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ESTIMATION OF ULTIMATE STRENGTH FOR STEEL PLATES DAMAGED BY CYCLIC LOADING

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SUMMARY

Ultimate strength of damaged steel plate is investigated by using elasto-plastic finite element method. Analytical model is simply supported at all edges and introduced initial deflection and residual stress. We defined "damage deflection" as the out-of-plate deflection at the plate center after the cyclic loading. The relationship between the damage deflection and ultimate strength of damage plate is discussed from analyzed results. The decreasing of ultimate strength depends on the only damage deflection when the damage deflection exceeds the limit value that is decided by width-thickness parameter. In the case that the damage deflection is smaller than the limit value, the ultimate strength is equal to the undamaged steel plate strength. From these results, the estimation procedure of ultimate strength of damaged steel plate is proposed. With proposed procedure, it is easily possible to estimate the strength of damaged steel plate by the width-to-thickness parameter and damage deflection.

INTRODUCTION

One of the typical earthquake damages of steel bridge piers is local buckling. Photo 1 shows the damage which was reported after the Hyogoken-Nanbu earthquake(1995). In Photo 1, a local buckling occurs at the panel between the stiffeners. These buckling damage decreases ultimate strength of the structures. Therefore, to recover the load carrying capacity, a damaged pier must be repaired.

Repair handbook[1] was referred to the repair works of the bridge pier damaged by the Hyogoken-Nanbu earthquake. This handbook describes the criterion for estimation of the damage level, as shown in Table 1. On the basis of damage level, the residual strength of pier can be predicted. However, as describing the handbook, this criterion was led from few experimental data and must be confirmed by more study.

There are some researches about post-buckling strength of the steel plate, which are carried out by Rohdes and Mateus in recently. Rodes[3] investigated the load-displacement and load-deflection relationship of plate with initial deflection in elastic range. Mateus[4] investigated the post-buckling strength with initial deflection by using FEM. These researches clarify the post-buckling strength under monotonic loading. For repair criterion, it is important to estimate the post-buckling strength under cyclic loading.

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The strength of damaged steel plate, which is called "residual strength" in this paper, is investigated by FEM analysis. From analyzed results, the estimation method for residual strength is proposed.

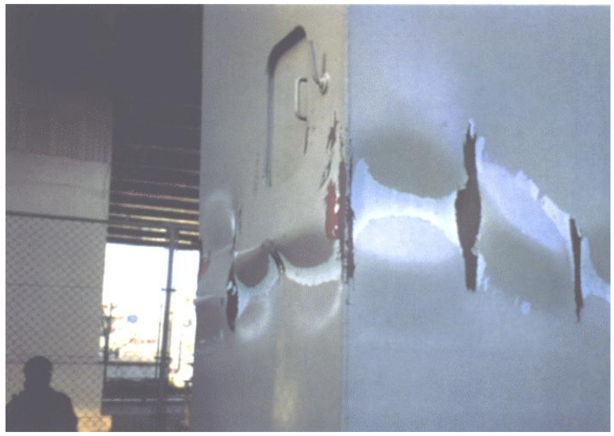
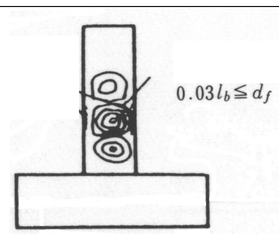
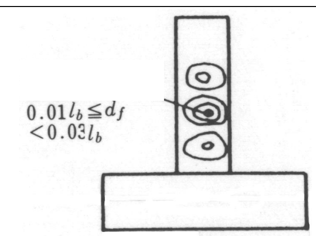
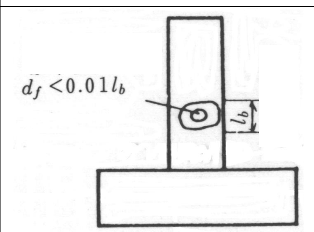


Photo 1 Buckling damage of steel bridge pier

Table 1 Criterion of steel bridge pier damaged by earthquake[2]

Damage Level	A: Severe	B: Moderate	C: Slight
Residual Deformation	$0.03l_b \leqq d_f$	$0.01l_b \leqq d_f < 0.03l_b$	$d_f < 0.01l_b$
Deformation State			
Residual Strength	Under $0.6P_u$	$0.8P_u$~P_u	P_u

d_f:deflection of plate, l_b: length between horizontal stiffeners ,P_u: Ultimate strength

ULTIMATE STRENGTH ANALYSIS OF BUCKLED STEEL PLATE

Aanalytical model

In this study, residual strength of buckled steel plate is investigated by using FEM program NASHEL[5]. Fig.1 shows the analytical model, which presents the steel plate between stiffeners. By taking the symmetrical condition into account, 1/4 finite element model is analyzed. In the analyses, elements are the iso-parametric shell element and constitutive equation is BMC model[6], which can express the stress-strain relationship under cyclic load. The material properties of SM490 steel grade are employed, as shown in Table 2.

In the analyses, material and geometrical imperfections are introduced. The initial deflection is considered as shown in Fig.3 and defined by the following equation.

$$w_{ini} = W_{ini} \sin\frac{\pi}{L} x \sin\frac{\pi}{L} y \qquad (1)$$

where, W_{ini} = L/150, which is the fabrication tolerance regulated in JSHB[7]. L: plate length and width.

Fig.2 shows the distribution of residual stress. The compressive residual stress σ_c is 0.3 σ_y.

Reference [8] proposed the equation (2) for estimation the ultimate strength under monotonic loading.

$$\frac{N_u}{N_y} = \begin{cases} 1 & (R \le 0.5) \\ \left(\frac{0.5}{R}\right)^{0.80} & (R > 0.5) \end{cases} \qquad (2)$$

where, R: width-to-thickness parameter, which is defined as follows.

$$R = \frac{L}{t}\sqrt{\frac{12(1-\nu^2)\sigma_Y}{\kappa\pi^2 E}} \qquad (3)$$

where, t: plate thickness, ν : poisson's ratio, σ_Y : yield stress, E: young's modulus κ (=4.0) buckling coefficient.

In order to verify the analytical modeling, the analyzed results under monotonic loading is compared with the equation (2). Fig. 4 shows that the analyzed results are in a good agreement with equation (2).

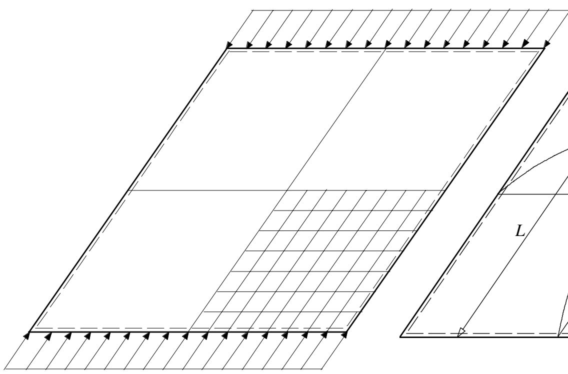


Fig.1 Analytical model

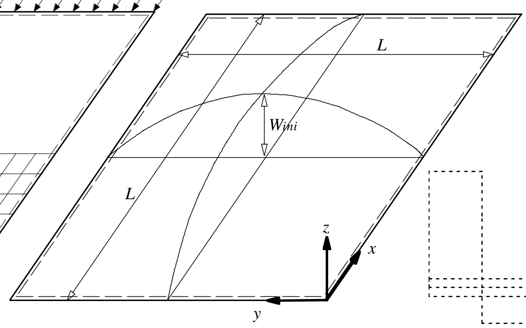


Fig.2 Initial deflection

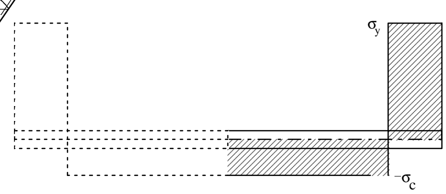


Fig.3 Distribution of residual stress

Table 2 Material properties

Steel grade	Young's modulus E (N/mm²)	Yield stress σ_Y (N/mm²)	Poisson's ratio ν
SM490	2.08×10^5	382.2	0.3

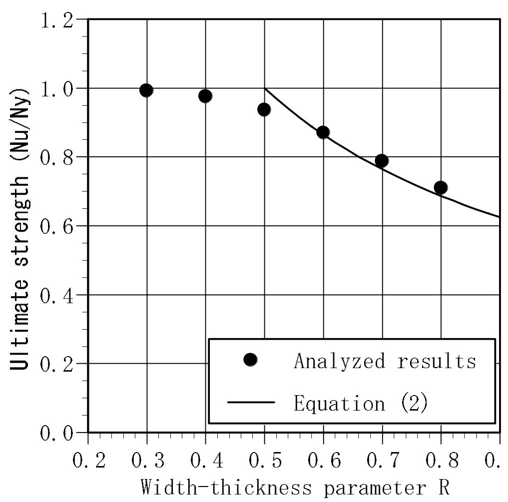


Fig.4 Ultimate strength vs. Width-thickness parameter

Aanalytical Procedure

Fig.5 shows the analytical procedure. STEP1: cyclic compression and tension are loaded at the two ends of analytical model. Analyzed model is damaged and buckled by this cyclic load. STEP2: monotonic compression is loaded at the two ends.

Fig.6 shows the relationship between the deflection at plate center and the load at the loading edge. In.Fig.6, W_{dam} is the deflection after STEP1; we call "Damage Deflection". N_r is the ultimate strength in STEP2; we call "Residual Strength". In STEP1, three loading types C0, C1 and C2 are considered as shown in Fig.7. In Fig.7, ε_y is yield strain. ε is average strain, which is given by dividing the displacement at the loading edge with plate length L. The analytical parameters are shown in Table 3.

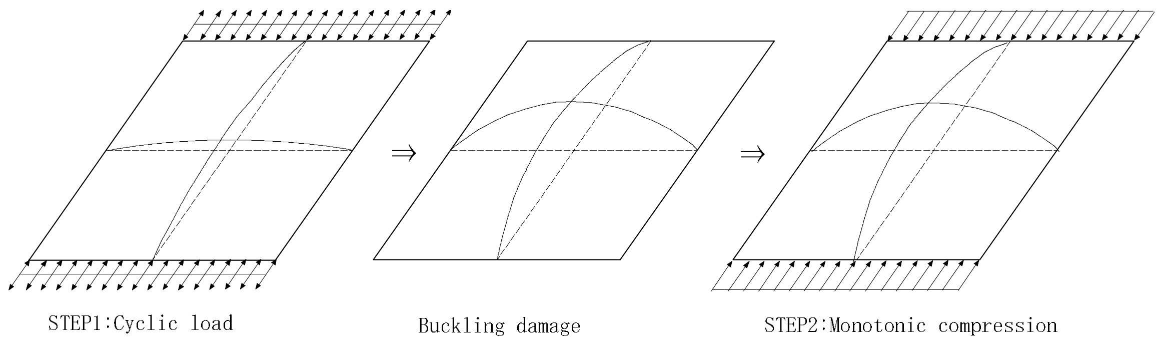


Fig.5 Analytical procedure

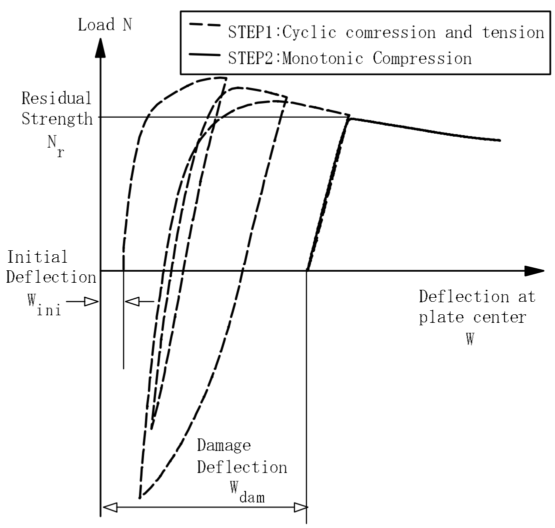
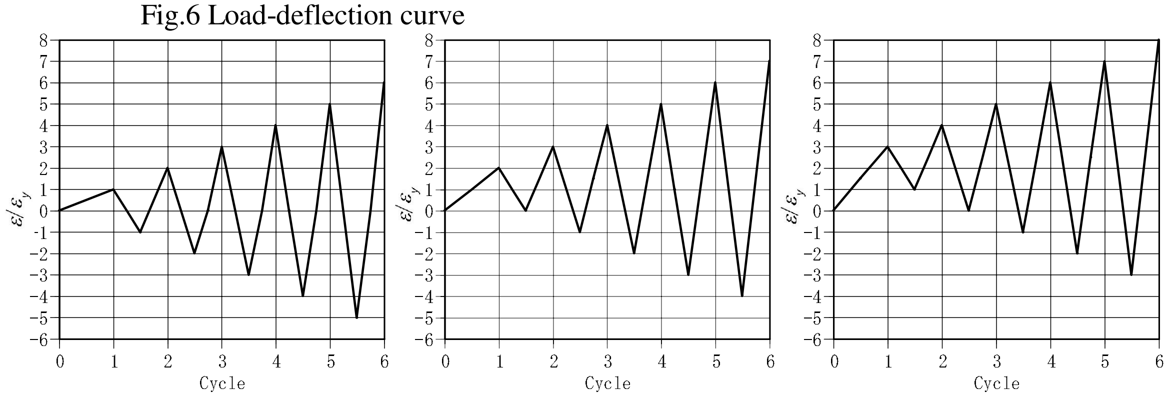


Fig.6 Load-deflection curve

Table 3 Analytical parameter

	Parameters
width-thickness parameter R	0.3,0.4,0.5,0.6,0.7,0.8
Load type in STEP1	C0,C1,C2
The number of cycle in STEP1	1,2,3,4,5,6



(a) C0 type (b) C1 type (c) C2 type

Figs.7 Loading pattern in STEP1

ANALYZED RESULTS AND DISCUSSION

Relationship between load and deflection

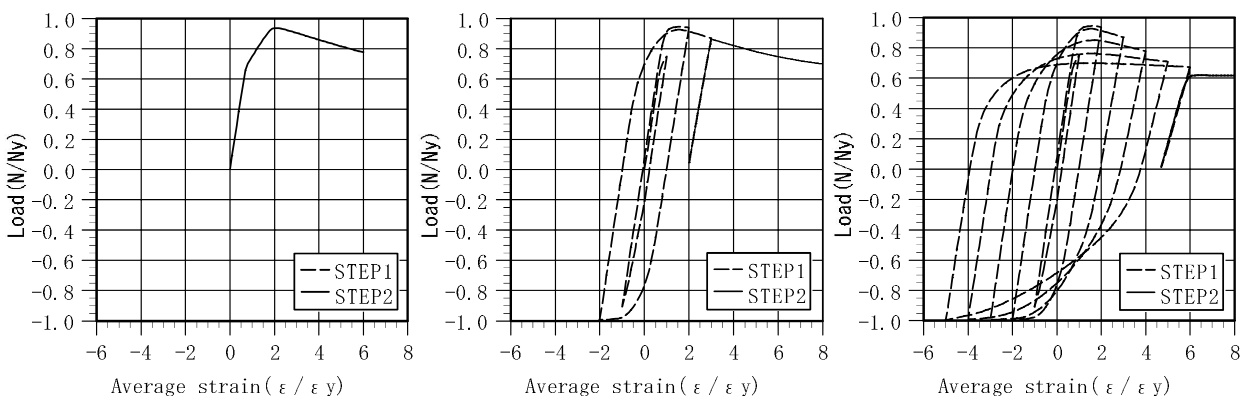
Figs.8 show the relationship between load at the loading edge and average strain in the case of R=0.5. The load is normalized by yield load and the average strain is normalized by yield strain. Fig.8(a) shows the case of monotonic loading. Fig.8(b) and (c) show the case of three and six cycles load in STEP1, respectively.

Figs.9 show the relationships between load and deflection in the same cases shown in Figs.8. The deflection is normalized by plate thickness. In these figures, the sign ▽ indicates ultimate strength in STEP2; residual strength. Fig.9(b) and Fig.9(c) indicate that the cyclic load makes the increment of the deflection and the reduction of residual strength.

Influence of width-to-thickness parameter

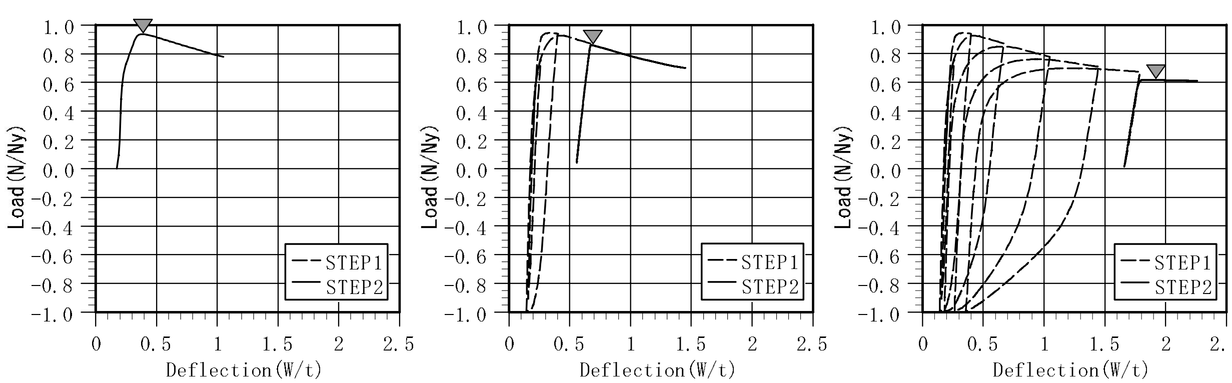
Fig.10(a) shows load-deflection relationship at STEP 2 in the case of R=0.7. In the notes of Fig.10(a), M means the case of monotonic loading. C0-1, C0-2, … and C0-6 means that C0 type cyclic loading is carried out one, two, … and six cycle(s) in STEP1, respectively. The start points of each line indicate damage deflection. This figure shows that the ultimate strength decreases with increasing of damage deflection.

Fig.10(b) shows the analyzed results in the case of R=0.5. This figure indicates the same tendency as the case of R=0.7. However, under the same cyclic loading, damage deflection in the case R=0.5 is smaller than the case of R=0.7.



(a) Monotonic Loading, R=0.5 (b) C0 type; 3 cycle, R=0.5 (c) C0 type; 6 cycle, R=0.5

Figs.8 Load vs. Average strain



(a) Monotonic Loading, R=0.5 (b) C0 type; 3 cycle, R=0.5 (c) C0 type; 6 cycle, R=0.5

Figs.9 Load vs. Deflection at plate center

Fig.10(c) shows the analyzed results in the case of R=0.3. The damage deflection is much smaller than the other cases (R=0.7,0.5). In this case, the load exceeds 1.0 because of strain hardening.

Relationship between damage deflection and residual strength

Figs.11 show damage deflection - residual strength relationship gained from analyzed results. Fig.11(a) shows the case of C0 type cyclic loading. The decreasing of ultimate strength depends on the only damage deflection when the damage deflection exceeds the limit value. When the damage deflection is smaller than the limit value, the ultimate strength equals with the undamaged steel plate strength, which is indicated as the point of left end in each curves.

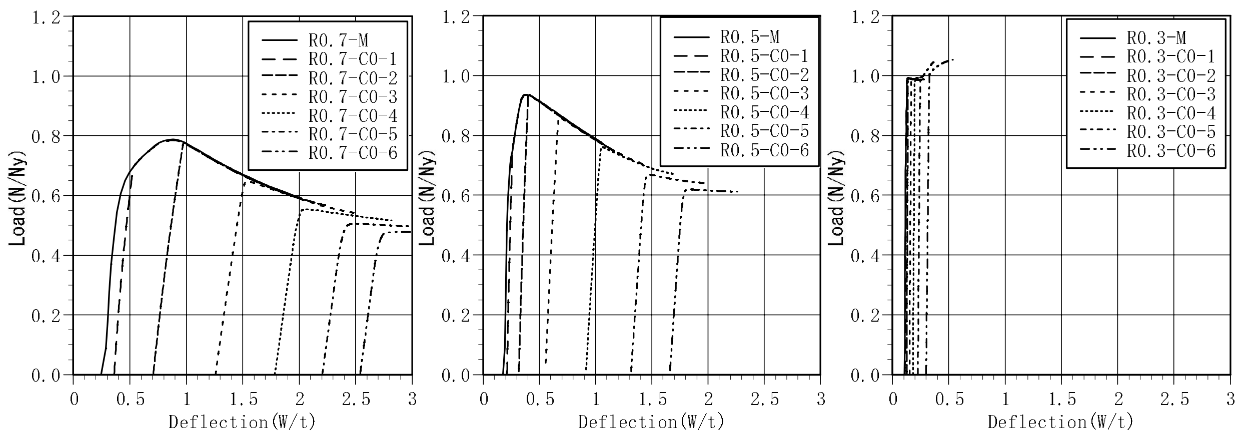
Fig.11(b) and Fig.11(c) shows the case of C1 and C2 type cyclic loading, respectively. The damage deflection - residual strength relationship indicates the same tendency as Fig.11(a).

ESTIMATION FORMULA OF RESIDUAL STRENGTH

In this section, buckling strength of simply supported plate with initial deflection are investigated by theoretical approach. After that, estimation formula of the residual strength is proposed.

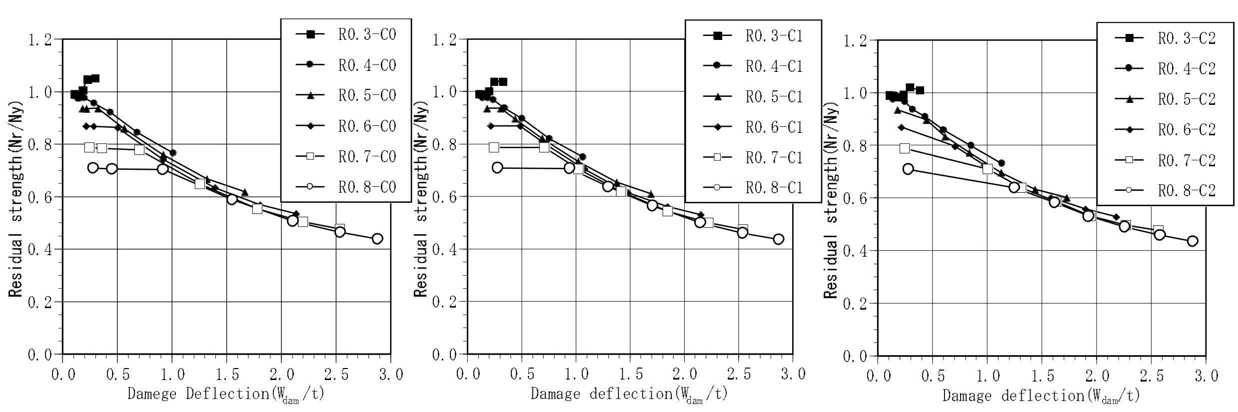
Theoretical buckling strength of steel plate with initial deflection

Reference [9] defined the equation for buckled plate as follows. The coordinate system is shown in Fig.12.



(a) R=0.7,C0 (b) R=0.5,C0 (c) R=0.3,C0

Figs.10 Residual strength



(a) R=0.7,C0 (b) R=0.5,C0 (c) R=0.3,C0

Figs.11 Relationship between damage deflection and residual strength

$$D\left(\frac{\partial^4 w}{\partial x^4} + 2\frac{\partial^4 w}{\partial x^2 \partial x^2} + \frac{\partial^4 w}{\partial y^4}\right) = -N_x \frac{\partial^2 w}{\partial x^2} \quad (4)$$

where, w: Plate deflection, N_x : Axial force along x direction, D: Flexural rigidity is defined as follows.

$$D = \frac{Et^3}{12(1-\nu^2)} \quad (5)$$

We assume that a plate has initial deflection w_0. If a plate is subjected to compression, additional deflection $\overline{w}$ will be produced and the total deflection will be $w = w_0 + \overline{w}$ as shown Fig.13. The left side of the equation (4) is obtained from the expressions for bending moments, and these moments depend on additional deflection $\overline{w}$. However, right side of the equation (4) is from the expressions for lateral load, which is related with the total deflection w. Hence equation (4) for this case of plate with initial deflection becomes the following equation.

$$D\left(\frac{\partial^4 \tilde{w}}{\partial x^4} + 2\frac{\partial^4 \tilde{w}}{\partial x^2 \partial x^2} + \frac{\partial^4 \tilde{w}}{\partial y^4}\right) = -N_x \frac{\partial^2 (w_0 + \tilde{w})}{\partial x^2} \quad (6)$$

To take boundary condition into account, the initial deflection and total deflection are defined by the following equations.

$$w_0 = W_0 \sin\frac{\pi}{L}x \sin\frac{\pi}{L}y \quad (7)$$

$$w = W \sin\frac{\pi}{L}x \sin\frac{\pi}{L}y \quad (8)$$

where, W_0:initial deflection at plate center ,W : total deflection at plate center

Substituting equation (7) and (8) in equation (6), the following equation is obtained.

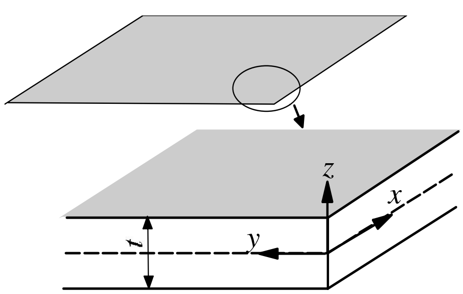


Fig.12 Coordinate system

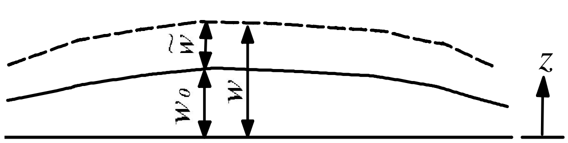


Fig.13 Definition of $w, w_0, \tilde{w}$

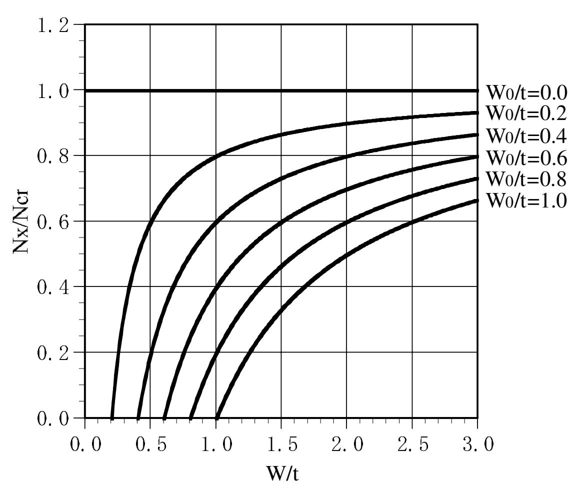


Fig.14 Nx vs. W/t

$$\frac{N_x}{N_{cr}} = 1 - \frac{W_0 / t}{W / t} \qquad (9)$$

where, $N_{cr} = \dfrac{4\pi^2 D}{L^2}$:buckling strength of plate without initial deflection

Fig.14 shows the load - deflection curves, which are given by equation (9). In this figure, the load is getting closer to buckling strength N_{cr} with increasing the deflection.

The surface stress at plate center(x=L/2,y=L/2,z=t/2) is maximum and become yield stress first in the plate. Assuming the ultimate strength is the load at the state when a plate yields, we can obtain the following condition.

$$\sigma_x = \frac{E}{1-\nu^2}\left(\varepsilon_x - \nu\varepsilon_y\right) = \frac{E}{1-\nu^2}\left(-z\frac{\partial^2 \tilde{w}}{\partial x^2} + \nu z\frac{\partial^2 \tilde{w}}{\partial y^2}\right)\Bigg|_{x=\frac{L}{2},y=\frac{L}{2},z=\frac{t}{2}} = \sigma_Y \qquad (10)$$

where, $\sigma_x, \varepsilon_x, \varepsilon_y$: stress and strain in the suffix direction

From equation (3), yield stress is given by the following equation.

$$\sigma_Y = \frac{4\pi^2 D}{L^2}\frac{R^2}{t} \qquad (11)$$

Substituting equation (7), (8), (11) in equation (10), we obtain the following equation.

$$W / t = \frac{2R^2}{3(1-\nu)} + W_0 / t \qquad (12)$$

Equation (12) indicates the deflection when the load is ultimate strength. Substituting equation (12) in equation (9), we obtain the relationship between ultimate strength and initial deflection as follows.

$$\frac{N_u}{N_y} = R^2\left\{1 - \frac{W_0 / t}{2R^2 / 3(1-\nu) + W_0 / t}\right\} \qquad (13)$$

Estimation formula of residual strength

In Fig.15, analyzed results are plotted except the case that the residual strength is equal to the buckling strength of undamaged plate. The residual strength depends on only damage deflection. The analyzed results are compared with the equation (13) as shown in Fig.15. The residual strength given from equation (13) is lower than analyzed results. This reason comes from the deference of ultimate strength definition between theoretical and analytical approach. In theoretical approach, the ultimate strength is defined as the load in the state when plate yields. In analyzed results, the maximum load is decided as the ultimate strength.

On the basis of equation (13), the equation curve (14) is fitted for analyzed results. From Fig.15, the curve (14) is in a good agreement with analyzed results. The equation (14) is proposed for the estimating the residual strength of damaged plate.

$$\frac{N_u}{N_y} = 1.09\left(1.0 - \frac{W_{dam}/t}{1.96 + W_{dam}/t}\right) \qquad (14)$$

Estimation procedure

If the damage deflection is smaller than the limit deflection, the ultimate strength equals with the strength of the undamaged steel plate. Substituting equation (14) in equation (2), we obtain following equation, which can expresses limit deflection.

$$W_{\lim}/t = \begin{cases} 0.176 & (0.3 \le R \le 0.5) \\ 2.14\left(\dfrac{R}{0.5}\right)^{0.8} - 1.96 & (0.5 < R \le 0.8) \end{cases} \qquad (15)$$

We proposed the estimation procedure for residual strength of damaged steel plate as shown in Fig.16. In order to estimate the residual strength, it is necessary to investigate the width-thickness parameter R and damage deflection W_{dam} of the damaged plate. Substituting width-thickness parameter R in equation (15), the limit deflection is given. If damage deflection is larger than the limit deflection, residual strength is given from equation (14). If damage deflection is smaller than the limit deflection, residual strength is equal to the ultimate strength of undamaged plate, which is given from equation (2).

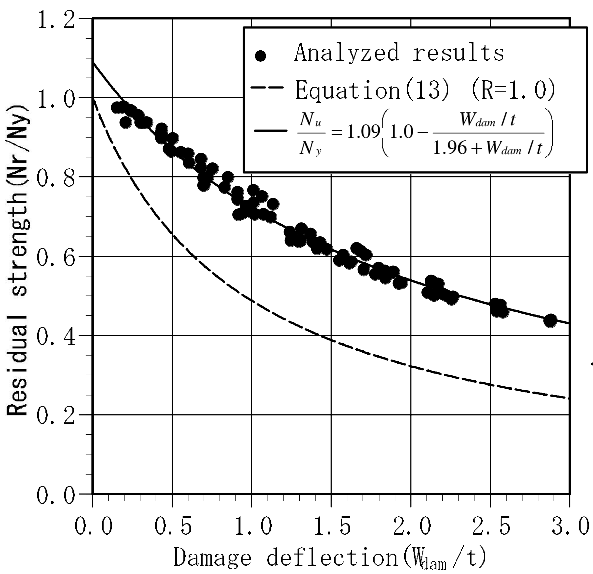


Fig.15 Estimation formula for residual strength

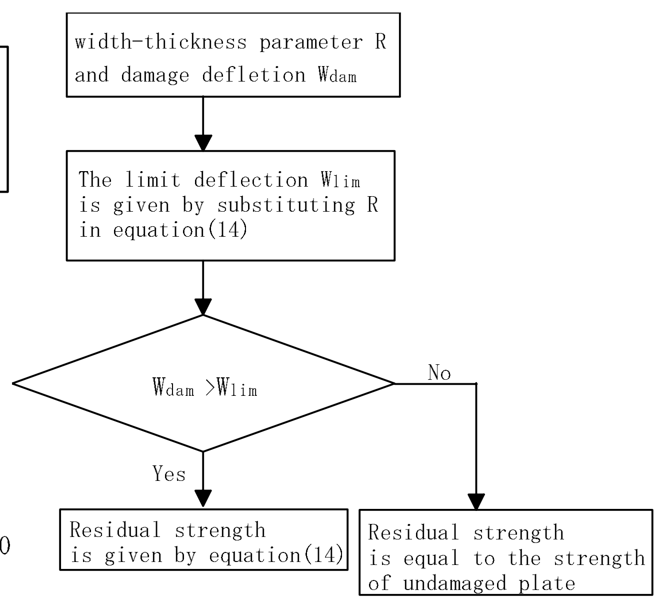


Fig.16 Estimation procedure

CONCLUSIONS

The deflection and ultimate strength of damaged steel plate with simple support are investigated by using FEM analysis. These results and discussions lead to the conclusions listed below.

1) The cyclic load makes the increment of deflection and reduction of residual strength. In condition under the same cyclic load, the larger the width - thickness parameter R is, the larger the deflection is.
2) If the damage deflection is smaller than the limit deflection, the ultimate strength equals with the strength of the undamaged steel plate. The limit deflection is given by equation (15).
3) When the damage deflection exceeds the limit deflection, the decreasing of residual strength depends on the only damage deflection. The residual strength is given by equation (14).
4) The estimation method for damaged steel plate is proposed. This method needs only the width-thickness parameter and damage deflection.

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