ULTIMATE STRAIN OF STEEL SHORT CYLINDERS UNDER AXIAL FORCE FLUCTUATION

Nagasaki University	Student Member	Graduate Student	Osman Tunc CETINKAYA
Nagasaki University	Member	Associate Professor	Shozo NAKAMURA
Nagasaki University	Member	Professor	Kazuo TAKAHASHI

1. Introduction

Extensive research has been carried out to understand the ductility and ultimate strength of short cylinders after the occurrence of substantial damage of the steel bridges due to the Hyogo-ken Nanbu earthquake. Ultimate strain formulae have been proposed [1] for steel cylinders subjected to combined compression and bending. In these formulae axial force is assumed to be constant. However, during earthquakes fluctuation of the axial force together with the bending moment is significant in portal frame bridge piers and arches subjected to in-plane excitation.

The influence of the axial force fluctuation on the ductility of short steel cylinders is studied in this research through the numerical analyses of parametric models. Based on the results ultimate strain formulae accounting for the influence of axial force fluctuation is proposed.

2. Parametric Models

The structural parameters of the short cylinder models used in the numerical analysis are listed in Table 1.The radius–thickness ratio parameter (R_t) is set as the main parameter. The length of the cylinders (L) is set to the critical length that gives a minimum ultimate strength in compression. A typical finite element mesh shown in Figure 1 is employed to analyze the cylinders by using the general purpose finite element analysis software “Marc”. Only upper half of a cylinder is modeled because of the symmetry and a simple supported boundary condition is assumed. To impose bending, the upper segment is constrained as a rigid plane. The cylinders are made of mild steel (SS400). Initial imperfections, i.e. the residual stresses and the initial geometrical deflection, are taken into account.

Table 1: Analyzed Models

MODEL	D (mm)	t (mm)	L (mm)	D/t	R_t	L/D
1	1062	20	173.6	53.1	0.050	0.164
2	1328	20	199.2	66.4	0.063	0.150
3	1988	20	252.6	99.4	0.094	0.127
4	2656	20	292.2	132.8	0.125	0.110
5	3980	20	350.2	199.0	0.188	0.088
6	5308	20	398.0	265.4	0.250	0.075
7	6636	20	411.4	331.8	0.313	0.065
8	7962	20	420.0	398.1	0.375	0.053
9	10616	20	407.0	530.8	0.500	0.038

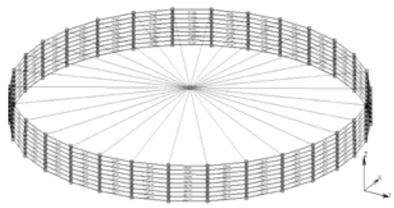

Figure 1: Finite Element Model

3. Methodology

Fluctuation of the axial force is simulated by applying an eccentric displacement load (P_δ) that results in linear axial force and bending moment increments at upper segment center of the cylinder, as shown in Figure 2. A load (P_i) that accounts for the initial value of the axial force fluctuation is applied to the upper segment center node and the desired final axial force (P_f) is achieved by adjusting the eccentricity (e). The results are compared with the constant axial force case, in which the final axial force of the fluctuating axial force case is applied to the center node as a fixed value. Axial force fluctuation amount (α=P_f/P_i) is set as a variable parameter and three cases of α values (3, 2 and 1.5) are studied respectively for three different final axial force levels of 0.6P_y, 0.4P_y and 0.2P_y (P_y=Squash load).

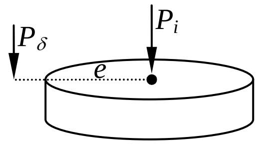

Figure 2: Loading method for axial force fluctuation

4. Influence of Axial force fluctuation

Comparison of the bending behavior of the constant and fluctuating axial force cases revealed that the ductility

Keywords: Short cylinders, axial force fluctuation, elastoplastic large displacement analysis, seismic design, steel bridges.
1-14, Bunkyo Machi, Nagasaki 852-8521 Tel. & Fax: 095-819-2613, E-mail: snakamura@civil.nagasaki-u.ac.jp

capacity is improved in the post-peak region when axial force fluctuation is considered. As an example Figure 3 is provided where the moment-rotation relationship of the constant and fluctuating axial force cases are compared for an axial force fluctuation pattern. It can be seen that improvement in the ductility becomes more significant in the further post-peak region. In Figure 4 ultimate strains of the fluctuating and constant axial force cases are compared when limit state is set as the strain level corresponding to the 95% of the maximum moment after the peak (M_{95} limit state). It can be seen that the improvement is valid for all models and the ratio of the ultimate strain follows a path that can be approximated with the curves shown in the figure (The higher results between R_t=0.06 and 0.1 are neglected)

5. Ultimate strain formulae

In order to consider the influence of axial force fluctuation in the estimation of ultimate strain, we propose correction functions to modify the existing constant axial case formula [1]. Correction functions (1-3) are developed based on the approximation curves in Figure 4. In addition, functions are developed for the further post-peak ductility corresponding to the 90% and 80% of the maximum moment after the peak. (M_{90}, M_{80})

$$\boldsymbol{M_{95}}: f(R_t, P_f/P_y, \alpha) = \frac{(0.095\alpha + 0.024)P_f/P_y + 1.001}{R_t^{[(0.017\alpha + 0.007)P_f/P_y - 0.006\alpha - 0.003]}} \geq 1 \quad (1)$$

$$\boldsymbol{M_{90}}: f(R_t, P_f/P_y, \alpha) = \frac{(0.193\alpha + 0.05)P_f/P_y + 0.981}{R_t^{[(0.003\alpha + 0.007)P_f/P_y - 0.005\alpha - 0.003]}} \geq 1 \quad (2)$$

$$\boldsymbol{M_{80}}: f(R_t, P_f/P_y, \alpha) = \frac{(0.396\alpha + 0.028)P_f/P_y + 0.967}{R_t^{[(0.004\alpha - 0.043)P_f/P_y - 0.013\alpha + 0.018]}} \geq 1 \quad (3)$$

Since there is constant axial force case formula only for the M_{95} limit state (equation 4), equation 5 and 6 are proposed for M_{90} and M_{80}.

$$\boldsymbol{M_{95}}: \frac{\varepsilon_u}{\varepsilon_y} = \frac{0.14(1.1 - P/P_y)^{1.8}}{(R_t - 0.03)^{1.4}} + \frac{3}{(1 + P/P_y)^{0.7}} \leq 20 \qquad (0 \leq P/P_y \leq 1.0) \quad (4)$$

$$\boldsymbol{M_{90}}: \frac{\varepsilon_u}{\varepsilon_y} = \frac{0.13(1.57 - P/P_y)^{2.62}}{(R_t - 0.03)^{1.25}} + \frac{3.30}{(1 + P/P_y)^{1.48}} \leq 20 \quad (0 \leq P/P_y \leq 0.6) \quad (5)$$

$$\boldsymbol{M_{80}}: \frac{\varepsilon_u}{\varepsilon_y} = \frac{0.25(1.56 - P/Py)^{2.89}}{(R_t - 0.03)^{1.19}} + \frac{4.54}{(1 + P/Py)^{2.29}} \leq 20 \quad (0 \leq P/P_y \leq 0.6) \quad (6)$$

Ultimate strain for a desired limit state can be estimated by multiplying the result of the constant axial force case formulae with the one of the correction function within the application range ($P_f \leq 0.6$, $1.25 \leq \alpha \leq 4$ and $0.03 \leq R_t \leq 0.5$). Conservative estimates can be obtained in this range with an error of less than 20% in most cases as shown in the comparison of the numerical analyses results in Figure 5.

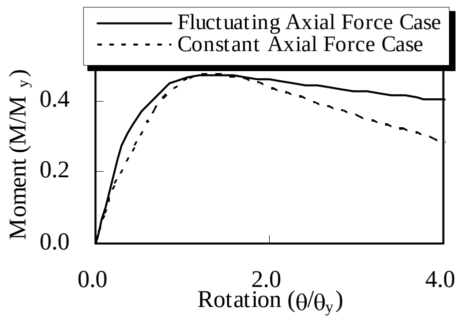

Figure 3: Bending Behavior (Model 4, P_f=0.6P_y, α=3)

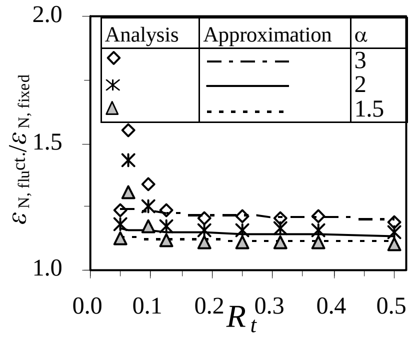

Figure 4: Comparison of the post peak ductility (M_{95}, P_f=0.6P_y)

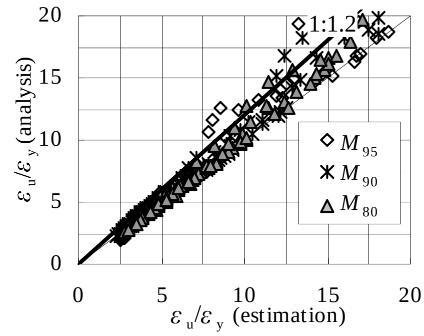

Figure 5: Estimation accuracy

6. Conclusions

The proposed formulae can be used to determine the ductility capacity of pipe section columns in portal frames and arch-ribs in arch bridges subjected to bending as well as axial force fluctuations. The formulae will result in the use of higher ductility as design values compared with conventional practice, making the seismic design more rational.

Reference

[1] Ge H, Kono T and Usami T.: Failure strain of steel segments subjected to combined compression and bending and application to dynamic verification of steel arch bridges. Journal of Structural Engineering (JSCE) 2004; 50A: 1479-1488.