Transactions of the **13th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 13), Escola de Engenharia - Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil, August 13-18, 1995

Study on a concrete filled steel structure for nuclear power plants (part 2). Compressive loading tests on wall members

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ABSTRACT : The problem of surface steel plate buckling is encountered in concrete filled steel structures (SC) structures where compressive stress is dominant. An experimental research program has been executed to obtain fundamental data for establishing a design method to prevent buckling in the inelastic buckling region of steel plates fixed to the concrete surfaces steel plate with headed stud bolts. Thus, 1/5 scale SC wall test specimens were manufactured and compressive loading tests were carried out. It was found that the buckling stress can be evaluated using Euler's equation for elastic buckling of columns with one fixed end and one pin-jointed end when the buckling stress is less than 0.6 the yield strength. However, when the buckling stress is greater than this value, the observed buckling stress is less than the calculated values due to the inelastic properties of the steel.

1 INTRODUCTION

In some portions of web and flange walls in nuclear power plant structures, compressive stress becomes dominant. In these cases, the problem of surface steel plate buckling is encountered in SC structures.

The following methods for preventing buckling have been investigated : 1) providing diaphragms, 2) attaching L-shaped ribs and 3) fitting headed stud bolts (hereinafter studs). Method 3) has been employed in SC structures, because it is the most economical and rational.

Compressive loading tests on SC walls have been previously carried out. The results indicated that the buckling stress can be evaluated based on Euler's equation for columns with one fixed end and one pin-jointed end. However, this evaluation is limited to the elastic buckling region, where the ratio of stud spacing (B) to steel plate thickness is more than 50.

Therefore, an experimental research was carried out to determine the plastic or inelastic buckling resistance of surface steel plates fixed with stud bolts. The obtained test data were utilized to establish a structural design method for SC walls subjected to a dominant compressive stress.

2 TEST OUTLINE

The test specimens were one-fifth scale models of actual SC walls. As shown in Fig. 1, a total of four specimens were tested. The test parameter was the width-thickness ratio (B/t), and four values, 20, 30, 40 and 50,

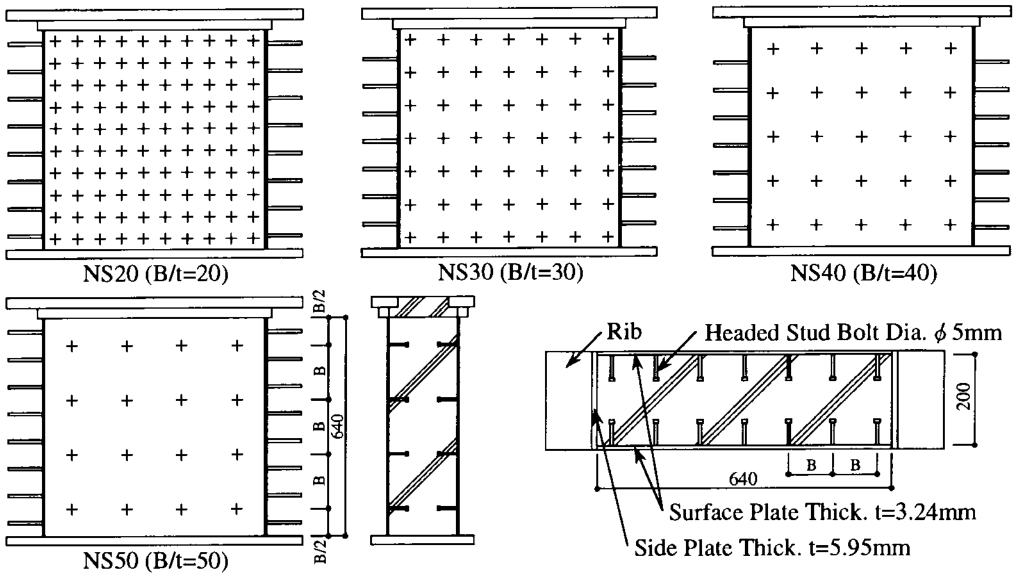
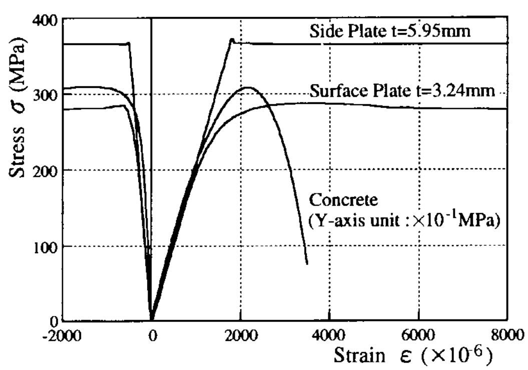
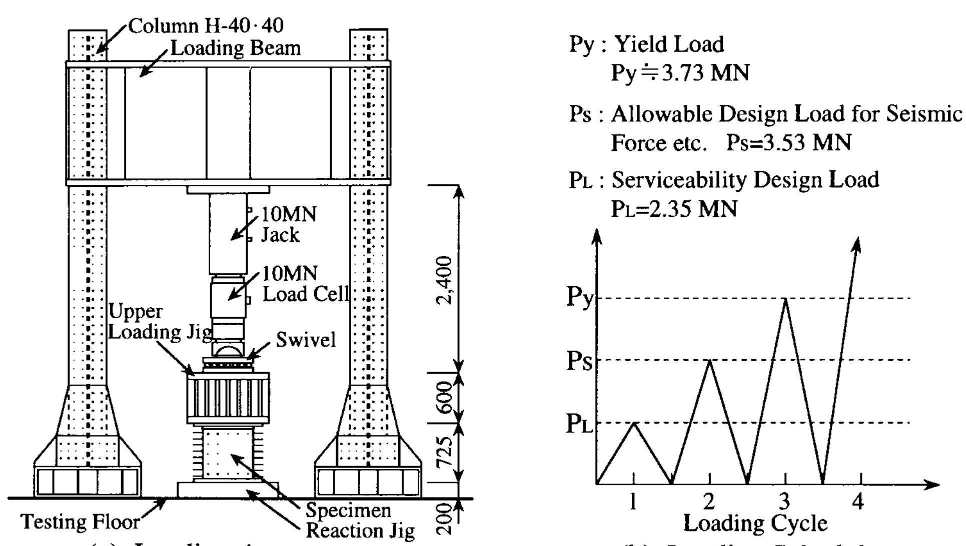


Fig.1 Dimensions of Test Specimens



Steel			
Plate Thickness	t (mm)	3.24	5.95
Upper Yield Strength	$_s\sigma_y$ (MPa)	—	378
0.2% Yield Strength	$_s\sigma_y$ (MPa)	287	366
Young's Modulus	$_sE$ ($\times10^5$MPa)	1.96	2.08
Poisson's Ratio	ν	0.28	0.28
Ultimate Strength	$_s\sigma_u$ (MPa)	427	465
Ordinary Concrete			
Maximum Aggregate Dia.	(mm)		10
Compressive Strength	σ_B (MPa)		31.2
Young's Modulus	$_cE$ ($\times10^4$MPa)		2.28
Poisson's Ratio	ν		0.18

Fig.2 Stress-Strain Curves and Properties of Steel and Concrete



(a) Loading Apparatus

(b) Loading Schedule

Fig.3 Loading Method

were set to achieve plastic, inelastic and elastic buckling. The thickness (t) of the surface steel plates in actual structures is 6~16mm. The thickness for the test specimens was a 3.2mm to ensure constant material properties. The design stud diameter to plate thickness ratio ϕ /t was 1.4~2.2, and a stud diameter of 5mm (ϕ /t=1.56) was chosen for the specimens. Concrete in an actual structure used has a compressive strength of 24MPa~33MPa, but for the specimen ordinary concrete with a compressive strength of 33MPa was used. The size of the specimen was determined to produce a clear buckling failure of the surface steel plate, with the width and height made over 3 times the stud spacing. The material properties and stress-strain relationships of the steel plates and the concrete in the specimens are summarized in Fig.2. The 10MN compressive test machine used and the test loading schedule are shown in Fig.3.

3. TEST RESULTS AND CONSIDERATIONS

3.1 Outline

The results of the test are summarized in Table 1. Photo 1 shows the buckling wave of surface plate. Photo 2 shows the damage to the inner concrete after the test, observed after the surface steel plates were removed. The following observations can be made :

1) The observed buckling stresses (see clause 3.4 below) increase with decreasing B/t ratios.

2) The ultimate compressive loads and the overall compressive strains at the ultimate loads decrease with increasing B/t ratio. The observed compressive strains at ultimate load are about 0.0033, greater than the value of 0.0022 obtained from concrete material tests, due to the confining effects of the steel plates.

3) The failure of the inner concrete initiated from the region where the surface steel plate buckled and the range of failure was 1~2 times the stud spacing B (0.5~1 times the wall thickness).

3.2 Load-Displacement Relationship

The observed relationships between the applied load P and displacement δ are shown in Fig.4, and their enveloped curves are shown in Fig.5. The load-displacement relationships can be calculated from the stress-strain relationships of the steel plates and concrete, as shown Fig.2. Fig.6 compares the calculated result with the observed one. From these figures the following observations can be made :

1) There was no sudden change in the load-displacement relationships due to the buckling or yielding of the steel plate.

2) The stiffness under loads of up to 3MN was unaffected by B/t. However, for loads over 3MN, the greater the value of B/t, the smaller the stiffness. This tendency is considered to result from the confining effects of the concrete.

3) The calculated P- δ relationship can simulate well the observed relationship for load in the range 0.5~3.5MN. However, for the greater load level, some discrepancies are observed. This suggests that an increase in displacement due to collapse of the concrete between the studs and steel plate occurred in the tests (see Photo 1&2).

3.3 Initial Stiffness and Ultimate Load

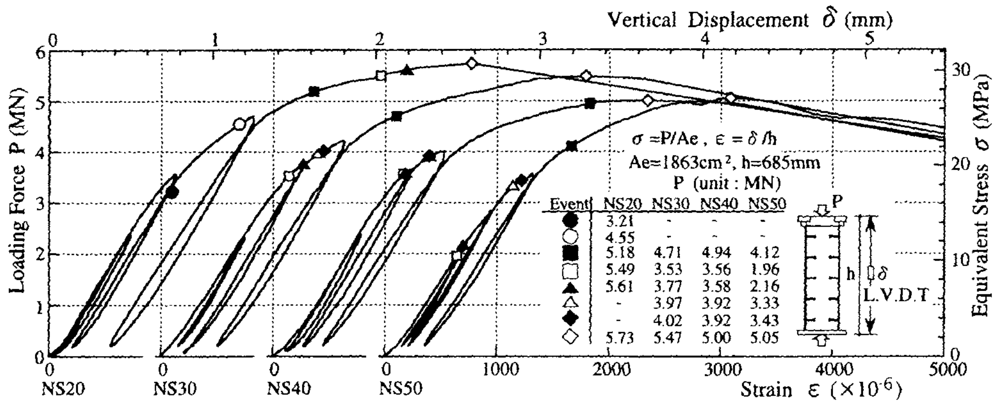
As shown in Table 1, the initial stiffnesses eK of the test specimens obtained from test results are 78%~88% of the calculated elastic stiffness cK. The same tendency was observed in our previous tests (Ref.5). The

Table 1 Test Results and Calculated Values

Specimen Mark	Experimental eK (MN/cm)	eσcr (MPa) Front / Back	eεcr ($\times 10^{-6}$) Front / Back	ePmax. (MN)	Calculated cK (MN/cm)	eK / cK	cσcr (MPa)	eσcr / cσcr Front / Back	cPmax. (MN)	ePmax. / cPmax.
NS20	54.4	284 / —	2944 / —	5.73	62.1	0.88	881	0.32 / —	5.33	1.07
NS30	49.0	212 / —	1632 / —	5.47		0.79	392	0.54 / —	4.76	1.15
NS40	52.7	222 / 225	1285 / 1217	5.00		0.85	220	1.01 / 1.02		1.05
NS50	48.1	134 / 186	943 / 945	5.05		0.78	141	0.95 / 1.32		1.06

eK, cK : Experimental and Calculated Initial Stiffness
eσcr, cσcr : Experimental and Calculated Buckling Stress
Front ; Front Surface Plate
Back ; Back Surface Plate
eεcr, cεcr : Experimental and Calculated Buckling Axial Strain
ePmax., cPmax. : Experimental and Calculated Ultimate Load
$cPmax.=Fc \cdot Ac+s\sigma y1 \cdot As1+s\sigma y2 \cdot As2$
Fc : Compressive Strength of Concrete
Ac, As1, As2 : Sectional Area of Concrete, Side Plate and Surface

$cK=(Ec \cdot Ac+Es \cdot As)/h$
Ec, Es : Young's Modulus of Concrete and Steel
Ac, As : Sectional Area of Concrete and Steel
$c\sigma cr= \pi^2 \cdot Es/\{12 \cdot \eta^2 (B/t)^2\}$
η : $\eta \approx 0.7$
B : Spacing Interval of Headed Stud Bolt
t : Thickness of Surface Plate
sσy1, sσy2 : Yield Strength of Side Plate and Surface Plate



#1 ● : Yielding of Partial S.P.
#2 ○ : Yielding of All S.P.
#3 ■ : Yielding of Side Plate
#4 □ : Buckling of Front S.P. with Gage
#5 ▲ : Buckling of Front S.P. with Eye
#6 △ : Buckling of Back S.P. with Gage
#7 ◆ : Buckling of Back S.P. with Eye
#8 ◇ : Maximum Load

S.P. : Surface Plate

Fig.4 Relation of Load Versus Displacement

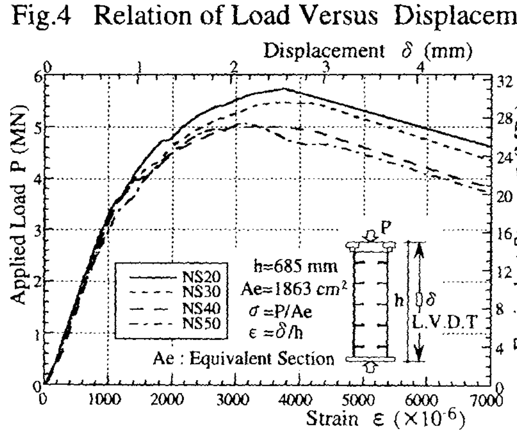


Fig.5 Enveloped Curves of Load Versus Displacement

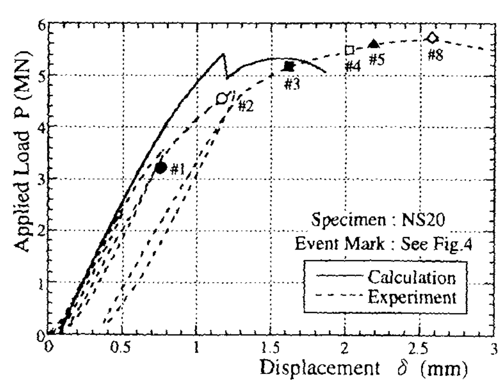


Fig.6 Relation of Calculated and Experimental P- δ

calculated ultimate loads $_cP_{max}$, shown in Table 1, were obtained under the assumption that the steel plates can not bear any compressive load after buckling. The measured ultimate loads $_eP_{max}$ coincide very well with the calculated values, except for specimen NS30.

3.4 Buckling of Surface Steel Plates

To accurately determine the buckling stress, wire strain gages were attached to the outside and inside surface of the steel plates. The relationship between the applied load and the strains in the steel plate in the buckled region is shown in Fig.7. Strains both outside and inside the surface of the steel plate increase in the same way before buckling. However, after buckling they separate suddenly and outside strain tends to become tensile and inside strain tends to become more compressive. The buckling stress of the steel plates is evaluated through the following data analysis. First, the steel plate is divided into n transverse layers and the strain distribution is assumed to be linear in the transverse direction. Next, the stress in each layer is determined from the stress-strain relationship of the steel (Fig.2), by assuming a strain value in each layer. Finally, the average stress in the steel plate is evaluated as the cumulative mean stresses in the n layers. The relationship between average stress and applied load is shown in Fig.7. As shown, the average compressive stress first increases, but suddenly turns to tensile after buckling. We define this turning point as the buckling stress of the steel plate. The buckling stresses and strains are summarized in Table 1. Fig.8 and Fig.9 show the relationship between the width-thickness ratio and the buckling stress and strain, respectively. From these results, the following conclusions can be drawn :

1) When the buckling stress is less than 0.6 of the yield strength, $_s\sigma_y$, it can be evaluated using Euler's equation for elastic buckling of columns, using B/t as the slenderness ratio.

2) When the buckling stress is greater than $0.6{}_s\sigma_y$, the test results become scattered. In this region, the buckling is perfect plastic buckling (B/t=20) or inelastic buckling (B/t=30,40). The main reason for this scattering is considered to be the inelastic characteristic of the steel employed in the test specimens, i.e. they did not have the perfect elastic-plastic characteristic shown in Fig.2. Another reason is that the fixedness of the studs might decrease as the applied compressive load increases.

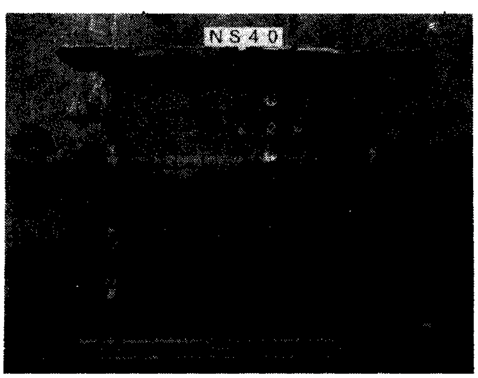


Photo.1 Buckling Wave of Surface Plate

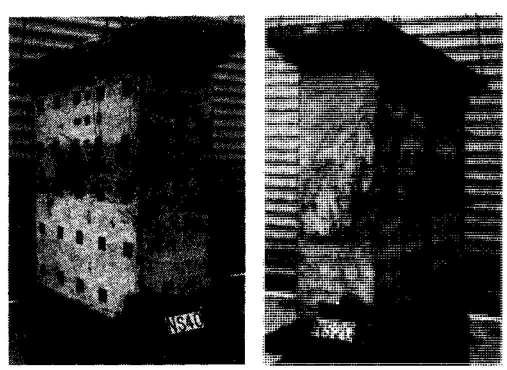


Photo.2 Condition of Cracks in the Final Stage

4 CONCLUSIONS

The following conclusions are obtained from the test results;

1) The buckling and yielding phenomena of steel plates have no influence on the overall load displacement relationship of SC walls.

2) The overall load displacement relationship of SC walls can be evaluated using the physical properties of the material.

3) When the buckling stress is less than 0.6 of the yield strength, the buckling stress can be evaluated using Euler's equation for elastic beswss3uckling of columns with one fixed end and one pin-jointed end.

4) When the buckling stress is greater than this value, the observed buckling stress is less than the calculated values using the above equation due to the inelastic properties of the steel used in the test.

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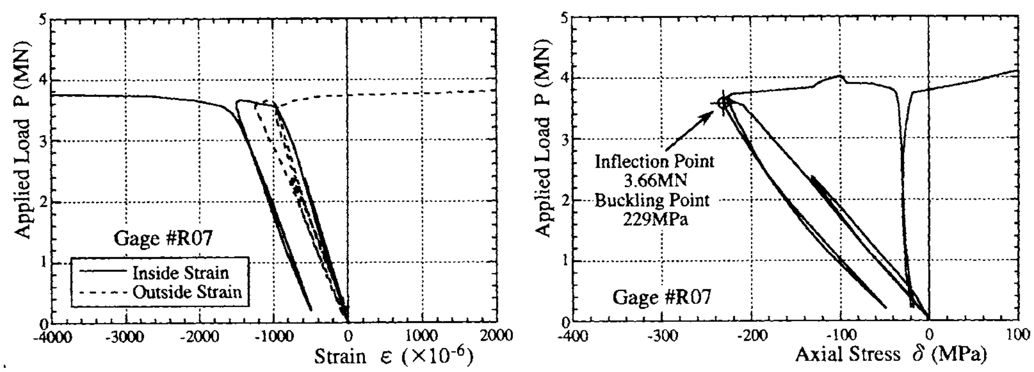

Fig.7 Relation of Load Versus Buckling Axial Stress

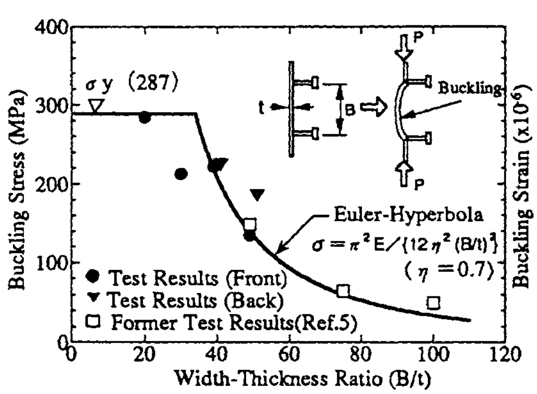

Fig.8 Relation of Buckling Stress Versus Width-Thickness Ratio

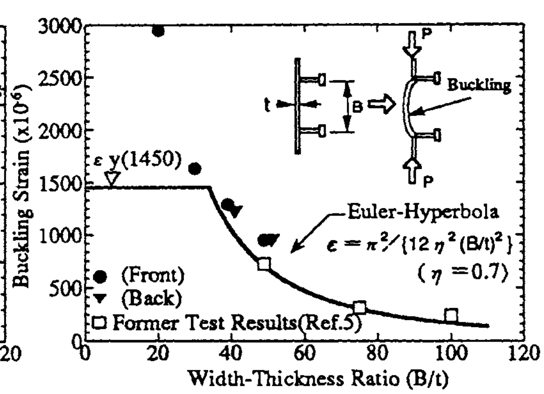

Fig.9 Relation of Buckling Strain Versus Width-Thickness Ratio