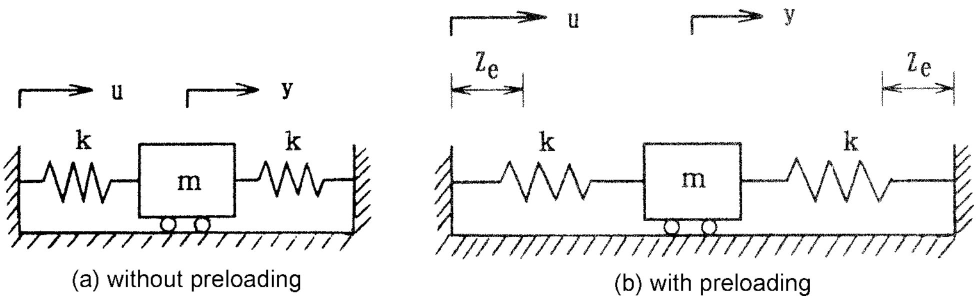

Fig. 11 Analytical model

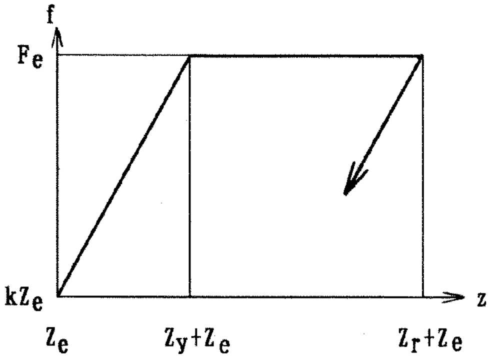

Fig. 12 Perfectly-elasto-plastic force-deformation relation

$$m\ddot{z} + k(z - Z_e - Z_p^-) + F_e = -m\ddot{u} \tag{3}$$

where F_e is yield force. When $\dot{z}$ becomes negative, displacement at the time when $\dot{z}=0$ is defined as Z_r+Z_e and Z_p^+ is given as follows.

$$Z_p^+ = Z_r + Z_e - Z_y \tag{4}$$

Then Eq. (1) is used. When right spring yields, that is, $z\text{-}Z_e\text{-}Z_p^- < -Z_y$ and $\dot{z}<0$, equation of motion is given as;

$$m\ddot{z} - F_e + k(z + Z_e - Z_p^+) = -m\ddot{u} \tag{5}$$

When z becomes positive, displacement at the time when $\dot{z}=0$ is defined as $Z_r–Z_e$ and Z_p^- is given as follows.

$$Z_p^- = Z_r – Z_e + Z_y \tag{6}$$

Then Eq. (1) is used.

kZ_p^+ and kZ_p^- are residual stresses which are released during shaking in left spring and right spring, respectively. When kZ_p^+ is not equal to kZ_p^-, they are statically equilibrated. Residual stress after shaking is evaluated as;

$$\sigma_{sy} = 0.5\{k(Z_e - Z_p^+) + k(Z_e + Z_p^-)\} \tag{7}$$

Unit of right hand side of Eq. (7) is force and that of left hand side is force per area. Model shown in Fig. 11 is used in this study. Thus, when force generated by spring per unit area is considered, units of both side of Eq. (7) are equal.

5. Results of analysis

Excitation term $\ddot{y}$ is given as $\ddot{y}=Y\sin\omega t$ in equation of motion. The natural circular frequency in elastic range is defined as $\omega_n=\sqrt{2k/m}$. The results for various values of F_e/mY force in the case of $\omega/\omega_n=1.0$ are listed in Table 3. Residual stress after 10 periods of excitation is obtained considering reduction rate of residual stress in the experiment. Values of ratio of residual stress after shaking to that before shaking σ_{yi} are obtained. Values for various values of ratio of σ_{yi} to the yielding force F_e are listed. Table 4 shows the results of $\omega/\omega_n=1.6$.

Table 3 Ratio of residual stress before and after shaking ($\omega/\omega_n=1.0$)

σ_{yi}/F_e	F_e/mY		
	20	40	80
0.9	0.61	0.84	0.95
0.8	0.63	0.88	1.00
0.7	0.65	0.93	1.00

Table 4 Ratio of residual stress before and after shaking (ω/ω_n=1.6)

σ_{yi}/F_e	F_e/mY		
	1	2	4
0.9	0.58	0.82	0.94
0.8	0.59	0.86	0.99
0.7	0.61	0.92	1.00

From these tables, it is found that reduction rate of residual stress increases as F_e/mY decreases, that is, the amplitude of excitation increases. Thus, obtained results from analytical method are the same as those from experiment. When ω/ω_n=1.0, reduction rate increases during shaking. On the other hand, when ω/ω_n=1.6, residual stress is reduced during 2 or 3 periods at the beginning of excitation. Reduction rate also increases as σ_{yi}/F_e tends to be 1, that is, residual stress approaches to yielding force. Since it is considered that yielding force of metal during resolidification is very low, condition where residual stress approaches to yielding force is satisfied. Thus, effectiveness of the proposed method can be shown by the response analysis using the simple mechanical model as shown in Fig. 11.

6. Conclusions

A reduction method of residual stress where welded metals are shaken during welding is proposed. Effectiveness of this method is examined. By the experiment, it is found that tensile residual stress near the bead is significantly reduced and reduction rate of residual stress increases as the amplitude of excitation increases. These properties are examined by an analytical method using a single-degree-of-freedom system with pre-loaded springs having elasto-plastic characteristics. From the analysis, it is obvious that reduction rate of residual stress increases as the amplitude of excitation increases. Thus, effectiveness of the proposed method can be demonstrated by experiment and analysis.

It is pointed out that reduction of tensile residual stress improves fatigue strength (Dieter 1961) (Frost 1999). It is expected to increase fatigue strength by using the proposed method.

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