博士論文（要約）

Seismic Retrofitting of Unreinforced Masonry Houses with Abaca Fiber Reinforced Mortar (FRM) and Abaca Rope Mesh(ARM)
(アバカ繊維補強モルタル(FRM)とアバカロープメッシュ(ARM)による
組積造構造物の耐震補強工法の研究)

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The vulnerability of Unreinforced Masonry (URM) structures have been proved by many past big earthquakes, due to their low seismic capacity. Most URM buildings are built with little or no consideration of seismic loading, and these are not capable of resisting the expected seismic ground motion, which caused damage and collapse of the buildings and have been the major cause of human and economic losses during the past earthquakes, such as the 2001 Gujarat Earthquake in India, the 2003 Bam Earthquake in Iran, the 2005 Kashmir Earthquake in Pakistan, the 2006 Java Earthquake in Indonesia, the 2008 Wenchuan Earthquake in China, the 2010 Haiti Earthquake, the 2015 Nepal Earthquake, and so on. Based on these facts, retrofitting of URM structures is the key issue for earthquake disaster reduction, especially for reducing human casualty. For this reason, there are many kinds of retrofitting materials and methods have been developed and used to strengthen the URM houses, such as Fiber Reinforced Polymers (FRP), steel mesh cage, surface treatment using Shotcrete, post-tensioning using rubber tires, etc. They can contribute somehow to increase strength and modulus for structural applications. However, they are relatively expensive and not available in many parts of the world, which is of prime importance in the third world countries. Therefore, we propose to use a natural fiber called Abaca fiber, which is a locally available and inexpensive material with high tensile strength, as reinforcement in cement lime mortar, Abaca Fiber Reinforced Mortar (FRM) and Abaca fiver rope in mesh style, Abaca Rope Mesh (ARM).

Abaca fiber or Manila hemp is known as one of the strongest natural fibers, native to the Philippines and widely distributed in the humid tropics countries including Indonesia. It is usually used as ropes, fishing nets, currency papers, tea-bags, clothing, automobile body parts, etc. In the last years, natural fibers reinforced composites have received high attention due to their high strength, low density, low cost, biodegradability, and their availability. Abaca fiber has advantages such as high tensile and flexural strength, light and long fiber up to 3 meter, has resistance to saltwater damage, but less durability

due to high moisture absorption and weakening of alkaline environment in cement. Only a few researches have been studying Abaca fiber as a retrofitting material of URM houses. This paper is an attempt to contribute to the development of a new retrofitting method for URM houses strengthened with FRM and ARM subjected to in-plane diagonal compression tests and out-of-plane bending tests. The purpose of the study is to develop a new retrofitting method for URM houses considering both mechanical aspects (high strength, large deformation and energy dissipation capacities), and social aspects (local availability, easy applicability and affordability of method) and to investigate the seismic behavior of FRM and ARM as retrofitting methods.

The experimental test specimens in this study consisted of twenty one in-plane brick wallets and fifteen out-of-plane brick wallets. Whereas Abaca fibers used were obtained from Asapack Company in Japan. For the FRM retrofitting, Abaca fibers were cut into four different lengths as of 10 mm, 30 mm, 80 mm, and 100 mm. The fiber content used was 1% of total weight. After cutting Abaca fibers with specific length, they were mix with cement lime mortar manually before applying to the wallets. While for ARM retrofitting, Abaca fiber were cut and separated become three small Abaca ropes with the thickness around 2-3 mm. Only one third part of Abaca ropes were used as a mesh. Then, Abaca rope were meshed vertically (six Abaca ropes for the in-plane wallets and twelve Abaca ropes for the out-of-plane wallets) and horizontally (six Abaca ropes for both) to the wallets prior to plastering, with the pitch of 40 mm. Abaca rope were meshed vertically first and then horizontally. The proportion of mortar mix used is 1:7.9:20 for cement:lime:sand. Cement water ratio of mortar was kept 0.14. The wallet dimensions were 275×275×50 mm^3 and consisted of 7 brick rows of 3.5 bricks each, while the dimension for out-of-plane wallet were 475x235x50 mm^3 and consisted of 6 brick rows of 6 bricks each. The mortar joint thickness was 5 mm. The URM wallets and those retrofitted by FRM and ARM were tested to evaluate the effects of the FRM and ARM retrofitting. The effectiveness of using Abaca fiber as reinforcement in FRM and ARM were also tested by shake table test. Three one fourth scaled house models were constructed and test, one used 30 mm fiber length for FRM house model and other two used Abaca rope with 40 mm spacing for ARM house models with and without connectors between meshes.

Based on the results of this experimental investigation, the following conclusions can be drawn. From the two ways of retrofitting methods using FRM and ARM, each method has its advantages and disadvantages:

- FRM retrofitting showed a slightly higher initial strength, bigger deformation capacity than URM, and ease on application.
- FRM with fiber length 80 mm showed a highest strength as of 4.0 kN and also biggest ductility up to 45 mm, compared to URM and FRM with shorter fibers and FRM with fibers longer than 80 mm.
- The effective fiber length in FRM reached the optimum value at fiber length 80 mm. As it is observed in case of fiber with 100 mm length, the strength and the ductility became smaller.

- In case that fiber with the length of over 80 mm is used, it showed less workability due to the fiber balling during mix with mortar.
- Variability of the fibers (as it is a natural fiber) and the workmanship contribute the variability of performance of retrofitted specimen.
- Wallet retrofitted by ARM exhibited a higher residual strength than that by FRM and bigger deformation capacities (20 times larger than URM-in plane and 30 times larger than URM-out of plane).
- ARM retrofitting with connectors exhibited less stress drop after initial crack occurred than that of ARM without connector, both for in-plane and out-of-plane wallets. This is due to the connecting effect of meshes set inside and outside of wallets, and reducing the gap between the mesh and the masonry. Wallet retrofitted by ARM also exhibited a lower risk of brick falling down and mortar spalling than that by FRM, due to the rough surface of Abaca rope confined both sides of the bricks wallets.
- ARM with connectors house model showed a higher energy dissipation capacity than that of URM, FRM, ARM without connector, and PP-band. All retrofitting ways (FRM, ARM without connectors, ARM with connectors) showed a higher energy dissipation capacity than URM
- The confinement of Abaca rope can prevent the bricks from falling down and surface finishing mortar from spalling, these combination effects contribute to reduce the dust generated during collapse that makes breathing difficult and cause people die due to asphyxiation.

Based on the results obtained from the tests, it can be concluded that FRM and ARM methods have high potential for retrofitting URM houses in developing countries. Especially ARM method with connectors has shown better results which can contribute a lot to increase seismic capacity of URM houses.