Effect Of Lateral Reinforcement On Mechanical Behavior Of Concrete Under Cyclic Loading

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繰り返し荷重を受けるコンクリートの力学的挙動におよぼす帯筋の拘束の影響

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The object of this investigation is to obtain the behavior of concrete confined by lateral reinforcement (hoop) under cyclic loading. The variables in this experiment are as follows: three different spacing of hoops, two different concrete covers, and four types of loading pattern.

The following conclusions were obtained.

(1) The lateral reinforcement is very effective for the improvement of the ductility of concrete.

(2) The stress-strain envelope curves under cyclic loading locate in the lower portion than those under monotonic loading in the range of large strain.

(3) Residual strain under cyclic loading, initial stiffness of unloading curve, and mean stiffness of reloading curve are very affected by the spacing of hoop, concrete cover and type of loading.

1. INTRODUCTION

The lateral reinforcement such as stirrup, tie, hoop or spiral reinforcement has the following effect in reinforced concrete members: (1) carrying of shearing force, (2) prevention of the buckling of longitudinal reinforcement and (3) confinement of concrete enclosed by the lateral reinforcement. Many researches have been carried out on the effect (1), which is a fundamental effect among them. However, the practical date on the effect (3), which is a secondary effect, are not sufficient. It is known that concrete confined by the lateral reinforcement has higher strength and larger ductility than unconfined concrete, but not quantitatively. Particularly, the latter merit is taken notice as one of the effective methods to improve the ductility of reinforced concrete members.

One of the most fundamental investigations on the effect of lateral confinement on the

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strength and deformation properties of concrete was reported by Richart, Brandtzaeg and Brown in 1928 [Ref. 1]. They discussed the mechanical behavior of concrete subjected to triaxial compression and of spirally reinforced concrete columns. Blume, Newmark and Corning [Ref. 2] have first proposed an important equation for the strength of confined concrete by using the test results from Richart et al. After that, Sargin, Ghosh and Handa [Ref. 3], Sundara Raja Iyengar, Desayi and Reddy [Ref. 4], et al., examined the confined effect of lateral reinforcement on the strength of concrete, and Somes [Ref. 5], Sargin et al. [Ref. 3], Kokusho and Hanashima [Ref. 6], Yamada, Kawamura and Taira [Ref. 7], Shimazu and Hirai [Ref. 8], Suzuki and Nakatsuka [Ref. 9], Muguruma, Tanaka and Sakurai [Ref. 10] and authors [Ref. 11] reported the effect of the spacing or volumetric ratio of lateral reinforcement. Also, Burdette and Hilsdorf [Ref. 12], Sundara Raja Iyengar et al. [Ref. 4], Uemura and Morimura [Ref. 13] examined the effect of the type of lateral reinforcement on the degree of confinement.

Only the behavior of confined concrete under static loading was discussed in all investigations mentioned above. On the other hand, Park and Kent [Ref. 14], and Okamoto and Yagishita [Ref. 15] reported the stress-strain relation of confined concrete under cyclic loading. However, detailed test data were not described in these two reports and there are few test data for the confined effect of lateral reinforcement under cyclic loading.

The object of the present paper is to obtain the behavior of concrete confined by lateral reinforcement (hoop) under cyclic loading.

2. EXPERIMENTAL PROCEDURE

The experiment was carried out in accordance with the test program as shown in Table 1.

Table.1 Outline of experiment

Notation of specimen	Spacing of hoop S (cm)	Cover of hoop C (cm)	Method of loading
P	—	—	Type-S : Monotonic loading
S 10 - C 0	10	0	Type-R1 : Cyclic loading with incremental
S 10 - C 1.5	10	1.5	strain amplitude
S 5 - C 0	5	0	Type-R2 : Cyclic loading with constant
S 5 - C 1.5	5	1.5	stress amplitude
S 2.5- C 0	2.5	0	Type-R3 : Cyclic loading with constant
S 2.5- C 1.5	2.5	1.5	strain amplitude

(1) Test Specimen

Eighty-eight concrete prisms of 15×15 cm in cross section and 45 cm in height were prepared for the experiment. Round bar of 6 mm in nominal diameter (cross sectional area $=0.256\ mm^2$, yield strength$=3160\ kg/cm^2$, tensile strength$=5170\ kg/cm^2$, elongation$=22.1\%$) was used as hoop and $\phi 3.2$ mm round bar was used as longitudinal reinforcement to keep the spacing of hoop to a specified value. The variables in the experiment are as follows: three different spacings of hoop (S$=10$ cm, 5 cm and 2.5 cm) and two different concrete covers (C$=0$ cm and 1.5 cm). $\phi 10 \times 20$ cm control cylinders were also prepared to obtain the properties of concrete used.

(2) Fabrication and Curing of Specimen

Ordinary portland cement, Yahagi river sand (maximum size = 2.5 mm) and Tenryu river gravel (size range = 2.5-15 mm) were used for concrete. Mix proportion of concrete was 1 : 2.27 : 2.47 and water-cement ratio (W/C) of concrete adopted was 60% by weight. Specimens were cast in steel molds and stored in a laboratory during 24 hours after casting, then they were remolded and cured in water at a temperature of $20° \pm 1°C$ until just before the test. Tests were carried out at the age of 28 days.

Compressive strength and splitting tensile strength of concrete obtained from ϕ 10×20 cm control cylinder specimens were 271 kg/cm² and 25.7 kg/cm² in average, respectively.

(3) Method of Loading and Measurement

A new type of stiff testing machine shown in Fig. 1 was used for the loading of specimen. The strain rate of specimen was controlled by the wedge action of steel blocks installed parallel to the specimen. The load was transmitted from the machine through steel platens having the cross section as same as the tests pecimen.

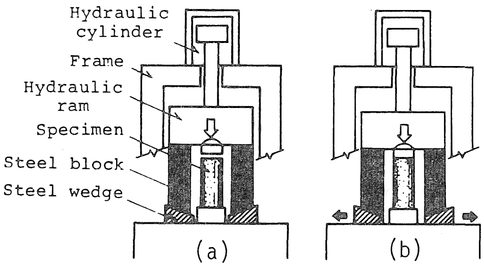

Fig.1 Mechanism of strain control of stiff testing machine

Four types of loading pattern listed in Table 1 were adopted in this tests. Type-S loading indicates the monotonic loading, and Type-R 1, R 2, and R 3 loading are the cyclic loadings. In Type-R 1 loading, the stran increment at the peak was kept to 1×10^{-3} at each loading cycle and in Type-R 2 loading, maximum load level of first ten cycles was kept to about 90% of static compressive strength and that of following ten cycles about 95%. In Type-R 3 loading, maximum strain at each loading cycle (ε_k) was kept to the strain at muximum load (ε_m) in first ten cycles, and $2\varepsilon_m$ in the following ten cycles.

As shown in Photo. 1, the longitudinal strain (ε) was measured by two differential transformers (D. T. F.) attached to the specimen (measuring length = 30 cm). In addition, the displacement between upper and lower loading platens was measured by two dial gage type linear transtormers (D. G.). During the loadings and unloadings the strain rate of specimen was controlled in about 1×10^{-3}/minute until the strain (ε) reaches to 10×10^{-3}.

3. TEST RESULTS AND DISCUSSION

Typical stress (σ) - strain (ε) curves of confined concrete are illustrated in Fig. 2.

(1) Fracture Mode of Specimen

Photo. 2 shows the typical fracture mode of prism specimen. In the unconfined concrete, the formation of slip planes due to shear-compression was observed at both ends of specimen and the cleavage type of fracture mode was observed at the center portion. In the confined

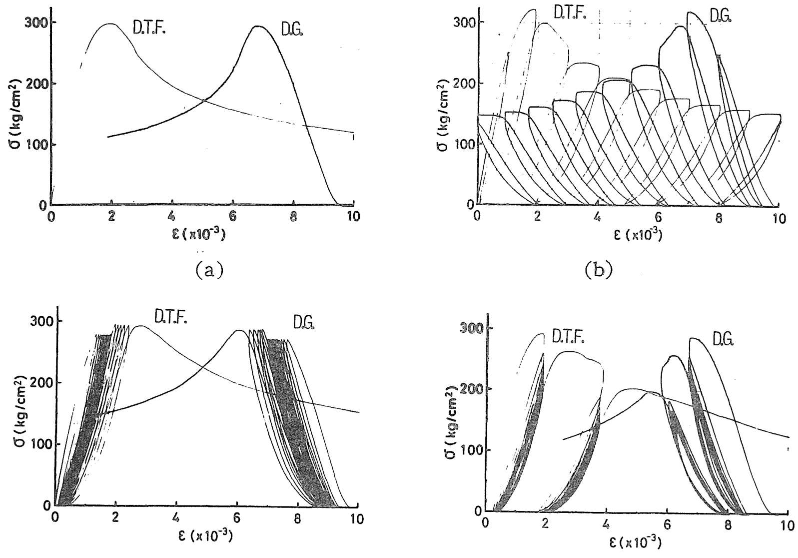

Fig.2 Typical stress (σ) - strain (ε) curves
(a) Type-S loading (b) Type-R1 loading
(c) Type-R2 loading (d) Type-R3 loading

concrete with hoop of C=0 cm, distinctive damages were not appeared up to $\varepsilon=10\times10^{-3}$. On the other hand, in the confined concrete with hoop of C=1.5 cm, concrete cover was spalled off at the center portion. In general, shear slip planes were formed between two adjacent hoops in the confined cocrete.

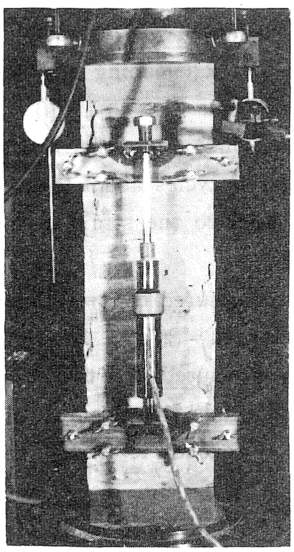

Photo.1 Strain measurement setup

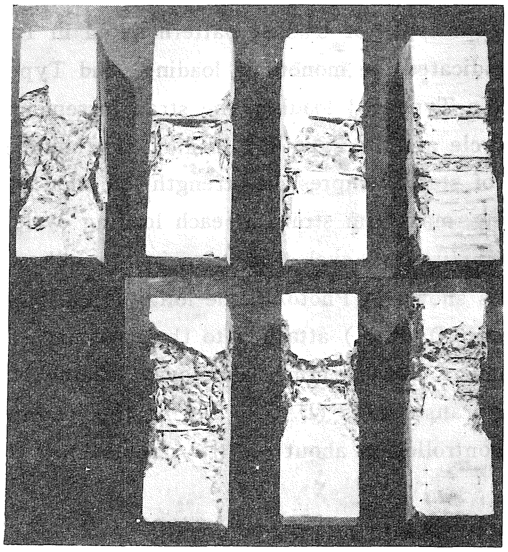

Photo.2 Fracture mode of specimens

According to the result of strain measurement of hoop, the yielding of most hoops occurred at about 90 % of maximum load, regardless of the hoop spacing and concrete cover.

(2) Compressive Strength and Strain at Maximum Load Under Type-s Loading

The relations between the relative compressive strength (F_c/F_{co}) or the relative strain at the maximum load ($\varepsilon_m/\varepsilon_{mo}$) and the volumetric ratio of hoop (P_w) are shown in Fig. 3, where F_{co} and ε_{mo} are the compressive strength and the ultimate strain of unconfined prism specimen, respectively. As shown in Fig. 3, the values of F_c/F_{co} and $\varepsilon_m/\varepsilon_{mo}$ increase with the increase of P_w and the rate of increase in $\varepsilon_m/\varepsilon_{mo}$ is larger than that in F_c/F_{co}, i. e., the lateral reinforcement is very effective for the improvement of the ductility of concrete.

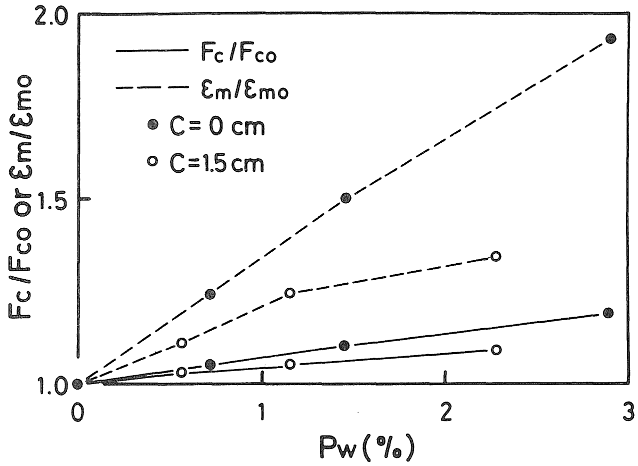

Fig.3 Relation between relative compressive strength (F_c/F_{co}) or relative strain at maximum load ($\varepsilon_m/\varepsilon_{mo}$) and volumetric ratio of hoop (P_w)

(3) Stress-Strain Envelope Curve Under Type-R1 Loading

Envelope curves of σ-ε relation under Type-R1 loading are shown in Fig. 4, where σ-ε curves under monotonic (Type-S) loading are also illustrated. it is shown in Fig. 4 that the envelope curves are similar to σ-ε curves under monotonic loading in the range of strain (ε) less than about $(3\text{-}4)\times10^{-3}$. However, the curves locate in the lower portion than those under monotonic loading in the range of large strain (ε), namely some deterioration was caused by cyclic loading.

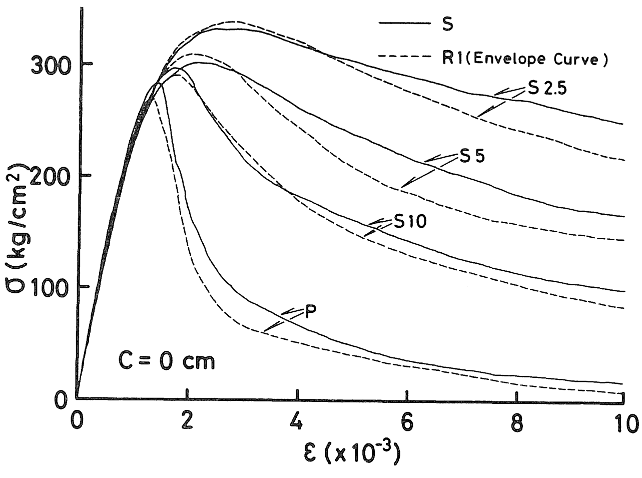

Fig.4 Comparison of envelope curves under Type-R1 loading with σ-ε curve under Type-S loading

The shape of envelope curve of the specimen with large amount of hoop can be approximately expressed by the equation proposed by Popovics [Ref. 16], but that of the specimen with small amount of hoop can not be fully expressed by Popovics's equation.

(4) Relation Between Residual Strain and Strain at Load Reverse Under Type-R1 Loading

The relation between the residual strain (ε_r) and the strain at load reverse (ε_u) is shown in Fig. 5, where they are normalized by dividing by the strain at the muximum load (ε_m). The $\varepsilon_r/\varepsilon_m$-$\varepsilon_u/\varepsilon_m$ relation in the range of $\varepsilon_u/\varepsilon_m$ larger than 1 is almost linear for the unconfined concrete (P), but this relation is expressed by a slightly convexed curve for the confined concrete. The relation in the confined concrete with C=0 cm is little affected by the spacing of hoop, while for the specimen with C=1.5 cm, the value of $\varepsilon_r/\varepsilon_m$ at a given value of $\varepsilon_u/\varepsilon_m$ increases with the increase of the spacing of hoop.

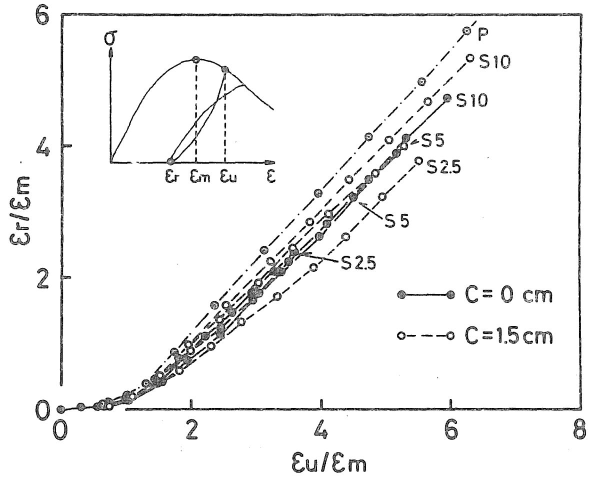

Fig.5 Relation between relative residual strain ($\varepsilon_r/\varepsilon_m$) and relative strain at load reverse ($\varepsilon_u/\varepsilon_m$) (Type-R1 loading)

(5) Initial Stiffness of Unloading Curve and Mean Stiffness of Reloading Curve

Fig. 6 shows the relations between E_u/E_i and $\varepsilon_u/\varepsilon_m$, and between E_r/E_i and $\varepsilon_r/\varepsilon_m$, where E_u is the initial slope (stiffness) of σ-ε curve when unloading, E_r is the mean slope (stiffness) of the reloading curve and E_i is the initial tangent modulus of virgin curve of each specimen. The purpose of investigating these relation is to obtain an information for modelization of the hysteresis characteristic of confined concrete. Namely, unloading curves can be approximately expressed by the quadratic equation and reloading curves by the linear equation, as previously shown in Fig. 2. It is shown in Fig. 6 that the value of E_u/E_i for the unconfined concrete (P) decreases linearly with the increase of $\varepsilon_u/\varepsilon_m$, however the value does not decreases for the confined concrete with small amount of hoop.

On the other hand, the value of E_r/E_i decreases with the increase of $\varepsilon_r/\varepsilon_m$ and the larger the spacing of hoop and concrete cover, the larger the derrease rate of E_r/E_i is. The mathematical representation of the relations shown in Fig. 6 will be proposed after an additional experiment is carried out.

(6) Relation Between Rate of Increase of Strain Under Type-R2 Loading and Number of Loading Cycle

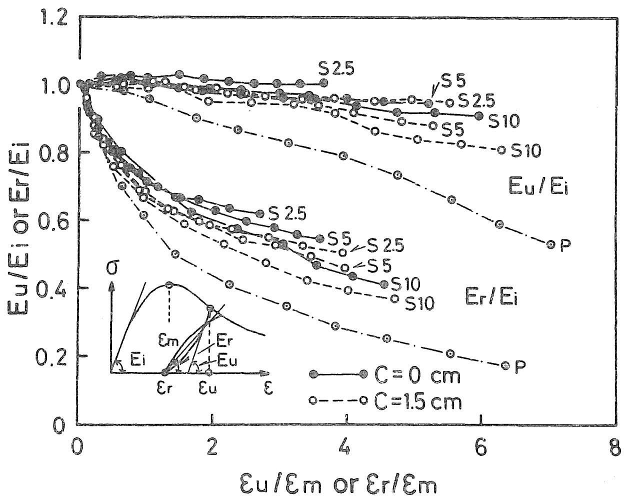

Fig.6 E_u/E_i-$\varepsilon_u/\varepsilon_m$ curve and E_r/E_i-$\varepsilon_r/\varepsilon_m$ curve (Type-R1 loading)

A typical relation between the rate of increase of the upper strain ($\varepsilon_N/\varepsilon_1$) under Type-R2 loading and the number of oading cycle (N) is shown in Fig. 7, which is the result of conretes subjected to about 90% of static compressive strength(F_c) as a constant maximum stress level (σ_k). The value of $\varepsilon_N/\varepsilon_1$ in the confined concrete with C=1.5 cm increases as the spacing of hoop is increased but the value seems to converge to a constant value. On the other hand, the larger the spacing of hoop, the smaller the value of $\varepsilon_N/\varepsilon_1$ is in the confined concrete with C=0 cm. This tendency is reverse, compared with the result for the specimen with C=1.5 cm. This may be resulted from that the peak strain (ε_1) at the upper limit load is larger as the spacing of hoop is smaller for the specimen with C=0 cm. It is suggested from these results that the value of initial maximum strain at first loading cycle has a great influence on the deformation characteristic of confined concrete under cyclic loading.

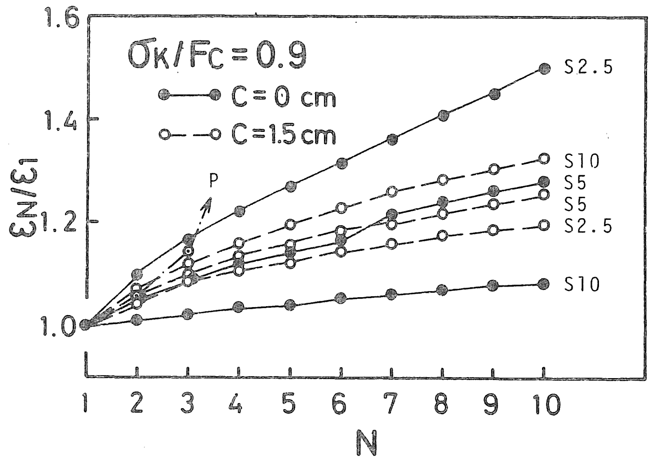

Fig.7 Relation between rate of increase of strain ($\varepsilon_N/\varepsilon_1$) and number of loading cycle (N) (Type-R2 loading)

(7) Relation Between Rate of Decrease of Stress Under Type-R3 Loading and Nnmber of Loading Cycle

Fig. 8 shows the relation between the ratio of stress reduction (σ_N/σ_1) under Type-R3 loading and the number of loading cycle (N), where maximum strain at each loading (ε_k) was kept to the strain at maximum load (ε_m) in first ten cycles, and $2\varepsilon_m$ in the following ten cycles. It is indicated in Fig. 8 that the value of σ_N/σ_1 for the cyclic loading with $\varepsilon_k=\varepsilon_m$ is little affected by the spacing of hoop and concrete cover, and the value of σ_N/σ_1 at N=10 was about 0.75. On the other hand, the value of σ_N/σ_1 for the cyclic loading with $\varepsilon_k=2\varepsilon_m$ is smaller as the spacing of hoop is larger, and the value of σ_N/σ_1 at N=10 was about 0.55 for the unconfined concrete.

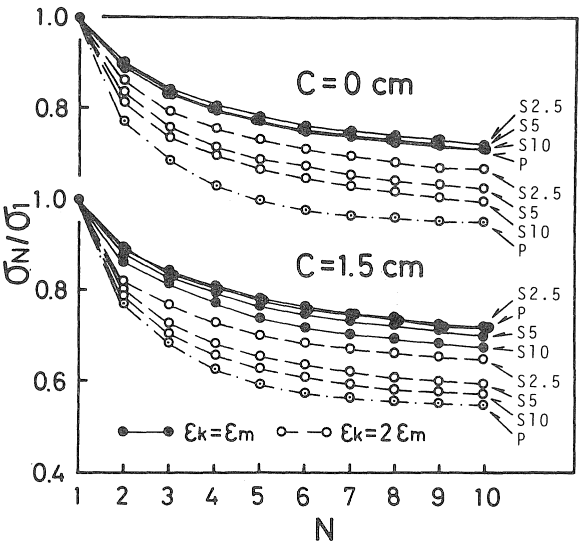

Fig.8 Relation between rate of decrease of stress (σ_N/σ_1) and number of loading cycle (N) (Type-R3 loading)

4. CONCLUSIONS

An experimental investigation was carried out to examine the effects of the spacing of hoop, concrete cover and type of loading on the mechanical behavior of confined concrete.

The following conclusions were obtained as far as this experimental study is concerned.

1) The lateral reinforcement is very effectvie for the improvement of the ductility of concrete.

2) The envelope curve under cyclic loading locates in the lower portion than those under monotonic loading in the range of large strain and some deterioration occurs under cyclic loading.

3) Unloading curves can be approximately expressed by the quadratic equation and reloading curves by the linear equation.

4) The relation between the residual strain (ε_r) and the strain at load reverse (ε_u) is little affected by the spacing of hoop for the confined concrete with concrete cover(C) of 0 cm, while the value of ε_r at a given value of ε_u increases with the increase of the spacing of hoop for the specimen with C=1.5 cm.

5) The initial stiffness (E_u) of unloading curve for the unconfined concrete decreases linearly with the increase of the strain (ε_u) of unloading curve but the value of E_u for the confined conrete with large amount of hoop decreases slightly. The mean stiffness (E_r) of reloading curve decreases with the increasing residual strain (ε_r) and the larger the spacing of hoop and concrete cover, the larger the decrease rate of E_r is.

6) The increase rate of strain ($\varepsilon_N/\varepsilon_1$) in the confined concrete with $C=1.5$ cm under cyclic loading at a constant upper load increases with the increase of the spacing of hoop but the value seems to converge to a constant value. On the other hand, the larger the spacing of hoop, the smaller the value of $\varepsilon_N/\varepsilon_1$ is in the confined concrete with $C=0$ cm.

7) The decrease rate of stress (σ_N/σ_1) under cyclic loading at a constant maximum strain ($\varepsilon_k=\varepsilon_m$) is little affected by the spacing of hoop and concrete cover, but the value under cyclic loading at $\varepsilon_k=2\varepsilon_m$ is smaller as the spacing of hoop is larger.

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