# Seismic Performance and Evaluation of Spiral-confined Drift-hardening Square Concrete Columns

李，剛剛

(Degree)
博士（工学）

(Date of Degree)
2025-03-25

(Resource Type)
doctoral thesis

(Report Number)
甲第9194号

(URL)
https://hdl.handle.net/20.500.14094/0100496475

(Form 3)

# Draft of Dissertation Abstract

Name: 李剛剛　LI GANGGANG

Department: Architecture

Dissertation Title

(If written in a foreign language, provide a Japanese translation as well.)

## Seismic Performance and Evaluation of Spiral-confined Drift-hardening Square Concrete Columns

(スパイラル筋で拘束されたドリフト硬化型正方形断面RC柱の耐震性能及び評価方法)

Academic Supervisor: SUN YUPING

* This is a cover sheet for draft of dissertation abstract.

# 1. Background

Concrete buildings constructed in earthquake-prone regions have been designed following the concept of ductility since it was introduced in the 1950s. Though numerous people's lives were saved from standing concrete buildings, the severe damage and residual deformation of ductile concrete buildings in and after earthquakes evidently demonstrated the low resilience of the quake-hit community. Motivated by the growing need to build resilient communities in earthquake-prone regions, it is of great importance and urgent to develop concrete components with high resilience.

Among several practical methods to achieve the resilient behavior of concrete columns, one simple and effective method is to utilize weakly bonded ultra-high strength (WBUHS) rebars as longitudinal rebars. Instead of ribs, the WBUHS rebars have spiraled grooves on their surface, giving a low bond strength that is about one-fifth of that of deformed rebars, and a nominal yield strength of 1275MPa, resulting in a much longer range of elasticity than normal-strength rebar. Plenty of investigations conducted by Sun et al. demonstrated that concrete columns, square or circular, longitudinally reinforced by WBUHS rebars could exhibit incessant increase of lateral resistance until so large a drift as at least 4.0% and quite good self-centering behavior, indicating high resilience.

To avoid the early developed splitting cracks causing shear failure in square beam-column, the WBUHS rebars were circularly arranged and the core was confined by spirals. However, the seismic performance of this type of drift-hardening columns has not been fully understood. Moreover, the previous studies regarding drift-hardening columns, experimental or numerical, have focused on flexural behavior. Information on the shear behavior of drift-hardening columns is scarce.

# 2. Objectives and scope

To date, though the efficiency of this type of square resilient concrete has been verified, its seismic performance of it is still in a not fully understood state. Therefore, it gives rise to the need for further information concerning the performance with respect to seismic-related indexes, including axial load ratio, shear span ratio, reinforcement steel content. Note that the performance includes not only flexural behavior but also shear behavior. As introduced previously in the review of the WBUHS rebar-reinforced concrete columns, the information on both the circular and the square drift-hardening columns is scarce. Therefore, it became one of the aims of this thesis.

The concrete contents of the research described in this thesis put particular emphasis on the following four aspects:

(1) Experimental investigation on flexural behavior of the square drift hardening columns under quasi-static cyclic loading and axial compression to simulate the behavior of this type of columns in major earthquakes. Parameters expected to have a large influence on flexural behavior, including axial load ratio, shear span ratio, longitudinal steel content and configuration of transverse reinforcement, are to be discussed.

(2) Parallel to the experimental investigation on the flexural behavior of the square drift-hardening columns, a method taking the low bond behavior between the WBUHS rebar and the concrete into account was developed to predict the lateral force-displacement response.

(3) Experimental investigation on Shear behavior of the square drift hardening columns under quasi-static cyclic loading and axial compression. It is to be discussed with respect to axial load ratio and transverse steel content.

(4) Parallel to the experimental investigation of the shear behavior of the square drift-hardening columns, a theoretical mechanism curve of shear resistance for drift-hardening columns was developed to evaluate the transient shear strength. According to the reinspection of the nature of shear resistance in reinforced concrete columns, not only the flexural mechanical response but also the shear response is deeply influenced by the contrasting mechanical properties—ultra-high yield strength and low bond strength.

## 3. Format of the dissertation

This dissertation consists of seven chapters, among which chapter one gives an introduction, chapter two to six deals with the above-listed research scops, and chapter 7 gives a summary. Outlines of each chapter are as follows:

1. Chapter one introduces the background and motivation of this research, reviews relevant literature on developing resilient concrete columns, with particular emphasis on the drift-hardening column, and presents the objectives and scope of the thesis.

2. Eight 1/3 scaled cantilever columns with eight WBUHS rebars (14.7 in nominal diameter, referred to as U15 hereafter) evenly arranged around the inner perimeter of spirals were fabricated and tested under constant axial load and quasi-static cyclic loading to expand the information regarding the seismic behavior of square drift hardening concrete columns. The experimental variables are (1) axial load ratio (10% and 21%), (2) shear span ratio (1.7 and 2.5, referred to as the short and tall specimen hereafter) and (3) transverse steel content (0.60% and 1.07%). First, the experimental program, including dimension and reinforcement details of specimens, materials properties of concrete and steel, instrumentation and test setup, will be introduced. Then, the test results are analyzed and comparatively discussed in aspects of damage propagation, strain observations, lateral force-displacement response, residual deformation and energy-dissipating ability.

3. Aiming at providing fundamental shear information on the drift-hardening concrete columns, six short 1/3-scaled square columns (a/D=1.7) were fabricated and tested under constant axial load and quasi-static cyclic loading based on the results in chapter two. The experimental variables are the axial load ratio and transverse steel amount. The test results will be comparatively discussed in aspects of damage propagation, strain observations, lateral force-displacement response, residual deformation and energy-dissipating ability. Emphasis and efforts will be put into giving and explaining the shear-related

Observations and findings, such as shear cracks propagation and parameters' influence on shear behavior. Parallel to the experimental work, ultimate shear capacity equations recommended in the AIJ standard (AIJ, 2010), ACI 318-19-19 code, and China standard (GB50010-2010) will be adopted to evaluate the shear capacity of the tested columns, and their accuracy and applicability will be examined.

4. Based on the experimental results introduced in chapter 2, four tall 1/3-scaled square columns (a/D=2.5) were built and tested under constant axial load and quasi-static cyclic loading to comparatively investigate the longitudinal reinforcement and configuration of transverse steel. Instead of eight WBUHS rebars, twelve were used to give higher longitudinal steel content. The experimental results will be introduced in the same procedure as chapter two and three. First, experimental-related details will be present, then, discussions mainly in aspects of damage observation, hysteresis behavior and energy-dissipating ability follow.

5. Chapter five presents an integrated analytical method to evaluate the cyclic lateral force-displacement response of the square drift-hardening columns mentioned above. The numerical method is based on the Finite Spring Method (FSM) to take the bond behavior between the WBUHS rebars and concrete into account. First, the constitutive models for concrete, rebar and bond are introduced in detail. Then, the procedures of this method will be given in detail. Finally, verification of this numerical method in predicting the hysteresis response of the square drift-hardening concrete columns and discussion between the predicted and tested results will be conducted.

6. Chapter six proposed a mechanism curve of shear resistance for evaluation of the transient shear strength of the drift-hardening columns. This shear curve theoretically considers the attenuating nature of shear resistance of concrete columns as a function of drift ratio, in which shear contribution from concrete, transverse reinforcement and axial load are considered in an additive manner. The flow of this chapter is structured as follows. First, review and examination on several shear curves for traditional RC columns is given. Then the details of the proposed drift-hardening column-oriented shear curves are introduced followed by the calibration of the parameters by experimental observations. Finally, the shear curve is to verified, and the predicted failure points are to further discussed in comparison with tested ones.

7. Chapter seven summarizes observations and findings obtained in chapter two through chapter six, followed by several future works or problems remaining to be further investigated and addressed.

# 4. Conclusions

This thesis consists of seven chapters. Except for chapter one, which presents backgrounds and motivation, chapter two through chapter five cover the experimental and analytical works. The main conclusions drawn in chapter two through six will be summarized as the conclusions made by the doctoral thesis below.

In chapter two, aiming at expanding the knowledge of seismic performance on square concrete columns reinforced by circularly arranged WBUHS rebars quasi-static experiment was conducted to investigate the influence of axial load ratio, shear-span ratio and transverse steel content on this type of columns. Through the test results and discussions described in this chapter, the following conclusions can be drawn.

1. All the tested spiral-confined square concrete exhibited stable hysteresis response, behaving in a drift-hardening and sound self-centering manner regardless of the difference in axial load ratio, shear-span ratio and transverse steel content until at least 4.0%. Both the drift-hardening and self-centering behavior meet the two characteristics of the resilient concrete columns, high strength reserve and high repairability. The stable drift-hardening and sound self-centering behavior also demonstrate the hoop configuration adopted could effectively confine the concrete, consequently, matching the ultra-high strength of WBUHS rebars. All the specimens were flexure-dominated until the end of test, except two short specimens with low transverse steel amount (0.60%) that finally failed in shear but at a larger drift than 5.0%.

2. All the specimens showed strong self-centering ability. When the drift ratio was below 2.0% drift, the residual drift ratios of all specimens were restrained below 1/12 of the transient drift ratio. If the transient drift ratio did not exceed 4.0% drift, the residual drift ratios were controlled under 1/7 of the transient drift ratio with the exception of specimen S-N10D06, which failed in shear at a larger drift than 5.0%. Even for specimen S-N10D06, the residual drift ratio at 4.0% was under 1/6 of the transient drift ratio.

3. Overall, all the specimens exhibited a nonlinear elastic feature with $h_{eq}$ around 0.08 before the 4.0% drift. The $h_{eq}$ showed marginal sensitivity to spiral steel content and shear-span ratio while the axial load ratio exhibited a slight influence on $h_{eq}$. The higher the axial load ratio was, the higher $h_{eq}$ was observed.

4. Neither anchorage failure at the top nor pull-out failure of WBUHS rebars in the bottom stub was observed during the test, evidencing the sufficient anchorage strength of the mechanical anchorage method adopted. Regarding the damage observations, except the two short specimens that failed in shear, most damage, including cracks and spalling of cover, of all specimens localized at the footing of the columns, showing the potential for quick repair.

In chapter three, aiming to give fundamental information on the shear behavior of square concrete columns reinforced by circularly arranged WBUHS rebars, quasi-static cyclic loading experiment was conducted to investigate the influence of axial load ratio and transverse steel content on this type of columns. Moreover, a mechanism of shear curve was proposed to give the transient shear strength of the drift-hardening column. Through the test results and discussions described in this chapter, the following conclusions can be drawn.

1. All the specimens failed in shear but at relatively large drifts beyond 4.0% with quick strength degradation and decreasing of stiffness. Though finally failing in shear, all the spiral-confined square concrete columns exhibited stable hysteresis response featuring drift-hardening and sound self-centering behavior regardless of axial load ratio and transverse steel amount, until when the shear failure was imminent.

2. Before the shear failure, when the drift ratio was under 2.0%, the residual drift never exceeded 1/10 of the transient drift ratio. If the drift ratio was under 4.0%, the residual drift could be reduced to below 1/8 of the transient drift ratio. Upon shear failure, not only was the lateral force-resisting mechanism destroyed, but the self-centering ability was lost as well. All the specimens experienced significantly large residual drift after shear failure.

3. Overall, the $h_{eq}$ of all specimens was around 0.08 until 4.0%, showing a nonlinear elastic behavior. The influence of the spacing of the spiral on $h_{eq}$ cannot be measured. On the other hand, as the more damage to concrete resulting from higher axial load, the higher axial load, the slightly higher energy dissipating ability.

4. While they were designed to fail in shear, shear failure didn't occur until the drift of 4.0% or more. The higher the axial load and the less the spiral steel content, the smaller the drift at the onset of shear failure. Moreover, the specimens with higher axial load experienced faster loss of strength.

5. Regarding the damage, diagonal shear cracks formed ahead of the impending shear failure, indicating the position of the failure plane. It is the diagonal shear cracks that caused significant damage to both cover and core concrete, considerably diminishing the repairability.

6. Assuming that the dilation of the core exerted pressure against spirals in the same way as hydrostatic pressure, the dilation of the core cannot be ignored at large drift for specimens having higher axial load. As much as about 20% and 10% of yield stain of spirals was used to restrain it at 4.0% for specimens with 30% and 21% axial load respectively in this chapter.

In chapter four, aiming at expanding the knowledge of seismic performance regarding square concrete columns reinforced by circularly arranged WBUHS rebars quasi-static experiment was conducted to investigate the WBUHS rebar amount and hoop configuration on this type of columns. Through the test results and discussions described in this chapter, the following conclusions can be drawn.

1. Regardless of axial load ratio, and transverse steel configuration, all the tested square spiral-confined columns developed stable lateral load-displacement response featuring pronounced drift-hardening and sound self-centering behavior until at least 4.0%, indicating high resilience. Especially, the two specimens with ties experienced no strength degradation until such large a drift as 8.0%.

2. For all specimens, before 2.0% drift, the residual drift ratios of all specimens were restrained below 1/10 of the transient drift ratio. If the transient drift ratio did not exceed 4.0% drift, the residual drift ratios were controlled under 1/8 of the transient drift ratio. At a larger drift than 5.0%, upon the two specimens without ties—N10S and N21S—failed in shear, the plastic strain in spirals caused significant residual deformation.

3. The higher the axial load, the slightly higher the energy dissipating ability. The transverse steel amount also showed a similar influence that the specimens without ties had slightly higher $h_{eq}$ until 4.0% drift.

Overall, the $h_{eq}$ of all specimens was around 0.08 before the 4.0% drift, showing a nonlinear elastic behavior.

4. The two specimens with ties exhibited flexure-dominated behavior until a larger drift than 6.0% in terms of crack propagation and hysteretic responses. Meanwhile, the two specimens without ties exhibited shear-dominated crack propagation, and failed in shear due to exhaustion of the shear-resisting mechanism at 6.0% drift. Moreover, it was observed that the inclination of the main shear crack had an angle of around 60 degrees.

5. Though stable hysteresis response until at least 4.0% was assured by 0.39% spiral steel amount, yield of spirals earlier than 4.0% was observed at the flexural compressive side of the columns largely due to the lateral deformation of WBUHS rebars. The higher the axial load ratio, the earlier the yield of spirals was found. Besides, from the measured strain in the south direction, the earlier yield of spirals was measured for N21ST, showing the deficiency of the transverse steel over the shear resistance. Therefore, referencing the tested results in chapter two, it is recommended that the spiral steel amount be at least 0.80% to the 2.23% steel amount of WBUHS rebars. Moreover, considering the ties not only effectively kept the cover concrete in place but also contributed to shear resistance, it is highly recommended that the ties be used as a detailing requirement for building the drift-hardening square concrete columns.

In chapter five, to reasonably and reliably evaluate the overall seismic performance of square drift-hardening concrete columns developed in the previous chapters, a numerical analysis method is presented in this chapter. Utilizing fine constitutive models developed by Sun et al., the cyclic response considering the bond slippage between WBUHS rebars was predicted and its reliability and accuracy were comparatively discussed in terms of hysteresis response, residual drift ratio and energy dissipation. Meanwhile, the strain in the WBUHS rebars was also given as evidence to discussions. From the comparisons between analytical and tested results discussed in this chapter, the following conclusions can be drawn.

1. The predicted hysteresis by the numerical method presented could accurately trace the loops of each loading level until such large a drift as 4.0% regardless of axial load level, shear span ratio, transverse steel amount and longitudinal steel amount. Because this method was initially developed for evaluating the flexural behavior of concrete columns, closer predictions of hysteresis response for flexural-dominated specimens were found as compared with the ones that shear was heavily coupled with flexure.

2. The numerical method could trace the development of strain in WBUHS rebars until at least 4.0% with satisfying accuracy, particularly for flexure-dominated specimens, which evidenced the high accuracy in predicting the hysteresis curves. For specimens that failed in shear, this method is also reliable in giving WBUHS rebars' strain of loops before shear failure is imminent with an acceptable overestimation.

3. As for residual drift ratio, when the concrete strength was around 40MPa, which is consistence with the concrete strength of the bond model adopted, numerical analysis showed quite good prediction of the

residual drift ratio until 4.0%. When the concrete strength was around 50MPa, though the developing trend of residual drift was also traced well until a large drift of 4.0%, the discrepancy between analysis and test could not be ignored. This can be primarily due to the limitation of this bond model on concrete strength.

4. Regarding the equivalent viscous damping coefficient—$h_{eq}$, the numerical method tends to give an underestimation of $h_{eq}$, while the developing features of $h_{eq}$ can be accurately captured. For example, the attenuating of $h_{eq}$ at an early loading range of 0.25%-1.5% and the nonlinear elastic stage of $h_{eq}$ from 2.0%-4.0% drift, showing the reliability of this numerical method in the evaluation of the energy dissipation of the square drift-hardening columns developed in this thesis.

In chapter six, a shear strength curve was proposed to give the transient shear strength versus drift ratio of drift-hardening square concrete columns. The proposed model has advantages over the previous models in two aspects:

1. This model gives the transient shear strength as a function of drift ratio, so it provides a convenient way for the performance-based shear design of the drift-hardening columns.

2. As the transient shear contribution from concrete can be known by just measuring the strain in WBUHS rebars, it becomes possible to monitor the real-time shear strength of drift-hardening concrete columns of buildings in severe earthquakes and the aftershocks follow. This method opens a feasible way to provide key information in quantifying the resilience of concrete buildings, which had been seen as one of the most important ends to build resilient communities.

Three current code-prescribed formulas were examined by the tested drift-hardening columns in chapter two. Then, based on the examination of current code-prescribed formulas and the proposed shear strength curve, the following conclusions can be drawn.

1. Of three representative design equations for the shear capacity of general concrete columns, the AIJ equation most conservatively evaluated the test results. The GB50010-2010 equation overestimated the test results. However, the calculated shear capacities by the ACI equation are closest to the test results on the unconservative side by about 7% on average.

2. A comparison between the measured and the calculated results indicated the proposed shear strength curve predicted the shear strength at shear failure reliably and accurately with an average error of less than 10.0% on the conservative side. Quite high accuracy was shown for specimens with 21% and 30% axial load, the predicted shear failure points were quite close to the measured point.

3. The proposed model was also used to predict the shear strength curve of eight flexure-dominated drift-hardening columns. Seven out of eight specimens' shear strength curves run above the envelop curves, and the maximum error for the unsuccessfully predicted one is under 12%.

（別紙１）　　　　　　　　　　　　　論文審査の結果の要旨

| | | | |
|---|---|---|---|
| 氏名 | 李　剛剛 | | |
| 論文題目 | Seismic Performance and Evaluation of Spiral-confined Drift-hardening Square Concrete Columns<br>（スパイラル筋で拘束されたドリフト硬化型正方形断面 RC 柱の耐震性能および評価方法） | | |
| 審査委員 | 区　分 | 職　名 | 氏　　　名 |
| | 主　査 | 教　授 | 孫　玉平 |
| | 副　査 | 教　授 | 藤永　隆 |
| | 副　査 | 准教授 | 水島　靖典 |
| | 副　査 | | |
| | 副　査 | | 印 |

要　旨

近年、世界各地で発生した巨大地震の被害状況より、これまでに主要な耐震構造である靭性型鉄筋コンクリート（ＲＣ）造構造物の殆どは、設計地震動に遭遇する際に崩壊することなく、人命保護できるという安全性を満たせたが、主要な構造部材である柱や壁などに修復できないほどの大きな残留変形を生じ、建物は人為的に取り壊されてしまう被災例が報告されている。2009 年に「Resilient City」というコンセプトのもとで、米国太平洋地震工学研究センターは「今後の耐震設計の考え方は靭性保証からレジリエンス確保へ移すべき」と提言した。つまり、今後の建築耐震構造には、設計地震時に崩壊しない狭義的な「安全性」のみならず、設計地震動を超越する巨大地震による被災度合いを低く抑制できる「復元性」と「修復性」を包括した「レジリエンス性」が求められるようになりつつあります。

レジリエンス性の高い RC 構造を実現するための方法の一つとして、低い付着強度を有する超高強度（WBUHS）鉄筋を部材の主筋として用いる方法が提案されている。従前のプレストレスを加える工法と比べて、WBUHS 鉄筋を用いる工法は施工が簡単でかつ水平耐力が高いという利点を有するので、孫らが WBUHS 鉄筋を用いた RC 柱と耐力壁の耐震性能に関する実験研究を通して、WBUHS 鉄筋を用いれば、RC 柱と耐力壁は、それぞれ部材角が 4.0%と 2.5%となるまでのドリフト硬化性に加え、残留部材角が小さく抑制できるという高い復元性と修復性を有することを実証した。一方、正方形 RC 柱の反曲点付近で設けている WBUHS 鉄筋の継手金具（カプラ）の影響で、大変形における割裂ひび割れの発生とそれに伴う破壊が生じる恐れがあることを指摘してきた。

そこで、本論文では、WBUHS 鉄筋を用いた正方形 RC 柱のレジリエンス性の安定と向上を確保するために、WBUHS 鉄筋を断面周辺に沿って円環状に配置する工法を提案し、円環状に配置された WBUHS 鉄筋である SBPDN 筋を有する正方形 RC 柱のドリフト硬化性と復元性を実験的に調べると同時に、このような RC 柱の耐震性能および実用時に不可欠な性能評価法の構築を目的とする。

本論文は７章からなっている。

第１章は序論であり、本研究の背景、関連研究の現状をレビューしたうえ、本研究の目的と具体的な研究内容、および本論文の構成を述べている。

第２章では、SBPDN 鉄筋を円環状に配置した正方形 RC 柱の耐震性能に関する基礎データを取得することを目的に、幅 300mm の正方形 RC 柱試験体を計 8 体作成し、一定軸力下における繰り返し載荷実験を行った。柱に作用する軸力の大きさ（軸力比 0.10 と 0.21）、柱のせん断スパン比（1.7 と 2.5）、および横補強筋比（0.60%と 1.07%）は実験変数であった。実験結果より、その結果、すべての柱は部材角 4.0%までの高いドリフト硬化性と優れた復元性を示せることと、被害は主に柱脚に集中し、修復しやすい曲げひび割れとかぶりコンクリートの剥離で、非常に高い修復性を有することなどが明らかになった。

第３章では、SBPDN 筋を円環状に配置した正方形 RC 柱のせん断性状およびせん断終局耐力に関する基礎データを取得することを目的に、せん断スパン比を一定（1.7）にして、せん断補強筋比（0.48%と 0.60%）および軸力比（0.10，0.21、0.30）を実験変数に取り、計６体の柱試験体を作製し、一定軸力下における繰り返し載荷実験を行った。その結果、現行設計規準に従って設計したせん断破壊先行する正方形ＲＣ柱は、SBPDN 鉄筋の応力発現が遅延されたことによって、部材角 4.0%までの高いドリフト硬化性を示しながら、残留部材角は最大経験部材角の 1/8 程度に抑制でき、せん断破壊は 4.0%以上大変形域に入ってから発生したことを明らかにした。また、せん断補強筋の増加は柱の最大耐力時の部材角を高めるのに極めて有効であることと、現行せん断耐力設計式は本提案柱のせん断終局耐力を適切に評価できないことを明らかにした。

第４章では、SBPDN 鉄筋量が本提案柱の耐震性能に及ぼす影響を究明することを目的に、柱のせん断スパン比（2.5）および SBPDN 鉄筋比（2.3%）を一定にして、せん断補強筋比（0.48%と 0.60%）およ

| 氏名 | 李　剛剛 |
|---|---|

び軸力比（0.10 と 0.21）を実験変数に取り、計4体の柱試験体を作製し、一定軸力下における繰り返し載荷実験を行った。その結果、せん断補強筋比 0.6%を有する本提案柱は部材角 6.0%まで顕著なドリフト硬化性を示せることと、主筋比 2.3%の柱は第3章で述べた柱（主筋比 1.53%）よりも高い二次剛性を有することなどを明らかにした。

第5章では、提案する RC 柱の履歴性状を適切に評価するための方法を確立することを目的に、孫らが提案した有限バネ要素法を準用し、NewRC モデルなどの材料構成則を用いて得られた履歴曲線の解析結果を、本論第2章から第4章にて述べた曲げ支配型とせん断支配型提案柱の実験結果との比較を行った。その結果、有限バネ要素法で求められた計算履歴曲線は、曲げ先行型柱のみならず、せん断先行型柱の実験結果を部材角 4.0%まで高い精度で追跡できることを明らかにした。また、残留部材角の計算結果は、曲げ先行型柱の実験結果を精度よく評価できるが、せん断破壊先行型柱のそれらをやや低く評価する傾向にあることを明らかにした。

第6章では、本提案正方形 RC 柱のせん断終局耐力が変形の増大に伴うコンクリートの劣化による低減を追跡できる、全せん断耐力モデルの構築を目的に、まず、現行規準に推奨されているせん断耐力設計式の精度検証を行った。第4章で述べたせん断破壊した試験体の実験結果と比較した結果、現行の RC 構造計算規準で推奨されている諸設計式は SBPDN 筋を用いた本提案柱のせん断終局耐力を 20%安全側に（AIJ 規準式）、または 7%（ACI 規準式）および 19%（中国規準式）危険側に評価することを明らかにした。この考察に基づき、梁アクションおよびアーチアクションの概念の下で、コンクリートが抵抗するせん断力の評価式を SBPDN 筋の部材長に沿うひずみ勾配から誘導し、本提案柱の全せん断力を算定するモデルを提案した。実験結果との比較により、提案したモデルの妥当性と精度を検証した。

最後に、最後に、第7章では、上記各章の研究成果を総括し、本研究の結論とした。また、SBPDN 筋を円環状に配置した正方形ドリフト硬化型 RC 柱の性能曲線および修復曲線の構築の必要性など、今後の研究課題を示した。

以上で述べたように、本論文は高いドリフト硬化性と復元性に加え、修復性に優れるドリフト硬化型 RC 柱の提案、提案した RC 柱のドリフト硬化性の実証、柱の履歴性能評価法、および全せん断のモデルの構築を行っている。本研究は、現行基準で想定されているレベルを超える巨大地震を凌駕できる次世代耐震要素の耐震性能について、様々な構造因子による影響と耐震性能の評価手法を研究したものであり、新しい耐震構造の特性とその評価法について重要な知見を得たものとして価値ある集積である。提出された論文は工学研究科学位論文評価基準を満たしており、学位申請者の李剛剛は，博士（工学）の学位を得る資格があると認める。