ELASTOPLASTIC BEHAVIOR OF DOUBLY CONFINED R/C COLUMNS IN STEEL TUBE AND HOOPS

Tetsuo YAMAWA*, Hong Tao HAO** and Keisuke MURANAKA***

山川 哲雄，郝 洪 湛，村中圭介

This paper summarizes test results and discusses the elastoplastic behavior, such as lateral strength, ductility and energy absorption capacity, of doubly confined R/C column in steel tube and hoops. The experimental results are compared with the theoretical results. The experimental results have conducted the following remarks. (1) If the amount of transverse reinforcement steel is almost the same, the double confinement method by steel tube and hoops will be superior to the single confinement method by steel tube only on the seismic behavior of the test specimens. (2) The double confinement requires higher strength concrete in order to enhance seismic performance for columns. According to the calculation results, the higher concrete strength is desired to be at least over 30 MPa in cylinder strength of the concrete. This suggestion is approved through the experimental test.

Keywords: confined concrete, hoops, R/C column, seismic performance, square steel tube

1. INTRODUCTION

Non-hooped R/C columns laterally confined in steel tube was proposed by Tomii and his research project team at Kyushu University in 1985[1][2] in order to prevent the brittle shear failures and improve load-carrying capacity, ductility and energy absorption capacity even if a large amount of longitudinal reinforcement (ratio of total area of longitudinal reinforcement to gross area of section in columns $P_L = 0.684$) was arranged in R/C short columns (shear span to depth ratio $M/VD=1.0$). This method also has the advantage that the steel tube itself acts as a column permanent form work. Experimental results reported in Ref. 2 showed that a hysteretic behavior of the tubed columns with $M/VD=1.0$ was excellent except for the tubed square columns with $P_L = 0.684$, in which a pinching effect in hysteretic loop and cyclic degradation of lateral load capacity were observed due to the deterioration of bond stress between longitudinal bars and concrete[1]. This mechanical behavior of the non-hooped square R/C columns was improved by further confinement with thick steel tube[2][3] or with bellows steel tube[4].

From the point of view of further confinement, seismic repair and retrofit of R/C columns, Yamakawa proposed the double confinement method to reinforce square R/C short columns ($M/VD=1.0, P_L = 0.671$) in steel tube and hoops on the basis of the preliminary research[5], and had carried out an experimental study on axial compression behavior of doubly confined R/C columns in steel tube and hoops. A total of 34 test specimens were loaded axially and concentrically in a 5-MN electro-hydraulic universal testing machine. As a result, the following conclusions were obtained[6].

(1) If the amount of transverse reinforcement steel is almost the same, the double confinement method by steel tube and hoops will be much superior to the single confinement method by steel tube only on compressive strength and ductility for confined concrete.

(2) Compressive strength for concrete doubly confined in steel tube and hoops may be approximately estimated by the simply superposed strength method using the known equations[7][8].

Based upon the experimental results mentioned above, an experimental program consisted of eight test specimens, with average compressive strength of 23.5 and 40.1 MPa, respectively was carried out under the combination of cyclic lateral forces and constant axial load in order to discuss seismic performance and its behavior of doubly confined R/C columns in steel tube and hoops.

2. TEST SPECIMENS

The details of the test specimens of R/C column are listed in Table 1. The test specimens are classified into two groups according to the difference in compressive strength of concrete. Average strength of low and high concrete cylinder is 23.5 MPa and 40.1 MPa respectively. In the designation on the specimens, the fifth letter L or H represents low or high compressive strength of concrete respectively. The mechanical properties and slumps of concrete are shown in Table 2. The maximum size of the aggregate was 13 mm. The mechanical properties of steel tubes and reinforcement bars are shown in Table 3. The specimen is about one-third or half scale model. A column size is 250×250×750 mm and its shear span to depth ratio $M/VD$ is 1.5. The stubs are attached to the top and bottom of the column. The total weight of a test specimen is about 1.3 ton. Four specimens in the same series were poured into the standing formswork simultaneously. The R/C columns without steel tube were designed as a shear failure type, especially a bond-splitting failure type. As shown in Table 1, the test specimens in low or high compressive concrete strength were classified into four types according to the transverse reinforcement arrangements. One was a standard R/C column. The others were singly confined R/C column in steel tube and doubly confined R/C columns in steel tube and hoops. Two different transverse reinforcement arrangements were provided to the doubly confined test specimens as shown in Table 1. Wall thickness of the two steel tubes was 6 and 3.2 mm respectively. The grease was coated on inside surface of the steel tube and small gaps (about 5 mm) between the steel tube and stubs were provided so that axial compressive force might not be transmitted through the steel tube. The steel tube plays a role of a transverse reinforcement only. The amount of

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transverse reinforcement steel for doubly confined specimens was designed almost
the same as for singly confined specimens with steel tube (see Table 1). The
amount and arrangement of longitudinal reinforcement bars were common in all
test specimens. The ratio of total area of longitudinal reinforcement to gross
area of the section was 4.38% in all test specimens. This value is close to the highest
limit ($P_h=5\%$) given by Chinese "Design Standard for Concrete Structures
(GBJ10-89)".

3. MEASUREMENTS AND LOADING ARRANGEMENT

Horizontal and vertical displacements, namely the story drift and axial
elongation or shortening of the columns were measured by displacement
transducers. The electric resistance strain gauges were pasted on the steel tube and
reinforcement bars. The locations of the strain gauges were concentrated in
the top, bottom and middle height regions of the columns.

The lateral loading program is shown in Fig. 1. At first several cyclic small
lateral forces were applied to all test specimens in order to obtain the initial lateral
stiffness. Then the loading pattern was a cyclic type with alternating displacement
reversals as shown in Fig. 1. The peak drift angles were increased stepwise until
$R=3\%$ with incremental drift angle of $\Delta R=0.5\%$ after three successive cycles at
each displacement level. On the other hand, the axial load which was kept constant
during the experiment was applied to the column by means of the servohydraulic
actuator. The magnitude of the constant axial load was $0.355\Delta f_d$, where $f_d$ is the
compressive strength of the concrete cylinder and $A_{c}$ is the cross sectional area of
R/C column.

The test setup of Ken-ken type as shown in Fig. 2 was used in this experiment.
The loading apparatus with the parallelly supporting mechanism was used to apply the cyclic shearing forces to the column shown in Fig. 3. The instrumentation
methods were designed to obtain the following data: (1) applied forces; (2)
horizontal and vertical displacement; (3) strains of the reinforcement bars and the steel tube.

4. EXPERIMENTAL RESULTS

Crack patterns for the two standard R/C columns (CC94L-RS, CC95H-RS)

![Fig. 1 Loading program](image)

![Fig. 2 Details of test setup](image)

Table 1 Specimens

<table>
<thead>
<tr>
<th>Low-strength concrete</th>
<th>CC94L-RS</th>
<th>CC94L-SS</th>
<th>CC94L-DeS</th>
<th>CC94L-DS</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-strength concrete</td>
<td>CC95H-RS</td>
<td>CC95H-SS</td>
<td>CC95H-DeS</td>
<td>CC95H-DS</td>
</tr>
</tbody>
</table>

Table 2 Mechanical properties and slumps of concrete

<table>
<thead>
<tr>
<th>Concrete strength</th>
<th>Specimen</th>
<th>$f_c$ (MPa)</th>
<th>$e_{v}$ (%)</th>
<th>$E_c$ (GPa)</th>
<th>Slump (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>CC94L-RS</td>
<td>21.9</td>
<td>0.18</td>
<td>22.0</td>
<td>190</td>
</tr>
<tr>
<td></td>
<td>CC94L-SS</td>
<td>25.3</td>
<td>0.25</td>
<td>23.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CC94L-DeS</td>
<td>23.8</td>
<td>0.20</td>
<td>23.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CC94L-DS</td>
<td>23.1</td>
<td>0.19</td>
<td>23.1</td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>CC95H-RS</td>
<td>42.7</td>
<td>0.26</td>
<td>26.8</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>CC95H-SS</td>
<td>41.0</td>
<td>0.24</td>
<td>26.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CC95H-DeS</td>
<td>40.9</td>
<td>0.27</td>
<td>25.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CC95H-DS</td>
<td>35.7</td>
<td>0.21</td>
<td>26.7</td>
<td></td>
</tr>
</tbody>
</table>

Notes: $f_c$ is compressive strength of concrete cylinder, $e_{v}$ is strain
corresponding to $f_c$, $E_c$ is modulus of elasticity of concrete.

Table 3 Properties of steel tubes and reinforcement

<table>
<thead>
<tr>
<th>Type</th>
<th>B/t</th>
<th>$f_y$ (MPa)</th>
<th>$e_{y}$ (%)</th>
<th>$E_s$ (GPa)</th>
<th>Slump (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel tubes</td>
<td>78</td>
<td>286</td>
<td>0.19</td>
<td>180.8</td>
<td></td>
</tr>
<tr>
<td>(250×250×3.2)</td>
<td>42</td>
<td>320</td>
<td>0.17</td>
<td>197.5</td>
<td></td>
</tr>
<tr>
<td>(250×250×6)</td>
<td>78</td>
<td>286</td>
<td>0.19</td>
<td>180.8</td>
<td></td>
</tr>
<tr>
<td>287</td>
<td>356</td>
<td>0.20</td>
<td>182.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal</td>
<td>199.9</td>
<td>379</td>
<td>0.21</td>
<td>182.0</td>
<td></td>
</tr>
<tr>
<td>reinforcement</td>
<td>D19</td>
<td>338</td>
<td>0.22</td>
<td>184.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D16</td>
<td>388</td>
<td>0.22</td>
<td>184.1</td>
<td></td>
</tr>
<tr>
<td>Transverse</td>
<td>D6</td>
<td>302</td>
<td>0.22</td>
<td>184.1</td>
<td></td>
</tr>
<tr>
<td>reinforcement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: $B$ is width of steel tubes, $t$ is thickness of steel tubes, $f_y$ is yield strength of steel, $E_s$ is modulus of elasticity of steel, $E_s$ is modulus of elasticity of steel. The symbol $\delta$ denotes the nominal cross-sectional area of the deformed steel bars (cm$^2$).

![Fig. 3 Loading conditions](image)
are illustrated for the drift angles $R=0.5$ and $1.5\%$ in Fig. 4. The bond-splitting cracks were observed due to a great amount of reinforcement and shear span to depth ratio $M/(V_D)=1.5$. Since tension longitudinal reinforcement ratio is larger than the limit reinforcement ratio due to bond-splitting failure[9], the above-mentioned phenomenon of the standard R/C column specimens are likely to happen. The measured strains of the longitudinal reinforcement at a corner of the cross section of the top or bottom of each column against the drift angle are illustrated in Fig. 5. According to the Fig. 5, the longitudinal reinforcements at the tension side did not yield except for CC95H-DS under cyclic lateral loading through the experimental results. Figures 6 and 7 show experimental results on $V$-$R$ and $\varepsilon$-$R$ relationships respectively, where $V$ is lateral force, $\varepsilon = (w-h)/h$ is the average vertical strain along the column center line and $h$ is the vertical relative displacement between top and bottom stubs. The bottom stub was fixed to the strong floor and the top stub was restrained by the paralleled supporting mechanism so that its rotation might not occur. The calculated shear forces due to the flexural failures excluding or including bond slip are illustrated by the solid or dotted lines including the $P-\delta$ effect and transverse confinement simultaneously in Fig. 6. Also, the calculated shear forces due to the shear failures are shown for the R/C column test specimens CC94L-RS and CC95H-RS only for your reference. In the low-strength concrete test specimens, a pinching phenomenon, that is to say, a bond slip is observed in their hysteretic loops as shown in Fig. 6. Also this phenomenon occurred in high-strength concrete test specimens not only CC95H-RS but also CC95H-SS. As shown in Fig. 7, almost the same average vertical compressive strains were measured for the test specimens of low-strength concrete in spite of the different transverse reinforcement. For the test specimens of high-strength concrete, the observed average vertical compressive strain decreased in the order of the specimen CC95H-RS, CC95H-SS, CC94L-DS and CC95H-DS. Measured tension strains, which are observed in the

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$R=0.5%$</th>
<th>$R=1.5%$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WEB</td>
<td>FLANGE</td>
</tr>
<tr>
<td>CC94L-RS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC95H-RS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 4 Observed crack patterns of test specimens CC94L-RS and CC95H-RS**

**Fig. 5 Measured strain of longitudinal reinforcement versus drift angle $R$ relationships**

**Fig. 6 Measured shear force $V$ - drift angle $R$ relationships**
specimens CC95H-DS and CC95H-DS shown in Fig. 7, indicate that the preferable seismic performance appears in spite of subjecting to high axial compression force. This fact is also found out in the hysteretic loops of the same specimens as shown in Fig. 6. Namely, the seismic performance of doubly confined R/C columns using high-strength concrete was remarkably improved because of preventing the bond slip between longitudinal reinforcement and concrete. For positive loading the skeleton curves of the hysteretic loops in Fig. 6 are figured in Fig. 8. Next the accumulated energy absorption capacity obtained from measured hysteretic loops for the specimens is illustrated in Fig. 9, where high energy absorption capacity of the doubly confined columns using high-strength concrete is observed. The degradation of seismic resistance of hooped columns is apparently observed in spite of the high or low-strength concrete through the results of experiments. If R/C columns are transversally reinforced by the steel tube, their seismic resistance is certainly improved. However, if the concrete strength is low, the improvement is small against not only single confinement by steel tube but also double confinement by steel tube and hoops. High seismic performance requires both double confinement and high-strength concrete. From the above-mentioned discussions, it can be said that the bond slip happened to six specimens except for specimens CC95H-DS and CC95H-DS as the experimental results through Figs. 4 - 9. The more detailed discussion will be made later together with the bond stress and strain relationship through the theoretical investigation (see Figs. 15 and 16).

5. THEORETICAL INVESTIGATION

Since occurrence of bond slip was observed from low-strength concrete specimens as a result of experimental test in spite of double confinement, the P-M interaction diagrams including or excluding the bond slip are calculated on the basis of some assumptions and are compared with the experimental results. In order to realize the calculations including the bond slip, the constitutive law with regard to the bond stress and bond strain must be assumed at first. The bond strain is defined by the amount of bond slip divided by the column height h in this paper. The bond stress-strain relationship is assumed as illustrated in Fig. 10.

Fig. 7 Measured mean vertical strain $\varepsilon = \delta / h$, - drift angle $R$ relationships

![Fig. 7 Measured mean vertical strain $\varepsilon = \delta / h$, - drift angle $R$ relationships](image)

![Fig. 8 Measured skeleton curves](image)

![Fig. 9 Accumulated energy absorption capacity](image)
with reference to the experimental study on bond behavior between deformed reinforcement bars and confined concrete in square steel tube by Morishita et al.[11]. This bond stress-strain relationship is different from that of general R/C columns[12], in which the bond stress-strain diagram descends after the peak bond stress. As test specimens are jacketed by steel tube, the deterioration of bond strength is not recognized even if the bond stress reaches its peak value (see Fig. 10).

As well as the relation mentioned above, the constitutive laws for both confined and unconfined concrete are also required. In this analytical investigation, a stress-strain curve model proposed by Mander et al.[7] is adopted for the confined or unconfined concrete due to the convenience of good approximation and simplicity[6]. Figure 11 shows the confinement of concrete section for each type of the specimen. The core concrete is doubly or singly confined concrete and the cover concrete is unconfined concrete. The compressive strength of singly confined concrete in square steel tube was proposed by Matsumura et al.[8] based on some experimental results. The compressive strength of doubly confined concrete in square steel tube and hoops is obtained by adding the strength, namely, by using the simple superposed strength method. Numerical examples with regard to the constitutive law for the core and the cover of high-strength concrete are illustrated in Fig. 12. The compressive strength enhancement ratio $\Delta f_c/f_c$ of confined concrete in hoops or steel tube only at different transverse reinforcement volumetric ratio $\rho$ is illustrated in Fig. 13 using the constitutive laws by Mander[7] and Matsumura [8], respectively. These numerical examples are limited in high-strength concrete due to insufficient space. Figures 12 and 13 show that hoops are more superior than square steel tube on compressive strength enhancement of confined concrete. This is the reason why the transverse confinement by steel tube is not so sufficient because of lack of the transverse bending stiffness of the wall of square steel tube. However, the square steel tube holds laterally the concrete and confine concrete uniformly along the longitudinal reinforcement. As mentioned previously, the role of the steel tube is a transverse reinforcement only. Therefore, not only the wall of square steel tube but also the longitudinal reinforcement bars in R/C columns confined by steel tube are unlikely to develop the local buckling.

The calculations of the P-M interaction diagrams and moment-curvature curves for the cross section of the test specimens are carried out on the basis of the following assumptions and procedure.

(1) The transverse section of the column is partitioned by a rectangular grid into a large number of small element area. Each element is uniaxially stressed, and plane sections before bending remain plane after bending.

(2) The $\sigma$-$\varepsilon$ curves for concrete as illustrated in Fig. 12 are used in the compression zone of the concrete. The tensile strength of the concrete may be neglected.

(3) The $\sigma$-$\varepsilon$ curve for the longitudinal reinforcement in tension or compression is idealized by an elastoplastic approximation.

That is to say, strain hardening is ignored.

(4) The bond slip is applied by the release of stress for the longitudinal reinforcement bars according to the bond stress-strain relationship as shown in Fig. 10. The bond stress is estimated by the shear force, which is assumed to divide the calculated moment by half height of the column.

The moment-curvature relations for the cross sections of the singly or doubly confined R/C columns are obtained by step-by-step application of the equilibrium equations. Iterative calculations are needed until an equilibrium condition between internal and external axial forces is satisfied. The P-M interaction diagrams for doubly confined R/C columns in steel tube and hoops calculated on basis of above assumptions are presented in Fig. 14. The diagrams shown in Fig. 14 are considerably affected by the bond slip for the low-strength concrete. However, the P-M interaction diagrams for the high-strength concrete doubly confined in steel tube and hoops are not influenced very much by the bond. This is the reason why the bond strength is higher. The bond strength is considerably affected by the concrete strength and lateral confinement. In order to enhance the double confinement effect, the high cylinder strength of the concrete must be used in doubly confined R/C columns in steel tube and hoops. Hence Fig. 14 suggests that the double confinement effect may be expected in case of the concrete cylinder strength of approximately 30MPa or more.

In general the bond slip hardly happens as the concrete strength and the transverse confinement increase for the specimens. This fact is presented by Figs. 15 and 16. As the test specimens CC94L-SS and CC95H-SS have not so high bond strength, the bond slip is likely to happen. The specimen CC94L-SS may reach its maximum lateral capacity without yielding of the steel. The ultimate lateral capacity for the specimen CC95H-SS is dominated by the compressive yield strength of extreme longitudinal reinforcing bars only. And the longitudinal reinforcement bars at the tension side do not yield. For the doubly confined low-strength concrete specimen CC94L-DS, the bond slip may happen due to low-strength concrete. Conversely the high-strength concrete test specimen CC95H-DS has no bond slip and its longitudinal reinforcement bars at both tension and compression sides yield...
because of the high bond strength (see Figs. 5 and 15). The yielding process of the longitudinal reinforcement at the lower or upper end of the column specimens CC95H-DS is almost the same in spite of excluding or including the bond slip, and their lateral capacities are the same. These calculation results support the measured strains of the longitudinal reinforcement at a corner of the top or bottom cross section of column specimens CC94L-SS, CC95H-SS, CC94L-DS and CC95H-DS as illustrated in Fig. 5.

The calculated P-M interaction diagrams and the experimental results are compared as shown in Fig. 16. The experimental results for specimens CC94L-SS, CC95H-SS and CC94L-DS are below or on the broken curves which take account of bond slip relationships. However, the experimental result for specimen CC95H-DS is above the solid curve excluding bond slip and its curve is near the broken curve including bond slip. These facts suggest that the bond slip is likely to happen to single confinement or double confinement in low-strength concrete specimens as shown in Figs. 5, 14, 15 and 16.

6. CONCLUSIONS

The following conclusions are reached on the basis of the study on the seismic behavior of the doubly confined R/C columns with the shear span to depth ratio of 1.5 and large ratio (P/E=4.38%) of total longitudinal reinforcement in columns.

1) If the amount of transverse reinforcement steel is almost the same, the double confinement method by steel tube and hoops will be superior to the single confinement method by steel tube on the performance in terms of strength and ductility for the R/C columns.

2) The double confinement requires high-strength concrete in order to enhance the seismic resistance of columns as a result of the experiment. The higher concrete strength is desired to be at least over 30 MPa in cylinder strength of the concrete according to the calculated results.

ACKNOWLEDGMENT

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REFERENCES


和文要約

1. はじめに
鉄筋コンクリート柱の水平耐力、韌性、エネルギー吸収能力など耐震性能の大幅な改善を意図して、富沢らによってRC短柱の鋼管横補強法が提案された①②）。鋼管のみで横補強した正方形RC柱は主筋量が少ない場合有効であるが、主筋量が極めて多くなると、または鋼管の板厚が薄くなると付着剤の劣化が生じやすくなり、耐震性能が十分発揮されないことが報告されている③④）。これに対し、富沢は正方形鋼管周りの面圧曲げ剛性の増大を意図し、蛇腹鋼管RC柱を開発した④）。一方、山川は既存の正方形鋼管と帯筋で二重に横補強した鉄筋コンクリート短柱の実験的研究を行った⑤）。正方形鋼管と帯筋で二重に横補強したコンクリートの構成則を明らかにするために、34の試験体の中心圧縮実験を行い、下記の結論を得た⑥）。

(1) 同じ横補強鋼材量であれば鋼管と帯筋で二重に横補強した方が、鋼管のみを圧縮強度でねじりよりもよりよくする。
(2) 鋼管と帯筋で二重に横補強したコンファインドコンクリートの圧縮強度は、既存の計算式⑦⑧）の単純圧縮でほぼ評価できる。

2. 試験体
試験体は低強度シリーズと高強度シリーズの各4つづきであり、Table 1参照）。コンクリートクリーンの平均圧縮強度はそれぞれ23.5と40.1MPaである。試験体のせん断スパン比（MV/D）は1.5であり、RC柱としてせん断破壊先行の試験体である。試験体に用いた鋼管の板厚は6mmと3.2mmで、主筋（主筋全部断面積の主筋全部断面に比）はすべてP=4.38%である。

3. 測定及び載荷方法
変位計を水平と垂直変位を測定した。載荷は建設計法水平加力装置（Fig.2参照）を用いて、一定圧縮強度（0.35σc）と正負載とし水平力を与えた。水準耐力は柱の部材角Rを0.5ffづつ同一振幅で、3サイクルずつ正負載と負の変形制御で3段まで行った（Fig.1参照）。

4. 実験結果
標準柱試験体（CC94L-RC, CC95H-RC）は曲げせん断びび割れ先行の付着びび割破壊ともいうべきせん断破壊を示している。しかし、中子筋付帯筋の横拘束効果が大きいので、柱の部材角Rが3mmで正負載とし水平力が可能となった。Fig.5に柱端または柱頭隅付近における主筋のびび割を示す。Figs.6,7に柱のせん断びび割と部材角Rの関係である履歴曲線と、柱の平均圧縮びび割と部材角Rの関係を示す。Fig.8に各試験体のスケルトンカーブに関する比較、及びFig.9に累積エネルギー吸収量に関する比較をそれぞれ実験結果として整理する。Fig.7から分かるように、低強度の柱試験体のV-R関係は強延形に由来する、付着びび割が生じ、エネルギー吸収能力の貧弱性に陥っている。R-Rの関係を安定した圧縮びび割を示したが、繰り返し水平載荷に対しておおよそに変化を示した（Fig.7参照）。鋼管のみで横補強した高強度柱試験体（CC95H-SS）で、コンクリートの強度

5. 理論解析
Fig.10に示すような付着応力ひずみ関係を用いて、付着すべきを無視した場合で解析を行った。山川らは鋼管で被覆されたコンクリートと異形鉄筋の付着特性に対する若林らの研究結果⑦⑧）を参照し、平均的な付着応力とすべきによる変形のひずみ（付着すべき量を材長で除し、無次元化した値を付着びび割と仮称）の関係を見た。付着すべきによる変形のひずみ関係は通常のRC断面柱⑦①）で異なり、鋼管で被覆されているので付着びび割が増加しても付着すべきを一定に保つことになる。

RC柱のカーバーコンクリートにはManderらのプレーンコンクリートの構成則を、そして鋼管または帯筋で横拘束されたコンクリートには、各々松村とManderのコンファインドコンクリートの構成則を適用したものである⑦⑧）。しかし、鋼管と帯筋で二重に横補強されたコアコンクリートの構成則はそれぞれの横拘束効果によるコンクリートの強度上昇を単純圧縮で、その上でManderの構成則を適用した。以上の構成則をFig.11に示す断面モデルに従って、高強度コンクリートの平均強度40.1MPaにおける計算結果をFig.12に示す。また、中子筋付帯筋の正方形鋼管による横拘束効果の比較をFig.13に示す。

下記の仮定を用いて、各試験体のP-M相関関係を求めるためにある。すなわち、柱の断面は小さな長方形状断面要素に分割し、柱の全断面に対して平面破壊仮定が成り立つ。Fig.10に示す応力ひずみ関係を適用し、引張側の鋼管を無視する。3（1）主筋の応力ひずみ関係は圧縮側においても、引張側においても完全塑性モデルを仮定し、鉄筋のひずみ硬化を無視する。Fig.10の関係を適用し、主筋の応力を緩和することによって簡便に考慮する。

コンクリート強度が付着すべきに対する影響を検討するために、二重に横補強した柱試験体（CC94L-DS, CC95H-DS）に対するP-M相関曲線を計算した。その結果をFig.14に示す。コンクリート強度が低くと鋼管と帯筋で二重に横補強しても付着すべきの影響が大きく、コンクリート強度が30MPaを超えるとその影響が少しずつ小さくなることが分かる。一般にコンクリート強度が高く、横拘束効果が大きくなると結果的に付着強度が高くなり、付着すべきが生じにくくなる。鋼管と帯筋で二重に横補強し、主筋を強度に配慮したRC柱では、コンクリート強度と横拘束効果のいずれが付着強度に影響を与えることをFig.15,16に示し、それはFig.5に示した実験結果とも符合している。

5. 結論
1）横補強鋼材量が同じであれば、板厚の厚い鋼管のみにより、鋼管と帯筋で二重に横補強した試験体が耐震性能において優れている。
2）二重に横補強した試験体がその耐震性能を発揮するには高強度のコンクリートを必要とし、その値は最小値30MPa以上である。

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