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Ductility of Steel Tube-Reinforced Concrete Composite Beams

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Summary

In this research, to improve the ductility of RC beams, the concrete-filled steel tubes (CFST) were employed instead of the round bars (RB) on the compression side. Two types of beams, i.e., the CFST-type beams and the RB-type beams were designed to have equal bending strength. A series of experiments was divided into two groups according to the loading patterns of static load and impact load. The experimental results show that the CFST improves the ductility capacity of beams more than two times in both cases of the loading patterns as compared with the RB.

1. Introduction

A great number of rock-sheds are constructed with the reinforced concrete (RC) or the pre-stressed concrete members and are widely used in Japan to protect vehicles against the falling rocks. The RC-beams used in the rock sheds are required to have the ductility capacity and the energy absorption capacity, because the design of such structures should be based on the energy absorption concept. The compression rupture of concrete governs the ductility capacity in the stage of small beam-deformation. Namely, the bending strength of RC beams decreases at the same time the compression reinforcing bars buckle after the rupture of concrete. Though the stirrups are arranged closely to improve the ductility capacity of RC beams, many stirrups are required to prevent the re-bars from buckling and to produce the confinement effect on the concrete in the compressive zone [1].

In this research, the concrete filled steel tubes (CFST) are employed instead of the round bars (RB) on the compression side to improve the ductility capacity of RC beams used in the rock sheds. Hereafter, such a RC beam and the RC beam with round bars on the compression side are referred as CFST-type beam and RB-type beam, respectively. The CFST-type beams are expected to have a high ductility capacity, because the CFST has a highest buckling load capacity. The CFST can also produce the confinement effect on the concrete filled into a steel tube [2,3].

A series of experiments was carried out on the CFST-type and RB-type beams subjected to two types of loading patterns, i.e., static load and impact load. The ultimate bending strengths of these specimens were designed to be equal. In this paper the ductility performance of such beams is discussed and evaluated from the experimental results. It is then remarked that the CFST improves the ductility capacity of beams more than two times as compared with the reinforcing bars usually used for the RC-beams.

2. Outline of Experiments

2.1 Test Specimens and Material Properties

Table 1 summarizes the tested specimens and material properties. Figure 1 shows the detailed dimensions of test specimens. All specimens are equally reinforced by three deformed bars on the tension side, but there is a difference in the compression reinforcements between CFST-beams and RB-beams. The stirrups are also arranged to prevent the shear force from affecting the beam strength.

	Type of Specimen	CFST-beams					RB-beams			
	Compressive Reinforcement	2-Steel Tubes (ϕ60.5x2.3)					4-Round Bars (ϕ16)			
	Tensile Reinforcement	3-Deformed Reinforcing Bars (ϕ25)								
(a)	Name of Specimen	C1	C2	C3	C4	CN	D1	D2	D3	D4
	Age at Loading (days)	38	40	114	111	39	38	40	114	111
	Concrete Strength (MPa)	52.5	54.2	54.4	51.4	52.8	52.5	54.2	54.4	51.4
	Test Program (Loading Type)	Static		Impact		Static			Impact	

	Reinforcement Material	Steel Tube (ϕ60.5x2.3)	Round Bar (ϕ16)	Deformed Bar (ϕ25)
(b)	Nominal Yield Point (MPa)	235	235	295
	Yield Point in tensile test (MPa)	406	369	408
	Ultimate Strength in test (MPa)	509	484	613

Table 1 (a) test specimens, (b) material properties

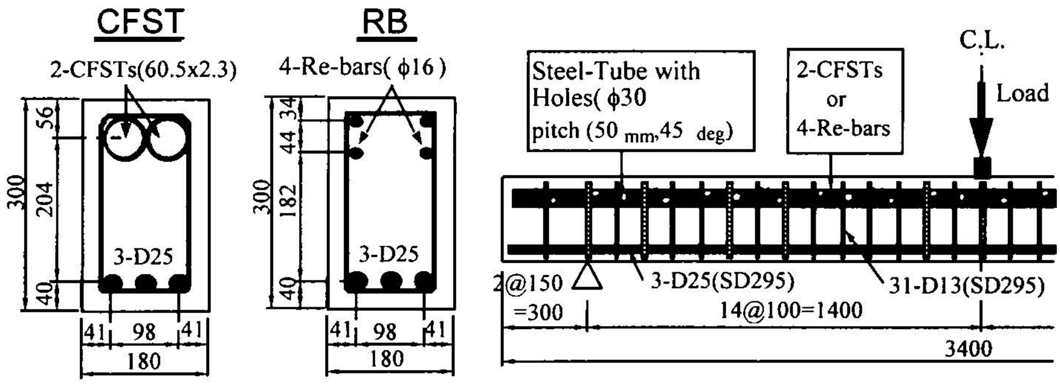

Fig. 1 Details of test specimens

Each specimen of CFST-beams has the same reinforcements of two mild-steel tubes on the compression side. In the specimens of C1, C2, C3 and C4, circular holes of ϕ30 *mm* are made along the tube-length at a distance of 50 *mm*, and are staggered with 45 *degrees* in the circumferential direction as shown in Fig. 1. These holes can form a series of concrete dowels which act in shear to resist the shear flow. Through these holes it is also easy to fill up the steel tube with concrete. The steel tubes without hole are used in the specimen CN for a comparison sake.

Each specimen of RB-beams D1, D2, D3 and D4 has the same reinforcements of four round bars on the compression side. Namely, RB-beams are the so-called doubly reinforcements-beams. The whole centroid-location and the total cross-section area of the four bars are almost equal to those of the steel tubes of CFST-beams. Therefore there is little difference in the nominal ultimate bending strengths between CFST-beams and RB-beams when the holes of steel tubes are not considered in CFST-beams. Using the section partitioning method, the design strength of concrete of 30 *MPa* and the nominal yield stress of reinforcements, the ultimate bending strengths of 96.0 *kNm* and 96.3 *kNm* are obtained for CFST-beams and RB-beams, respectively.

2.2 Test Procedures

The test program is divided into two groups according to load types. The first group of C1, C2, CN, D1 and D2 beams and the second group of C3, C4, D3 and D4 beams were tested under the static load and an impact load, respectively. In all experiments, the specimen is simply supported with the span length of 2.8 *m*, as shown in Fig. 1. A central point load is applied to the specimen through a steel rectangular block having the contact surface of 5 *cm* x 18 *cm*.

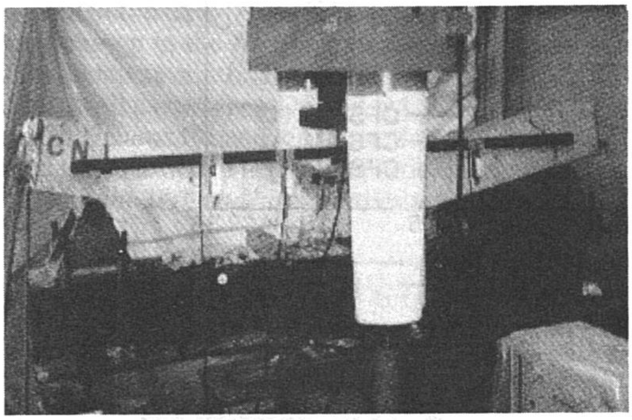

Fig. 2a Test set-up in statically loading

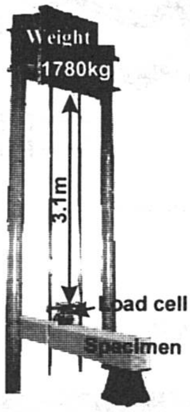

Fig. 2b Impact loading

2.2.1. Static Loading
In the static loading tests, a conventional compression testing machine shown in Fig. 2a was used and the ram stroke at a speed of 0.5 *mm/min* was applied in the early stage of loading. After the yield load of the tension reinforcement the test was continued at a ram speed of 4 *mm/min*. Loads, beam deflections and reinforcement strains were measured.

2.2.2. Impact Loading
In the impact loading tests, an assembled iron block of 1780 *kg* weight is set free falling from 3.1 *m* height to the specimen as shown in Fig. 2b. There is no rig preventing the beam from bounding. A load-cell, on which the free-fall weight hits directly, is set on the specimen. Instead of measuring the beam displacement at the loading point, the weight movement is measured by means of a displacement transducer connected to the weight by a wire. Data of strain-gauges, a load cell and the displacement and deceleration transducers were recorded in 0.2 msec sampling intervals.

3. Test Results and Considerations

3.1 Statically Loading Tests

3.1.1. Effect of Concrete-Filled Steel Tubes
Figure 3 shows the load and the mid-span deflection relationships under static loading tests. The CFST-type beams C1 and C2 show almost same load-deflection curves, and the RB-type beams D1 and D2 also do so. Therefore the experiments are reliable. Since both types of beams have been designed to have an equal ultimate bending strength, there is little difference of the ultimate strength between the two types. However there is a clear difference of the final deflection between the two types. This is due to the fact that the CFST improves the ductility capacity. Figure 4a shows the failure of specimens C1 and D1 at the mid-span. When the compression concrete is crushed heavily, the reinforcing bars of D1 buckle between the stirrups, followed by the decrease of the beam strength. Such a buckling mode does not appear in the case of the CFST-type, though a few circular holes of CFST are deformed to an ellipse. Thus the ductility improvement is achieved by using the CFST for the compression reinforcement.

The strength of the beam CN, in which the steel tubes without circular holes are used, is suddenly decreased from 220 *kN* to 180 *kN*, when the mid-span deflection reaches to 22 *mm* (see Fig. 3). At this stage of loading, concrete cracks vertically on the compression side over the support, as shown in Fig. 4b(i). The CFST slides out as the mid-span deflection is increased as shown in Fig. 4b(ii). Comparing CN with C1 and C2, the circular holes made along the steel tube are clearly confirmed the formation of a series of concrete dowels which act in shear.

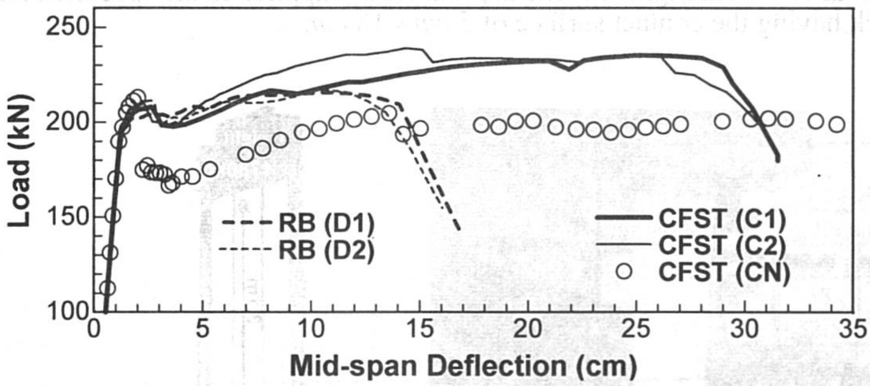

Fig. 3 Load-deflection curves (Improvement in ductility using CFST)

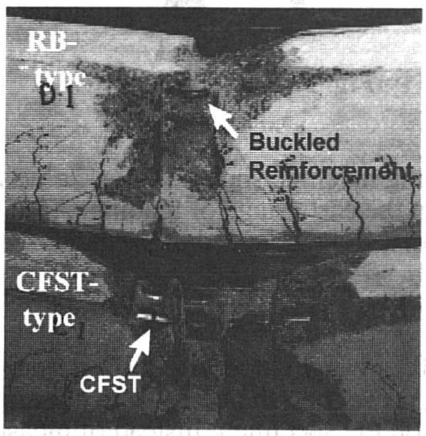

Fig. 4a CFST and buckled reinforcement

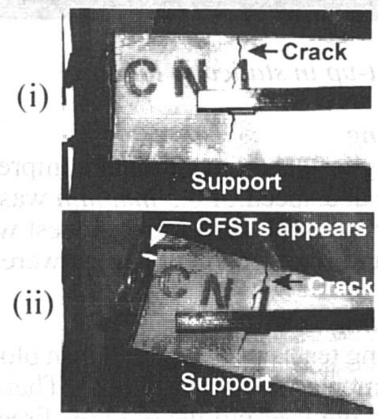

Fig. 4b Typical crack on CN

Specimen		Yield Deflection δ_Y (mm)	Ultimate Load P_U (kN)	Deflection at $0.95P_U$ δ_L (mm)	Ductility Factor δ_L/δ_Y	Energy Absorption E_n (kNm)
CFST Type	C1	17.5	235	292	16.7	64.2
	C2	15.4	238	278	18.1	61.4
	CN	16.4	213	340	20.7	65.2
RB Type	D1	18.5	217	143	7.7	29.2
	D2	15.0	217	132	8.8	26.7

Table 2 Ductility capacity in static loading tests

3.1.2. Bending Strength and Ductility Capacity

The experimentally observed ductility-factor for each beam and the relative values are summarized in Table 2, in which, δ_Y is the yield deflection when the strain at mid-span of tension reinforcement reaches the yield strain, P_U is the ultimate load, δ_L is the limit-state deflection when the load decreases to $0.95P_U$, δ_L/δ_Y is the ductility factor and E_n is the energy absorption capacity evaluated as the area below the load-deflection curve in Fig. 3. It is clear from Table 2 that the CFST-type beams exhibit the ductility factor and the energy absorption capacity more than two times as compared with the RB-type beams. The beam CN having the CFST without holes exhibits also an excellent ductility capacity, though the beam strength suddenly decreased after the peak load as shown in Fig. 3. This is due to the fact that in the case of the CFST without holes, the bond-slip occurs along the whole surface of the CFST and the extreme crushing the CFST subjected to the bending moment does not appear. It can be concluded that the beam CN can absorb much energy, however, its use is not recommended due to sudden decrease in strength caused by bond-slip.

3.2 Impact Loading Tests

3.2.1. Impact Load - Time History

Figures 5(a) and 5(b) show the time history of the impact load and the weight displacement corresponding to the CFST-type (C3 & C4) and the RB-type (D3 & D4), respectively. A peak load, which is not shown in the figure, appears as an impulsive wave for an instant. Maybe, it has no effect on the beam strength. The results are reliable, because there is not any difference between C3 and C4 as well as between D3 and D4. The weight of 1780 *kg* and 3.1 *m* free-fall was incapable of breaking the beams C3 and C4 at one fall. On the other hand the beams D3 and D4 were crushed and touched the test-bed. These observations are indicated in Fig. 5(a) and 5(b) as "*rebound*" and "*crush & touch the test-bed*", respectively.

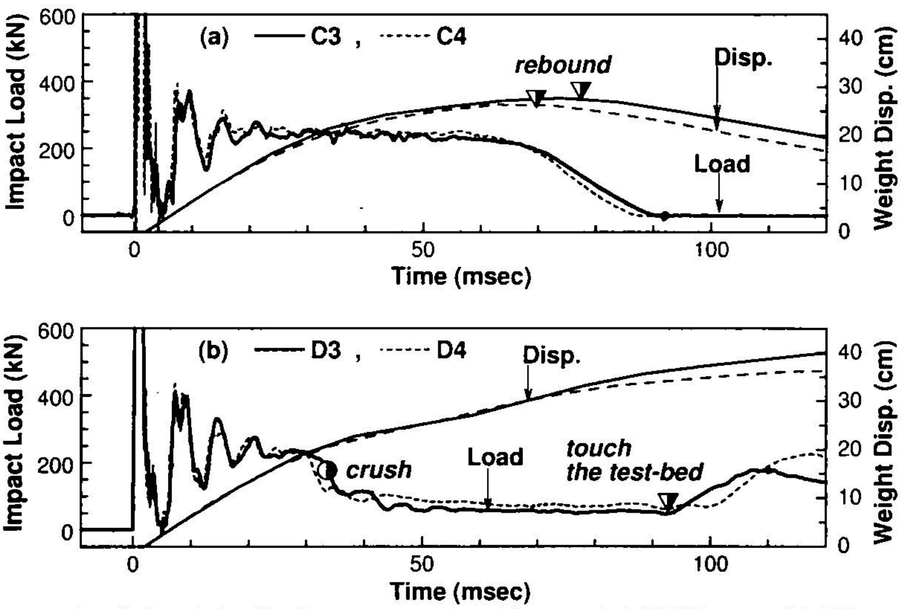

Fig. 5 Impact load & weight displacement -- time history: (a) CFST-type, (b) RB-type

3.2.2. Impact Load vs. Beam Response and Energy Absorption

The typical relations between the impact load and the weight displacement are shown, with a solid line, in Figs. 6(a) and 6(b). The energy absorption is also shown with a dashed curve. Furthermore the static load-deflection curves for C1 and D1 are also compared with the impact loading tests as shown in Fig. 6. Only for the CFST-type beam C4, the second fall of the weight from the height of 2.0 *m* was carried out, because the first fall did not cause heavy crush on the beam. In Fig. 6(a) the data due to the second fall are linked to that at the final beam displacement in the first fall, and are represented by a thin line and a thick line, respectively.

Even in the second fall the weight-rebound is seen in Fig. 6(a). This means that the beam, which is being in the limit state because of the considerable cracking, still has a little strength. The beam C4 has absorbed an energy of 81.4 *kNm* which is 1.3 times as large as that of the CFST-type beams tested statically. On the other hand, at the "crush" point in Fig. 6(b) the RB-type beam D4 has absorbed an energy of 41.9 *kNm* which is 1.5 times as large as that of the RB-type beams tested statically. The final beam-deflection due to an impact load is slightly larger than that in the static loading test, however there is little difference in the resistance strengths between the impact test and the static test when the impact loads are roughly averaged. Therefore the resistance strength and the energy absorption capacity of these beams can be estimated conservatively from the static test results.

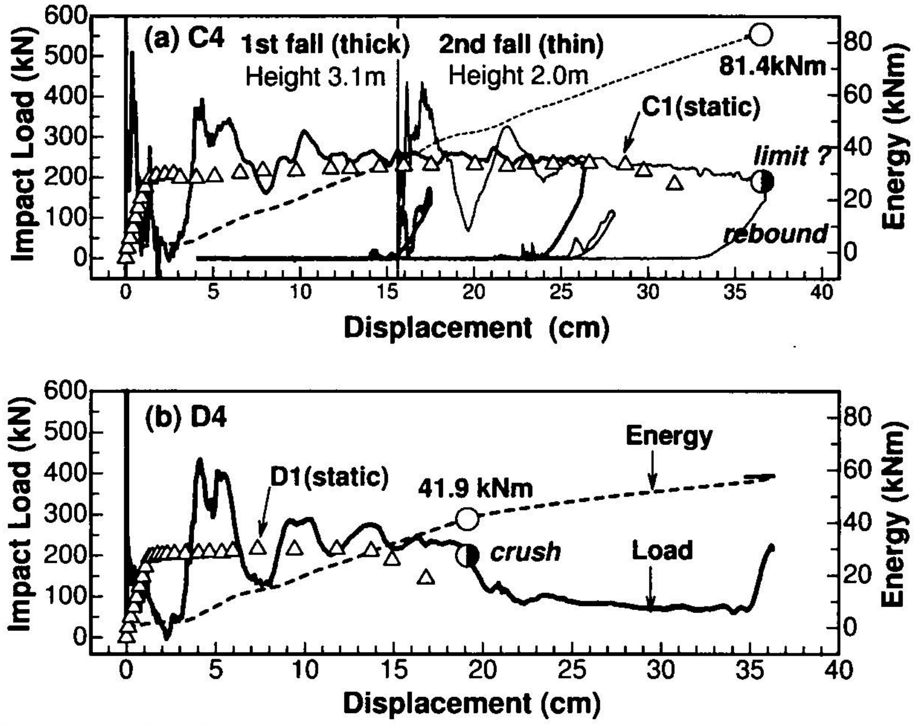

Fig. 6 Impact load and energy absorption -- weight displacement: (a) C4, (b) D4

4. Conclusion

The concrete-filled steel tubes (CFST) were employed as the compression reinforcement of RC-beams which are called CFST-type beams. These beams are expected to be used in rock-shed structures. A series of experiments was carried out with two types of the loading patterns, i.e., static load and impact load. It is shown that the CFST improves the ductility capacity and the energy absorption capacity more than two times as compared with the reinforcing bar commonly used for the RC-beams. The CFST is effective for reinforcing the RC-beams used in rock-shed structures in which the design should be based on the energy absorption concept.

5. Acknowledgment

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6. References

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