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BEHAVIOR OF CONCRETE-FILLED STEEL TUBES

(Part-1, Compression Members)

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Bridge Division
Ministry of Construction
Public Works Research Institute

P R E F A C E

In our country, bridge piers are subjected to strong motions due to earthquake. Furthermore, size of bridge piers are strictly limited in metropolitan highways and in monorails. High ductility and high resistance is, therefore, required for bridge piers in Japan. In this regard, use of concrete-filled steel tubes is examined.

Steel Tubes have pretty high resistance; however, steel tubes are liable to yield local buckling and to lose ductility after yielding local buckling. Concrete piers with adequate reinforcing have good ductility; however, they are large-sized. Concrete-filled steel tubes are thin steel tubes with concrete and shear connectors in the tubes. When they are subjected to a strong motion, concrete prevents the local buckling of thin steel tubes, steel tubes giving adequate reinforcing to the concrete. Therefore, even small-sized concrete-filled steel tubes have excellent ductility and resistance.

Sometimes, concrete-filled steel tubes were used for bridge piers or building members. However, they were used just to increase the rigidity of the members or to stiffen the steel tubes, and they were not designed as composite structures. In our report, concrete-filled steel tubes are regarded as composite structures to expect higher resistance and ductility. At present, many problems are not settled to design concrete-filled steel tubes as composite structures, such as provisions for shear connectors, plate thickness and so on. In the report, these problems are examined in detail, based on the results of full-size tests, and design recommendations are presented.

The following reports are coming in series.

- | | |
|----------|---------------------|
| Part I | Compression Members |
| Part II | Long Columns |
| Part III | Bending Members |
| Part IV | Beam Columns |

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Bridge piers should be designed to resist earthquakes which are expected during the lifetime of the structures. However, we cannot but say that it is waste of national budget to construct the bridge piers which can resist the severest earthquake. In this regard, the concept of "minimum total cost" should be introduced.

On the other hand, admitting the above, brittle structures which may cause disasters due to the collapse of the structures should be avoided as far as possible. Ductile structures, which will not collapse even in the strongest earthquake, yielding some local failures, is desirable for bridge piers. For example, Fig. 1 (a) shows the ductile structures, Fig. 1 (b) showing the brittle structures. Ductile structures may yield some local failures, but they will not lose resistance even in the region of large deformation.

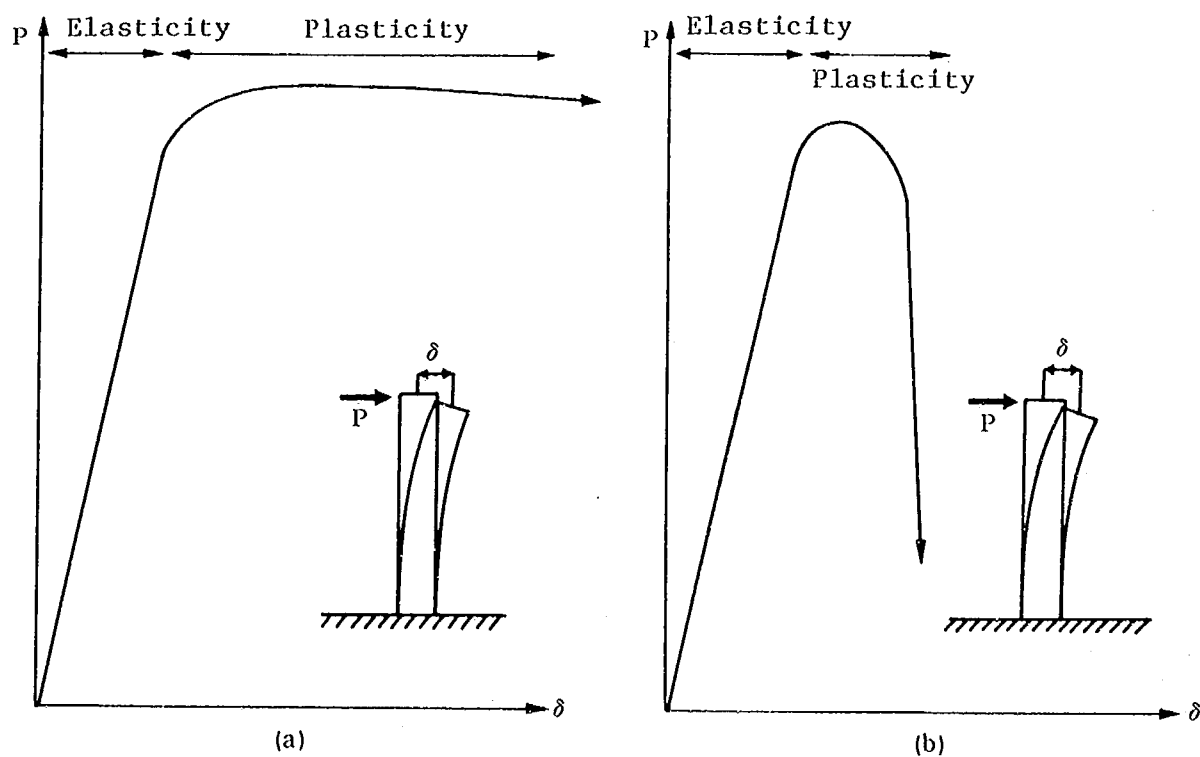


Fig. 1 Ductile and Brittle Structures

Steel tubes are ductile or brittle depending on the Diameter - Thickness ratio (D/t). Thin steel tubes are economical in the elastic design, but they are usually brittle. Thick steel tubes are usually ductile, but they are not economical in the elastic design. Therefore, it is very difficult to determine the adequate D/t value for bridge pier design.

In this regard, behavior of composite concrete-filled steel tubes is excellent. Concrete prevents the local buckling of thin steel tubes, steel tubes giving adequate reinforcing to the concrete. Therefore, concrete-filled steel tubes have excellent resistance and ductility. However, we do not have good design specifications to design the concrete-filled steel tubes as composite structures. In the following chapters, the behavior of the concrete-filled steel tubes is examined in detail based on the full-size tests with 3000 ton testing machine of the P.W.R.I. . In this report, the test results of the short compression members are described.

As described in the Preface, concrete-filled steel tubes are sometimes used for bridge piers and building members; however, they are used to give the rigidity to the members or to stiffen the local buckling of the steel tubes. Higher economy can be expected by designing the concrete-filled steel tubes as steel-concrete composite structures. In this regard, the following problems should be settled.

1. When steel and concrete are both elastic, Poisson's ratio of the concrete (about $1/6$) is much smaller than that of the steel (about 0.3). Therefore, under axial compression, concrete and steel will separate from each other in a cross section (Fig. 2). When steel and concrete are connected by studs or something, steel will be subjected to compression for hoop direction. On the other hand, when steel and concrete are not connected, the both will behave independently, and they will not be composite structures. So, how to give enough bond between steel and concrete is a important problem. Natural bond may not be enough and studs may be required.

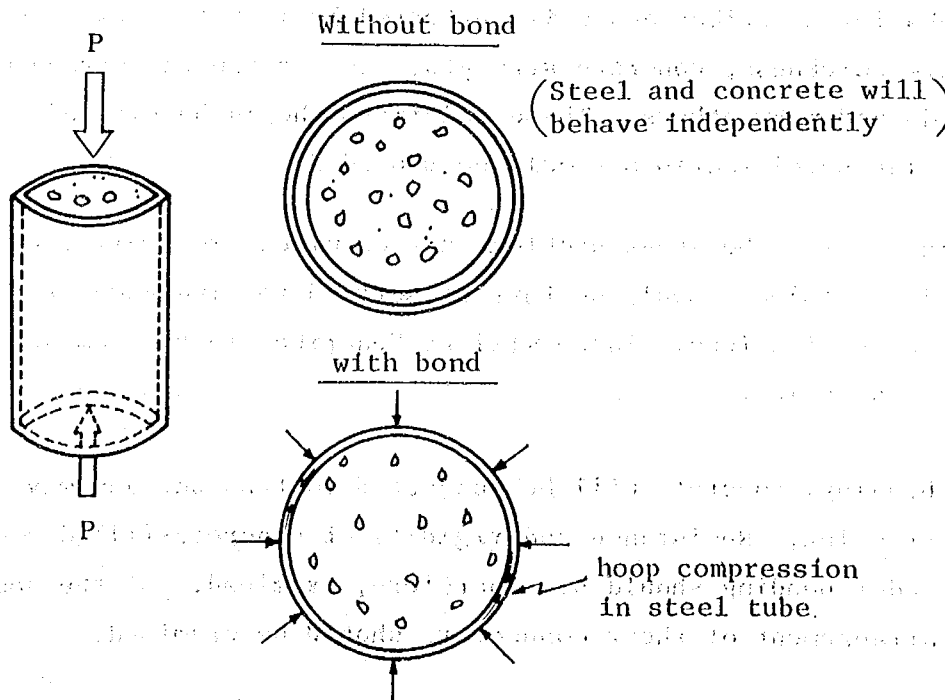


Fig. 2 Behavior in Elasticity

2. When steel and concrete are plastic, Poisson's ratio of the concrete increases to about 0.5 which is much larger than that of the steel. Therefore, steel tube will be subjected to tension for hoop direction. At this time, steel and concrete will behave together without the bond, and high resistance and ductility is expected. These effects should be examined.

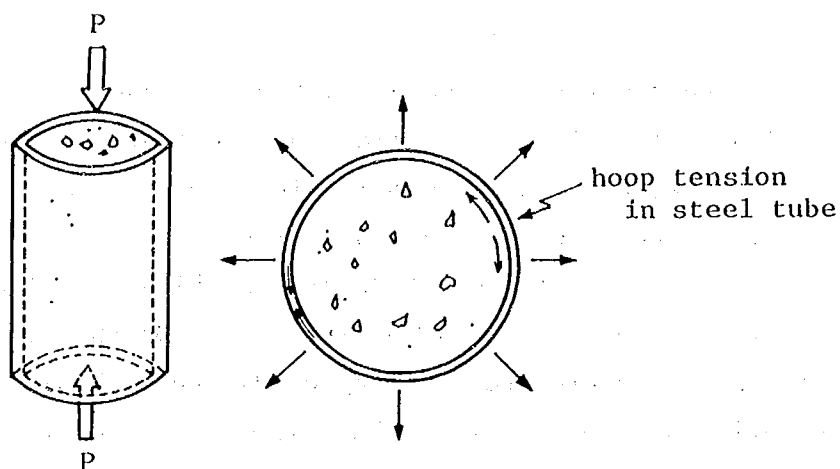


Fig. 3 Behavior in Plasticity

3. The behavior described above is affected by many factors such as plate thickness, concrete strength, steel strength, arrangement of studs and many others. These relations should be cleared up and design specifications should be provided.

In this report, the above problems are examined. Meanwhile, the following problems should be further settled to give complete design specifications. These will be described in the coming reports in series.

4. Under bending, concrete will be subjected to tension, and may yield cracking. Resistance and rigidity of concrete-filled steel tubes under bending should be, therefore, examined. At the same time, arrangement of shear connectors should be examined.

5. Under repeated loadings, the resistance of concrete-filled steel tubes may decrease, due to the extension of cracking, the accumulation of plastic strain, the stress concentration due to studs and so on. Furthermore, the bond between concrete and steel may be lost. These should be examined in detail.
6. The resistance of long columns composed of concrete-filled steel tubes should be examined. The evaluation of slenderness ratio is pretty complicated in composite structures.

CHAPTER - 3 OUTLINE OF THE TESTS

In the compression tests, ten full-size specimens were fabricated. We needed full-size specimens in order to provide studs inside the steel tubes, and also to examine the bond problem in detail. The configuration of the specimens are shown in Fig. 4, the specifications being shown in Table 1.

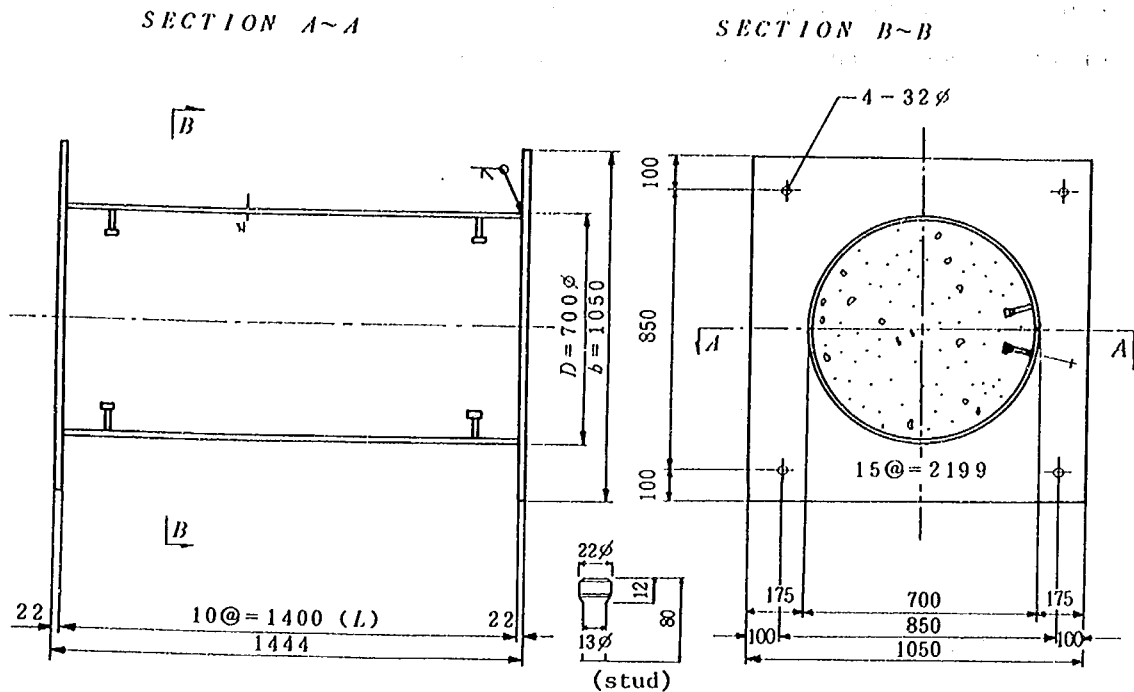


Fig. 4 Configuration of Test Specimen

Table 1. Specifications for The Test Specimens

No.	Diameter x plate thickness	Concrete	Stud	Yield strength of steel	Concrete strength	Remarks
A-1	700 x 6	without	without	4600	254	for cyclic loading
A-2	" x 8	"	"	4720	"	
A-3	" x 8	"	"	"	"	
A-4	" x 12	"	"	4000	"	
B-1	700 x 6	with	with	4600	"	for cyclic loading
B-2	" x 8	"	"	4720	"	
B-3	" x 8	"	"	"	"	
B-4	" x 12	"	"	4000	"	
B-5	" x 8	"	without	4720	"	
B-6	" x 8	"	with	"	410	

Steel plate material is SM 50Y, which has nominal yield strength of 3600 kg/cm². Tensile strength of the material was tested by test pieces taken from bent up steel tubes. The results are shown in Table 2.

Table 2. Yield Strength of Steel

Size	Yield strength (kg/cm ²)	Breaking strength (kg/cm ²)	Elongation (%)
φ 700 x 6	4570	5700	23.4
	4620	5750	23.0
	4630	5670	22.1
average	4600	5700	22.8
φ 700 x 8	4720	5650	25.8
	4720	5660	26.0
	4720	5620	25.7
average	4720	5640	25.8
φ 700 x 12	4000	5710	22.4
	4030	5770	22.1
	3970	5770	21.6
average	4000	5750	22.0
nominal	3700 up	5000 ~ 6200	15 up

The steel tubes are bent up as shown in Photo 1, and welded from inside and outside as shown in Photo 2 and Photo 3. The welding was carried out as shown in Fig. 5 and Table 3. The studs were welded by a stud-gun, as shown in Photo 4.

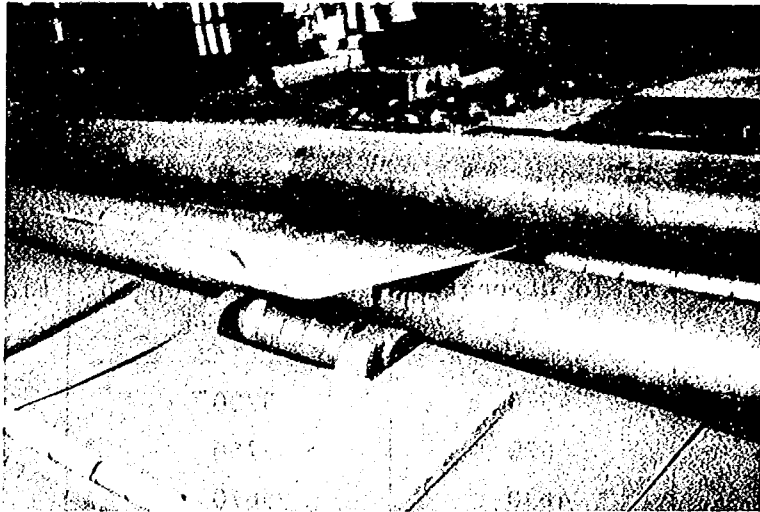


Photo-1. Bending Process of Steel Tubes

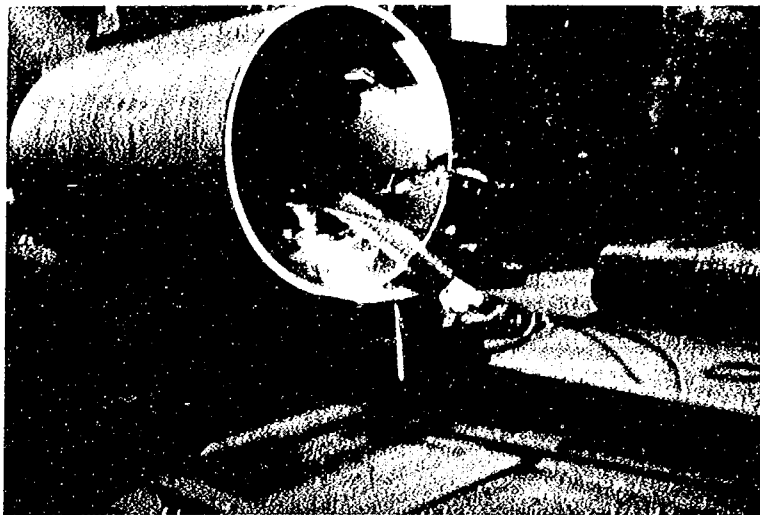


Photo-2. Welding (Inside)

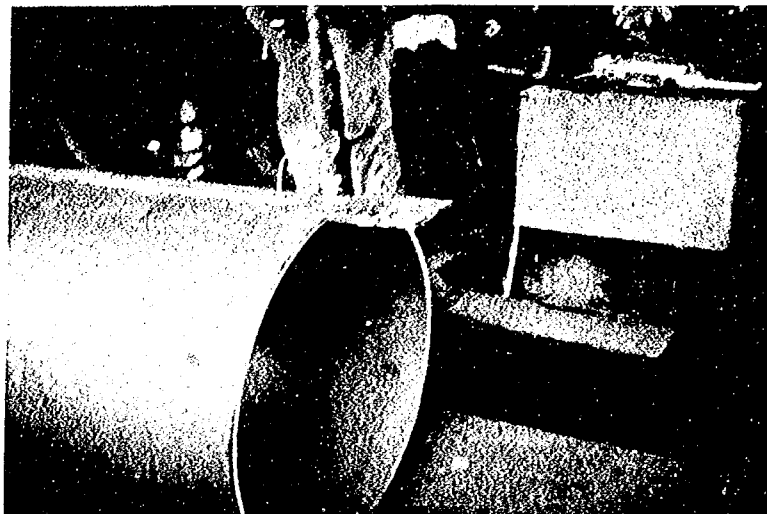
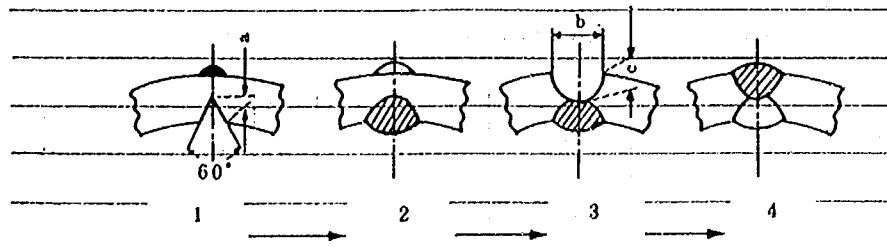


Photo-3. Welding (Outside)



Dimensions

Plate thickness	a	b	c
12	3	10	5
8	2	8	3
6	2	-	-

Fig. 5 Welding Process

Table. 3 Specifications for Welding

Plate thickness	Place	I	V	Velocity
12 (mm)	Inside	560 ^A	38 ^V	37 ^{cm/mm}
	Outside	580	36	30
8	Inside	430	35	50
	Outside	580	38	45
6	Inside	370	32	85
	Outside	580	36	60

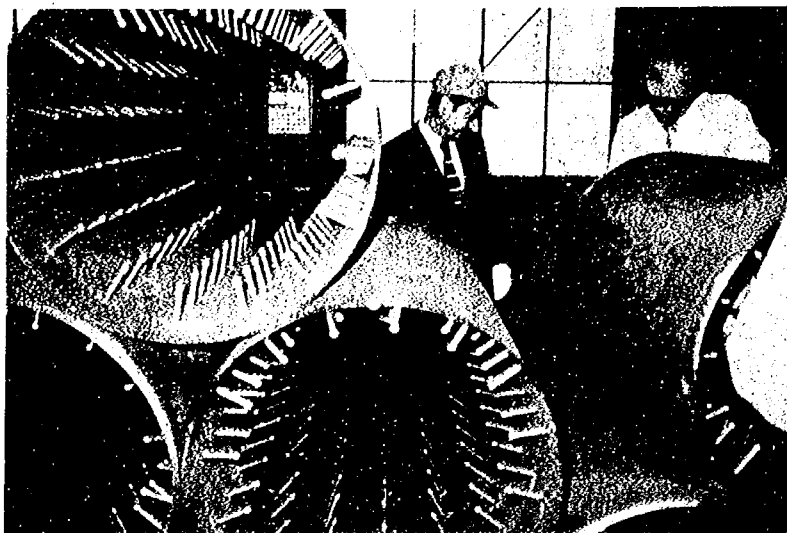


Photo-4. Stud Welding

Table 4. Specifications for Concrete

Nominal	Unit	Water	Cement	Fine aggregate	Coarse aggregate
$\sigma = 210\text{kg/cm}^2$	1 m ³	152kg	249kg	826kg	1110kg
$\sigma = 400\text{kg/cm}^2$	1 m ³	151kg	357kg	650kg	1179kg

Concrete Strength

Nominal	(1)	(2)	(3)	Average
210	241	247	247	245
400	438	436	429	434

The specifications for the concrete and the concrete strength are shown in Table 4. After casting the concrete, the concrete will yield shrinkage, which will prevent uniform loading of the specimen. Therefore, non-shrinkage mortar was casted at the top and the bottom of the specimen three weeks after casting the concrete, and then top and bottom plates were welded to the specimen. Both top and bottom plates were ground up by facing machines in order to obtain uniform loading. (Photo 5 - Photo 7)



Photo-5. Mortar Casting

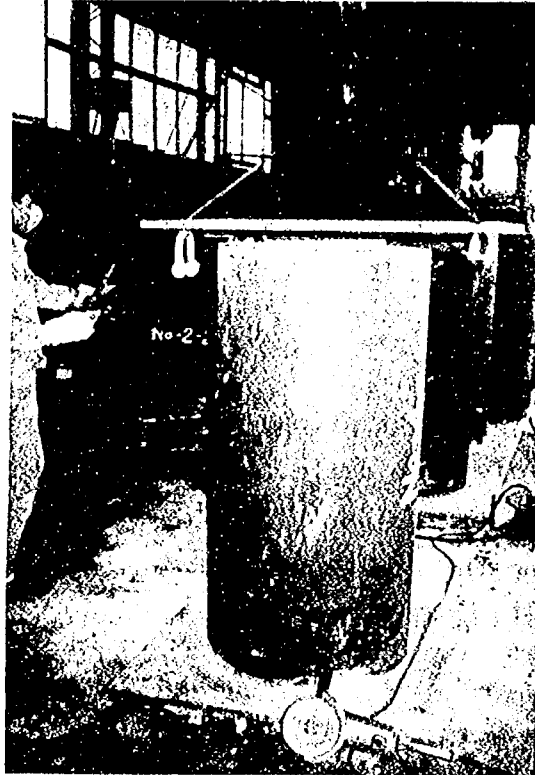


Photo-6. Bottom and Top Plate

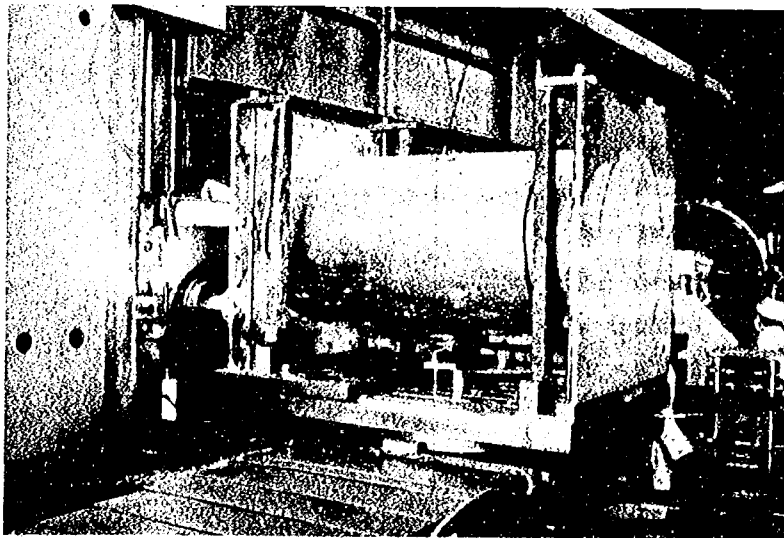


Photo-7. Grinding of Top and Bottom Plate

Specimens A-1 to A-4 are steel tube specimens without concrete in them. A-3 is same as A-2, but it is for cyclic loading.

Specimens B-1 to B-6 are concrete-filled steel tubes. B-1 to B-4 are the same ones as A-1 to A-4 respectively, except for the concrete and the studs in them. B-5 is originally same as B-2, but it is not provided with studs. B-6 is also same as B-2, but it has high strength concrete in it.

In the tests, total deformation, strain of the steel tubes (128 points) and out-of-plane deflection of the steel tubes (52 points) were measured by automatic computer system. Fig. 6 shows the strain gauges, Fig. 7 showing the measurement of out-of-plane deflection. Photo 8 shows the testing machine and the measurement system.

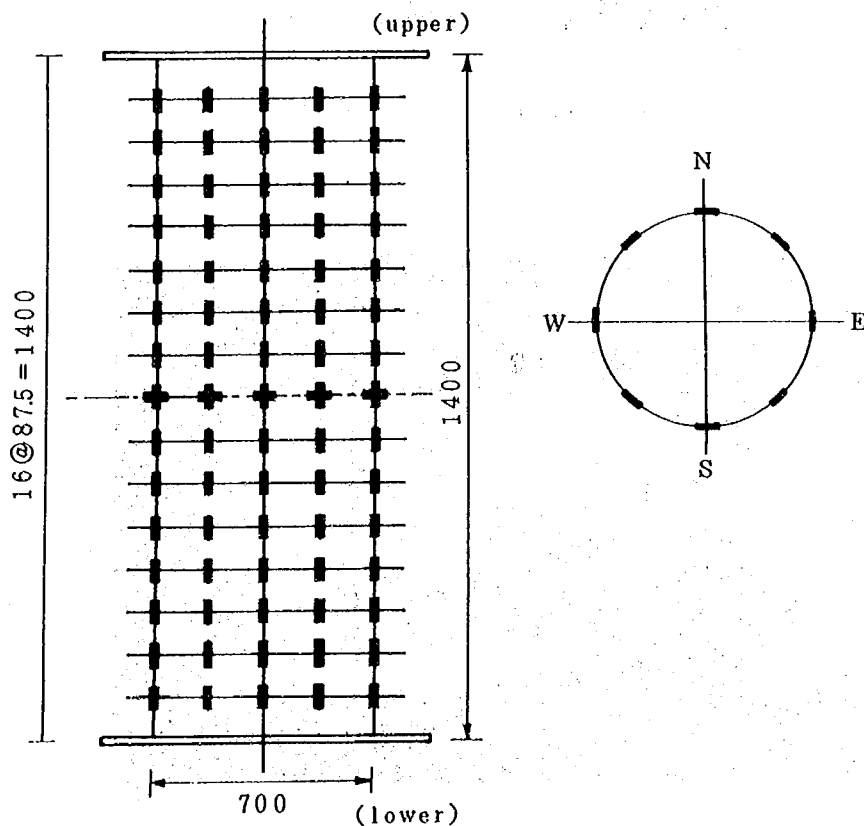


Fig. 6 Measurement of Strain

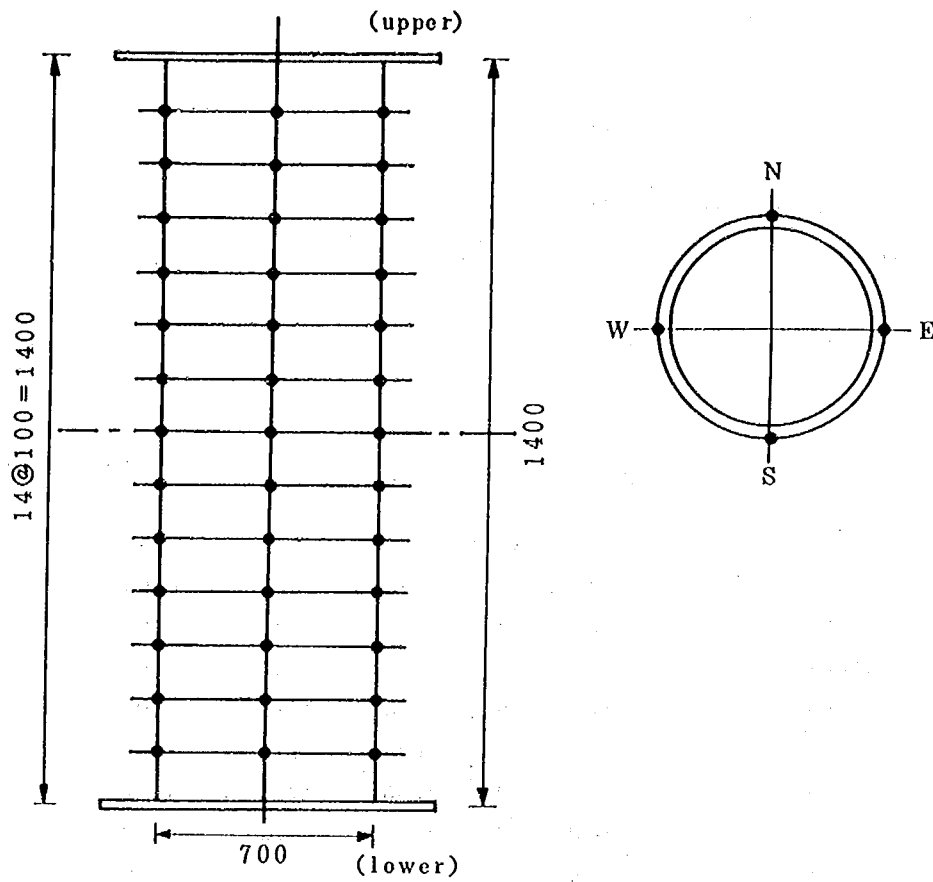


Fig. 7 Measurement of Out-of-Plane Deflection

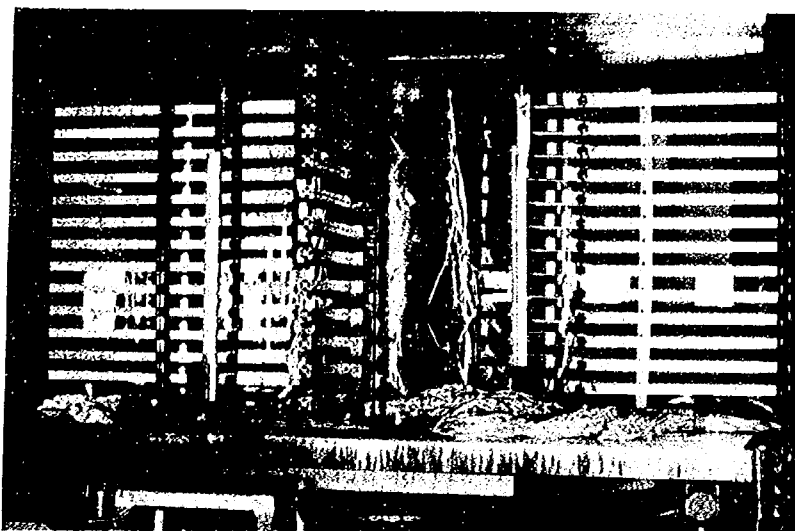


Photo-8. Measurement of Out-of-Plane Deflection

CHAPTER - 4 TEST RESULTS AND ANALYSIS

4.1 Resistance of concrete-filled steel tubes

The theoretical values and the test results of the resistance of the specimens are listed in Table 5, where,

Table 5. Theoretical and Experimental Resistance

No.	Experimental Resistance	Theoretical Resistance					Experimental $\frac{Sc+Sb}{Sc+Sb}$	Experimental $\frac{Sc+Sy}{Sc+Sy}$
		Sc(t)	Sb(t)	Sy(t)	Sc+Sb(t)	Sc+Sy(t)		
A-1	540	-	567	602	567	602	0.95	0.90
A-2	753	-	786	821	786	821	0.96	0.92
A-3	760	-	786	821	786	821	0.97	0.93
A-4	1087	-	1010	1037	1010	1037	1.07	1.05
B-1	1509	911	567	602	1478	1513	1.02	1.00
B-2	1730	900	786	821	1686	1721	1.03	1.01
B-3	1722	900	786	821	1686	1721	1.02	1.00
B-4	2230	879	1010	1037	1889	1916	1.18	1.16
B-5	1694	900	786	821	1686	1721	1.00	1.10
B-6	2663	1595	786	821	2381	2416	1.12	1.10

Sc ; resistance of the concrete, obtained from the cylinder test result of the concrete.

Sb ; resistance of the steel tube, obtained from the local buckling strength of the steel tube. Effects of residual stresses and initial defections are considered in the following Donnell-Wan equations.

$$\sigma_{cr} = \sigma_y \left(N - \sqrt{N^2 - \sigma_{cl} / \sigma_y} \right) \dots\dots\dots (1)$$

in which,

σ_{cr} ; local buckling strength, where effects of initial imperfections are considered.

σ_y ; yield strength of the steel

σ_{cl} ; elastic local buckling strength of the steel tube,
which is obtained from

$$\sigma_{cl} = \frac{E}{\sqrt{3(1 - \nu^2)}} \frac{t}{R}$$

E, ν ; Modulus of elasticity and Poisson's ratio of the steel.

R, t ; radius and plate thickness of the steel tube.

N ; constant obtained from

$$N = \frac{1}{2} \left(1 + \frac{\sigma_{cl}}{\sigma_y} + \frac{U \cdot E}{2\sigma_y} \right)$$

U ; measure of initial imperfections.

$U = 0.001$ is recommended in the Highway Bridge Specifications in Japan.

S_y ; resistance of the steel tube, obtained from the yield strength of the steel.

As shown in Table 5, the resistance of the specimen A-1 to A-4 is sometimes lower than the theoretical values (S_b), because the effects of initial imperfections is significant in the thin plate steel tubes.

The followings three cases can be considered about the theoretical resistance of the specimens B-1 to B-6.

Case 1 ; When the steel tube and the concrete behave independently, the resistance will be $S_c + S_b$.

Case 2 ; When they are connected together, the concrete will prevent the local buckling of the steel tube, then the resistance will be $S_c + S_y$.

Case 3 ; When the concrete is confined by the hoop tension of the steel tube in plastic region, the concrete strength will be higher than the cylinder strength, then, the resistance will be higher than $S_c + S_y$.

Table 5 shows that the resistance of the specimens B-1 to B-3 is about the same as $S_c + S_y$, because even in these thin-plate specimens, local buckling is prevented by the concrete. The resistance of the specimen B-4 is higher than $S_c + S_y$, because the thick steel tube confine the concrete and the concrete strength is higher than the cylinder strength. Therefore, the resistance of the Case 2 is expected in the thin plate concrete-filled steel tubes, the resistance of Case 3 being expected in the thick plate ones.

On the other hand, the resistance of B-5 is smaller than that of B-2, and it is nearly same as the resistance of Case 1, where the steel tube and the concrete behave independently. Studs may be, therefore, needed to expect the resistance of Case 2.

Finally, the resistance of the specimen B-6 is much higher than $S_c + S_y$, that is, the resistance of Case 3 is obtained. The steel tube of B-6 is same as that of B-2, so, it is rather thin plate. Actually, the resistance of B-2 was that of Case 2.

Therefore, the status of the concrete is another important factor in estimating the total resistance. That is, in B-2 specimen, the concrete was broken into small blocks in plastic region, but the high strength concrete of B-6 specimen was not broken even in plastic region. This is why high resistance was obtained in B-6 specimens. Therefore, high-strength or high-quality concrete is needed to expect the resistance of Case 3.

4.2 Ductility of concrete-filled steel tubes

The ductility of the specimens can be examined by load-deformation curves, which are shown in Fig. 8 to Fig. 17.

Fig. 8 to Fig. 10 show that the thin plate steel tubes have small ductility, and lose strength after attaining the maximum strength, Photo 9 shows the local buckling of A-2 specimen which cause the loss of ductility. Fig. 11 shows that the thick plate steel tube has good ductility. Thick plate steel tube will not yield local buckling as shown in Photo 10.

Fig. 12 to Fig. 17 shows that even thin plate concrete-filled steel tubes have good ductility.

Furthermore, the ductility is not lost in repeated loadings. Therefore, concrete-filled steel tubes are good for bridge piers as far as compression members are concerned. Even B-5 specimen without studs shows good ductility.

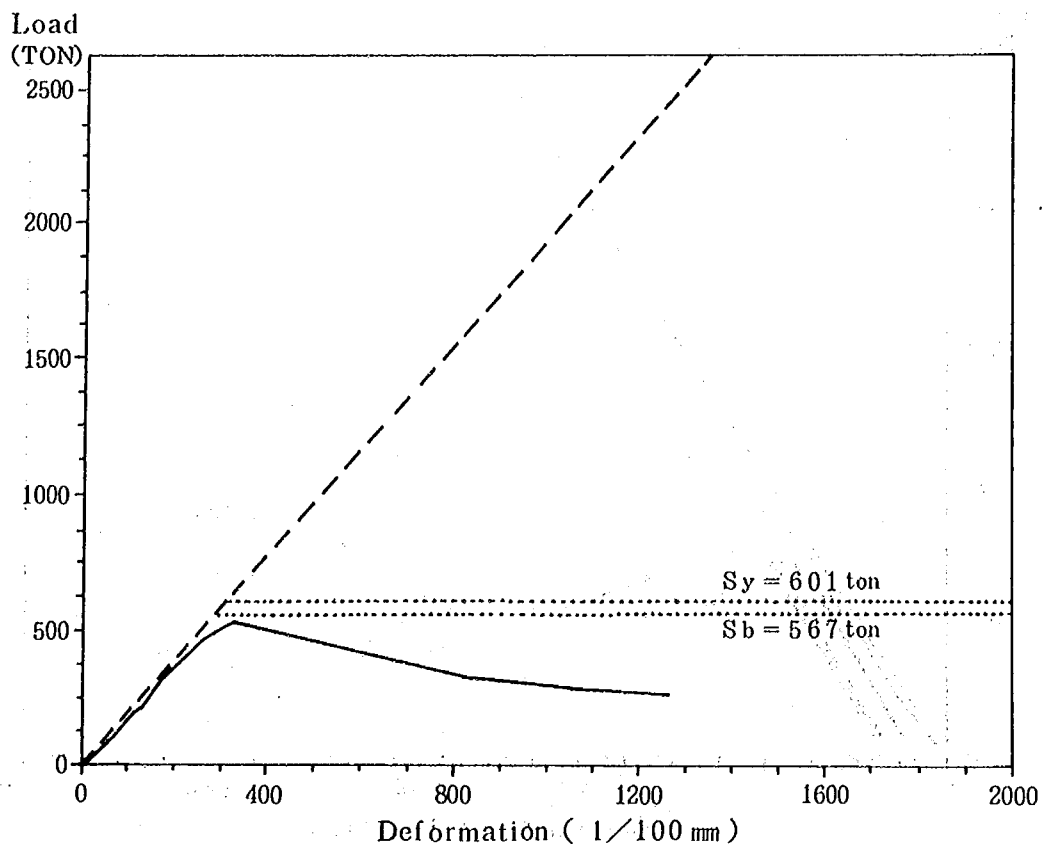


Fig. 8 Load - Deformation Curve (A - 1)

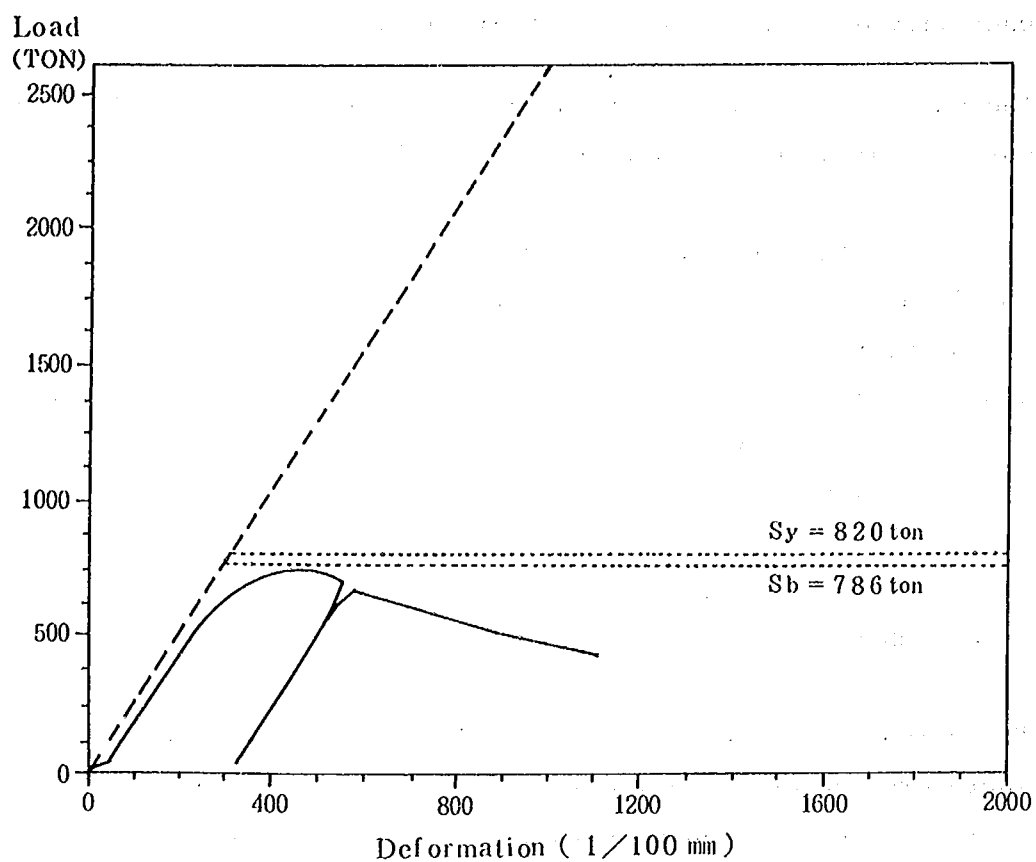


Fig. 9 Load - Deformation Curve (A - 2)

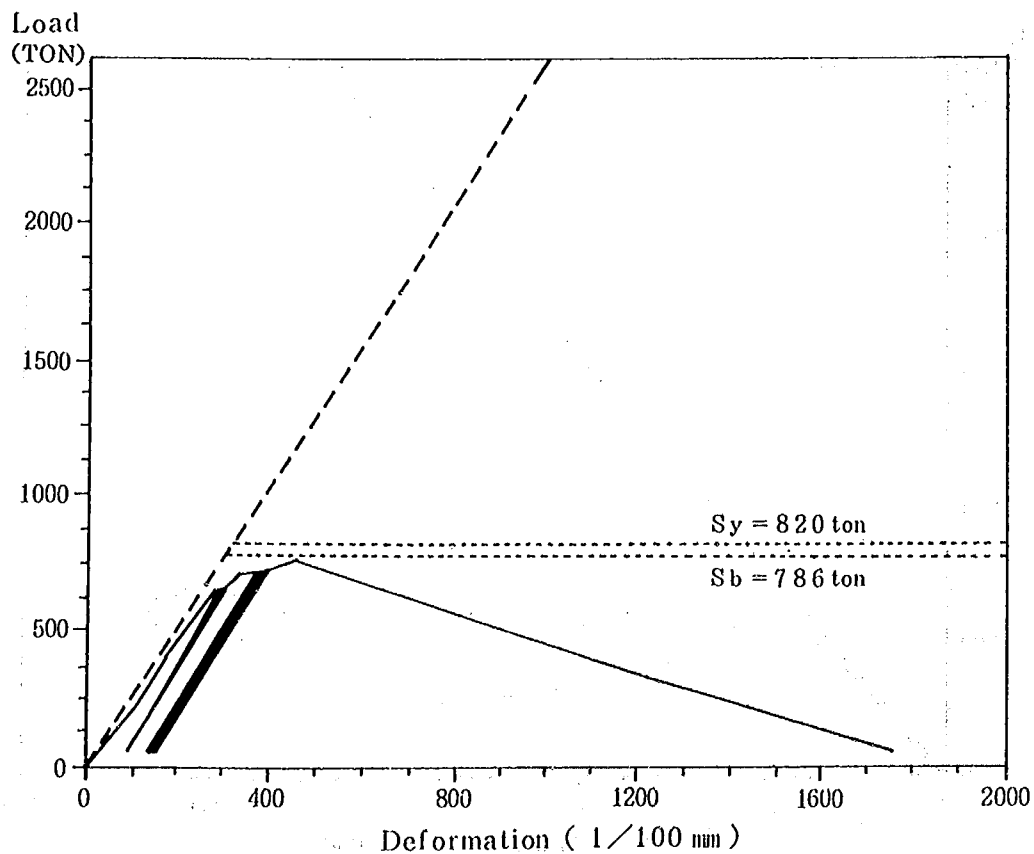


Fig. 10 Load - Deformation Curve (A - 3)

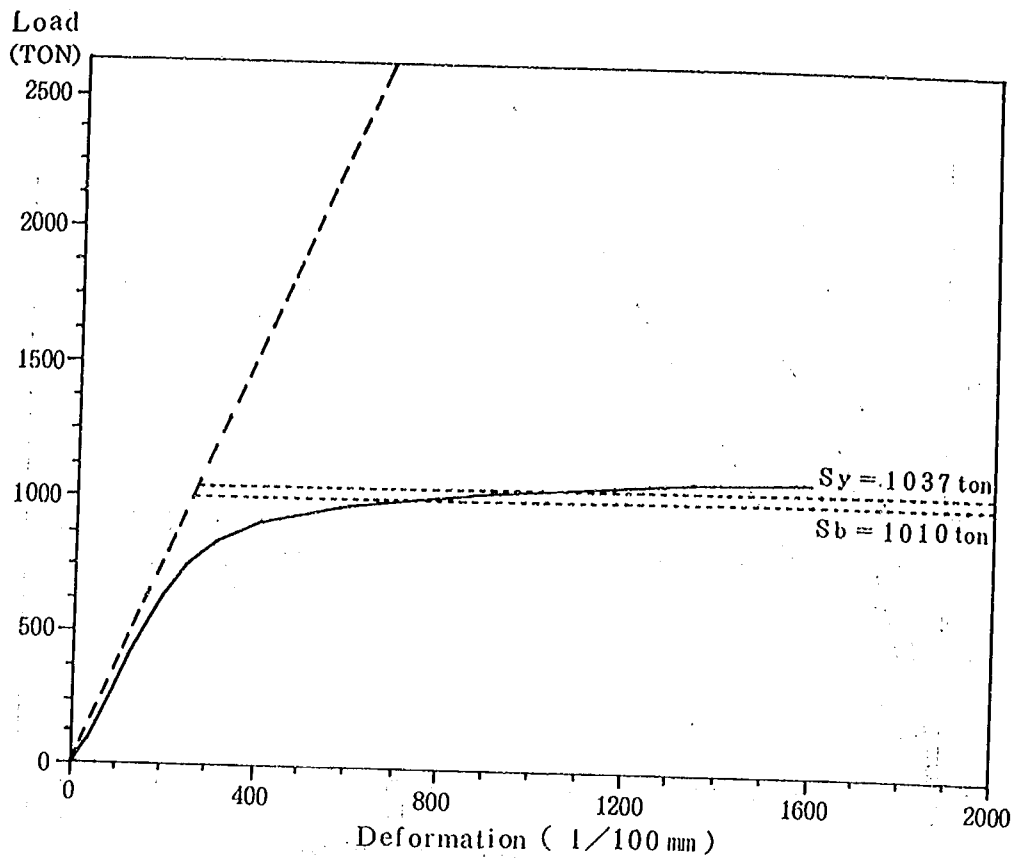


Fig. 11 Load - Deformation Curve (A - 4)

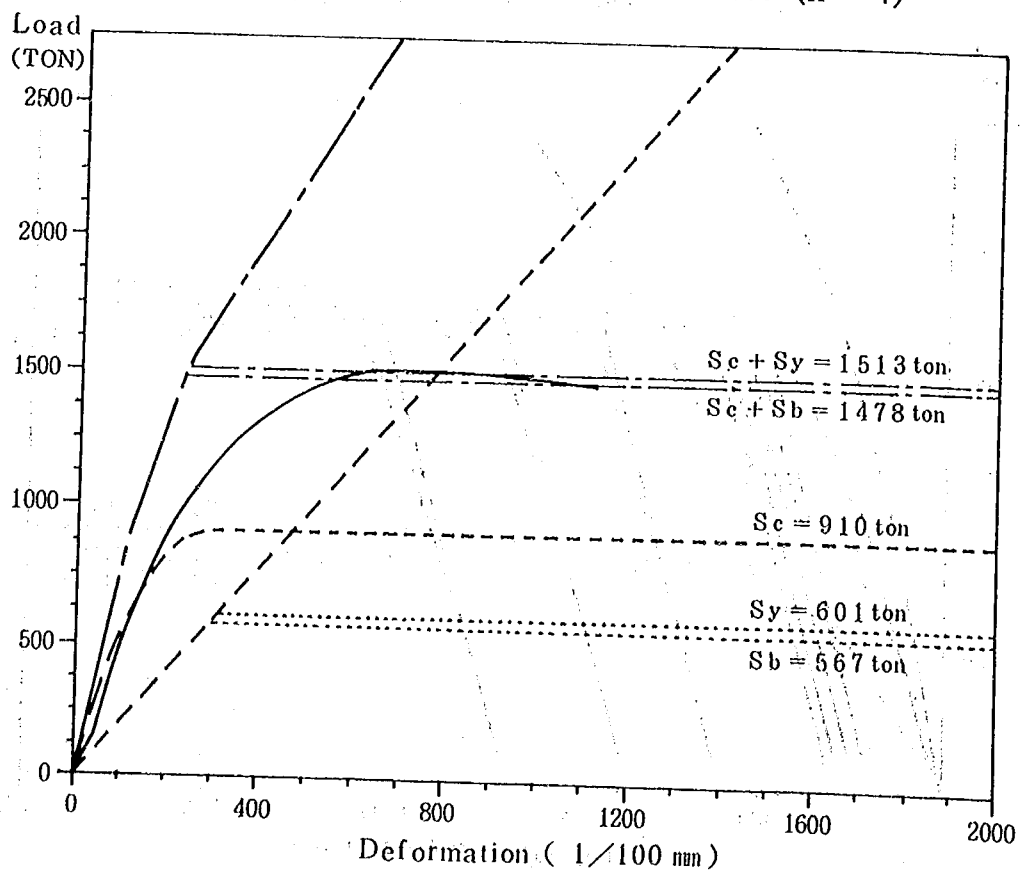


Fig. 12 Load - Deformation Curve (B - 1)

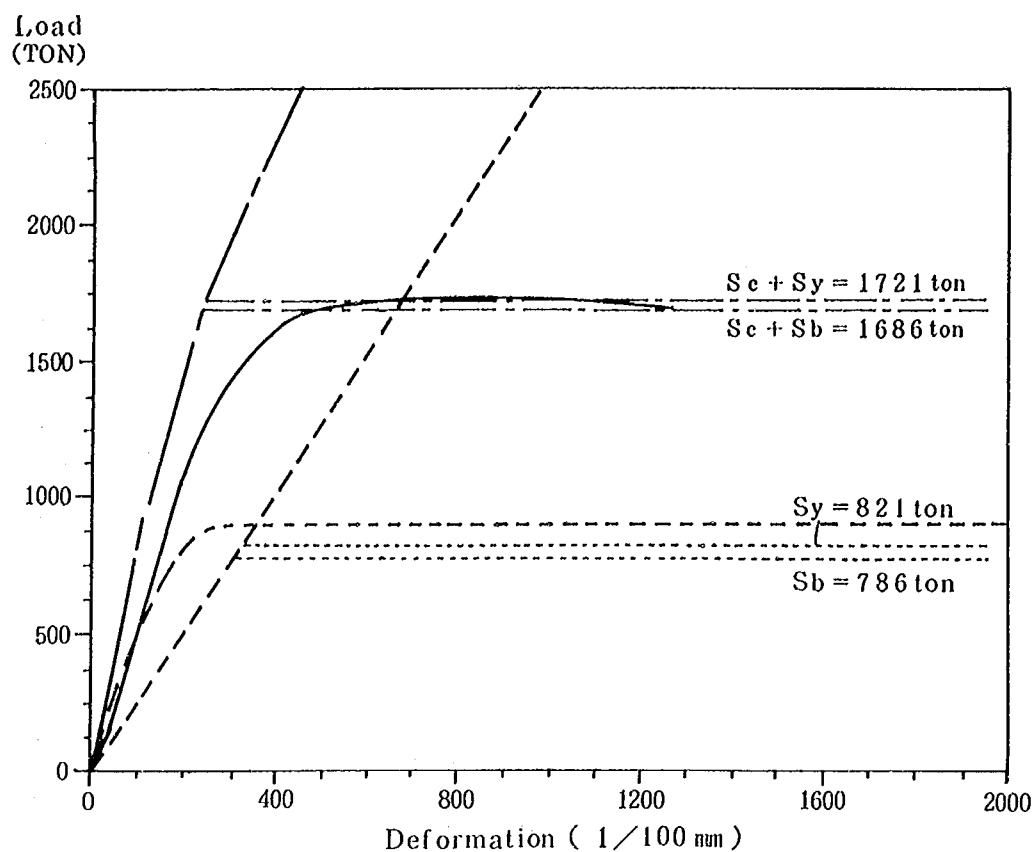


Fig. 13 Load - Deformation Curve (B - 2)

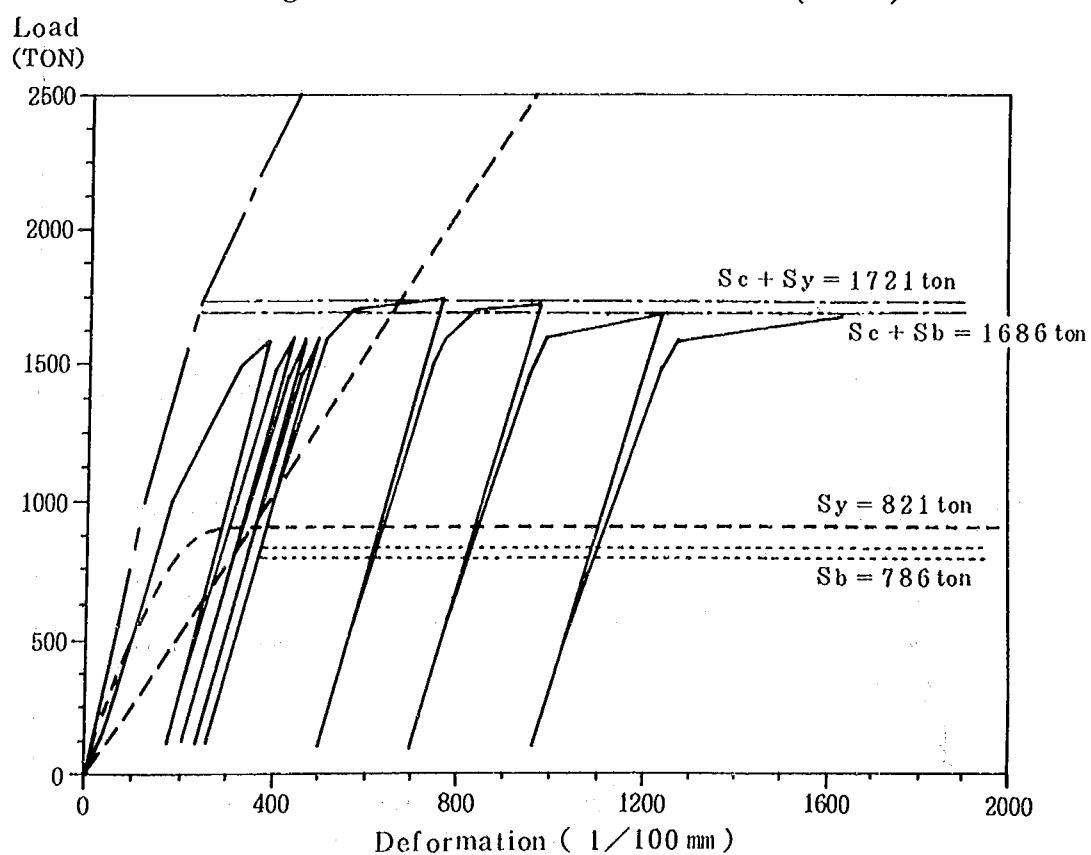


Fig. 14 Load - Deformation Curve (B - 3)

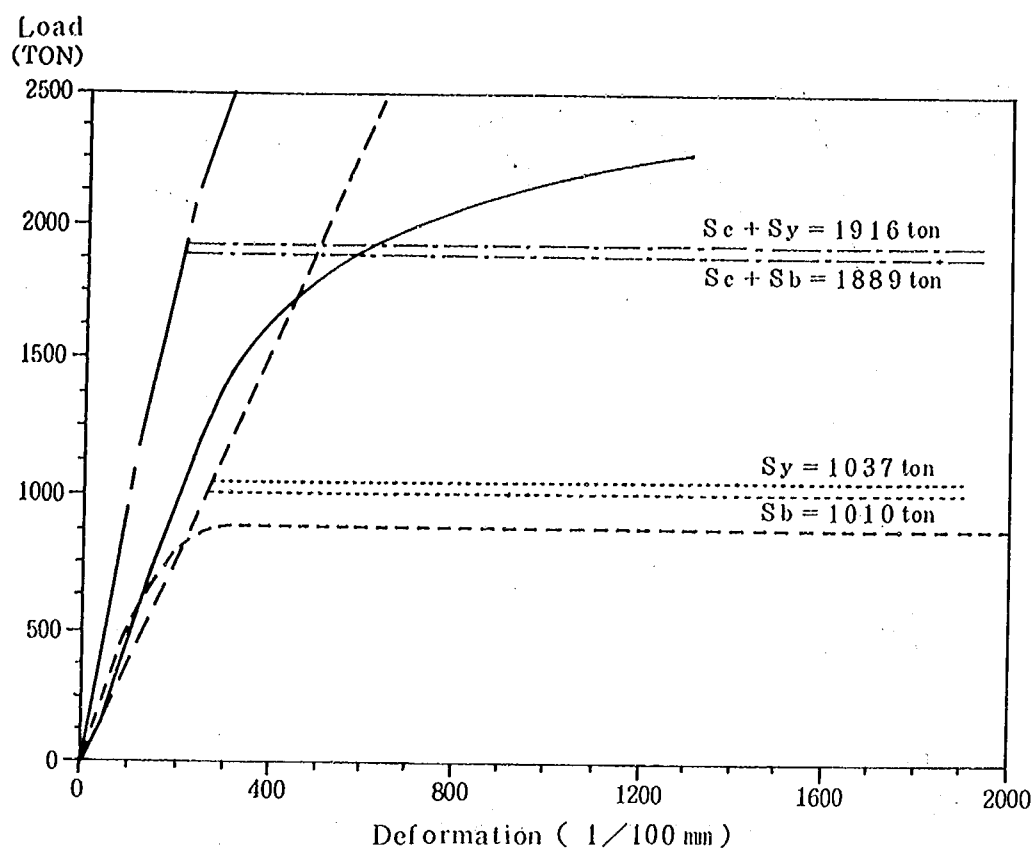


Fig. 15 Load - Deformation Curve (B - 4)

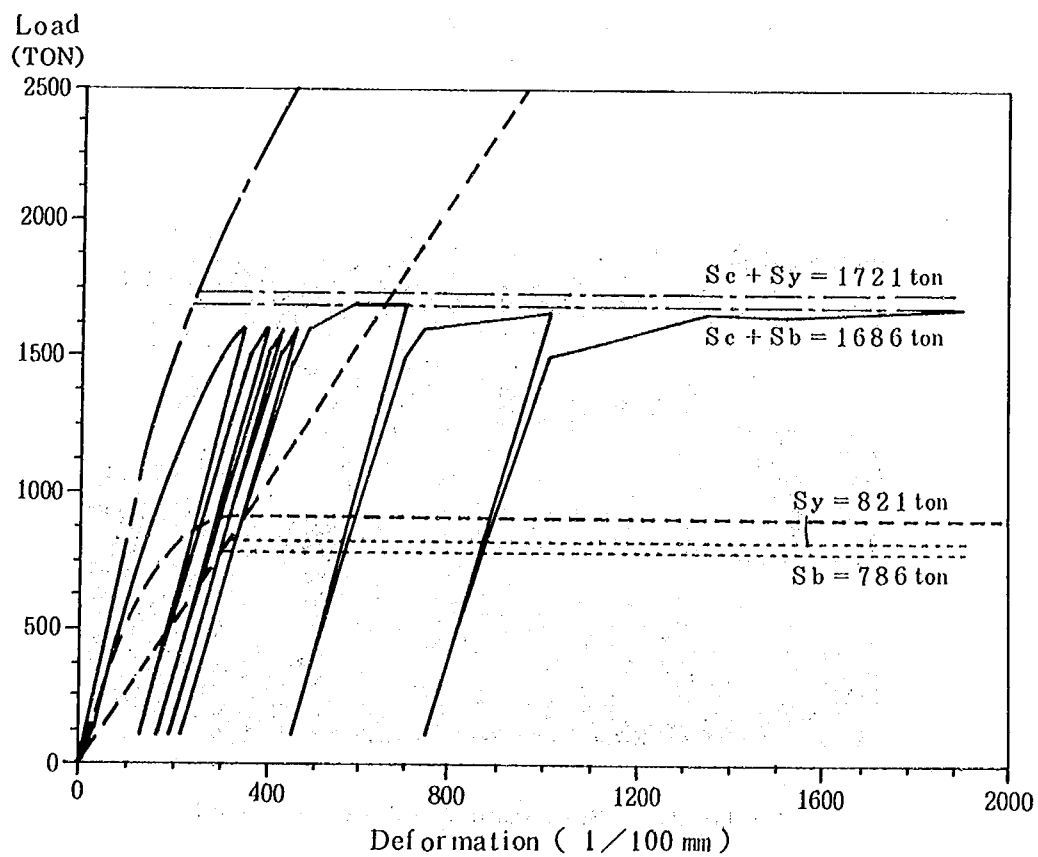


Fig. 16 Load - Deformation Curve (B - 5)

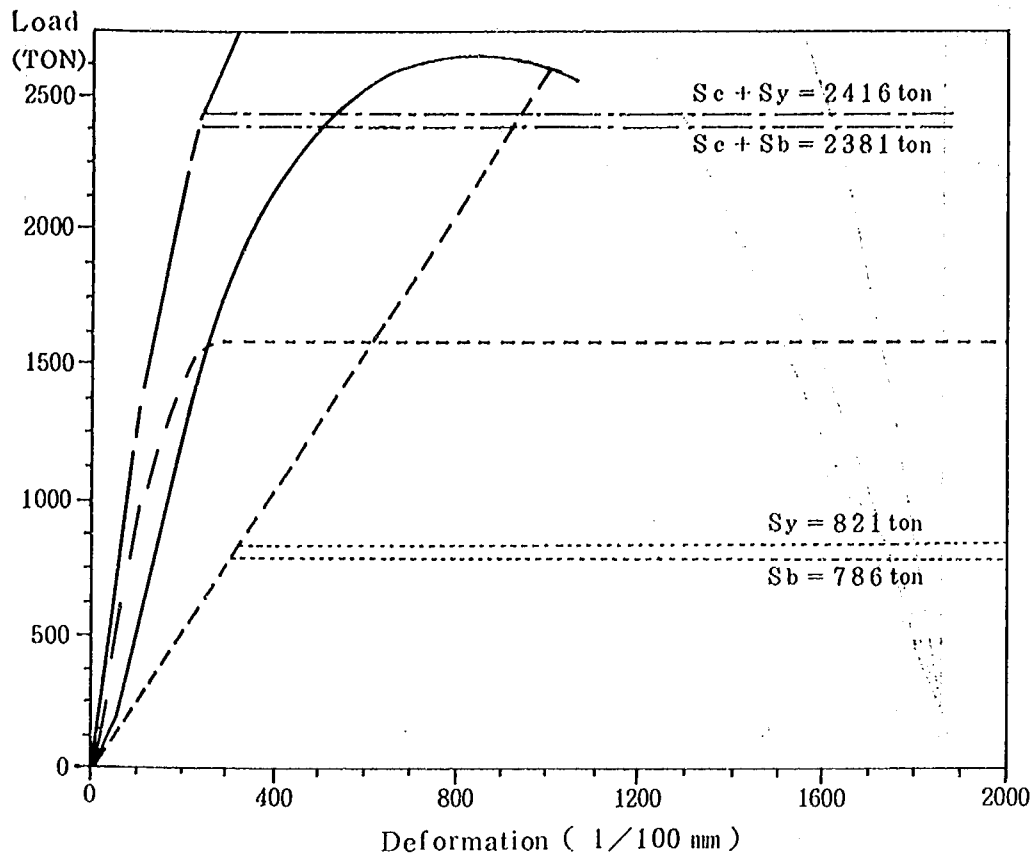


Fig. 17 Load - Deformation Curve (B - 6)



Photo-9. Specimen A - 2 After Loading

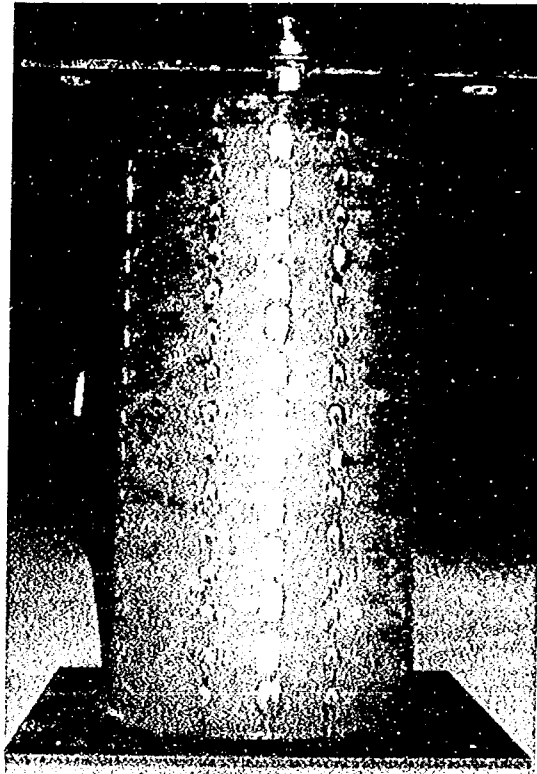


Photo-10. Specimen A - 4 After Loading

Photo 11 shows the B - 2 specimen after loading. Concrete-filled steel tubes are also subject to local buckling as shown in the photo, however, even in the plastic region the local buckling did not spread out, and the specimen did not lose the resistance. Photo 12 shows the B - 3 specimen which was loaded to large-deformation region. At that time, pipe diameter was widened significantly at the center due to the hoop tension force. But, it did not lose the resistance. Therefore, as far as hoop tension action is expected, concrete-filled steel tubes will keep their ductility.

In the previous section, it was described that high strength concrete was required to expect the resistance of Case 3. It depends on whether the concrete is broken or not. Photo 13 shows the concrete after loading, where no local buckling of the steel tube is observed. Photo 14 shows the concrete where local buckling is observed. In the Photo 14, the concrete is broken in small blocks. It is reasonable to conclude that, if the concrete is strong enough, the concrete will not be broken even

in the plastic region, and therefore, the resistance of Case 3 can be expected, while if the concrete is not strong enough, the concrete will be broken into small blocks in plastic region, and at that time, the resistance of Case 3 cannot be expected, the hoop tension not being enough. Actually, specimen B-6 did not yield any local buckling, and showed the resistance of Case 3 (Photo 15).

In the load-deformation curves shown in Fig. 12 to Fig. 17, the rigidity of the specimens are somewhat lower than the theoretical rigidity, where stress-strain curve of the concrete is supposed as follows.

$$\sigma = \sigma_{ck} \frac{\epsilon}{0.002} \left(2 - \frac{\epsilon}{0.002} \right) \quad 0 \leq \epsilon \leq 0.002 \quad \dots (2)$$

In the equation, the ratio of the modulus of elasticity is 8.5 at $\epsilon = 0$, which may be reasonable for the concrete.

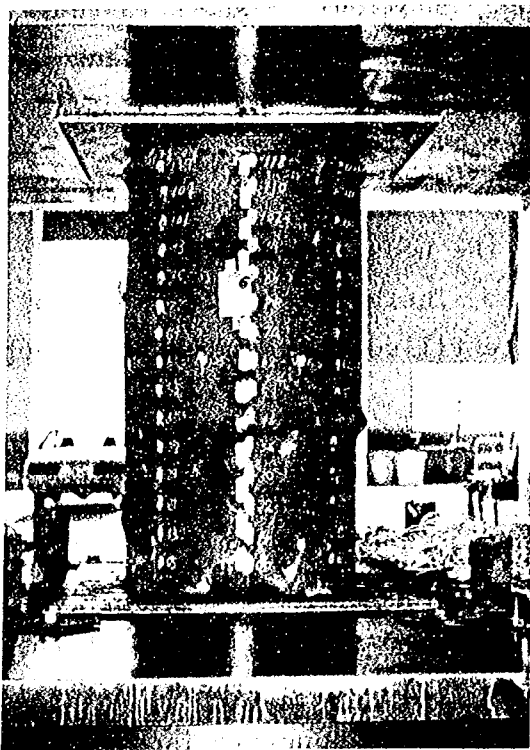


Photo-11.
Specimen B-2 After Loading

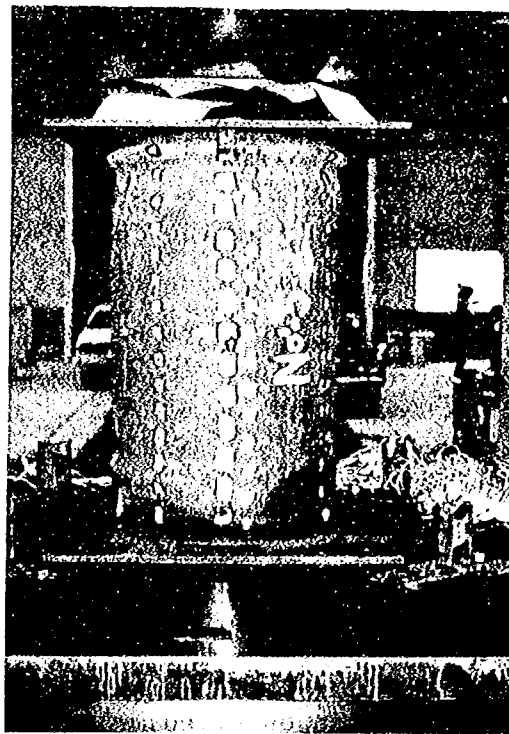


Photo-12.
Specimen B-3 After Loading



Photo-13.
Concrete After Loading

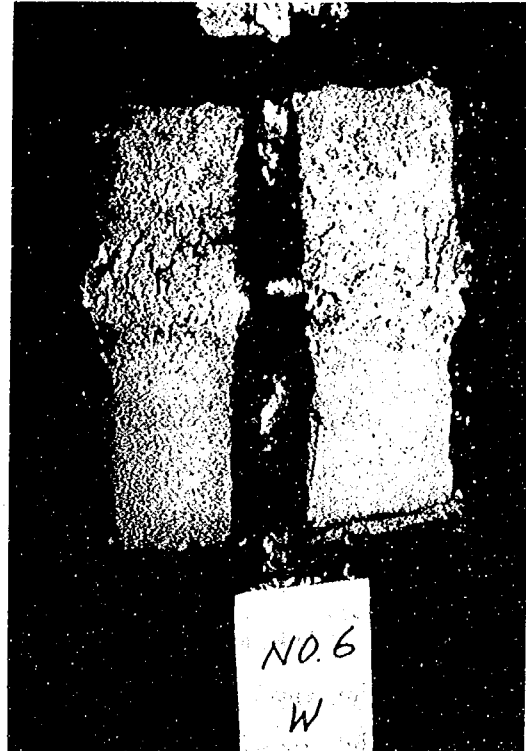


Photo-14.
Concrete After Loading

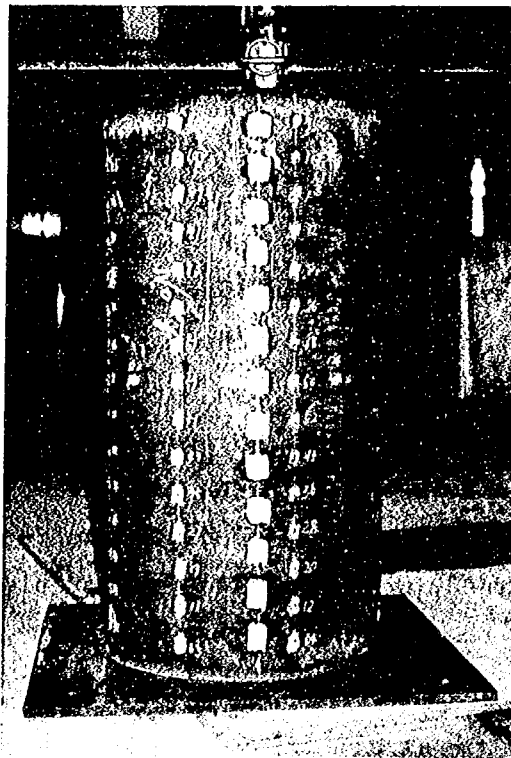


Photo-15. Speimen B - 6 After Loading

The followings can be considered to explain the above.

1. The residual stresses due to the studs may bring about lower rigidity. Actually, specimen B-5, which has no stud, shows pretty high rigidity.
2. It is reported that the quality of the concrete cast and cured in the airtight condition in a pipe is not so good. Therefore, the rigidity of the concrete itself might have been lower than expected.

4.3 Behavior of longitudinal strain

Fig. 18 to Fig. 27 shows the behavior of the longitudinal strains of the specimens. All the strain were measured at the surface of the steel tubes. The figures shows the strains where local buckling was observed. Therefore, local buckling behavior can be observed from the figures.

Fig. 18 to Fig. 20 show that the local buckling of the specimens is pretty elastic, because they are thin plate steel tubes, while Fig. 21 shows that A-4 specimen did not yield local buckling and showed only elasto-plastic behavior.

Fig. 22 to Fig. 27 shows a little disturbance of the strains which may be caused by residual stresses due to studs. They also show that the rigidity of the specimens is somewhat lower than the theoretical values, which was described in the previous section. But, besides these, no special problem can be observed. The residual stresses due to studs may cause fatigue problems if subjected to highly cyclic loadings, but as far as bridge piers are concerned, we can neglect the problem.

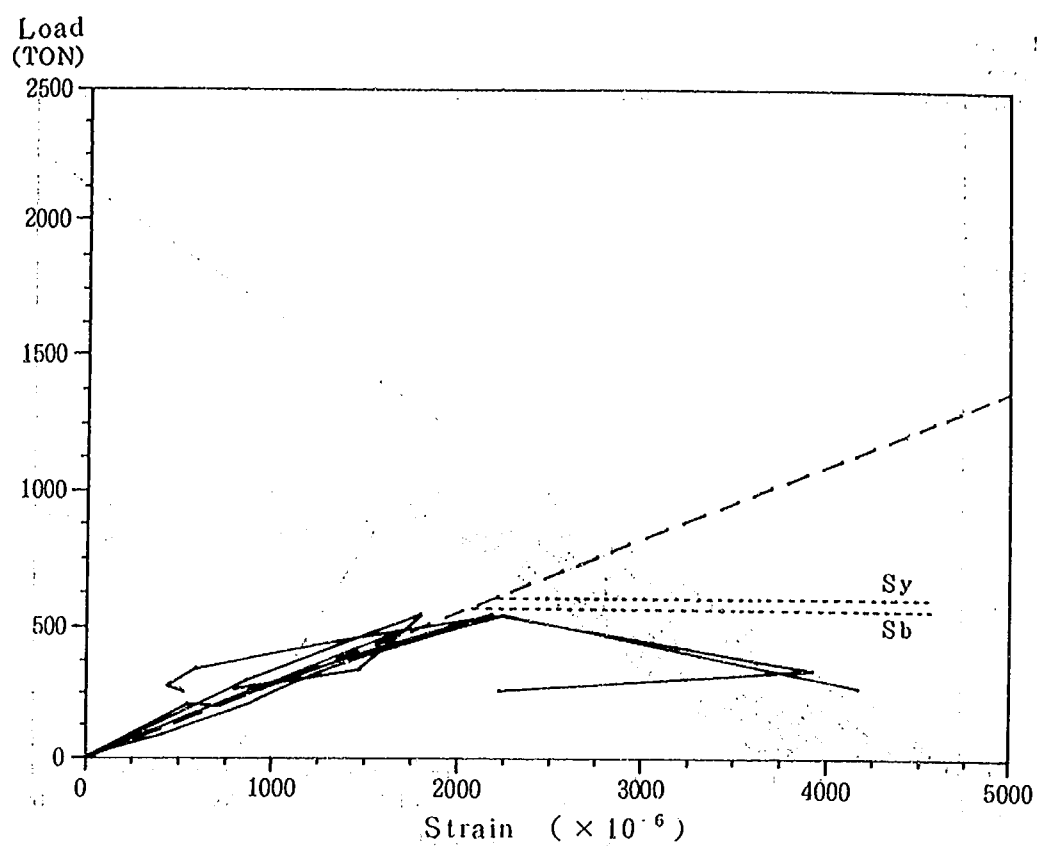


Fig. 18 Load - Strain Curve (A - 1)

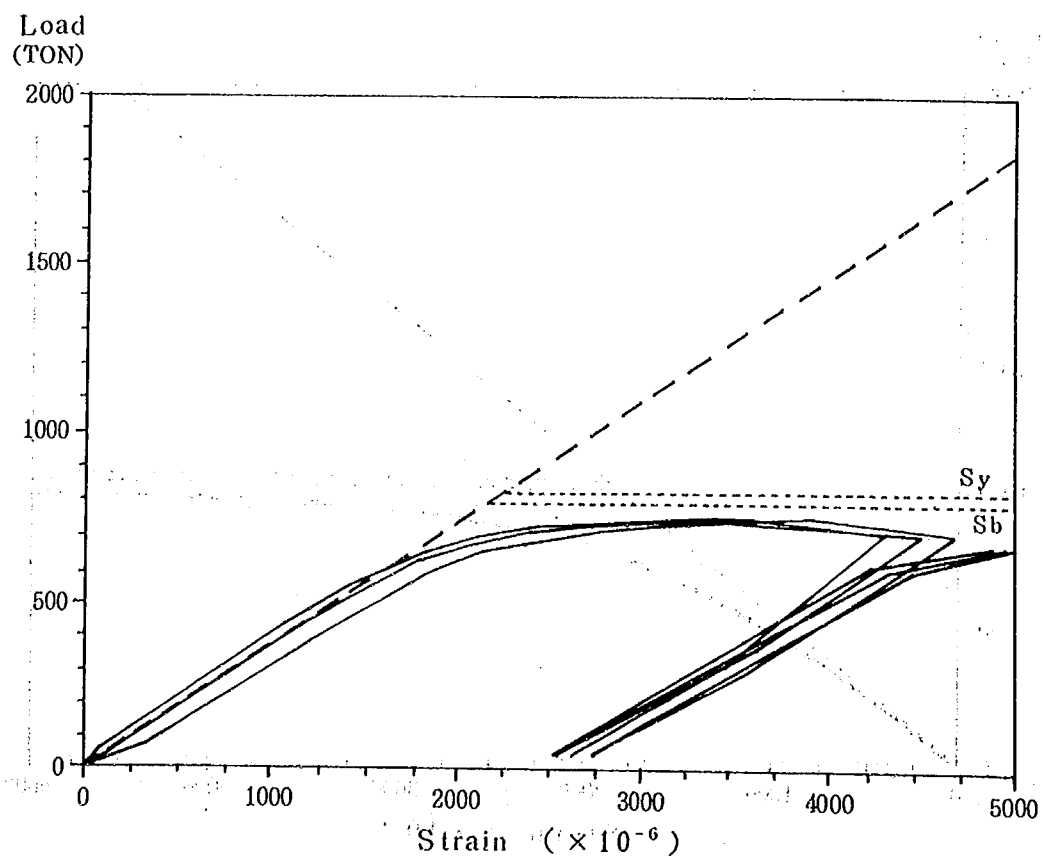


Fig. 19 Load - Strain Curve (A - 2)

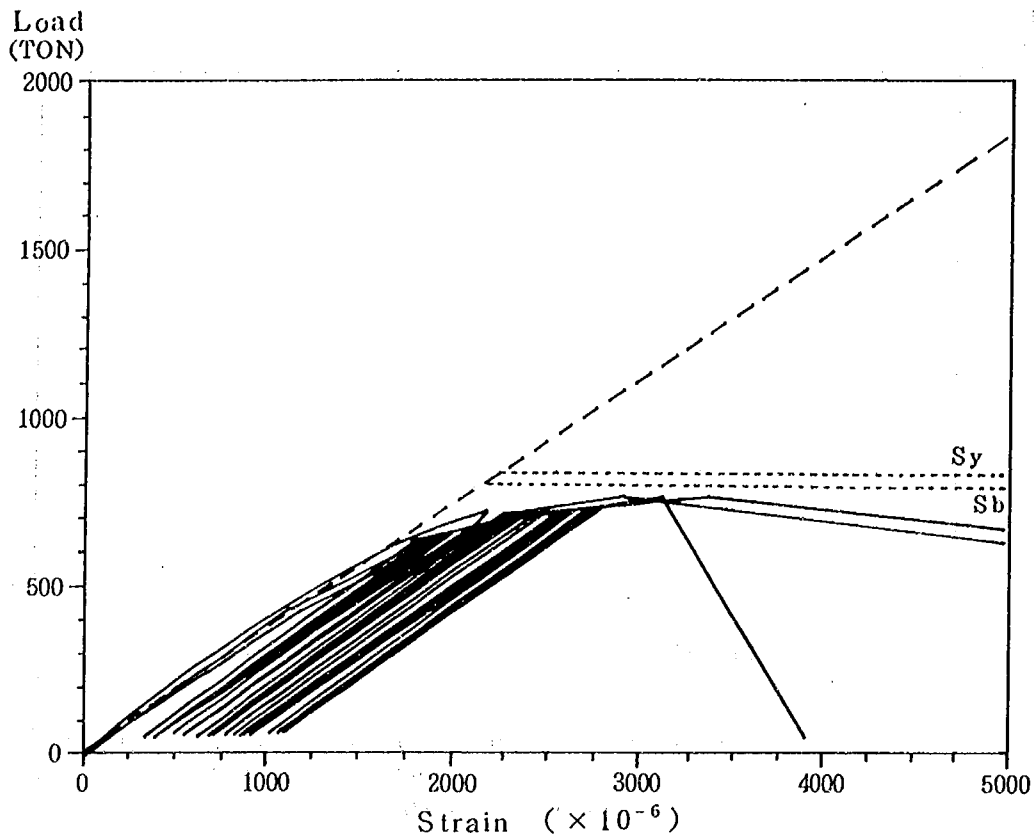


Fig. 20 Load - Strain Curve (A - 3)

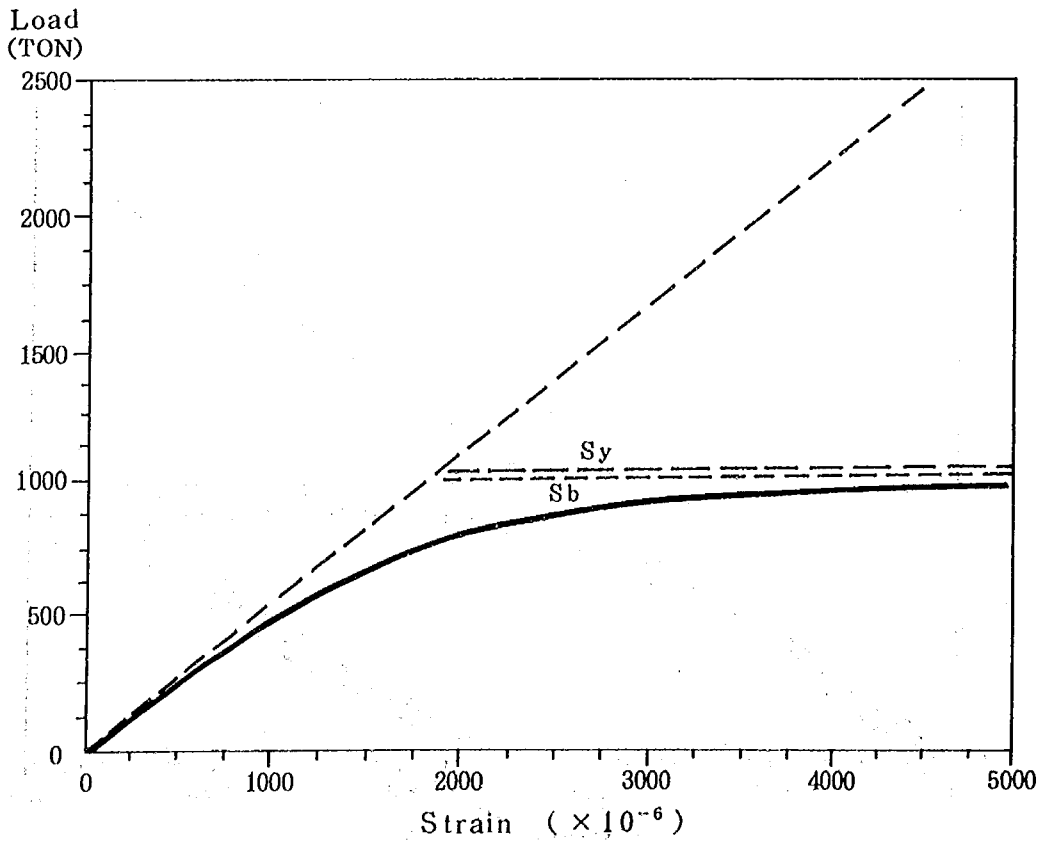


Fig. 21 Load - Strain Curve (A - 4)

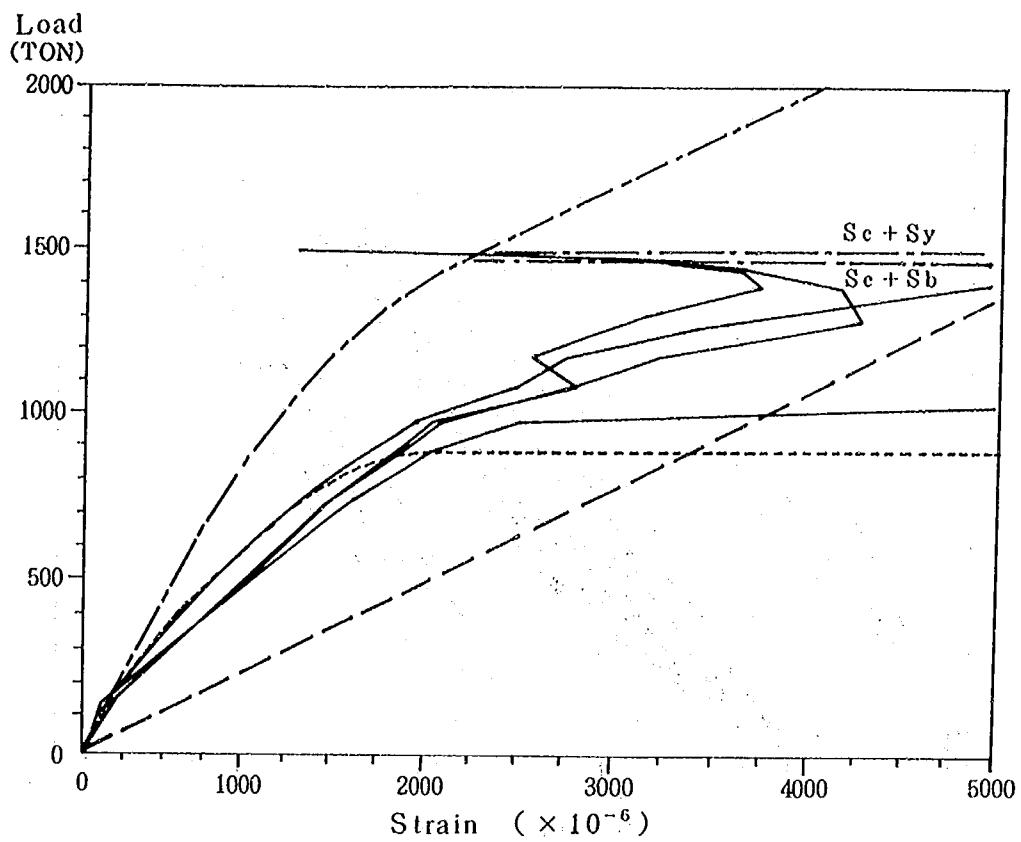


Fig. 22 Load - Strain Curve (B - 1)

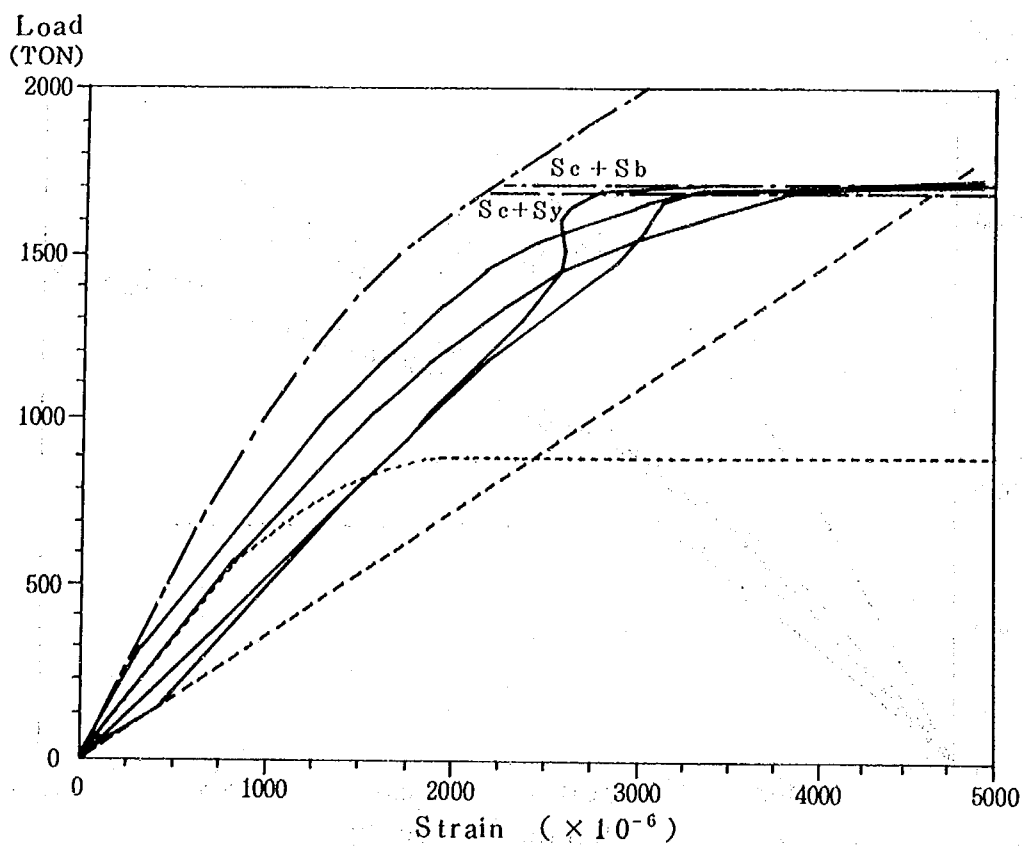


Fig. 23 Load - Strain Curve (B - 2)

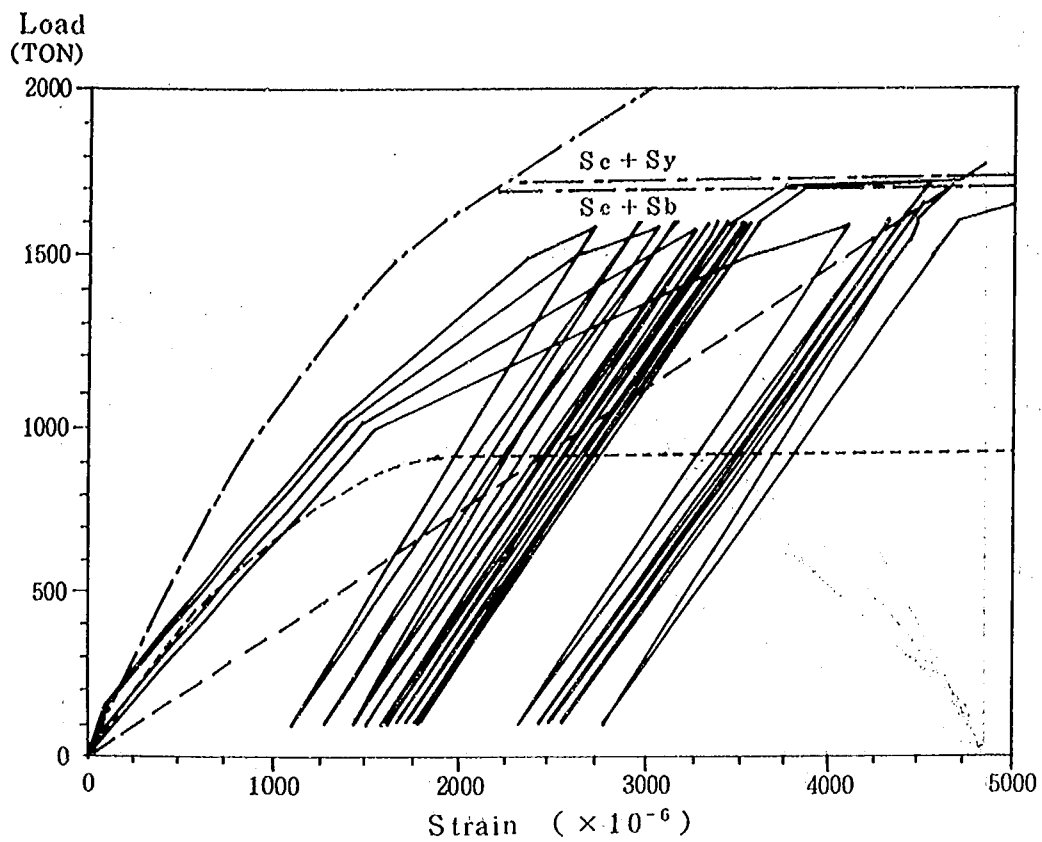


Fig. 24 Load - Strain Curve (B - 3)

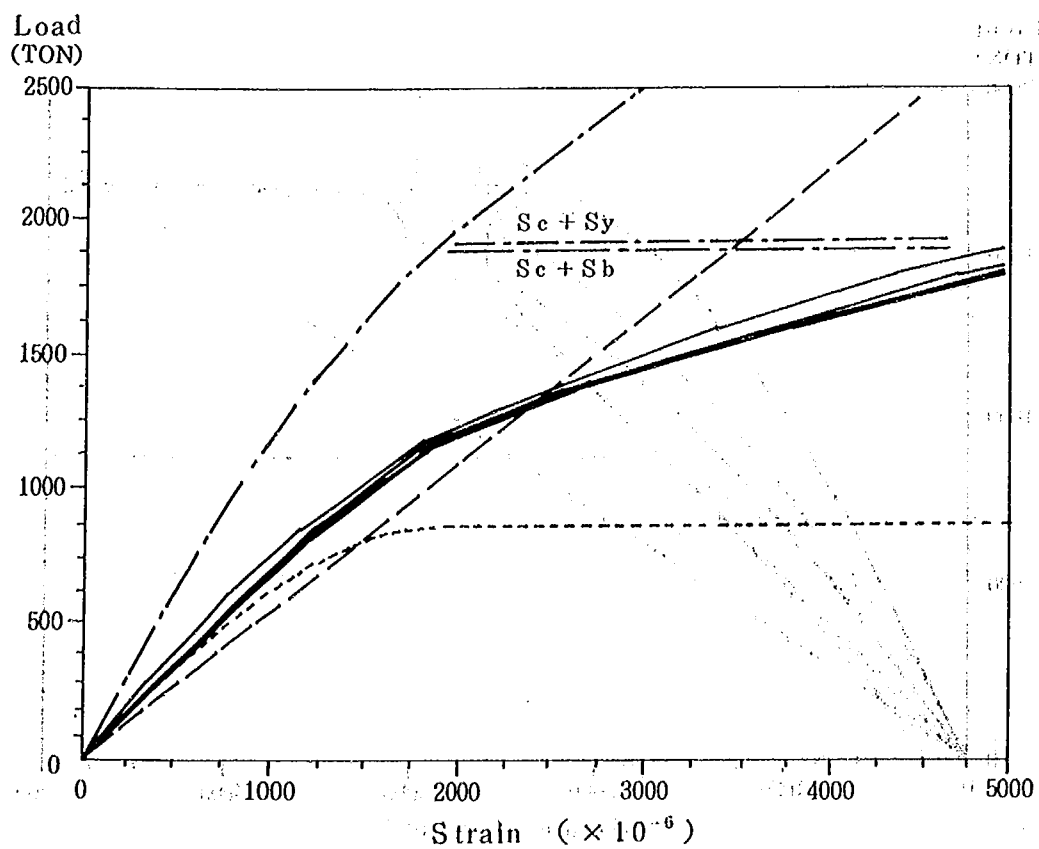


Fig. 25 Load - Strain Curve (B - 4)

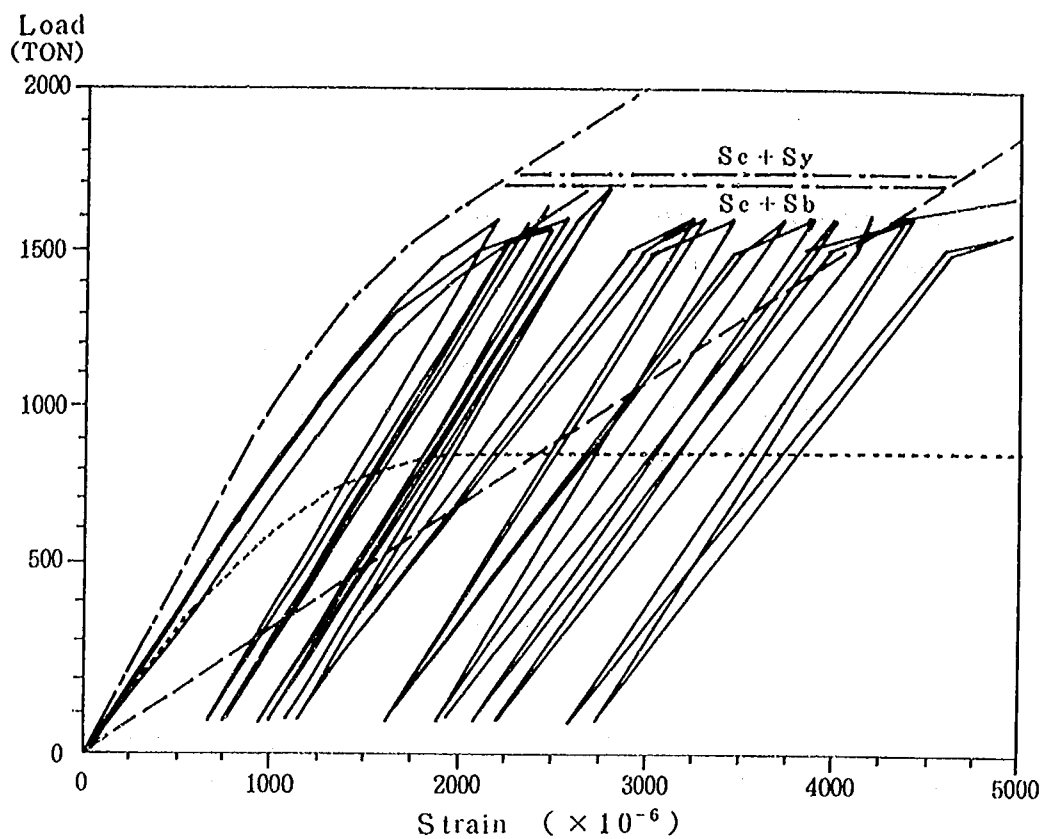


Fig. 26 Load - Strain Curve (B - 5)

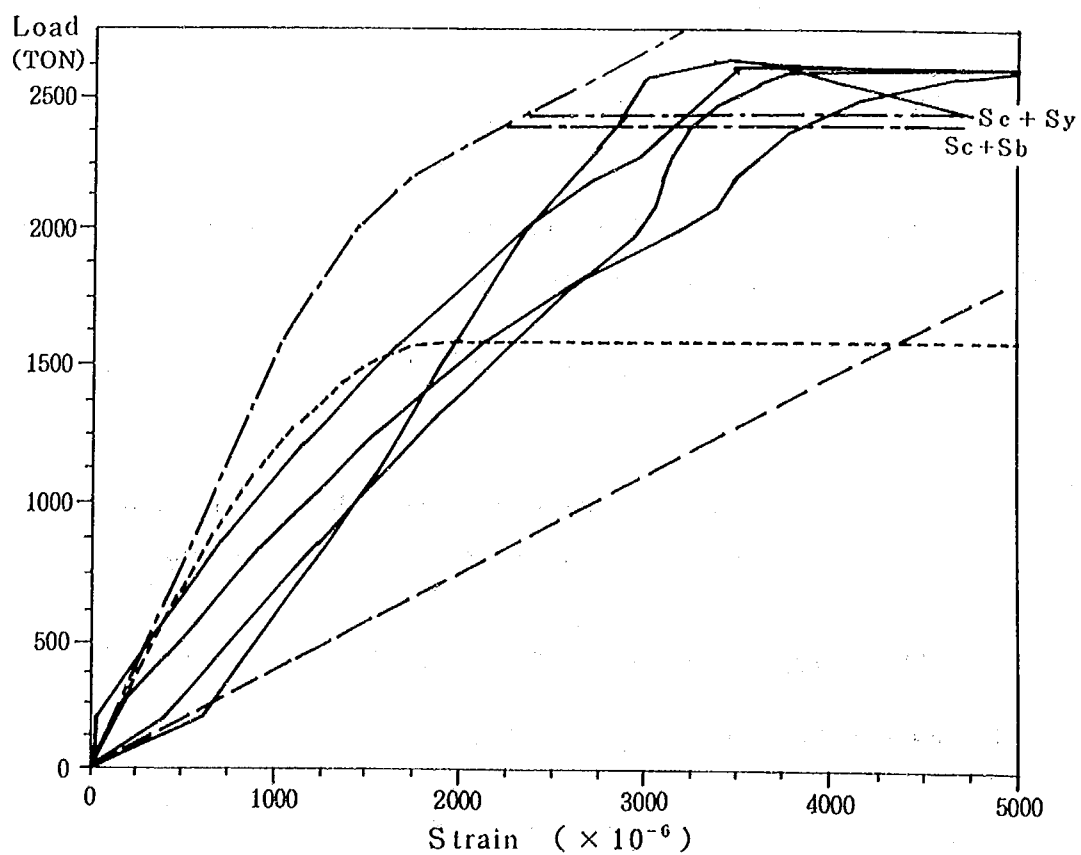


Fig. 27 Load - Strain Curve (B - 6)

4.4 Behavior of hoop strain

As described in Chapter 2, the concrete and the steel tube of a concrete-filled steel tube will separate from each other in elastic region. Regarding the problem, the following theoretical solution can be obtained.

First, when the steel and the concrete behave independently, the hoop strains of the steel tube and the concrete is expressed by the following formulas.

$$\epsilon_{hs} = -\nu_s \cdot \epsilon_x \quad \dots\dots\dots (3)$$

$$\epsilon_{hc} = -\nu_c \cdot \epsilon_x \quad \dots\dots\dots (4)$$

where, ϵ_x means longitudinal strain, and ν_s and ν_c means the Poisson's ratio of the steel and concrete respectively.

When they are connected together by the bond stress σ_{co} , the hoop strain of the steel is expressed by the followings (fig. 28).

$$\epsilon_{hs} = -\left(\nu_s \epsilon_x + \frac{\sigma_{co} \cdot R}{E_s \cdot t} \right) \quad \dots\dots\dots (5)$$

where, R and t is the radius and the thickness of the steel tube. The hoop strain of the concrete is

$$\epsilon_{hc} = -\left(\nu_c \epsilon_x - \frac{(1 - \nu_c) \sigma_{co}}{E_c} \right) \quad \dots\dots\dots (6)$$

If the concrete and the steel behave together, ϵ_{hs} must be equal to ϵ_{hc} . Therefore, σ_{co} can be expressed as follows.

$$\sigma_{co} = \frac{\nu_c - \nu_s}{[(R/t)/E_s + (1 - \nu_c)/E_c]} \epsilon_x \quad \dots\dots\dots (7)$$

and ϵ_{hs} can be expressed as

$$\epsilon_{hs} = -\epsilon_x \left(\nu_s - \frac{\nu_s - \nu_c}{[1 + (1 - \nu_c) \frac{t \cdot E_s}{R \cdot E_c}]} \right) \dots\dots\dots (8)$$

Now, to examine the behavior of the concrete-filled steel tubes, Where the maximum resistance is attained, let's assume that $E_s/E_c = 15.0$. Assuming that $\sigma_y = 4000 \text{ kg/cm}^2$, the required bond stress is expressed as follows.

$$\sigma_{co} = \frac{533}{R/t + 12.5} \text{ (kg/cm}^2\text{)} \dots\dots\dots (9)$$

and the hoop stain is expressed as follows, assuming that $E_s/E_c = 7.0$ in this case

$$\epsilon_{hs} = \left(0.3 - \frac{2}{15[1 + 5.83(t/R)]} \right) \epsilon_x \dots\dots\dots (10)$$

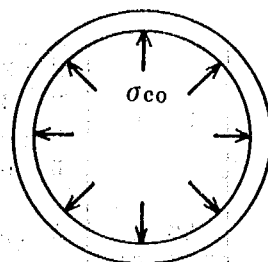
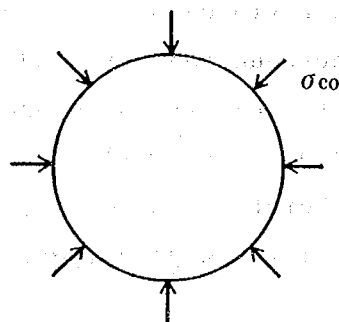


Fig. 28 Bond Stress

If the concrete and the steel behave independently, the hoop strain will be expressed by equ.(3), and if they behave together, the hoop strain will be expressed by equ.(10), the required bond stress being expressed by equ.(9).

When the bond is kept, the Poisson's ratio of the specimen is not 0.3, but $\left(0.3 - \frac{2}{15 [1 + 5.83 (R/t)]} \right)$.

So, let's call this as modified Poisson's ratio. In Table 6, the bond stress σ_{co} and the modified Poisson's ratio is listed.

Fig. 29 to Fig. 38 show the behavior of hoop strains. In the figures, the theoretical curves obtained from equ.(3) and equ.(10) are also shown. The hoop strains of the specimens A-1 to A-4 are just same as the theoretical curves. The hoop strains of the specimen B-1 to B-4 and B-6 are same as the theoretical values, obtained from modified Poisson's ratio, however; the hoop strains of the specimen B-5 is rather like the theoretical values, obtained from Poisson's ratio of 0.3. Therefore, it is concluded that the natural bond between concrete and steel is not enough to connect them together, and without studs, the concrete and the steel will behave independently, while they will behave together with adequate studs. Therefore, studs may be required to design the concrete-filled steel tubes as composite structures.

Table 6. Modified Poisson's Ratio
of the Specimens

Specimen	B - 1	B - 2 B - 3 B - 5 B - 6	B - 4
R/t	58.3	43.8	29.9
σ_{co} (kg/cm ²)	7.5	9.5	12.8
Modified Poisson's Ratio	0.179	0.182	0.189

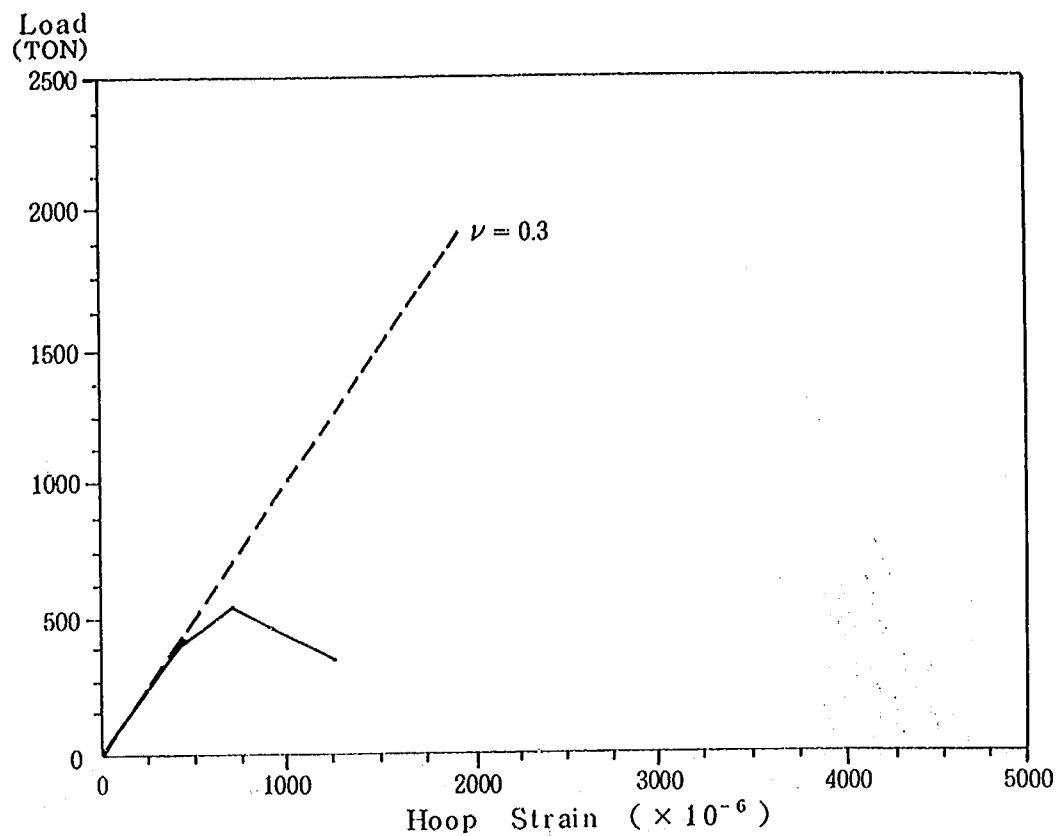


Fig. 29 Load - Hoop Strain Curve (A - 1)

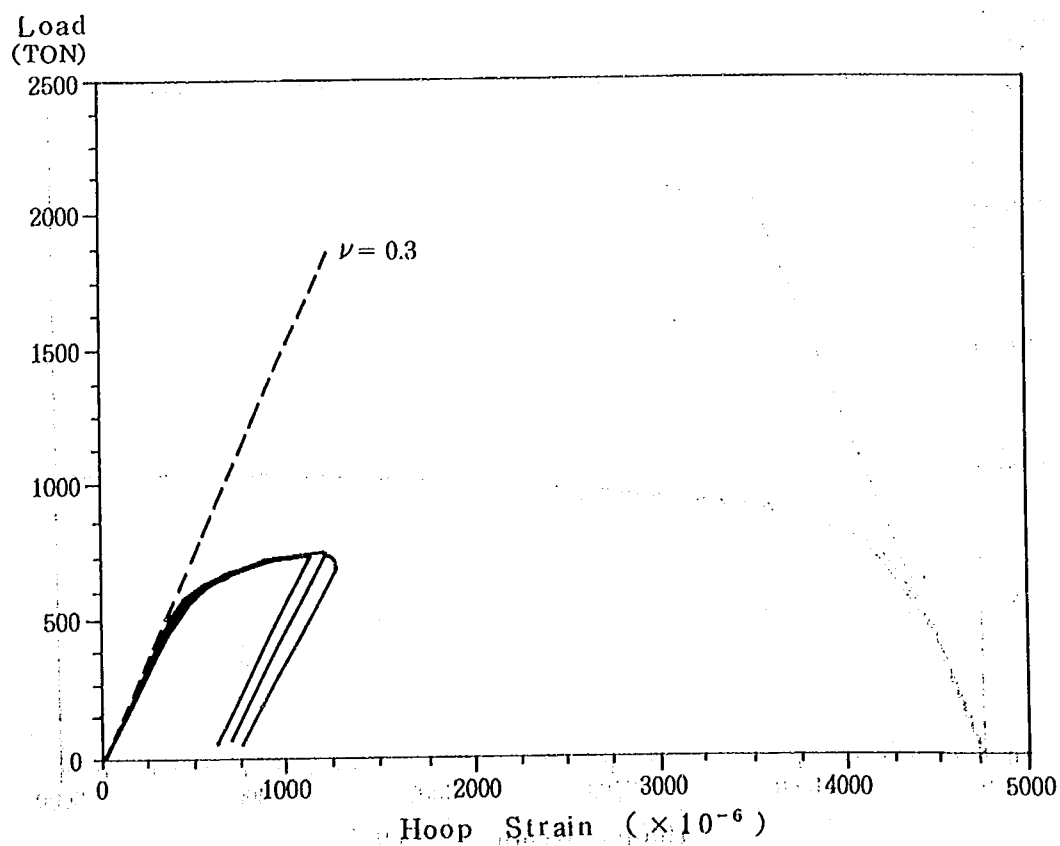


Fig. 30 Load - Hoop Strain Curve (A - 2)

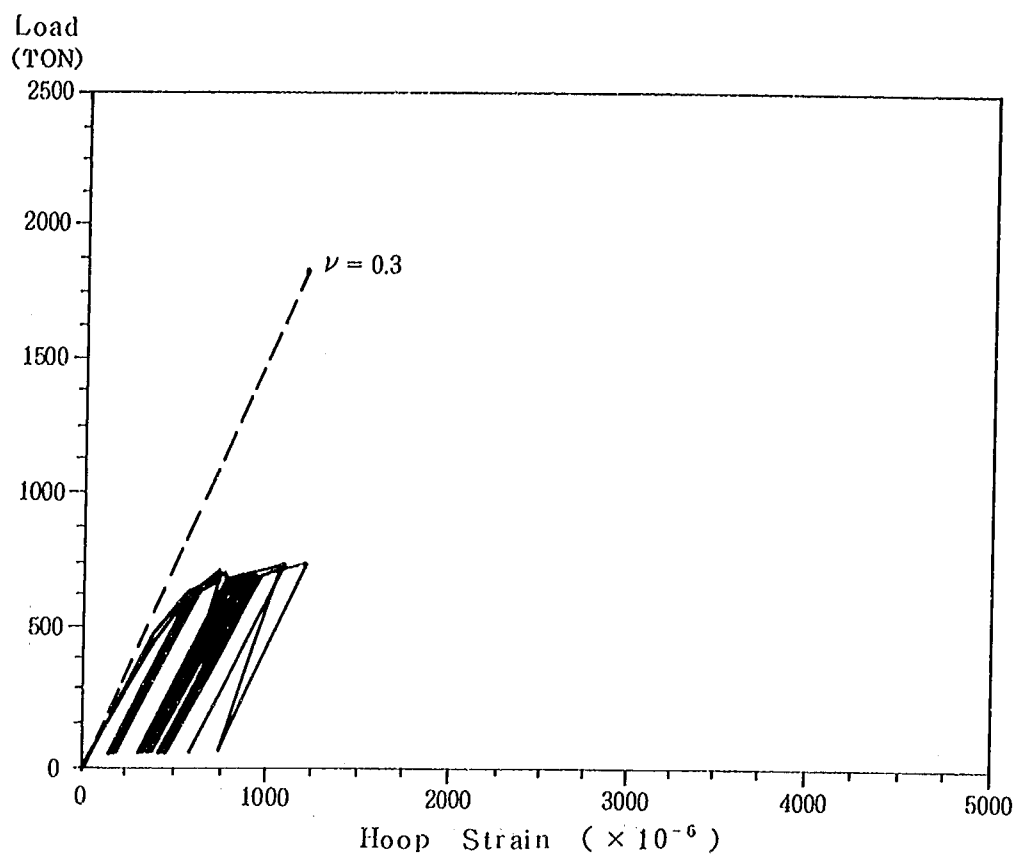


Fig. 31 Load - Hoop Strain Curve (A - 3)

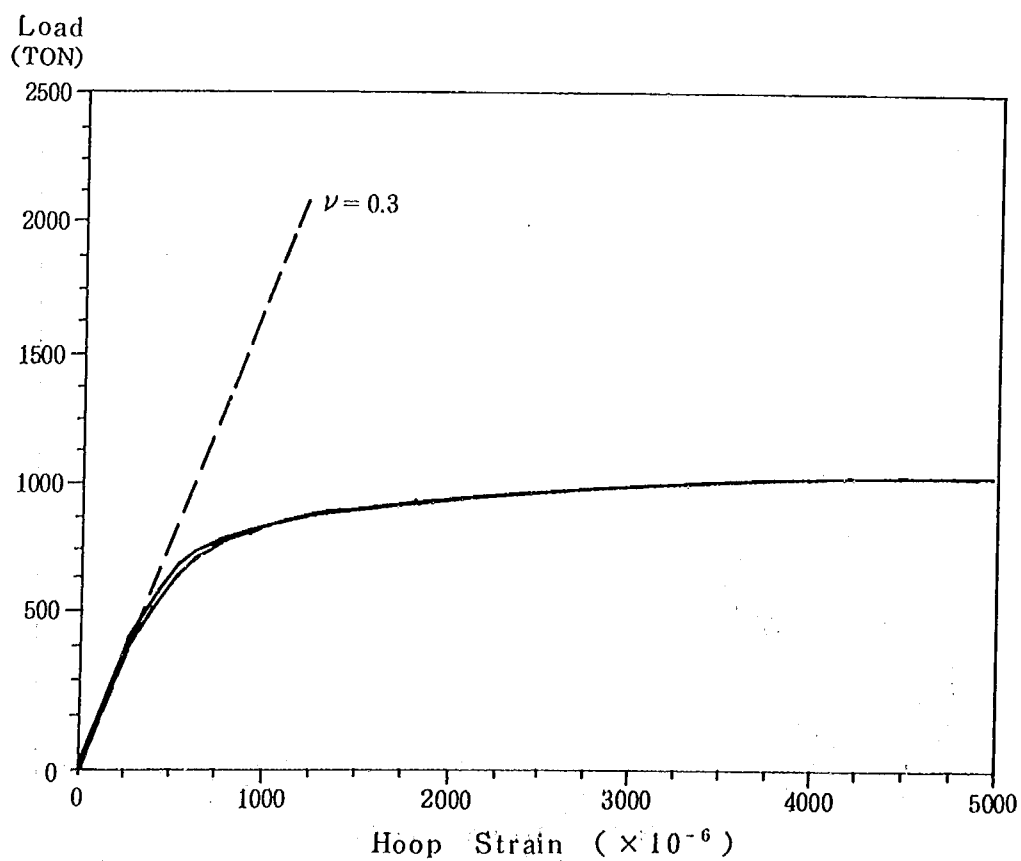


Fig. 32 Load - Hoop Strain Curve (A - 4)

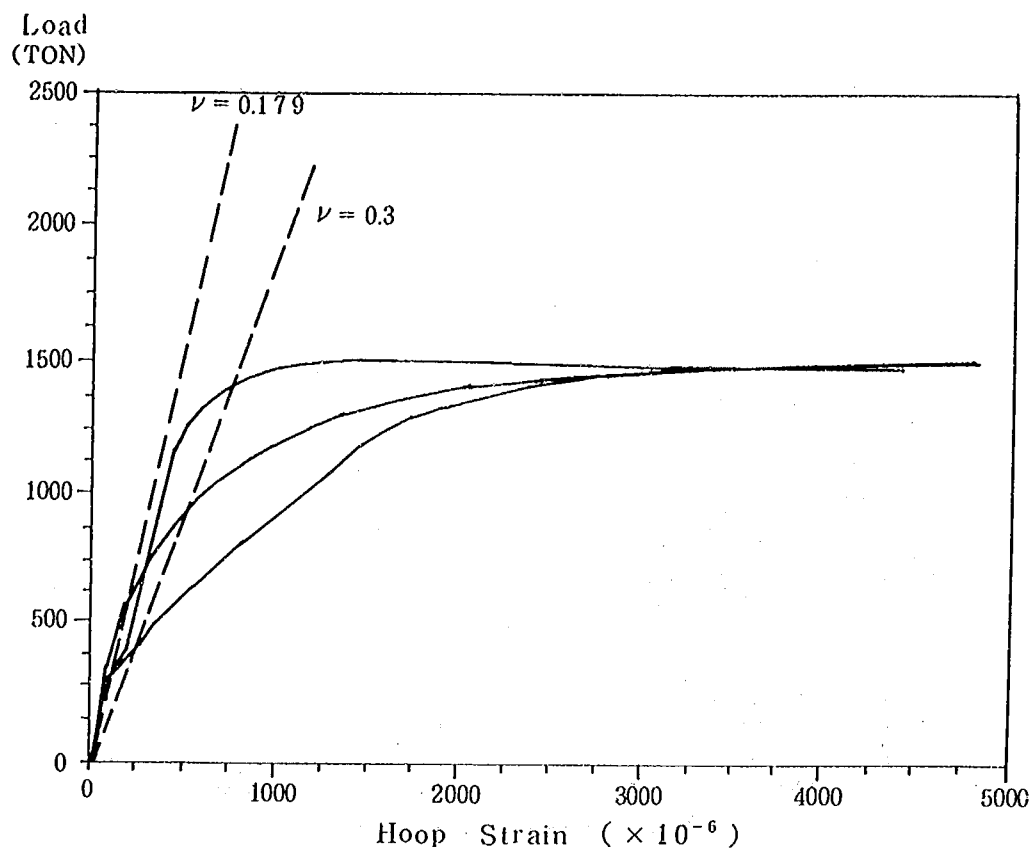


Fig. 33 Load-Hoop Strain Curve (B - 1)

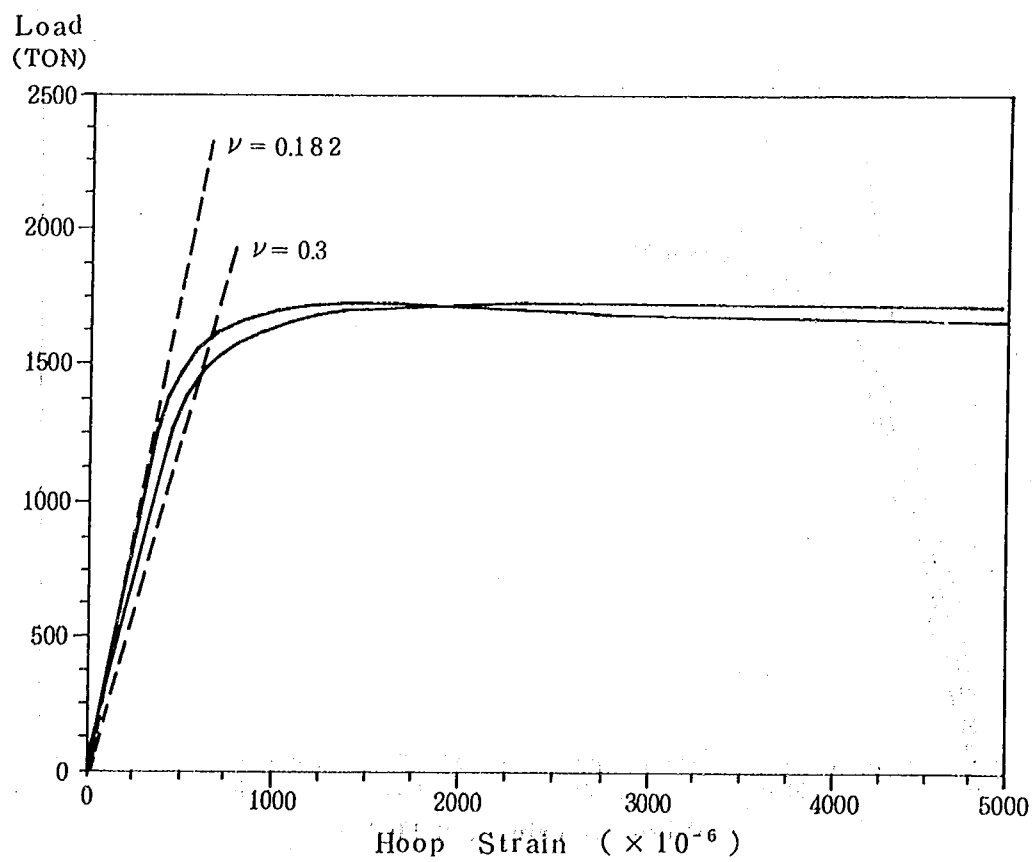


Fig. 34 Load-Hoop Strain Curve (B - 2)

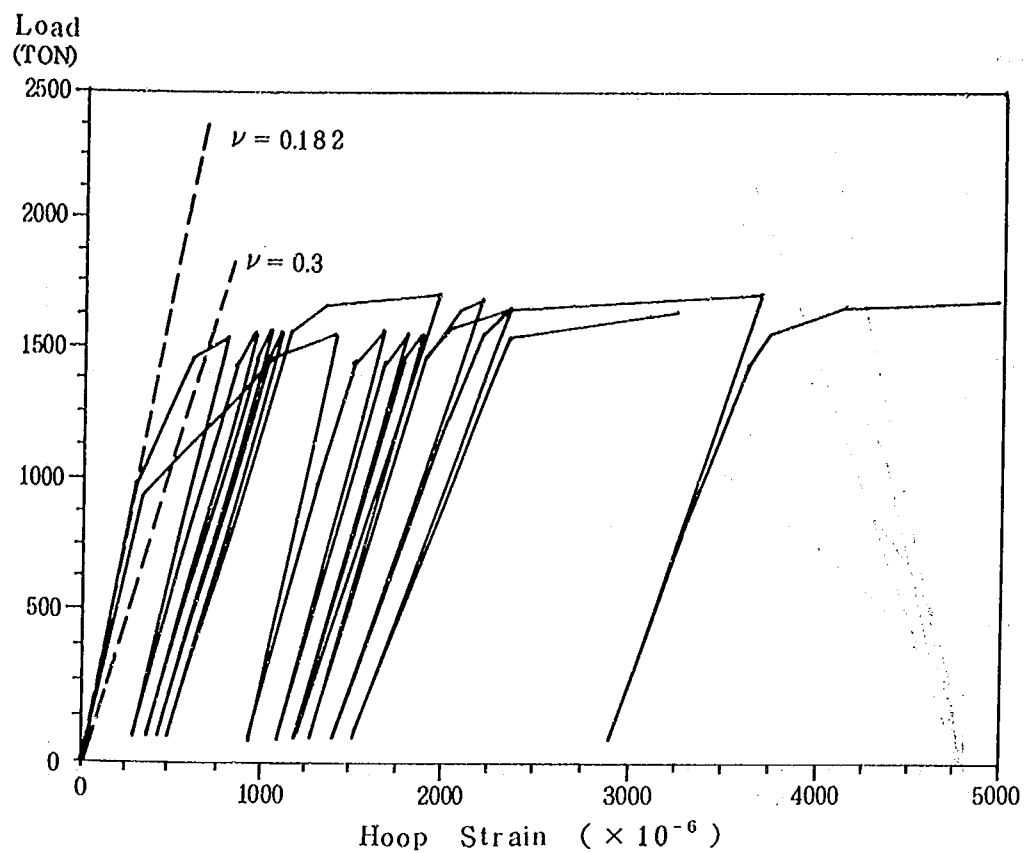


Fig. 35 Load - Hoop Strain Curve (B - 3)

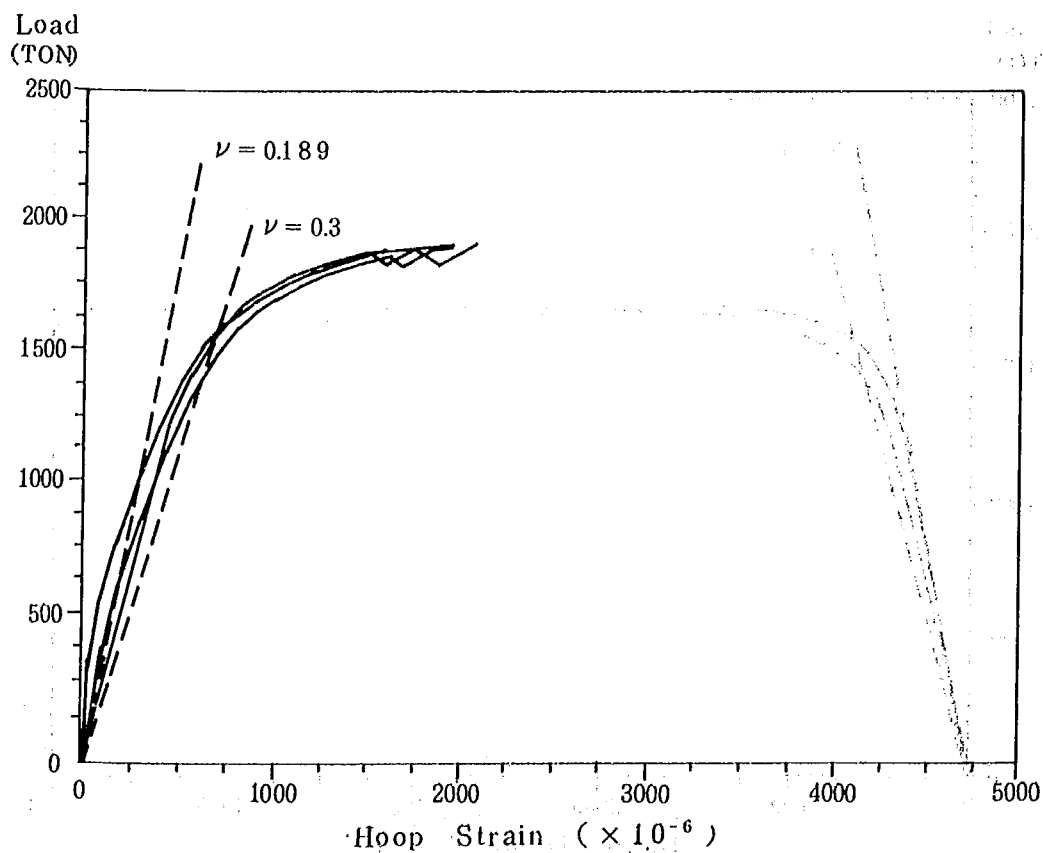


Fig. 36 Load - Hoop Strain Curve (B - 4)

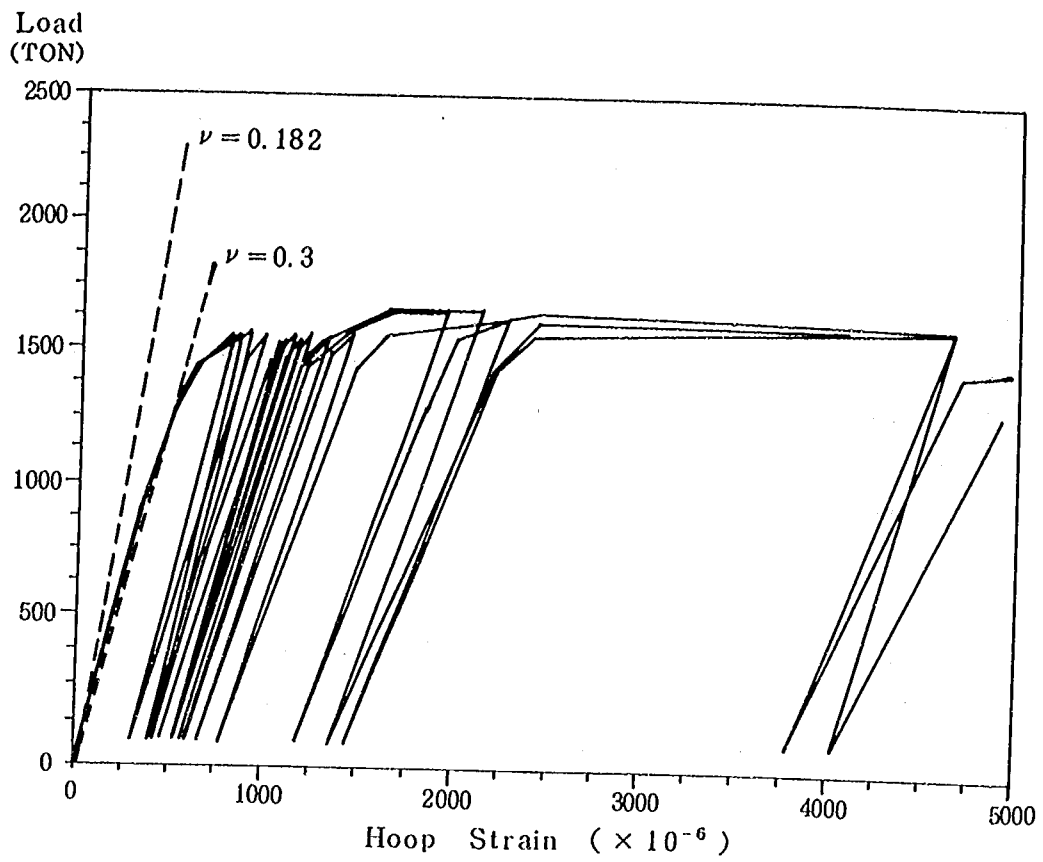


Fig. 37 Load - Hoop Strain Curve (B - 5)

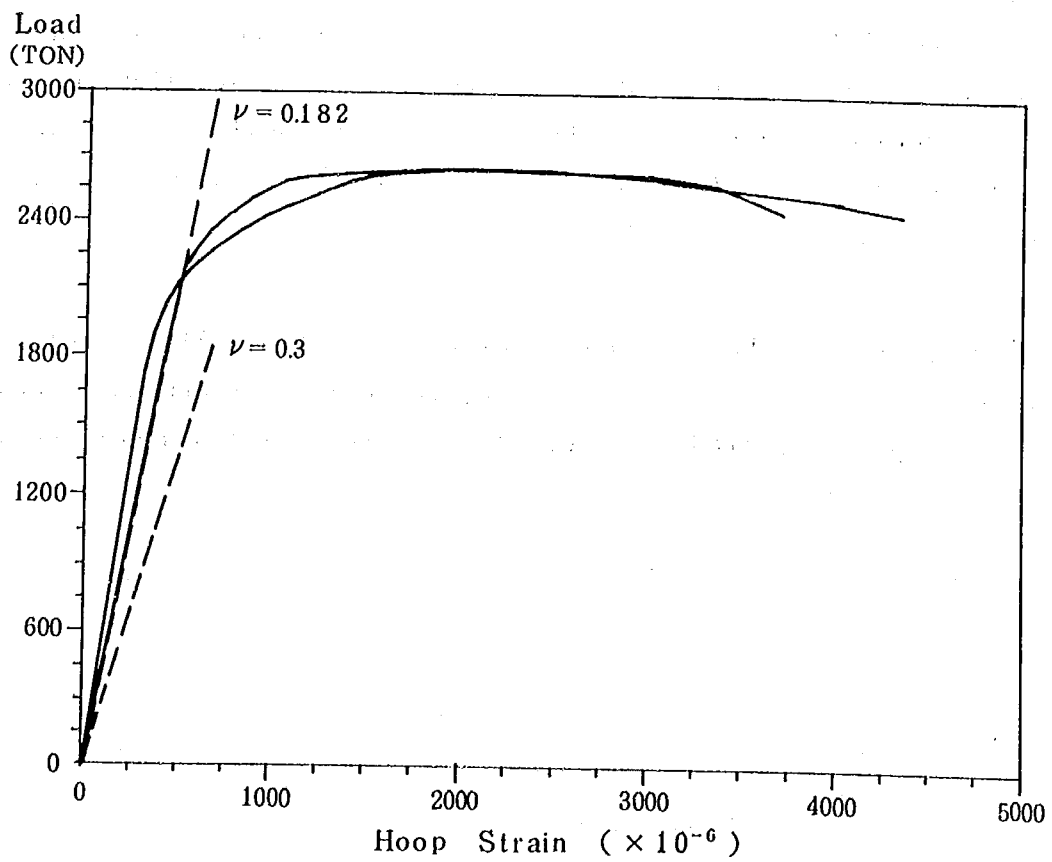


Fig. 38 Load - Hoop Strain Curve (B - 6)

CHAPTER - 5 CONCLUSION

The followings may be concluded about the behavior of concrete-filled steel tubes under compression.

- (1) When studs are provided, the sum of the steel yield strength and the concrete cylinder strength can be, at least, expected irrespective of the steel plate thickness and the concrete strength. When thicker plate is used, or high strength concrete is used, higher resistance can be expected because of the hoop tension action of steel tubes.

On the other hand, when studs are not provided, the resistance of concrete-filled steel tubes will be the sum of the buckling strength of the steel tubes and the concrete cylinder strength, because they behave independently.

- (2) Concrete-filled steel tubes have good ductility, while steel tubes themselves have usually small ductility. Steel tubes of the concrete-filled steel tubes will yield local buckling and the concrete inside will be broken if the plate is not thick, or if the concrete is not strong, but it will not impair the resistance and the ductility significantly. But in this case, hoop tension effect cannot be expected.
- (3) Judging from the hoop strain behavior, concrete-filled steel tubes without studs cannot be designed as composite structures. Adequate studs may be required for composite concrete-filled steel tubes.

References

1. Tomie, M., et al, "Design Problems of Concrete-filled Steel Tubes"
Column No. 73, 1979.7
2. Tomie, M., et al, "State-of-the-art of Concrete-filled Steel Tubes"
Concrete Engineer, Vol. 13, No. 2, 3, 1975
3. Kishida, H., et al, "Bending Strength of Concrete-filled Steel Tubes"
JSSC, Vol. 15, No. 164
4. Oki, T., et al, "Concrete-filled Steel Tubes in Compression"
Journal of the Japan Society for Architectural
Engineers, Vol. 69, 1961
5. Saito, J., et al, "Concrete-filled Steel Tubes with Low Strength
Mortar", Report of Ohbayashigumi, Vol. 9, 1974
6. "Specification for Concrete-filled Steel Tubes" Japan Society for
Architectural Engineers 1980.2 .
7. L.H. DONNELL, C.C. WAN ; "Effect of imperfections on Buckling of
Thin Cylinders and Columns Under Axial
Compression", JOURNAL OF APPLIED
MECHANICS, 1950.3 .
8. N.J. GARDNER, E.R. JACOBSON ; "Structural Behavior of Concrete
Filled Steel Tubes", ACI JOURNAL,
1967.7 .
9. P.K. Neogi, H.K. Sen, J.C. Chapman ; "Concrete-filled Tubular Steel
Columns under Eccentric Loading",
THE STRUCTURAL ENGINEER, No.5,
Vol. 47, 1969.5 .

10. C.G. SCHILLING ; Buckling Strength of Circular Tubes, ASCE,
Vol. 91, No. ST.5, 1965
11. Yamada, M., "Experimental Study on the Concrete-filled Steel Tubes"
Journal of the Japan Society for Architectural
Engineers, Vol. 103, 1964.10 .
12. Oki, T., "Concrete-filled Steel Tubes under Eccentric Loading"
Journal of the Japan Society for Architectural Engineers,
1965.9 .