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MECHANICAL PROPERTIES OF A REINFORCED CONCRETE-FILLED TUBES

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SUMMARY

Though we reported at the 12th WCEE that reinforcement of the central part of a section prevents instantaneous shear failure and maintains adequate remaining strength against large seismic forces, such reinforcement is still not sufficient to resist an extraordinary load. To explore the retention of ductility under larger-than-design seismic loads, we studied the mechanical properties of reinforced concrete-filled tubes (RCFT) with a series of loading tests. The results show that although composition effects between tubes and concrete are relatively small, the steel bars contribute to maintaining the maximum strength and protecting the inner core of the concrete up to large displacements, and the thickness of the tube is important for shear and moment. A series of tests verified that from the perspective of seismic design, an RCFT is superior to reinforced concrete (RC) and concrete filled tubes (CFT) because of its high reliability and easy repair. These benefits are attributable to a well-maintained skeleton after damage, making RCFT suitable for the piers of urban viaducts and other such critical applications

INTRODUCTION

Since the 1995 Hyougoken-Nanbu Earthquake, Japan has required that structural members must keep their own structural skeletons intact and not collapse despite large displacements, even in a very large earthquake. We reported at the 12th WCEE that an RC section with its central part reinforced with a double steel bar cage, can retain the integrity of its own structural skeleton, prevent instantaneous collapse and maintain its remaining strength under larger-than-design seismic loads (**Fig.1**). This means that an RC section reinforced with a double steel bar cage can save lives and property. However, such reinforcement does not increase the maximum strength beyond that of a similar conventional RC section, and it cannot resist an extraordinary load although it does not completely collapse.

To retain ductility and the same strength after the highest impact of very-large earthquake, we improved the proposed RC member by making it a reinforced concrete filled tube (RCFT), comprising an RC member and an enveloping steel plate in a circular or a rectangular shape. An RCFT can endure an extraordinary load, exceeding the design load, as shown in **Fig.2 (**work represented as a product of force and displacement), and possibly be reusable after an easy repair unless the deformation of the structure is severe.

A similar member is the concrete filled tube (CFT), which is already used in various structural domains. However, design methods for CFT are subtly different the compression and bending moments and most designs do not emphasize retaining ductility after a maximum load.

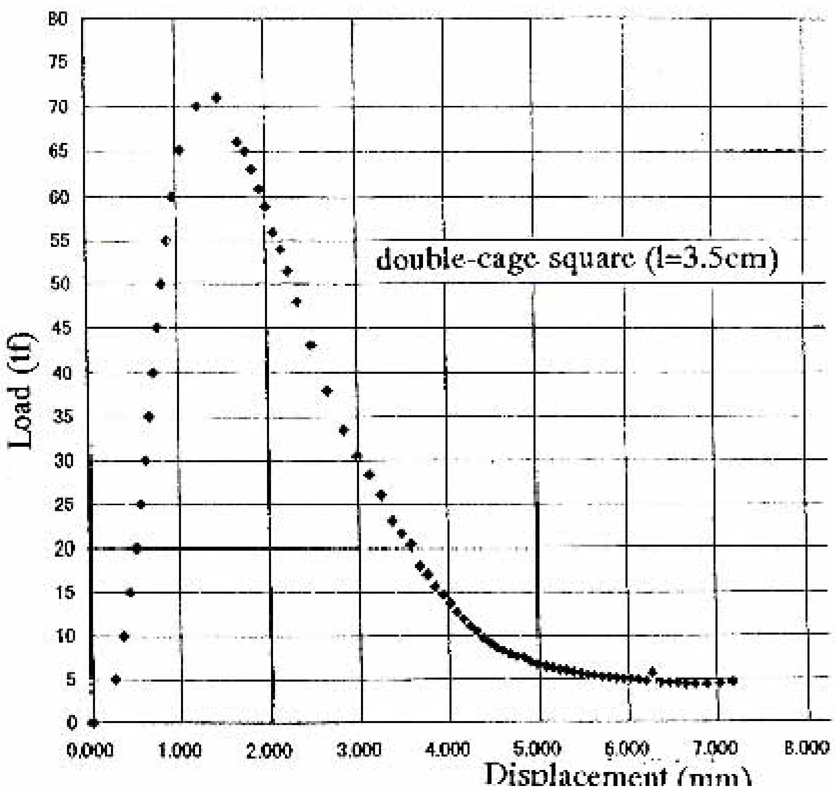


Fig.-1 Load-displacement curves of a square column with a double cage

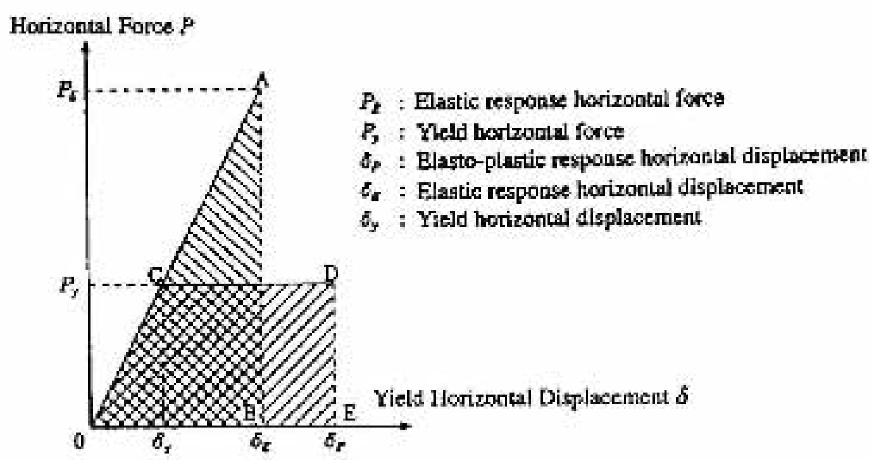


Fig.-2 Elasto-plastic response displacement of a bridge pier

We performed a series of loading tests on RCFT to confirm their behavior under compressive force, bending moment and horizontal loading tests. The compression test was performed instead of a shear test and is designated “compressive shear test (**Fig.-3**).

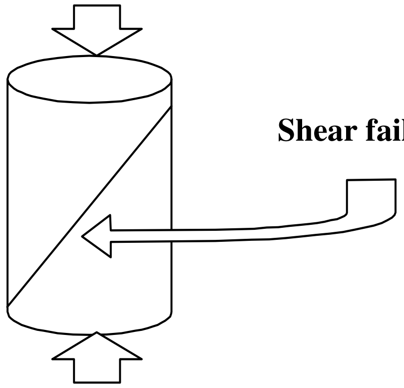


Fig.-3 Concept of compressive shear test

COMPRESSIVE SHEAR TESTS OF RCFT

Circular type

To extend our report to the 12th WCEE, we first performed a series of compressive shear tests on circular cross-section RCFT. In total, 29 specimens were tested, classified as illustrated in **Fig.-4.** Each specimen was 300 mm high and 150 mm in diameter. Steel plates of thickness 3.2, 4.5 and 6.0 mm were used. The ribbed pipe was 6 mm. The longitudinal steel bars were 6 mm in diameter and the hoop bars 3 mm. Concrete strengths were 23.5 MPa and 39.2 MPa. Specimens are identified with labels such as 32LM-SC,which can be understood thus.

An initial N or R means a normal steel pipe or a pipe with ribs, respectively.
The first numbers give the thickness of the steel pipe.
The next letters show the concrete strength, L=23.5 MPa. H=39.2 MPa..
CH means an unfilled steel pipe.
The third letters denote the reinforcing methods. M: no reinforcement, meaning CFT, B: large diameter, S: small diameter, W: double steel cage.
The fourth letters indicate the shape of the specimen, with N (or nothing) for a: circular and S: for a square cross section.
The last letters show the type of test. C: compression test, B: bending test.

RC | normal pipe | pipe with ribs | CFT | RCFT with a large cage | RCFT with a small cage | RCFT with a double cage

Fig.-4 Models of specimens for the compressive shear test

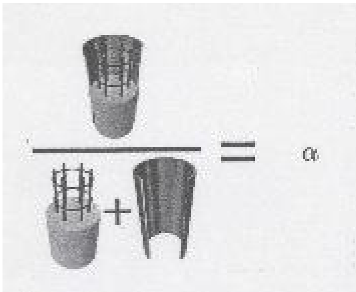
Some results of the compressive shear tests are shown in Table-1, which gives the strengths of steel pipes, the strengths of the reinforced concrete and their combined values, and the maximum loads on each specimen. The strengths of RCFT mainly depends on the thickness of steel pipe and the strength of the RC. Reinforcement and ribs also contribute to greater strength. Small diameter reinforcement protects the center of an RC section and withstands a greater load than a large diameter, as we reported in 12th WCEE. In the case of RCFT, the surrounding steel plate eclipses that effect. The composite efficiency between steel and concrete is relatively small because the amount of steel presents as pipe exceeds the total amount of steel bars. The effect of

Table-1 Composite efficiency of circular RCFT for axial force

Specimen	Strength of pipe α (kN)	Strength of RC β (kN)	Total strength $\alpha+\beta$ (kN)	load(kN)	Composite efficiency
N32HM-C	492	878	1370	1515	1.11
N32LM-C		377	869	976	1.24
N32LB-C		463	955	1052	1.10
N32LS-C		513	1005	1041	1.04
N32LW-C		549	1041	1136	1.09
N45HM-C	820	878	1698	1964	1.16
N45LM-C		377	1197	1348	1.12
N45LB-C		463	1283	1373	1.07
N45LS-C		513	1333	1369	1.03
N45LW-C		549	1369	1440	1.05
N60HM-C	958	878	1836	1829	1.00
N60LM-C		377	1335	1374	1.03
N60LB-C		463	1421	1508	1.06
N60LS-C		513	1471	1471	1.00
N60LW-C		549	1507	1564	1.04
R60HM-C	1079	878	1957	2147	1.10
R60LM-C		377	1456	1569	1.08
R60LB-C		463	1542	1640	1.06
R60LS-C		513	1592	1658	1.05
R60LW-C		549	1628	1812	1.11

Table-2 Ductility of circular RCFT for axial force (unit: mm)

specimen	Dis-p. at yielding(σ_y)	Ditto at max. load(σ_r)	Dis-p. at 95% of max. load(σ_{95})	Ductility σ_r/σ_y	Ditto σ_{95}/σ_y
N32CH-C	1.6	4.4	5.3	2.7	3.3
N32HM-C	3.6	3.6	4.1	1.4	1.6
N32LM-C	1.8	3.1	16.1	1.7	9.1
N32LB-C	1.8	8.5	20.2	4.6	11.0
N32LS-C	2.5	10.6	20.2	4.3	8.1
N32LW-C	2.5	11.0	24.9	4.5	10.1
N45CH-C	2.2	6.0	7.7	2.7	3.5
N45HM-C	4.0	4.0	5.9	1.5	2.2
N45LM-C	2.0	14.9	28.7	7.5	14.4
N45LB-C	1.8	9.9	21.0	5.6	12.0
N45LS-C	2.5	12.9	22.4	5.2	9.1
N45LW-C	2.3	11.5	21.7	5.0	9.4
N60CH-C	2.5	11.3	13.7	4.5	5.5
N60HM-C	4.8	4.8	7.2	1.8	2.8
N60LM-C	2.9	20.0	25.7	6.9	8.8
N60LB-C	2.0	18.7	26.1	9.4	13.1
N60LS-C	2.2	16.6	23.2	7.6	10.6
N60LW-C	2.2	15.6	24.7	7.1	11.3
R60CH-C	2.0	15.6	19.0	8.0	9.7
R60HM-C	5.9	5.9	14.8	1.4	3.6
R60LM-C	2.7	23.0	24.2	8.5	8.9
R60LB-C	2.1	22.2	38.9	10.5	18.4
R60LS-C	4.4	16.6	36.7	5.1	8.4
R60LW-C	2.5	20.2	33.8	8.2	13.7



$$\sigma_r = \frac{\delta_r}{\delta_y} \quad \cdots 1)$$

$$\sigma_{95} = \frac{\delta_{95}}{\delta_y} \quad \cdots 2)$$

Fig.-5 Definition of composite efficiency @ @ @ @ @ @ @ Definition of ductility

ribs inside steel pipe is showed in the composite efficiency.

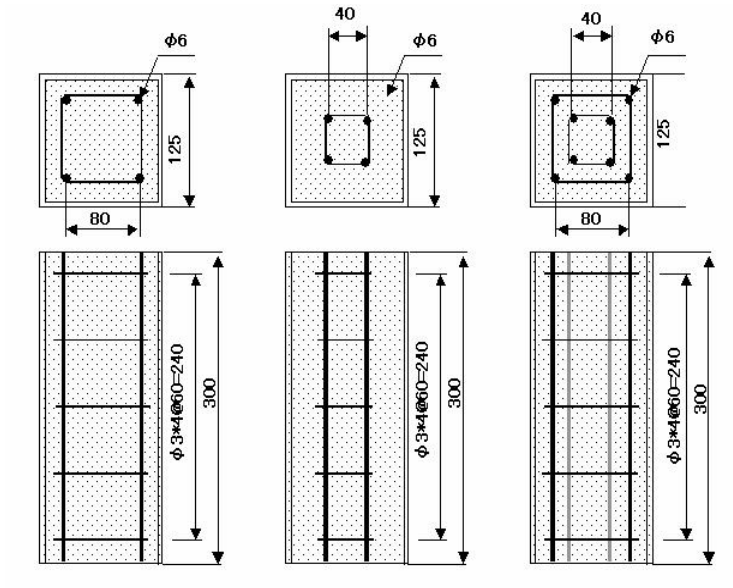
For our purposes, the composite efficiency of RCFT is defined as shown in **Fig.-5.** However, beyond the maximum load, RCFT still supports almost the maximum load even when it has shrunk as much as a few cm. Table-2 indicates the compressive displacements of the 30 cm-high specimens at the yield point, the maximum loading point and 95% of the maximum loading. The ratios of the displacement at the yield point to those at the latter 2 points are defined as ductility in formulas 1) and 2). The values of σ_r and σ_{95} of RCFT are very large compared with CFT. Among these, RCFT with a small diameter reinforcement has a little less ductility than those with a large one and a double cage. This means that reinforcing of the central core of a section reduces its ductility slightly by increasing its strength. The effect of ribs is also demonstrated.

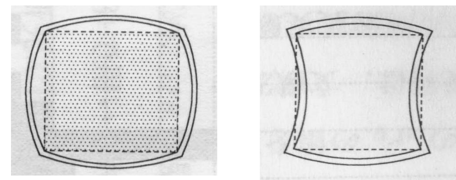
Square type

Although a circular tube effectively restricts the concrete it contains, and it looks beautiful, the circular section is inconvenient to combine with other members. A square or a rectangular section is better for handling than a circular one. We performed a series of tests on square sections with nearly the same areas, except for RCFT with ribs. ***Fig.-6*** shows the reinforcement of RCFT.

Photo-1 Situation of circular RCFT

Photo-2 Situation of square-typed RCFT





Buckling mode on RCFT and CFT   Buckling mode on hollow pipe

Fig.-7 Buckling modes of square typed RCCT

Fig.-6 Reinforcements of square-typed RCFT

The rupture modes of the circular and the square-typed RCFT specimens are completely different. Photo-1 shows specimens of the unfilled pipe and of a CFT broken by the axial force. The unfilled pipe buckled in elephant foot mode and CFT and RCFT were damaged by shear failure of the inside concrete. Accordingly, their strength depends on the concrete strength.
In contrast, in a square-typed RCFT the unfilled pipe buckles in the shape of a long snare drum as shown in **Fig.-7.** RCFT and CFT are damaged at a few elephant-foot buckling nodes in **Fig.-7** and **Photo-2**. The inside concrete is crushed along the nodes and the crashing face extends through the section.

Table-3 Composite efficiency of square-typed RCFT for axial force

Specimen	Strength of pipe α (kN)	Strength of RC β (kN)	Total strength $\alpha+\beta$ (kN)	load(kN)	Composite efficiency
32LM-SC	421.67	449.35	871.02	865.05	0.99
32HM-SC		598.65	1020.32	1115.79	1.09
32HB-SC		606.98	1028.65	1028.44	1.00
32HS-SC		632.54	1054.21	984.49	0.93
32HW-SC		585.62	1007.29	1176.81	1.17
45LM-SC	788.02	449.35	1237.37	1064.53	0.86
45HM-SC		598.65	1386.66	1312.97	0.95
45HB-SC		606.98	1395.00	1301.20	0.93
45HS-SC		632.54	1420.55	1329.45	0.94
45HW-SC		585.62	1373.64	1373.01	1.00
60LM-SC	1083.42	449.35	1532.77	1444.03	0.94
60HM-SC		598.65	1682.06	1512.70	0.90
60HB-SC		606.98	1690.39	1561.75	0.92
60HS-SC		632.54	1715.95	1563.71	0.91
60HW-SC		585.62	1669.04	1599.42	0.96

Table-3 shows the strength of square-type steel pipes, of their enclosed RC, and the sum of the steel and RC values, as well as the maximum loads on each specimen. In square-type RCFT, the strength of the steel pipe is the dominant influence in spite of the high-strength concrete, and the advantage of a composite is not apparent. Despite the constriction effect of the steel pipes (Fig.-8), it does not increase the strength of the specimens, which is limited by the elephant-foot buckling of the outer steel pipe. The accumulated loads of the steel pipe and RC are almost the same as for RCFT with a double cage, and the load capacity of RCFT remains at the maximum up to more than a 20 mm displacement, though in other types of members the capacity does decrease at low displacement.

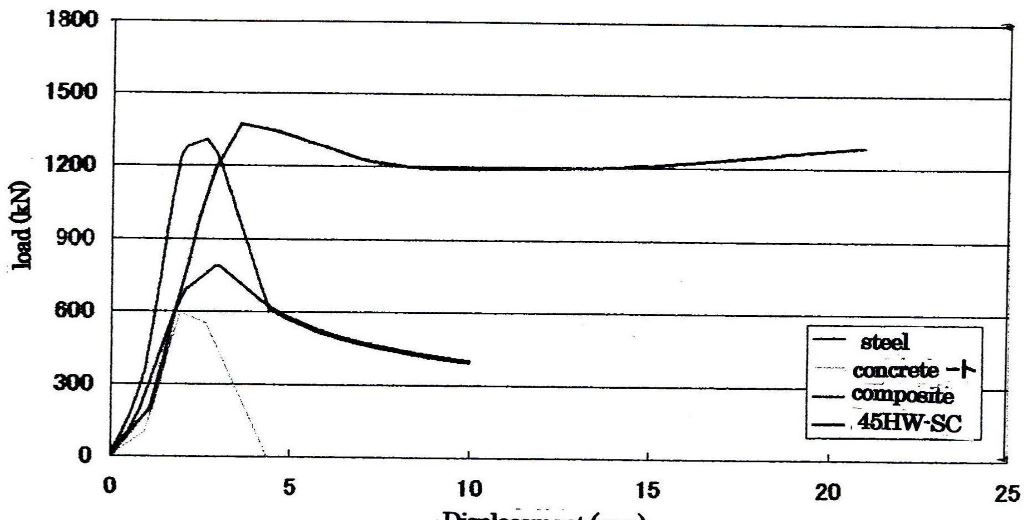


Fig.-8 Composite curves of square-typed RCFT with a double cage

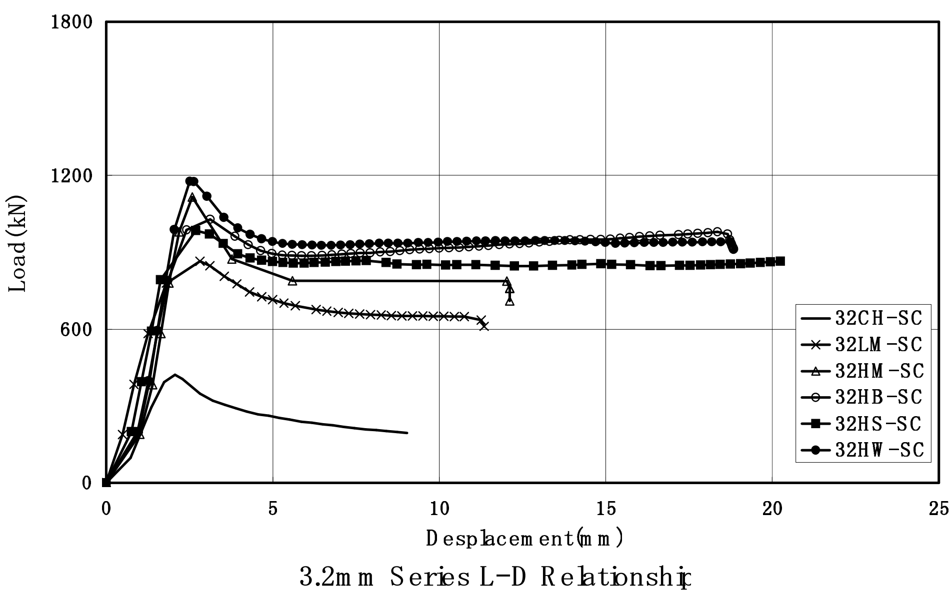


Fig.-9 Comparison of displacement curves of square-typed RCFT

Table-3 shows that the thinner thickness of pipe is more efficient. Fig.-9 shows the relationship between load and displacement. The ductility of RCFT with 3.2 mm plate σ_r and σ_{95} is 1.43~1.70 and 1.70~2.01. Corresponding values for 4.5 mm, σ_r and σ_{95} are 1.25~1.63 and 1.93~2.08, and for 6.0 mm, σ_r and σ_{95} are 1.27~1.67 and 2.45~2.75. It was difficult to find any apparent difference in ductility σ_r with different thicknesses of steel pipe, but ductility σ_{95} is slightly larger in RCFT with thicker pipes. Since σ_{95} of CFT with low-strength concrete, which ranges from 2.69~3.37, is greater than σ_{95} with high-strength by as much as 1.63~2.26, the strength of the interior concrete is not of primary importance in preventing instantaneous collapse. Comparing the square-typed and circular RCFT, the ductility of the circular type greatly exceeds that of the square type.

Through a series of compressive shear tests, we found that enveloping RC with a circular steel pipe increases its strength against axial force, and together with the steel pipe the RC's ductility shows a significant gain, resisting collapse up to very large strain values.

CONCLUSION

Unfortunately, we cannot report the results of the bending and the horizontal loading tests for RCFT because of the saturated capacity of this program. Therefore, we draw several conclusions from the compressive shear tests of RCFT.

The authors will present the results of the tests of bending and horizontal loading on RCFT and CFT on another occasion.

1. RCFT and CFT have high-strength and large ductility against axial and shear forces.
2. The reinforcement in RCFT is not effective until the maximum load is applied, but contributes to maintaining the maximum resistance up to very large vertical displacements.
3. The effect of ribs inside the steel pipe is apparent in composite efficiency and ductility.
4. The circular type of RCFT is more effective than the square type in both domains.
5. Balancing pipe thickness and concrete strength is important for good results.

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