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Dynamic restoring force characteristics of steel tube filled with super-high strength concrete

Motoo Saisho
Kumamoto University, Japan

Kazuaki Mitsunari
Araigumi Co., Ltd, Japan (Visiting: Kumamoto University, Japan)

ABSTRACT: To make the practical use of super-high strength concrete in aseismic design of building structures, dynamic loading tests of steel tubular beam-columns, which were filled with super-high strength concrete, have been carried out and the fracture and restoring force characteristics have been investigated. From the test results it is concluded that the strength of concrete-filled steel tubular members is fairly larger than that predicted by the method of superposed strength (Ref. 1) even if super-high strength concrete is used. But it is also shown that the plastic deformation capacity, which is caused by the crack of steel tube, decreases as the strength of concrete is higher. A mathematical model to predict the accumulated plastic deformation capacity of concrete-filled steel tube related to the concrete strength and loading rate effect is proposed. This model can also be applied to aseismic design criteria of building structures composed of super-high strength concrete.

1. INTRODUCTION

By the use of the super-plasticizer and silica fume, super-high strength concrete can be produced now and it is comparatively easy to cast. It is expected by many designers of structure to make the practical use of super-high strength concrete to improve the design possibility of building structures especially super-high-rise buildings. But it is well known that the ductility of structural material becomes to be lower as its strength is higher. Furthermore it is also well known that super-high strength concrete fails like an explosion when it is subjected to dynamic load like seismic load. In aseismic design against strong ground motion, the brittle fracture of structural members may be a cause to collapse the whole structure. From this reason the brittle fracture under dynamic load need to be studied to make the practical use of super-high strength concrete in aseismic design of structures.

In this study it is considered that concrete-filled steel tubular structures are suitable to use super-high strength concrete which is generally difficult to improve the workability of concrete. In order to realize the aseismic design of super-high strength concrete structures, dynamic loading tests of circular steel tube filled with super-high strength concrete have been carried out and the hysteretic behavior and fracture of structural members are studied in relation with the strength of concrete.

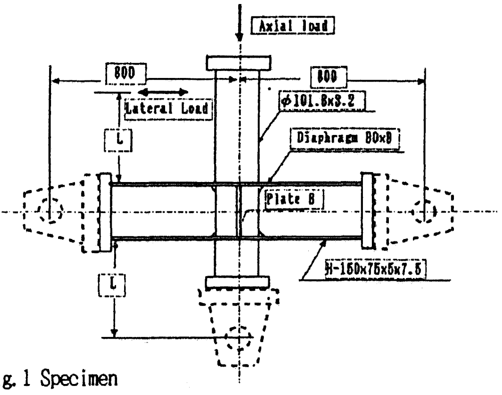


Fig. 1 Specimen

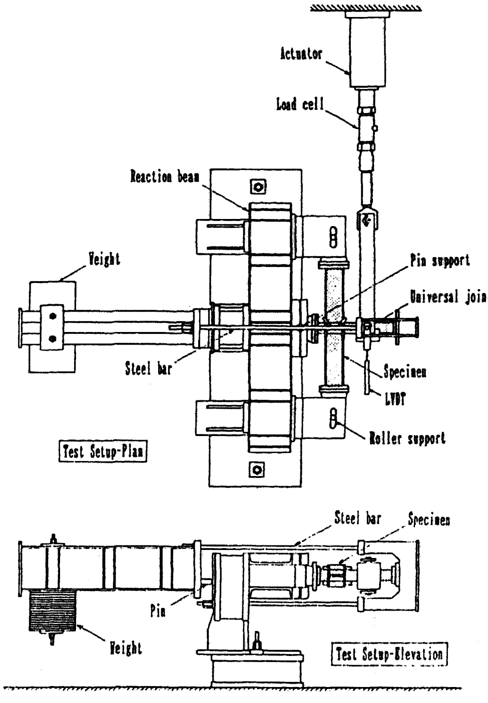


Fig. 2 Test setup

Table 1 Specimens and test results

Specimen	Loading	L (cm)	N (KN)	N/Nu	Mu (KJ)	Concrete		Steel tube			Test results	
						σc (MPa)	εc (%)	σy (MPa)	σu (MPa)	εy (%)	μcr	αcr
SCTDI-SH-A	Dynamic	25	344	0.271	18.6	136.	0.361	323	375	0.157	164	164
SCTDI-SH	"	"	145	0.120	14.7	128.	0.351	"	"	"	184	242
SCTDI-H	"	"	"	0.226	13.4	43.9	0.295	345	392	0.168	232	214
SCTDI	"	"	"	0.323	9.56	17.2	0.258	"	"	"	280	177
STDI	"	"	"	0.474	7.03	-	-	323	375	0.157	-	-
CTDI-SH-A	"	50	344	0.278	18.4	131.	0.324	"	"	"	219	218
CTDI-SH	"	"	145	0.125	14.7	121.	0.366	"	"	"	-	-
CTDI-H	"	"	"	0.226	13.4	43.9	0.295	345	392	0.168	-	-
CTDI	"	"	"	0.323	9.56	17.2	0.258	"	"	"		
TDI	"	"	"	0.474	7.03	-	-	323	375	0.157	-	-
SCTSI-SH-A	Static	25	344	0.271	18.6	136.	0.361	"	"	"	192	193
SCTSI-SH	"	"	145	0.120	14.7	128.	0.351	"	"	"	194	252
SCTSI-H	"	"	"	0.226	13.4	43.9	0.295	345	392	0.168	311	284
SCTSI	"	"	"	0.323	9.56	17.2	0.258	"	"	"	-	-
STSI	"	"	"	0.474	7.03	-	-	323	375	0.157	-	-
CTSI-SH	"	50	"	0.125	14.7	121.	0.366	"	"	"	-	-
CTSI-H	"	"	"	0.226	13.4	43.9	0.295	345	392	0.168	-	-
CTSI	"	"	"	0.323	9.56	17.2	0.258	"	"	"	-	-
TSI	"	"	"	0.474	7.03	-	-	323	375	0.157	-	-

σc:Compression strength, εc:Strain at σc, σy:Yield stress, σu:Ultimate stress, εy:Yield strain
(σy, σu and εy were derived from stub-column test. σy and εy are 0.2% off-set values.)

2. DYNAMIC AND STATIC LOADING TESTS

2.1 Specimens

Specimens are, as shown in Fig.1, cross-form type composed of cold-formed circular steel tube columns in which concrete is filled and H-steel beams. The length of steel tube column (L) is 25cm or 50cm and the section of it is 101.6x3.2(JIS STK400). Slip between steel tube and concrete was prevented by the end-plate of column. The mechanical properties of steel tube and filled concrete are explained in Table 1. To examine the effect of concrete strength on the fracture of member, three kinds of concrete were tested which were ordinary concrete (20Mpa), high-strength concrete (50Mpa) and super-high strength concrete (130Mpa). Their water-cement ratios were 0.65, 0.30 and 0.20 respectively. In the mixture of the concrete super-plasticizer and silica fume were used.

2.2 Loading procedure and measurements

Constant axial force (N) and alternating repeated lateral force were loaded at the column-end through an universal joint as shown in Fig.2. The constant axial load, whose values are shown in Table 1, were loaded by a weight basing on the lever-principle.

The time history of forced displacement at the loading point (D) in dynamic loading test is shown in Fig.3. The maximum velocity of displacement (D) was about 10cm/s and the maximum strain rate of steel tube was about 0.2cm/cm/s.

To examine the effect of loading rate, static loading tests were also carried out. In static loading test the hysteretic displacement (D) at the loading point is the same as that of the dynamic loading test.

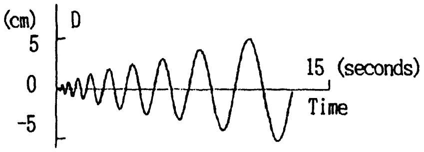


Fig.3 Time-history of measured displacement

In static test the load was given in step-by-step. After small incremental displacement was given, the forced deformation was kept in one minute in every step to complete the stress-relaxation and to exclude the effect of loading rate.

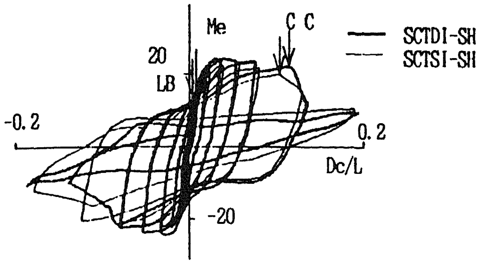
Lateral load and displacement at the loading point were measured by load cell and LVDT respectively. Axial strain and circumferential strain of steel tube measured by wire strain gages. Strain gages were attached to the surface of steel tube 3cm apart from the column end whose distance is nearly equal to the half of the calculated wave length of local buckling. In dynamic loading tests the accelerations of loading apparatus were measured by accelerometers and the inertia force in lateral load was decided. The inertia force in axial load (N) was obtained from the strain of steel bar which gave the axial load. All data were measured at the same time and the data acquisition was carried out in every 10 milliseconds.

In static test data-acquisition in every incremental step was executed after stress-relaxation fully achieved to exclude the effect of loading rate.

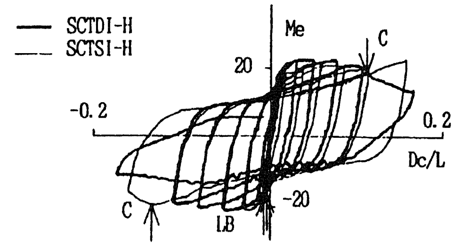
3. TEST RESULTS

3.1 Load-deformation relationships

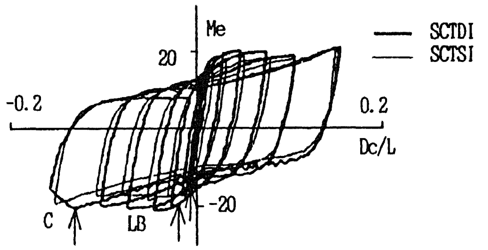
In Figs.4 there are the load-deformation



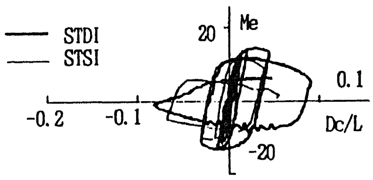
Specimens filled with super-high strength concrete



Specimens filled with high strength concrete



Specimens filled with ordinary concrete



Specimens not-filled with concrete

Fig.4 Load-deformation relationships

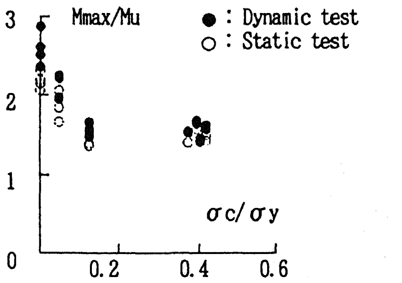


Fig.5 Ratio of maximum end-moment of test to the calculated strength

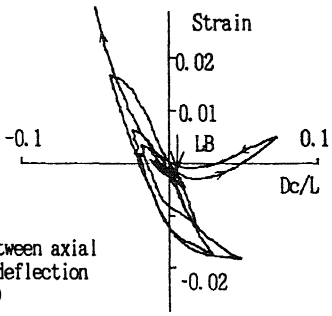


Fig.6
Relation between axial strain and deflection (SCTDI-SH-A)

relationships. The load (Me) in this figure is the end-moment of column and the deformation (Dc/L) is the ratio of the column deflection to its length. In these figures we can see clear differences of restoring force characteristics among them which show that the rate of loading and the strength of concrete effect on the hysteretic behaviors of concrete-filled steel tube.

The arrows (LB) and (C) mean the points where local buckling and crack have occurred in the steel tube respectively. There is the clear degradation of restoring force in this figure where local buckling and crack of steel tube have occurred. Particularly under dynamic load the fracture is brittle and the degradation of restoring force is larger than that under static load. This behavior shows the effect of loading rate on the hysteretic behavior of concrete-filled steel tube. Local buckling and crack of steel tube are still more studied in the following sections because they are important factors in the design of concrete-filled steel tube.

The maximum end-moment of column (Mmax) is shown in Fig.5 in which Mu is the ultimate strength calculated by the method of superposed strength. (Ref.1) The ratio of Mmax to Mu is influenced by the concrete strength and rate of loading, but Mmax of every specimen is fairly lager than the value of Mu.

3.2 Local buckling and crack of steel tube

Fig.6 shows the relationship between the deflection of column and the axial strain of steel tube. This relation shows the compatibility condition and will be expressed by a straight line in case that there is not local buckling in the steel tube. Based on this reason the occurrence of local buckling (LB) can be given by the point where the relation between strain and deflection starts to separate from the straight line through the origin. The occurrence of crack of steel tube could be decided by visual observation in static loading tests. On the other hand the occurrence of crack in dynamic loading test was obtained from the point of clear degradation in the load-deformation relationships because it was not observed visually and measured in the test.

4. PLASTIC DEFORMATION CAPACITY

4.1 Effect of concrete strength on plastic deformation capacity

To show the effect of concrete strength on the

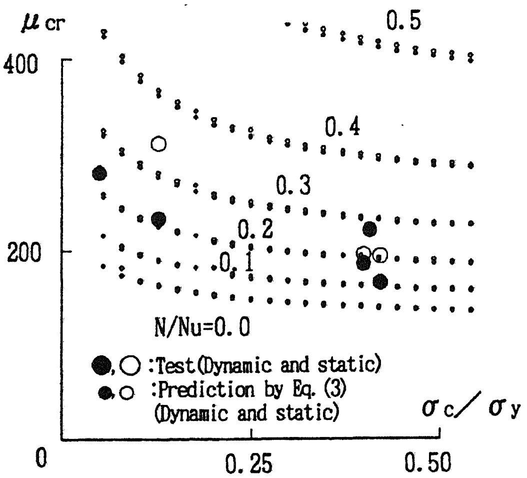


Fig. 7 Accumulated plastic deformation capacity of test results and prediction by Eq. (3).

deformation capacity of the members, the accumulated plastic deformation until the occurrence of crack in relation with the concrete strength filled in tube is given in Fig. 7 in which the accumulated plastic deformation is defined in each direction of displacement. Although the axial loads of the specimens are different among them, it is clearly shown that the plastic deformation capacity decreases as the strength of concrete increases. This behavior means that we should pay attention to the ratio of concrete strength to steel strength in the design of concrete-filled steel tube.

4.2 Prediction of plastic deformation capacity

The occurrence of crack of concrete-filled steel tube subjected to repeated and alternating load has been analyzed under the following assumptions which are explained in Fig. 8.

a) The cross section of member remains plane during bending until crack occurs.

b) Stress in steel tube is equal to the yield stress.

c) Stress distribution of concrete is given by the equivalent stress whose value is assumed to be 70 percents of the compression strength of concrete.

d) When accumulated plastic tension strain (εt) reaches a critical value (εt)cr, crack of steel tube will occur.

Under these assumptions the equation to express the plastic deformation capacity is derived.

According to the assumption a), the tension strain (εt) in the tube is expressed by Eq. (1), in which $\kappa/\kappa y$ is ductility ratio expressed by curvature.

$$\varepsilon t/\varepsilon y=(1-\cos(\theta n))\,\kappa/\kappa y \qquad (1)$$

where θn is the angle to define the neutral axis as explained in Fig. 8 and derived from the equilibrium of axial forces explained in the assumptions a) and b).

From the assumption d) and Eq. (1), the critical value αcr (=(εt)cr/εy) is given by Eq. (2) in which $\kappa/\kappa y$ is approximated by the ductility ratio (Dc/Dy) expressed by the deflection of member.

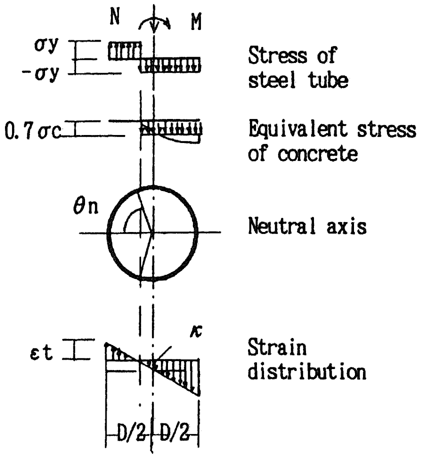


Fig. 8 Assumed strain and stress distribution

$$\alpha cr=(1-\cos(\theta n))\,\Sigma(Dc/Dy) \qquad (2)$$

By the use of Eq. (2), the critical value αcr of each specimen which is defined by the occurrence of crack is obtained and shown in Table. 1. In spite that the concrete strength of specimen is not the same in each other, the values of αcr are nearly constant. From this result it is concluded that αcr is the characteristic value of steel tube and given by the average value. The effect of loading rate on the value of αcr is neglected because the number of specimen is too small to show it. Finally the accumulated plastic deformation capacity (μcr) can be expressed by the following equation.

$$\mu cr=\alpha cr/(1-\cos(\theta n)) \qquad (3)$$

The calculated results by Eq. (3) are shown in Fig. 7 and compared with test results. In this calculation the effect of loading rate is considered only in the values of σy and σc. (Ref. 2, 3) In Fig. 7 it is shown that Eq. (3) predicts well the test results.

5. CONCLUSION

Under strong seismic load, steel tube members filled with super-high strength concrete may fail in brittle-fracture which is caused from crack of steel tube. The plastic deformation capacity of concrete-filled steel tube can be predicted well by the proposed Eq. (3).

REFERENCES

1) Wakabayashi, M. and et al. 1982. Design of composite structures, New architecture series, No. 42, Shokokusha. (in Japanese)
2) Dilger, W.H. and et al. 1984. Ductility of plain and confined concrete under different strain rates, ACI Journal, Vol. 81, No. 1: 73-81.
3) Fujimoto, M and et al. 1987. The experimental research concern with fracture and deformation of steel brace under dynamic loading, Summaries of AIJ annual meeting, Structures II: 791-798. (in Japanese)