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# INELASTIC BEHAVIOR OF CONCRETE FILLED CIRCULAR STEEL TUBULAR COLUMNS SUBJECTED TO UNIFORM CYCLIC BENDING MOMENT

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## ABSTRACT

In order to investigate the inelastic behavior of concrete filled circular steel tubular columns, experimental studies were conducted. Eight one quarter-scale annealed specimens were tested under constant axial load and increasing uniform bending moment. Five specimens were subjected to monotonic bending and three specimens were subjected to alternately reversed cyclic bending moment. Test results demonstrated the large ductility of concrete filled circular steel tubular columns. In the monotonic bending test increasing of bending moment capacity due to confinement effect was recognized, but this increasing was slightly reduced in the cyclic bending test. Hysteretic behavior of specimens subjected to cyclic bending was influenced distinctly by the magnitude of applied axial load. Even for specimen subjected to cyclic bending moment under high axial load, large deformation capacity was recognized, but the very large amount of accumulated axial shortening was also observed.

## KEYWORDS

Concrete Filled Circular Steel Tubular Column; Flexural Behavior; Uniform Bending Test; Axial Load Ratio; Ductility; Bending Moment Capacity; Axial Shortening

## INTRODUCTION

Concrete filled steel tubular columns are noted for their high seismic performance and used mainly for columns of tall buildings in Japan. Due to large shear force capacity, concrete filled steel tubular columns predominantly fail in flexure. Therefore, it is important for structural design to elucidate their inelastic flexural behavior. In Japan and other countries of high seismic risk, the vast majority of experimental studies discussed on shear-bending tests of members(Sakino and Tomii, 1981; Sakino and Ishibasi, 1985; Tsuji and Yang, 1994; etc.). Shear-bending tests produce the condition of columns in moment resisting frame subjected to seismic horizontal load, but on the other hand their test results contain the large effects of moment gradient and restriction from strong rigid edge loading beams. It is very difficult to remove their effects.

The purpose of this investigation is to elucidate the inelastic flexural behavior of concrete filled circular steel tubular columns more accurately. In order to obtain flexural behavior of section without the effects of edge restriction, uniform bending tests under constant axial load were conducted. In this paper the test results are reported and discussed.

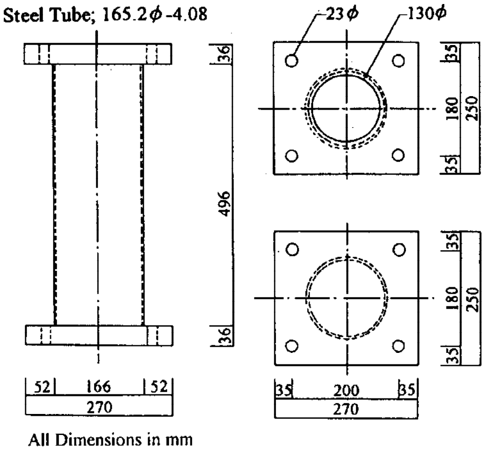


Fig. 1. Details of the specimen

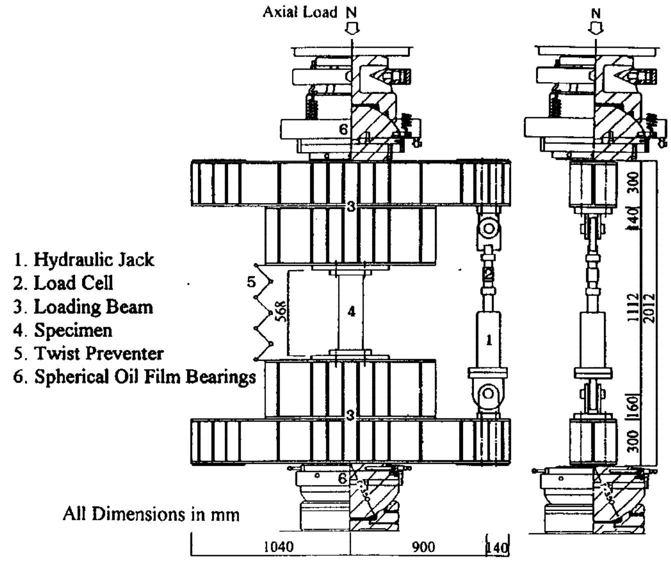


Fig. 2. Test device

Table. 2. Mechanical properties of steel tube

| Specimen Name | Type of Test | Concrete Strength $_c\sigma_B$ (MPa) | N/No | Type of Bearings | exMu (kN-m) | clMu (kN-m) | exMu / clMu |
|---|---|---|---|---|---|---|---|
| VMAC | stub column | 33.1 | ----- | ----- | (689) | (654) | 1.05 |
| CMAC | | ----- | ----- | ----- | (1428) | (1294) | 1.10 |
| CMA0 | monotonic bending | 31.3 | 0.0 | H | 43.6 | 39.0 | 1.12 |
| CMA2 | | | 0.2 | H | 48.0 | 43.5 | 1.10 |
| CMA4 | | | 0.4 | H | 47.6 | 41.6 | 1.14 |
| CMA6 | | | 0.6 | H | 41.4 | 33.4 | 1.24 |
| CMA8 | | | 0.8 | H | 31.6 | 19.1 | 1.65 |
| CCA2 | reversed bending | 33.6 | 0.2 | H | 47.2 | 44.2 | 1.07 |
| CCA4 | | | 0.4 | C | 44.9 | 42.3 | 1.06 |
| CCA6 | | | 0.6 | C | 46.2 | 34.1 | 1.35 |

Remarks: 1. N/No is axial load ratio, where N is applied axial force, and No is nominal squash load (=$_cA\,_c\sigma_B + _sA\,_s\sigma_y$).
2. H indicates spherical oil film bearings and C indicates cylindrical bearings.
3. exMu is experiential ultimate moment and clMu is theoretical full plastic moment.
Values in the parentheses indicate experimental ultimate axial load or nominal squash load (kN).

## EXPERIMENTAL PROGRAM

### Specimens

Eight one quarter-scale specimens were tested under constant axial load and increasing approximately uniform bending moment. Three specimens were subjected to alternately reversed cyclic bending and the others were subjected to monotonic bending moment. Both of hollow and concrete filled stub column compression tests were also conducted. External diameter of circular steel tube was 165.2mm and ratio of external diameter to wall thickness was 40.5. Ratio of clear height of specimens to external diameter was 3.0. Both ends of steel tube were welded to steel plates with thickness of 36 mm. The details of specimen are shown in Fig. 1. All steel tubes were annealed to remove residual stresses in the cross section. Table 2 shows material properties of steel tube obtained from coupon tensile test. Yield stress of steel tube was 317MPa. Cylinder strength of concrete was 31.3MPa(at the age of monotonic bending tests), 33.1MPa(at the age of stub column tests) or 33.6MPa(at the age of cyclic bending tests). Main variable was a magnitude of axial load ratio which was defined by ratio of applied axial load to nominal squash load No (=$_cN_o + _sN_o = _cA\,_c\sigma_B + _sA\,_s\sigma_y$, where $_c\sigma_B$ is the cylinder strength of concrete and $_s\sigma_y$ was the yield stress of steel tube, $_cA$ and $_sA$ are sectional areas of concrete and steel tube, respectively). Axial load ratios were taken as five levels from 0 to 0.8 in monotonic bending tests and three levels of 0.2, 0.4, 0.6 in cyclic bending tests.

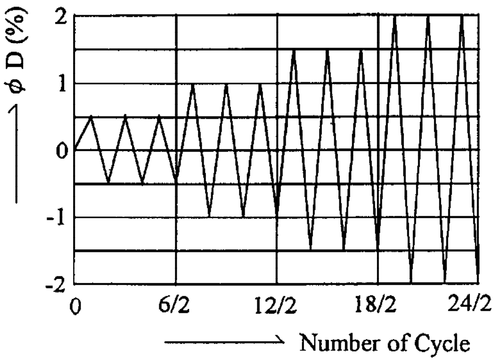
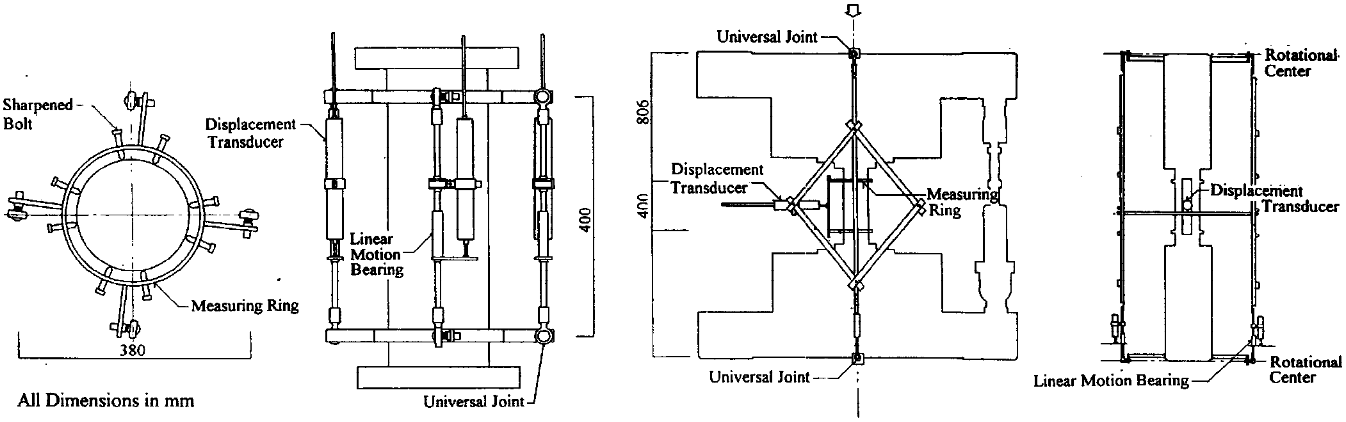


Fig. 3. Loading program

Table. 2. Mechanical properties of steel tube

| Yield Stress $s\sigma_y$ (Mpa) | Tensile Strength $s\sigma_u$(Mpa) | $\frac{s\sigma_u}{s\sigma_y}$ | Elongation (%) | $\varepsilon_{st}$ (%) |
|---|---|---|---|---|
| 317 | 429 | 0.738 | 25.8 | 1.56 |

Note: $\varepsilon_{st}$ is the strain at initiation of strain hardening



(a) Vertical displacement measuring device (b) Horizontal displacement measuring device

Fig. 4. Measuring device

## Test Procedure and Measurements

Test device is shown in Fig. 2. Bending moment was applied by a hydraulic jack attached to loading beams. Axial load was applied by a hydraulic universal testing machine through cylindrical bearings or spherical oil film bearings. Axial load was kept constant by adjusting the load of testing machine for each change in the load of the hydraulic jack. Even though not indicated in the figure, counterweight was equipped to balance the weight of test devise. Cyclic bending tests were conducted in a manner of controlling curvature. Loading program is shown in Fig. 3.

Two steel rings were equipped as shown in Fig. 4(a) for measurements. The distance of both rings was 400mm. Inter-ring longitudinal displacements were measured by using four transducers to obtain rotations and axial shortenings of specimens. Horizontal displacements from rotational center of test device were measured by using the device shown in Fig. 4(b) to calculate N-Δ moments Both longitudinal and circumferential strains were measured by strain gauges mounted to the outside surface of the steel tube.

## TEST RESULTS AND DISCUSSION

## Stub Column Tests

Figure 5 shows axial load-longitudinal strain relationships obtained by stub column tests. In case of the concrete filled steel tube, axial load exceeded nominal squash load and 10 percent increasing of capacity was recognized. In case of the hollow steel tube, load-strain relationships have clear yield point and yield plateau, and axial yield load was nearly equal to nominal squash load. Therefore, it can be said that residual stresses were almost removed.

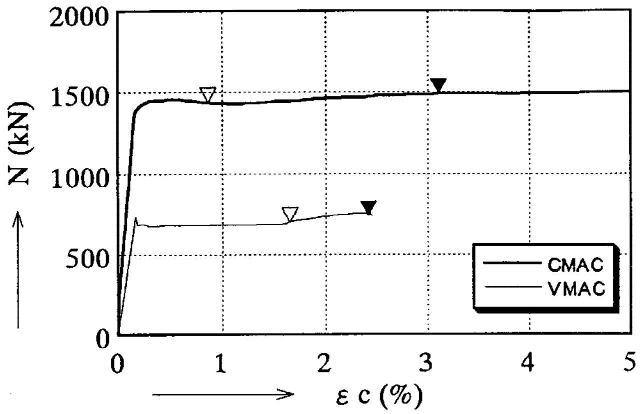


Fig. 5. Axial load-longitudinal strain relationships

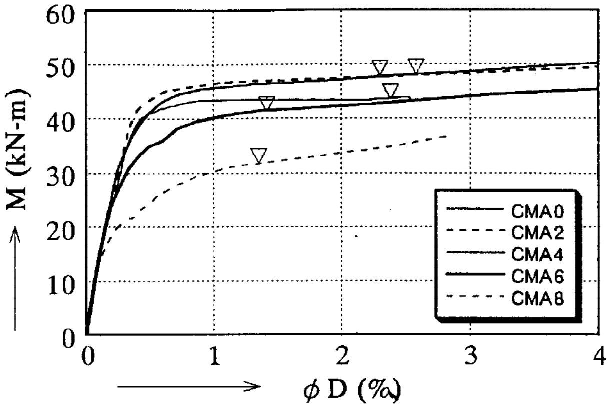


Fig. 6. Moment-curvature relationships for specimens subjected to monotonic bending

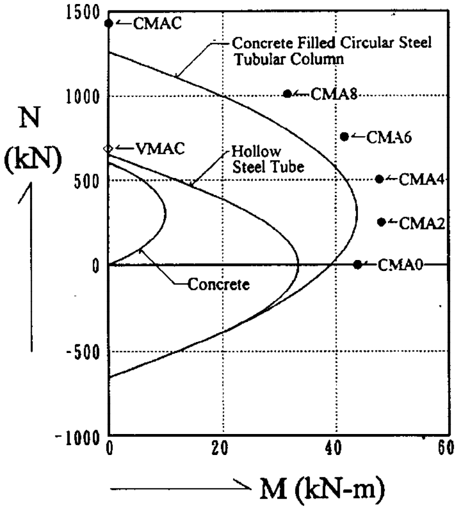


Fig. 7. Axial load-ultimate moment interaction curves

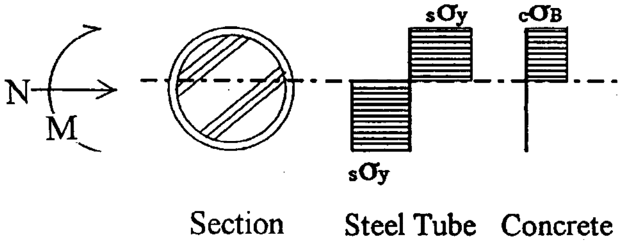
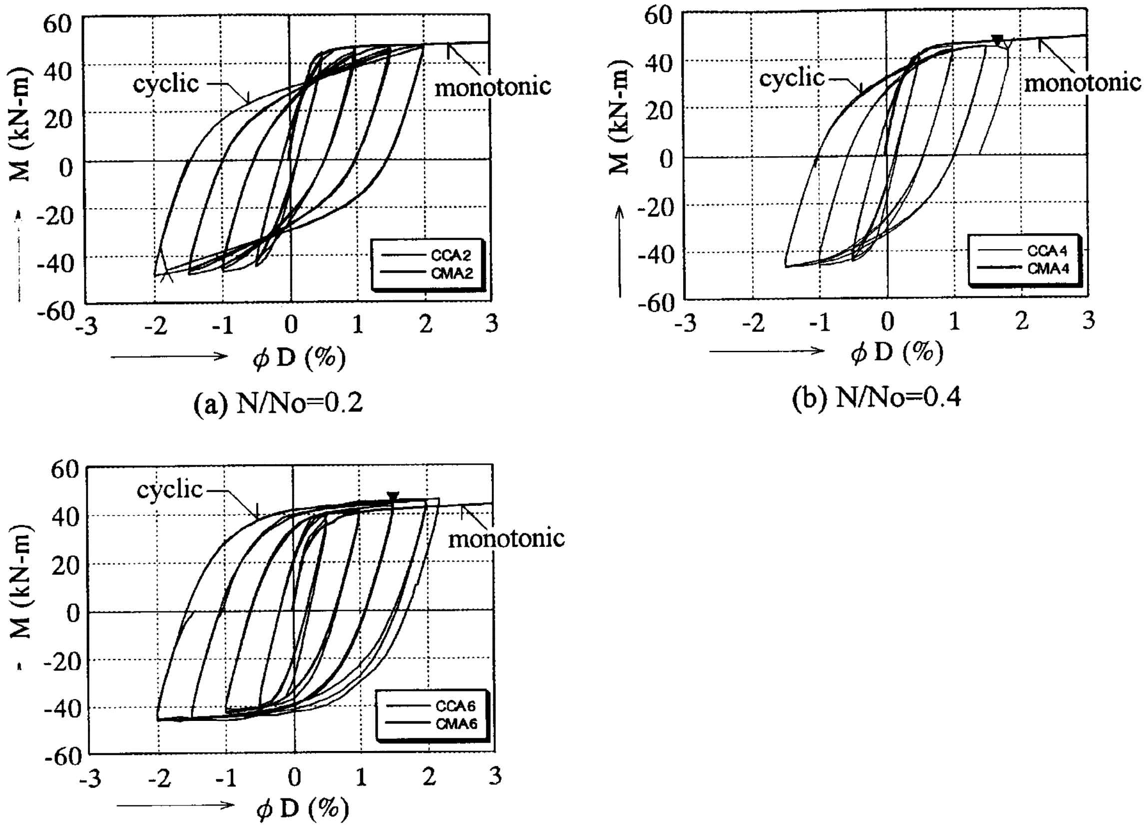


Fig. 8. Assumed stress blocks

Monotonic Bending Tests

Figure 6 shows moment-curvature relationships of specimens subjected to monotonic bending. The ordinate is a bending moment of mid height section including N-Δ moment, and the abscissa is a non-dimensional curvature which is the product of inter-ring average curvature φ and external diameter D. Decreasing of bending moment capacity was not observed for all specimens. Remarkable yield plateau in moment-curvature relationships was observed for the specimens subjected to lower axial load of N/No≦0.4 (CMA0, CMA2, CMA4), but was not observed for the specimens subjected to higher axial load of N/No≧0.6 (CMA6, CMA8). Remarkable local buckling was not observed in any specimen.

Figure 7 shows a theoretical interaction curve between the axial load and ultimate bending moment along with the experimental results. The theoretical ultimate bending moments are ideal full plastic moments obtained by assuming stress blocks shown in Fig. 8. To exclude the strain hardening effect, the bending moments at the point where the maximum longitudinal strain in steel tube reached ε st are adopted as experimental ultimate bending moments exMu. Where ε st is the strain at the initiation of strain hardening in the coupon tensile test (cf. Table 2). These moments are indicated in Fig. 6 by symbol▽. Comparisons between the ratio of exMu to theoretical full plastic moments clMu are shown in Table 1. At any axial load ratio level, experimental ultimate moments exceed theoretical full plastic moments, the reason for which is considered to be a confinement effect. This effect results in increasing of compressive strength of concrete introduced by a confinement of steel tube, and also in increasing of tensile strength of steel tube introduced by restrain from infilled concrete.



(a) N/No=0.2

(b) N/No=0.4

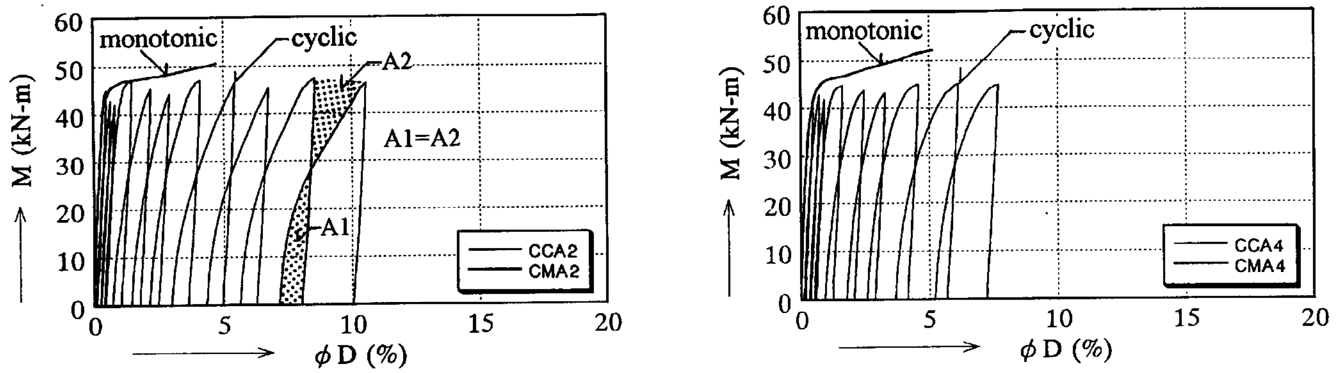
(c) N/No=0.6

Fig. 9. Moment-curvature relationships

Cyclic bending Tests

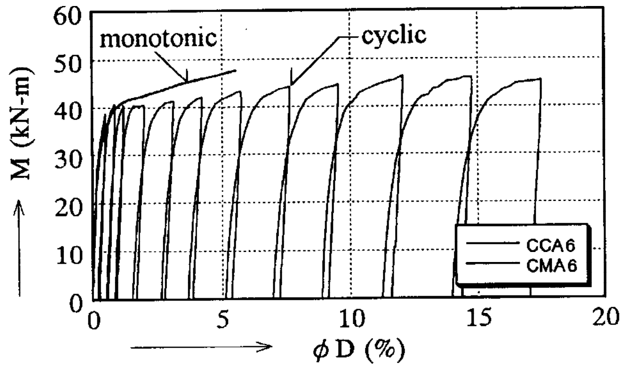
Hysteretic Loop. Figure 9 shows moment-curvature relationships of specimens subjected to cyclic bending. The ordinate and abscissa are same as those in Fig 6. The monotonic moment-curvature relationship of the specimen under corresponding axial load ratio is also shown for comparison in each figure of Fig. 9. Symbols ▼ and ∨ in figure indicate the initiation of local buckling observed by the naked eye and the point of occurrence of cracking at the ends of steel tube welded to end plates, respectively. Remarkable deterioration of moment capacity is not observed even in the hysteretic loops of the specimen subjected to high axial load of N/No=0.6. Therefore, it can be said that concrete filled circular steel tubular columns have large flexural ductility. Hysteretic behavior was influenced distinctly by the magnitude of axial load; in the case of specimens subjected to lower axial load of N/No $\leqq$0.4 (CCA2, CCA4), a pinching effect was slightly observed in the hysteretic loops and skeleton curves of loops were similar to monotonic moment-curvature relationships, in case of specimen subjected to higher axial load of N/No=0.6 (CCA6), a shape of hysteretic loops was spindle type and skeleton curve was not similar to monotonic moment-curvature relationship.

Bending Moment Capacity. Comparisons between the ratio of experimental ultimate moment exMu to theoretical full plastic moment clMu are shown in Table 1. The clMu is calculated by the method described in the preceding section. The exMu of the specimen subjected to cyclic bending is defined as the maximum bending moment in the hysteretic loops, because the maximum bending moment which do not include the strain hardening effect cannot be defined from strain measurements. For specimens subjected to lower axial load of N/No$\leqq$0.4 (CCA2, CCA4), the ratio of exMu to clMu is larger than 1.0, but smaller than that for the specimen subjected to monotonic bending under the corresponding axial load, the reason for which is due to the effect of local buckling of steel tube and deterioration of concrete. For the specimen subjected to higher axial load of N/No=0.6 (CCA6), the ratio of exMu to clMu is larger than that for the specimen subjected to monotonic bending, the reason for which is considered to be strain hardening effect due to cumulative large compressive strains, which results in the enhancement of bending



(a) N/No=0.2

(b) N/No=0.4



(c) N/No=0.6

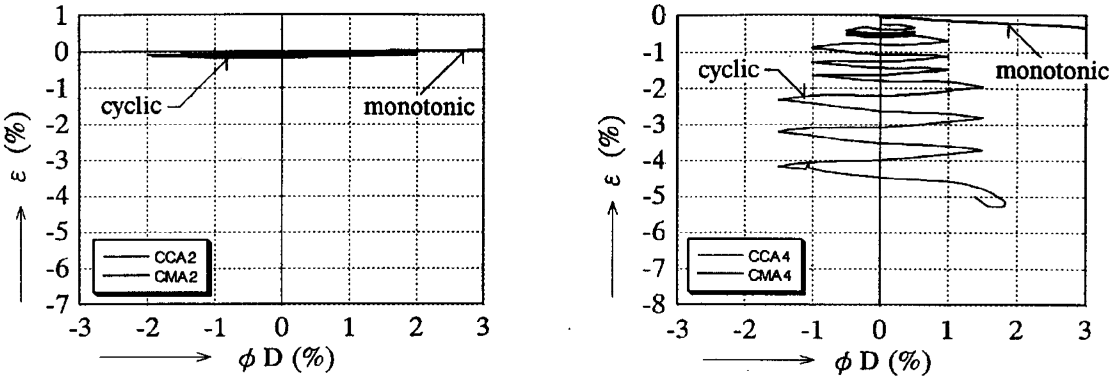
Fig. 10. Moment-cumulative curvature relationships

moment capacity before the degradation due to the local buckling of steel tube becomes more remarkable. It can be said that cyclic bending results in slight decrease of bending moment capacity due to the effect of local buckling of steel tube if the axial load is relatively low, but results in slight increase due to the strain hardening effect if the axial load is high, hence the cumulative compressive strains are large.

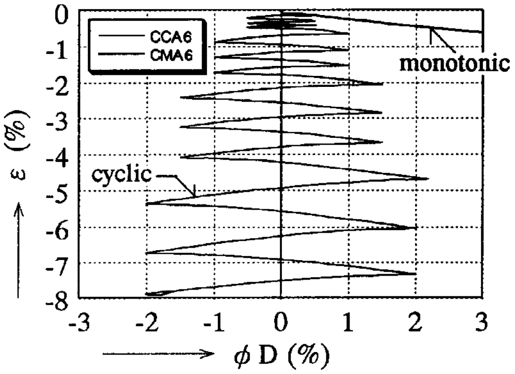
Cumulative Deformation. Figure 10 shows moment-cumulative curvature relationships of specimens subjected to cyclic bending, and monotonic moment-curvature relationship of the specimen under corresponding axial load ratio are also shown for comparison. The moment-cumulative curvature curves were obtained by overlapping the half loops in positive direction. Each half loop is overlapped so that an envelop curve of the obtained moment-cumulative curvature curve has the same energy absorption as the original loops have, in other words area A1 shown in Fig. 10(a) is equal to area A2.

The following observations can be made, if the comparisons between specimens are done by a manner shown in Fig. 10 from the view point of energy absorption capacity.

(1) Slight degradation due to the cyclic bending can be seen in all specimens. It is noteworthy, however, that the deformation capacity of specimens subjected to cyclic bending are still satisfactory.
(2) The total cumulative curvature of the specimen under high axial load (CCA6) is much larger than that of the specimen under low axial load (CCA2), even though the both specimens are loaded according to same loading program shown in Fig. 3. This means that the higher the axial load applied is, the larger the energy absorption of specimen is.
(3) Decreasing of moment capacity in three successive cycles at the same curvature amplitude is observed for the specimen under low axial load (CCA2), increasing of that is observed for the specimen under high axial load (CCA6); the former phenomenon is observed in typical RC columns, the latter in typical steel columns with a compact section.

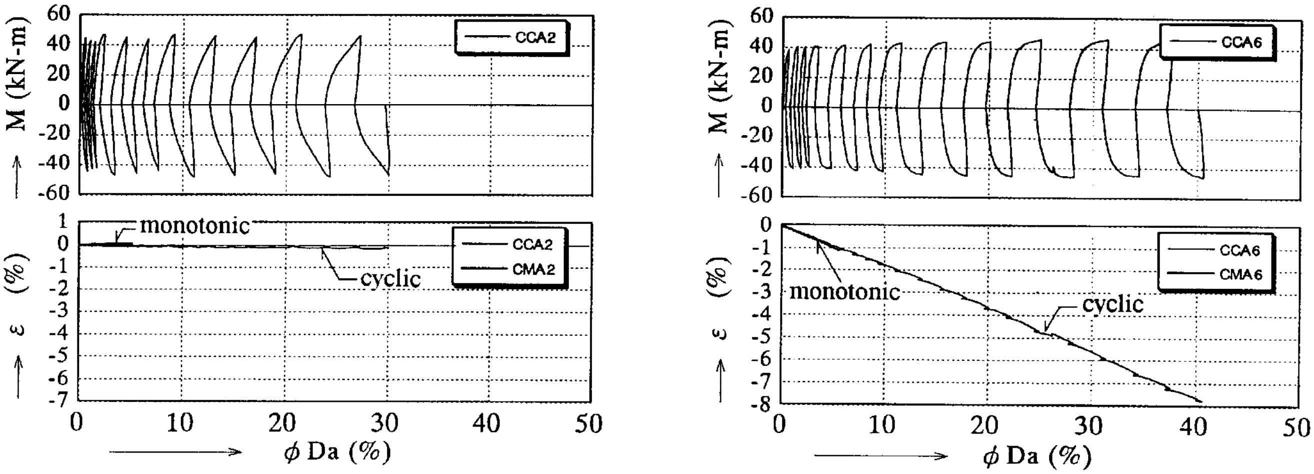


(a) N/No=0.2 (b) N/No=0.4



(c) N/No=0.6

Fig. 11. Longitudinal strain-curvature relationships



(a) N/No=0.2 (b) N/No=0.6

Fig. 12. Longitudinal strain-cumulative curvature relationships

Axial Shortening. Figure 11 shows longitudinal strain-curvature relationships of specimens subjected to monotonic and cyclic bending. When subjected to cyclic bending moment, axial shortenings were accumulated and became large compared with the case of monotonic bending. The accumulated amount of axial shortening was influenced distinctly by the magnitude of axial load. It should be noted that total axial shortening reached to the value as large as 7.5 percent of the column height in case of the specimen subjected to cyclic bending under high axial load (CCA6). Figure 12 shows axial shortening-cumulative curvature relationships. The cumulative curvatures were obtained by simply connecting the loops of both positive and negative direction. Figure indicates that axial shortenings have linear relation to cumulative curvature.

## CONCLUSIONS

Concrete filled circular steel tubular columns were tested under increasing uniform bending moment and constant axial load. In the monotonic bending test increasing of bending moment capacity due to confinement effect was observed, but this increasing slightly reduced in the cyclic bending test. Test results demonstrate the ductile inelastic flexural behavior of concrete filled circular steel tubular columns. Hysteretic behavior of specimens subjected to cyclic bending moment was influenced distinctly by the magnitude of axial load. The concrete filled circular steel tubular column subjected to cyclic bending moment behaved in a very ductile manner, and absorbed large energy even under high axial load of 0.6No. It should be noted, however, that the very large amount of accumulated axial shortening took place in the column subjected to cyclic bending under high axial load.

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