Structural Performance and Evaluation of Square Steel Tube Encased Concrete Columns Confined by Circular Thin Steel Tube

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論文内容の要旨

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専　　攻　建築学専攻

論文題目（外国語の場合は，その和訳を併記すること。）

Structural Performance and Evaluation of Square Steel Tube Encased Concrete Columns Confined by Circular Thin Steel Tube

（円形薄肉鋼管で横補強した正方形鋼管内蔵コンクリート柱の構造性能及び耐力評価に関する研究）

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（注）2，000字～4，000字でまとめること。

Doctoral Dissertation Abstract

1. Backgrounds

Earthquake, as one of the most destructive natural disasters, has consistently exerted profound and widespread effects on human society and civilization. It not only results in significant material losses but also impacts people's lives, economies, and infrastructure. In order to meet the objectives required in current seismic design, and overcome the disadvantages inherent in concrete structures, there has been a growing interest in concrete-steel composite structures, which combine steel and concrete elements to enhance the seismic capacity of building structures, providing greater ductility, strength, and overall stability. The steel-concrete composite structures encompass various types of component forms, such as Steel-Reinforced Concrete (SRC) structures, Concrete-Filled Steel Tube (CFST) structures, and so on. However, the use of SRC columns in complex commercial buildings has been limited recently due to the complexities involved, and CFST columns have their own drawbacks, including the relatively complex joint connections between columns and beams, a reduced lateral confinement effect on concrete due to the outer steel tube also bearing vertical stress, and the necessary fire resistance measures. Therefore, in order to overcome the difficulties and problems inherent in conventional SRC and CFST columns and to further promote the application of composite structures to the logistic warehouses located in the regions with high seismicity, a new type of steel-composite composite component is desirable.

2. Research Objectives

Based on the above-mentioned backgrounds, a new type of SC columns was proposed in this doctoral dissertation. This type of SC column consists of a square steel tube encasing a circular concrete column, which is confined by circular thin steel tubes. The proposed circular SC columns can make full use of the sound confinement effect by the outer circular steel tubes, which can also act as form for the columns. However, to promote the application of the proposed circular SC columns, several important issues still need to be addressed as described below:

(1) The effect of the grades of encased square steel tubes (FA rank, FB rank, and FC rank) on overall seismic performance of the proposed SC columns: On one hand, the overall structural performance of the proposed circular SC columns is dependent upon the grades of the encased inner steel tubes and the confinement effect by the outer thin steel tubes. On the other hand, the closer to FA rank the inner steel tubes, the worse the cost performance. To make more economical and reliable design of the proposed SC columns, it is necessary to clarify the influence of grades of the inner square steel tubes on the seismic performance of SC columns, and obtain basic data on the impact of the steel grades.

(2) The influence of infilling concrete into the inner square steel tube on seismic performance of the proposed SC columns: It is apparent that without concrete being infilled into the inner steel tubes can save construction time and upgrade cost performance. However, if the grade of the inner square steel tubes is not high enough, the inner square steel tubes might prematurely buckled inwards, significantly

reducing the ultimate capacities of the proposed SC columns. Therefore, to find the optimum grade of the inner steel tubes, information on the effect of the presence of infilling concrete is indispensable.

(3) Quantitative evaluation of the confinement effect by circular thin steel tubes: In the proposed SC columns, in addition to the thin steel tube fabricated by welding, a new type of thin steel tube will be proposed. This new type of thin steel tube is fabricated by at first bending a flat steel plate with targeted thickness into semi-circular plate with connection flange at both ends of the semi-circular plate, and then clamping two plates by high-strength bolts and nuts along the height of the circular tube. The new type of circular steel tube is referred to as bolted tube in this paper. The bolted thin steel tube is developed to avoid potential rupture of the connection portion observed in the welded thin steel tubes. The bolded thin steel tube also has some advantages over the welded steel tube such as simplification of the assembly and disassembly, which enables structural engineers to easily observe the damage of concrete after suffering earthquake events. However, the discontinuity of the bolted steel tube inevitably may sacrifice some confinement effect. Therefore, to rationally evaluate the structural capacities of the proposed circular SC columns, the confinement effect by the bolted steel tube needs to be confirmed and further compared with that by the welded thin steel tube.

(4) Development of an evaluation method for the seismic capacities of the proposed SC columns: Although numerous seismic evaluation methods have been proposed for SRC components, it is not clear if these methods can be applied to the proposed circular SC columns. Particularly, it is not clear how we should model the encased square steel tube when conducting flexural analysis of the proposed SC columns.

Objectives of this doctor thesis are, 1) to obtain more experimental information on structural performance of the square steel tube encased concrete columns confined by circular thin steel tubes, 2) to investigate the effects of the grades of square encased steel tubes (FA rank, FB rank, and FC rank) on structural performance of the proposed SC columns, 3) to study the influence of the infilling concrete within the inner steel tube, 4) to compare and analyze the confinement effect of circular thin steel tubes with different thicknesses and joint methods, and 5) to find the reasonable design equation for assessing ultimate flexural strength of the proposed SC column section by comparing the experimental results with the calculated ones by representative code-prescribed equations, and to propose an numerical analysis method to evaluate the overall structural performance of the proposed SC columns.

3. Format of Thesis

This dissertation consists of six chapters, and the key points of each chapter are summarized as below:

Chapter One introduces backgrounds of this dissertation, reviews previous researches in the literature, and describes research objectives of this study.

Chapter Two explores the axial performance of the circular SC short columns through axial compression tests. The SC short columns were composed of a FA rank square inner steel tube and an outer circular thin steel tube. The primary objectives of this chapter are, 1) to compare the effect of infilling concrete in the inner steel tube on the axial behaviors of the SC short columns and the impact of local buckling of the inner steel tube, 2) to compare the confinement effect of outer circular thin steel tubes with different joint methods on concrete strength, 3) to study the influence of the outer-diameter-to-thickness ratio of circular thin steel tube on the strength enhancement ratio of confined concrete. Ten short columns were made and tested under concentric loading. The experimental variables included the infilling concrete into inner steel tube, the joint method of outer circular thin steel tube (welded steel tube and bolted steel tube), and the thickness of outer steel tube (1.6mm and 2.3mm, outer-diameter-to-thickness ratio was 111.4 and 78.1, respectively).

Chapter Three is intended to obtain fundamental data on structural performance of the proposed circular SC columns confined by welded thin steel tubes with outer diameter-to-thickness ratio of about 189. The primary research targets are the impact of different grades of inner square steel tubes on the structural performance of the SC columns, the influence of the presence of infilled concrete within the encased steel tube, and 3) verification of the confinement effect by the welded circular thin steel tubes. To these ends, a total of thirteen circular SC columns with diameter of about 300 mm were made and tested under reversed cyclic loading and constant axial compression to investigate the structural performance, ultimate strength, and defamation capacity. The experimental variables included the axial load ratio (0, 0.15, 0.25), the grades of inner square steel tubes (FA rank, FB rank and FC rank), the infilling concrete into the inner steel tube or not, and the presence or absence of main longitudinal rebars.

Chapter Four aims to experimentally verify effectiveness of the bolted circular thin steel tube on the cyclic performance of the proposed SC columns through comparing their cyclic behavior with those of the SC columns confined by the welded circular thin steel tube. Based on the observations made in chapter three, six circular concrete columns were made and tested under reversed cyclic lateral force and constant axial compression. All the specimens were confined by the bolted thin steel tubes. The primary experimental variables included the axial load ratio (0.15, 0.25), the grades of inner square steel tubes (FB rank and FC rank), the infilling concrete into the inner steel tube, and the thickness of the bolted circular thin steel tubes.

Chapter Five deals with the calculation method of the ultimate flexural strength of the proposed SC column sections as well as numerical analysis method of the overall structural performance of the proposed SC columns. To predict the ultimate flexural strength of the proposed SC column sections, the design equations recommended in the AIJ standard for SRC columns and the AIJ design guideline for CFT columns were adopted. To take the confinement effect by the outer steel tubes into account, the compressive strength of concrete confined by the bolted steel tube will be evaluated by modifying the model proposed by Sun et al for the confinement by the welded thine steel tube defined. In addition, the

core points of numerical analysis method lie in the consideration of confinement effect and discretization of the inner steel tube as longitudinal bars under the rule of equal-area. To verify validity and accuracy of the analytical method, the theoretical predictions by the refined method are compared with the experimental results in terms of hysteresis loop, residual drift ratio, and the axial strain of steels.

Chapter Six summarizes the conclusions obtained through chapter two to chapter five, and presents several suggestions to deal with the problems remained to be solved.

4. Results and Conclusions of Doctoral Thesis

This doctor dissertation consists of six chapters. Based on the experimental and analytical results summarized in this paper, primary finds obtained from chapter two through chapter five will be summarized below as the conclusions of this doctor dissertation.

(1) Encasing FA rank square steel tube with concrete infilled could enhance both strength and ductility of concrete and well utilize the confinement effect by the outer circular thin steel tubes, both welded and bolted. Without concrete infilled, local buckling of the encased square steel tube tended to decrease ductility of concrete.

(2) Confinement by the bolted circular steel tubes were superior to that by the welded thin steel tubes from the perspective of enhancement of ductility of concrete. The bolted thin steel tubes did not rupture until as large strain as about 0.06, ensuring secure confinement effect to concrete. On the other hand, the welded thin steel tubes tended to prematurely rupture along the welding seams, implying that careful attention must be paid to the welding process.

(3) Confinement efficiency of the welded circular thin steel tubes could be accurately evaluated by the semi-empirical formula (proposed by Sun et al. [1]) if the steel plates meet requirement of the JIS. Confinement effect of the bolted thin steel tubes could also be evaluated by the semi-empirical formula when the D/t ratio was smaller than 78, but the confinement efficiency of the bolted tubes with D/t ratio larger than 111 should be assumed as half of that by welded tubes for conservativeness.

(4) The stress-strain relationships of concrete in the proposed SC columns could be evaluated by the stress-strain curve model (proposed by Sun et al. [2]), which incorporates the strength enhancement ratio $K1$ for the concrete confined by bolted thinner steel tube with very good accuracy. In particular, for the SC columns confined by the bolted steel tubes, the calculated stress-strain curves traced the experimental curves very well until axial strain of about 0.06.

(5) For the SC columns with a FA rank square inner steel tube encased, sufficient load-carrying capacity and high ultimate drift ratio up to 0.04 rad could be achieved even without infilling concrete and under axial load ratio of 0.25. For the specimens with FB rank square steel tube encased, the effects of infilling concrete and the existence of longitudinal rebars became significant compared to series-A specimens. Under axial load ratio of 0.15, without infilling concrete, the SC columns with FB rank steel tube encased could exhibit ultimate drift ratio of 0.03 rad. On the other hand, when the

axial load ratio increased to 0.25, the SC columns with vacant FB rank steel tube showed abrupt drop in the lateral resistance near the drift level of 0.02 rad. For the SC columns with C rank square tube encased, to ensure an ultimate drift angle beyond 0.02 rad, the infilling of concrete was indispensable.

(6) The higher the axial compression, the larger the ultimate lateral load-carrying capacity of the SC columns because the confinement effect by outer steel tube became more significant along with the axial load level. But the higher axial compression tended to cause the rupture of the welding seam of the outer steel tube at smaller drift level, and hence careful attention must be paid during the process of welding.

(7) With concrete being infilled, the SC columns with FC rank steel tube encased could exhibit an ultimate drift angle of 0.02 rad even under relatively high axial compression with axial load ratio of 0.25. To ensure sufficient ultimate drift angle to the SC columns under axial load level up to 0.25, it is recommended to encase at least B rank steel tube with concrete infilled.

(8) Due to the high confinement efficiency of the circular thin steel tube, the maximum lateral resistances of almost all specimens exceeded the calculated results by the AIJ SRC standards and AIJ CFT design guideline. Therefore, to conduct rational design of the proposed SC column section, confinement effect by the circular thin steel tube should be taken into consideration.

(9) The bolted circular thin steel tube with diameter-to-thickness ratio of 189 could provide sufficient confinement effect to concrete and make the SC columns behave in a very ductile manner up to large drift. It is noteworthy that the bolted thin steel tubes in the specimens under relatively high axial load did not rupture until the end of loading at about 0.09 rad, which is the advantage of the bolted thin tubes over the welded thin steel tubes.

(10) When the diameter-to-thickness ratio of the bolted steel tube was as large as 189, the SC columns with concrete infilled into the inner square steel tubes of FB and even FC ranks exhibited as large ultimate drift ratios (0.04 rad) as those of the SC columns confined by the welded steel tube.

(11) Confinement by the bolted circular thin steel tube could ensure the SC columns with hollow square steel tube of FB ranks encased an ultimate drift angle of 0.03 rad even the column was under axial compression with axial load ratio of 25%. Increasing the thickness of the outer bolted steel tube had little significant impact on the peak lateral resistance due to the discontinuity near the connecting portion of the bolted steel tube, but could mitigate the degradation of lateral resistance at large drift for all SC columns with FB rank and FC rank square steel tubes encased.

(12) A modified CFT equation by taking into account of the confinement effect could give an accurate

prediction of the ultimate flexural strength of the SC column sections. For the welded specimens (with FA rank, FB rank and FC rank inner steel tubes encased), the ratio of the experimental flexural strength to the calculated result by the modified CFT equation varied between 0.94 and 1.19, having a mean value of 1.10 and a standard deviation of 0.08. Similarly, the ratio of the experimental flexural strength to the calculated result by the modified CFT equation for the bolted specimens varied between 0.96 and 1.17, having a mean value of 1.05 and a standard deviation of 0.08.

(13) For the proposed SC columns confined by welded circular thin steel tube, although the numerical analysis results show an overestimation in terms of initial stiffness, the peak load-carrying capacity and the overall structural behavior could be accurately predicted and traced using the numerical analysis method present in this thesis.

(14) The overall structural performance of the proposed SC columns confined by bolted circular thin steel tube could be reliably and accurately predicted using the numerical analysis method presented in this thesis combining with the assumptions that the confinement efficiency of the bolted tubes is equal to that of the welded tubes for the columns with concrete filled into the inner tubes, but half of the welded tube for the columns with hollow steel tube encased, respectively.

5. Suggestions and Future Works

Due to the constraint of time, there are still several important aspects have not been covered in this dissertation. In order to promote the applications of the proposed SC columns in this doctor dissertation necessary further researches are listed below:

(1) Further Investigation of the confinement effect on concrete by bolted circular thin steel tube：Although experimental and numerical analysis have been conducted on the confinement effects of the outer bolted circular thin steel tubes with thicknesses of 1.6mm and 2.3mm, as well as their influence on the structural performance of whole specimens, further research needs to be conducted on the discrepancy in confinement effect between the two different thicknesses of bolt steel tubes by adding more test specimens. Furthermore, it is also crucial to analyze how the deformation and expansion of the connection wings of bolted steel tubes influence the confinement effect. Optimizing the size and quantity of high-strength bolts at the bolted steel tube wings is also a priority.

(2) Exanimation of axial behavior on square cross-section SC short columns confined by square thin steel tube: Chapter two of this doctor dissertation investigated the axial performance of circular-section SC columns. However, in practical engineering, square cross-section columns exhibit excellent flexural behavior, and compared to other shapes, square columns have the advantages of easy fabrication and connection, simplifying the construction process. Therefore, a detailed examination of the performance of SC columns with square cross-sections is necessary. This includes a focus on the confinement effect

of square thin steel tubes on concrete, with the aim of optimizing and improving their confinement effectiveness.

(3) Investigation for local buckling of the steel tube: Local buckling, as indicated by the experimental results in Chapters two to four, could reduce the load-carrying capacity and stiffness of the proposed SC columns, significantly impacting overall structural performance. To facilitate robust structural design, a comprehensive understanding of the mechanisms and effects of local buckling is essential. Hence, Parametric studies on various design parameters—such as column dimensions, concrete and steel material properties, axial compression ratios, and loading conditions—are necessary. These studies can help identify key factors influencing local buckling behavior.

6. Keywords

SC column, square steel tube encased, welded circular thin steel tube, bolted circular thin steel tube, seismic behavior, confinement effect, quantitative evaluation

7. References

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[2] Sun. Y et al. (1999), “Stress-Strain Relationship of High Strength Concrete Confined by Circular Steel Tube, *Proc. of the JCI,* Vol.21, No.3, pp. 601-606. (In Japanese)

（別紙１）　　論文審査の結果の要旨

氏名	張　弛　（チョウ　チ）		
論文題目	Structural Performance and Evaluation of Square Steel Tube Encased Concrete Columns Confined by Circular Thin Steel Tube （円形薄肉鋼管で横補強した正方形鋼管内蔵コンクリート柱の構造性能及び耐力評価に関する研究）		
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要　　旨

物流倉庫建築物は、経済活動において非常に重要な役割を担っているものである。既往の物流倉庫建築物に用いられる構造形態として、鉄骨鉄筋コンクリート（SRC）柱や鉄筋コンクリート（RC）造柱と鉄骨梁からなる混合構造が主流であるが、柱における配筋作業や柱・梁接合部における鉄骨と鉄筋のおさまりが複雑になる問題が指摘されているほか、その使用上の制約からブレースを配置できる構面数が限定される傾向にある。物流倉庫建築物の耐震安全性などを確保すると同時に、空間設計の自由度が高い、新たな構造形態の開発が求められる。

その新しい構造形態の一つとして、倉富らによって提案されている、SRC 柱から主筋を排除したうえ、鉄骨を囲むコンクリートを外から薄肉鋼管で横拘束される正方形鋼・コンクリート（SC）柱がある。この鋼管拘束正方形 SC 柱は、従前の SRC 柱や RC 柱と比べて、主筋の配筋工程の省略ができるほか、外鋼管は SC 柱の型枠を兼ねることができ、非常に高い施工性が期待できる。一方、コンクリートを拘束するための正方形外鋼管の拘束効率が低いことから、SC 柱に十分な変形能を確保するために、比較的厚肉の鋼管の使用が想定され、経済性に難がある。

本論文では、円形鋼管の高い拘束効率に着目して、角形鋼管を円形断面コンクリート柱内部に内蔵したうえ、柱全体を薄肉円形鋼管で拘束する新しい円形 SC 柱を提案し、薄肉円形鋼管の拘束効果を実験的に明らかにしたうえ、提案する円形 SC 柱に対して、実験と解析の両面からその力学的性能を明らかにすることと、提案円形 SC 柱の実用時に欠かせない、柱断面の終局曲げ耐力などの評価手法を構築することを目的とする。

本論文は６章からなっている。

第１章は序論であり、本研究の背景、既往の SC 柱の力学的性状や終局耐力評価に関する研究現状を子細にレビューしたうえ、既往の鋼管拘束 SC 柱の構造性能における研究対象はすべて角形鋼管で拘束された正方形断面柱であることを踏まえ、薄肉円形鋼管で拘束された円形 SC 柱の力学的性状を解明するための課題を解説するとともに、本研究の目的と具体的な研究内容を述べている。

第２章では、薄肉円形鋼管の拘束効果の解明と拘束薄肉円形鋼管のより簡易な製作方法の開発を目的に、鋼管拘束コンクリート短柱（断面直径 175mm）の中心圧縮実験を行った。円形鋼管の製作方法（溶接とボルト結合）、径厚比（111 と 78）、角形鋼管の内蔵の有無、および内蔵角形鋼管へのコンクリートの充填の有無を実験変数に取り、計 10 体の試験体を製作した。実験結果より、内蔵角形鋼管にコンクリートを充填する場合は SC 短柱が外薄肉円形鋼管の拘束効果を十分に期待できるが、コンクリートを充填しなければ、内蔵鋼管の局部座屈に起因する靭性劣化と溶接薄肉鋼管の溶接部における早期破断が生じる恐れがあること、ボルト結合薄肉円形鋼管は、径厚比 78 の場合は溶接鋼管とほぼ同じ拘束効果を発揮でき、径厚比 111 の場合は溶接鋼管の拘束効果の約半分しか発揮できないが、軸ひずみが 0.06 となる大変形域までボルト結合鋼管が破断することなく、SC 柱に十分な靭性をもたらせること、薄肉円形鋼管で拘束されたコンクリートの応力―ひずみ特性が NewRC モデルによって比較的精度よく評価できることなどを明らかにした。

第３章では、提案する円形 SC 柱の力学的特性に関する基礎データを取得することと薄肉円形鋼管が SC 柱の終局耐力と変形能力に及ぼす拘束効果を究明することを目的に、せん断スパン比が 3.0 の SC 柱を計 13 体製作し、一定軸力下における繰り返し載荷実験を行った。試験体はすべて直径 300mm の断面を有するコンクリート柱をレザー溶接で製作された薄肉鋼管（径厚比が 189）で拘束されたものである。実験変数は内蔵角形鋼管の構造性能ランク（FA, FB, FC）、内蔵鋼管へのコンクリート充填の有無、軸力比（0, 0.15, 0.25）、および主筋の有無である。実験結果より、内蔵角形鋼管のランクに関係なく、すべての試験体は現行規準の算定式に基づく計算耐力を発揮できること、FA ランク角形鋼管を内蔵した SC 柱は、

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充填コンクリートの有無にかかわらず、軸力比が 0.25 と比較的高い軸力下においても部材角 0.04rad までの終局変形能力を有すること、軸力比が 0.25 下における、FB または FC ランクを内蔵した SC 柱に部材角 0.03rad までの変形能を期待するには、角形鋼管内にコンクリートを充填する必要があることと、主筋の存在は SC 柱の終局耐力の向上に寄与するが、変形能にほとんど影響を及ぼさないことなどを明らかにした。

第 4 章では、溶接薄肉鋼管より施工性と経済性に優れるボルト結合薄肉円形鋼管が SC 柱の耐震性能に及ぼす影響を実験的に究明するために、ボルト結合鋼管の径厚比（189、132）、内蔵角形鋼管の構造ランク（FB、FC）、内蔵鋼管へのコンクリート充填の有無、および軸力比を実験変数に取り、計 6 体の SC 柱試験体（断面直径が 300mm）を作成し、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、部材角が 0.09rad と載荷装置の限界になるまでボルト結合鋼管が破断することなく、円形 SC 柱に十分で確実な拘束効果を提供できること、FC ランクの角形鋼管にコンクリートを充填すれば、軸力比が 0.25 までの軸力を受けても、FC ランクの角形鋼管を内蔵した円形 SC 柱は部材角 0.04rad までの終局変形能を有することなどを明らかにした。

第 5 章では、本論で提案した新しい円形 SC 柱の終局曲げ耐力および履歴性能曲線を評価するために、まず、現行設計規準に推奨されている二つの終局耐力算定方法の適用性と精度の検証を行った。その結果、軸力比がゼロの試験体を除けば、SRC 規準式による計算耐力は本論第 3 章と第 4 章で述べた試験体（18 体）の実験結果を 11%～52%（平均で 33%）安全側に評価するのに対して、CFT 指針式による計算耐力も実験結果を 7%～35%（平均で 19%）安全側に評価していることが明らかになった。そのような結果を踏まえ、本論では薄肉鋼管の拘束効果を第 2 章で述べた知見に従い評価したうえ、CFT 指針式を修正した。修正した CFT 指針式による計算曲げ耐力は実験結果を平均で 7%（標準偏差 0.07）精度よく安全側に評価できることを明らかにした。また、提案円形 SC 柱の大変形までの履歴曲線を追跡するための手法を提示し、提案した手法による解析結果は実験結果を大変形域まで比較的精度よく追跡できることを明らかにした。

最後に、第 6 章では、以上各章の研究成果を総括し、本研究の結論とした。また、本論で扱えなかった高力ボルト結合薄肉鋼管の厚さによる影響の定量評価および内蔵角形鋼管の局部座屈耐力に及ぼす充填コンクリートの影響メカニズムと評価方法の確立など、今後の研究課題を示した。

以上で述べたように、本論文は新しく提案された薄肉円形鋼管で拘束された鋼・コンクリート合成柱の力学的特性および終局耐力について、実験と解析の両方からの検討結果を踏まえ、提案円形 SC 柱の実用時に不可欠な終局耐力および履歴性状の評価方法を研究したものであり、靭性能に優れた新しいハイブリッド構造部材の力学特性とその評価方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、学位申請者の張　弛　(チョウ　チ)は，博士（工学）の学位を得る資格があると認める。