（ 続紙 1 ）

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論文題目	Development of Seismic Retrofitting Techniques for Historical Masonry Structures with Application of High Performance Materials （高性能材料を用いた歴史的組積造構造物の耐震補強技術の開発）		

（論文内容の要旨）

This study is motivated by strong needs for seismic rehabilitation of historical unreinforced masonry (URM) structures. Three important aspects of this study are summarized as follows: The first goal involves the development of finite element (FE) models for pinning retrofitted masonry walls. The second goal is to perform an extensive study on the use of polymer cement pastes (PCPs) as bonding agent in pinning retrofitted masonry walls in place of epoxy resin. The third goal presents application of newly developed Cu-Al-Mn shape memory alloys (SMAs) to retrofitting URM structures. The work is presented in 6 chapters, and the contents of each chapter are summarized below.

Chapter 1 gives introduction on the thesis work with arguments defining motivation driving this work with its subsequent objectives. This chapter highlights some major problems associated with the present scenarios of masonry retrofitting which provided impetus for this research work.

Chapter 2 presents literature survey with summary on the previous works related to masonry structures. The relevant works are reviewed under six different categories: 1) Behavior of URM buildings, 2) Resistance mechanism of URM and reinforced masonry (RM) constructions, 3) Existing retrofitting techniques for URM walls, 4) Pinning retrofit technique, 5) Numerical modeling of URM and RM structures, and 6) Application of SMAs in retrofitting URM buildings.

Chapter 3 covers FE modeling of pinning retrofitted masonry walls to predict restoring force characteristics observed during the experimentation under cyclic loading. Here a simplified equivalent vertical bar model is proposed for two-dimensional representation of inclined bars inserted into URM walls. In addition to numerical modeling, theoretical predictions are given to verify the experimental and numerical observations. The first section of this chapter reports FE modeling of in-plane loaded masonry walls with an opening. The second section is aimed at FE modeling of out-of-plane loaded masonry walls. The developed FE models serve as an important tool for verification as well as check for design specification to pinning retrofitted walls. To state the effectiveness and robustness of the retrofitting technique and the adopted numerical models, sensitivity analysis is performed with study of masonry wall’s response with respect to the changes in masonry mechanical properties. The evaluation shows almost no sensitivity to variations in masonry material constants in RM specimens, demonstrating the robustness of pinning retrofitting technique under cyclic loading conditions and the stability of the proposed simplified FE modeling.

Chapter 4 introduces application of PCPs as bonding agents to pinning retrofitted masonry specimens. Epoxy resin, which was used in existing retrofitting projects, has its limitations being

an organic adhesive, low fire resistance, high cost, and poor durability. On the other hand, the use of ordinary mortar would result in workability problems that keep their usage out of context. For these reasons, Chapter 4 reports an extensive study carried out to propose the best possible type of PCP for masonry retrofitting among various commercially available PCPs. To limit the seepage of water from PCP to masonry and subsequently increase the workability, PCP in combination with water penetration barrier agents (impregnants) is proposed. The best possible combination of PCP and impregnant is met through extensive experimental works. Chapter 4 reports on various experimental works performed on masonry assemblages to check the applicability of particular PCPs as bonding agents namely, workability test, pull-out test, compression test, shear test and one-point bending test. FE simulation and theoretical prediction on three-point bending test is also reported in this chapter. The best combination of PCP and impregnant, showing strong bond with minimum strength variation at different open times and also better resistance when tested as an masonry assemblage, was attained for SBR PCPs with BPA impregnant as pretreatment agent.

Chapter 5 deals with the experimental and numerical study on applicability of Cu-Al-Mn SMAs in masonry retrofitting. Previous usage of steel reinforcing bars comes with its limitations resulting in pinching, or degradation of stiffness and strength under cyclic loading caused by inelastic elongation of reinforcing bars. With the recent development on cost effective and highly machinable Cu-Al-Mn SMAs, Chapter 5 reports on the proposal of masonry retrofitting that incorporates Cu-Al-Mn SMA bars as reinforcing elements, which can result in highly improved performance. This chapter is divided into two sections with first one reporting on quasi-static cyclic tests and the second one on dynamic loading tests. Half-scale bricks are used in both tests. Experimental observations are verified using FE models. Additionally sensitivity studies are done to check the robustness of the adopted numerical model with variation in masonry mechanical properties and boundary conditions. From the quasi-static cyclic tests, the steel reinforced masonry (ST-RM) specimen showed pinching while the SMA reinforced masonry (SMA-RM) specimen did not. Dynamic test results show ST-RM specimens with substantial residual deformation of the wall at the end of excitation confirming the instability caused by residual elongation of steel reinforcing bars. This ultimately resulted in premature collapse at the exceedance of instability limit due to the P-Delta effect. SMA-RM specimens, on the other hand, exhibited stable rocking behavior without significant residual rotations even for base excitation exceeding the gravity acceleration. The primary reason for this stable rocking response is attributed by the superelastic property of SMA reinforcing bars, which ensured no residual strain during and after the loading. The results demonstrats the applicability and superiority of the Cu-Al-Mn bars to retrofitting URM walls as a partial replacement of steel bars.

Chapter 6 briefly summarizes the works reported in this thesis, highlighting the main findings. This final chapter ends with recommendations for further studies.

（続紙 2 ）

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（論文審査の結果の要旨）

本論文の成果は大きく二つに分類できる。一つ目は、無補強煉瓦壁一面に目地部から斜め下向きにドリル孔を設け、このドリル孔に鋼棒を挿入し接着剤で固定する耐震補強（以下、ピンニング補強と呼ぶ）法に関するものである。この内容はさらに、(a)補強煉瓦壁の力学モデルの構築と、(b)補強で用いる接着材の耐久性向上の二つに分類できる。二つ目は、煉瓦壁に挿入する補強材の一部に新型銅系超弾性合金を用いることで、通常の鋼材補強の場合に見られる繰返し載荷時の補強効果低減を回避する手法の開発に関するものである。本論文で得られた主な成果は以下の通りである。

(1-a)ピンニング補強法により補強された煉瓦壁の力学モデル構築

汎用非線形有限要素プログラムを用いて補強煉瓦壁の繰返し載荷時の履歴特性が予測可能な力学モデルを構築した。ここでは斜め向きに挿入される補強鋼材を忠実にモデル化するのみでなく、複数の斜め補強材を等価な一本の縦補強材に置換する手法を提案し、提案モデルにより予測精度を確保した上で大幅な計算負荷低減や繰返し演算の収束性向上が可能となることを、多数の解析や実験結果との比較を通じて実証した。また、煉瓦壁では煉瓦や目地モルタルの力学特性のバラツキが大きいのが特徴であるが、これらのバラツキを考慮した場合でもピンニング補強法により安定した補強効果が得られることを、提案モデルを用いたパラメトリックスタディを通じて実証した。

(1-b)ピンニング補強法における接着剤の耐久性向上

従来のピンニング補強では、接着剤として有機系のエポキシ樹脂が用いられてきたが、有機系接着剤は耐久性、耐火性、経済性の面で不利であり、無機系接着剤の利用が強く望まれている。しかし、ピンニング補強では補強鋼材とドリル孔の隙間が 1mm 程度と非常に小さく、通常のモルタルを接着剤として用いると水分が煉瓦に吸収され、鋼棒を挿入できなくなるという施工上の問題があった。本研究ではこの問題を解決するために、前処理剤及び接着剤として用いるポリマーセメントモルタルの配合について、多数の組合せに対して試験体を試作し施工性確認実験と強度実験を行い、高い施工性と優れた構造性能を両立できる最適な前処理剤と接着剤の配合を見出すことに成功した。また見出した配合を用いた実寸規模の煉瓦壁試験体を作成し、準静的載荷実験とその有限要素解析を通じて、本配合を用いた接着剤の有効性を確認した。

(2)新規超弾性合金の利用による繰返し載荷時の補強効果低減回避策の検討

上記のピンニング補強法や、国内外で多く採用されている煉瓦壁に縦孔を設け鋼材を挿入接着する補強法（center core technique）では、繰返し載荷時に曲げひび割れが生じた目地部周辺で補強鋼材が塑性化し、剛性や強度が大幅に劣化するピンチングと呼ばれる現象が生じることが報告されている。本研究では、我国で独自に開発され従来よりも大幅なコスト低減が見込まれる新規開発中の超弾性合金（5～10%程度のひずみを与えても残留変形が残らず旗状の履歴を持つ合金）を補強材の一部として用いることでピンチングの問題を解決できることを、1/2 スケールの煉瓦壁を用いた準静的繰返し実験と振動台実験により実証した。

本論文で得られた上記の成果は、学術上、実際上寄与するところが少なくない。よって、本論文は博士（工学）の学位論文として価値あるものと認める。また、平成 23 年 7 月 23 日、論文内容とそれに関連した事項について試問を行って、申請者が博士後期課程学位取得基準を満たしていることを確認し、合格と認めた。