学　位　論　文　内　容　の　要　旨

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学　位　論　文　題　名

Experimental Investigation and Analytical Modeling of Masonry Wall for In-Plane Shear Strength after Strengthening by Various FRPs
(種々の FRP で補強された組積壁構造の面内せん断耐力に関する実験的研究と解析モデル)

Recent earthquakes in Nepal, Pakistan, Afghanistan, and elsewhere in the world caused an extensive damage to human lives and properties and left over a large inventory of unreinforced masonry (URM) buildings that are still in service. Some of them are as old as 700 years and have great historical significance and are included in UNESCO heritage buildings. The majority of those URM buildings which have been constructed with little or no attention to seismic considerations demonstrate the need for strengthening due to their poor seismic performance posed by their inherent brittleness and low tensile strength. In the event of an earthquake, apart from the existing gravity loads, horizontal racking loads are imposed on walls. Hence if the stress state within the wall exceeds masonry strength, brittle failure occurs, followed by possible collapse of the wall and the building. Therefore, URMs are vulnerable to earthquakes, and should be confined and/or reinforced whenever possible. So, there is an urgent need to improve the performance of URM structures by retrofitting and strengthening them to resist potential earthquake damage.

This research work investigates the in-plane shear performance of externally strengthened masonry walls using two types of fiber reinforced polymer (FRP) sheets, they are: synthetic FRPs and FRPs with natural fibers. Among these two types, Carbon FRP (CFRP), Polyethylene Terephthalate-FRP (PET-FRP) and Nylon-FRP are the synthetic one and FRP made from Jute and Cotton fibers are the natural one. Although the conventional FRPs possess superior mechanical strength over natural FRPs, they have got some serious drawbacks such as high density, high cost and poor recycling and non-biodegradable properties. On the other hand, the strength of bio-fibers is not as great as conventional fibers, but their specific properties are comparable and compatible with conventional resins and masonry. Moreover, the durability of the natural fibers can be enhanced due to embedment of the fibers within the resin.

Among the three synthetic FRPs, PET-FRP has a low tensile strength but possess a higher fracturing strain (more than 10 percent) than CFRP (about 1.5 percent) which has drawn a significant attention as a unique alternative to CFRP or GFRP due to its pronounced ductile behavior and relatively low material cost. On the other hand, Nylon-FRP has a higher fracturing strain (about 15 percent) but with low tensile strength than PET-FRP and CFRP. Regarding natural fibers, Jute possesses higher tensile strength (about 250 MPa) and fracturing strain (about 22 percent) than Cotton (about 75 MPa and 10 percent, respectively).

Fifteen masonry walls made from clay brick were tested for static lateral loading under constant compression, after bonding these FRP sheets on their surfaces in three different configurations, namely cross-diagonal configuration, FRP in grid system and fully wrapped with FRP. Strengthening is considered on both sides of the wall to ensure uniformity and symmetrical stiffness of those walls. The ultimate shear strength and deformation at peak load were the two important observations. The mechanisms by which load was carried were observed, varying from the initial uncracked state to the final

fully cracked state. The propagation of potential flexural and diagonal cracks were noticed in each masonry wall and at the end several failure modes were observed. For FRP strengthened walls, damages and distresses on FRPs were marked and categorized as either FRP debonding or fracture. Based on the experimental results and observations, the following remarks were outlined:

(1) This experimental study demonstrates the ability of all of the FRPs such as CFRP, PET-FRP, Nylon-FRP, Jute-FRP and Cotton-FRP sheets to enhance the shear resistance to a great extent; more than twice the capacity of the URM wall in the case of diagonal bracing and about three times in the case of gird configuration and walls fully wrapped with FRPs. Among the synthetic FRPs, PET-FRP and Nylon-FRP have a better ductility performance than CFRP, as they show pronounced ductile behavior in pre-peak regime and softening behavior in post-peak regime. Ductility is a must needed criterion rather than strength for a structure to absorb substantial seismic energy and ensure structural integrity and margin of safety against collapse. Though the CFRP increases the shear capacity of a masonry wall, it substantially reduces the ductility of the wall, which may eventually cause an explosive type of masonry failure. On the other hand, Jute-FRP and Cotton-FRP also enhanced the shear capacity of masonry wall to almost thrice of that of URM wall and they also showed better ductile behavior than CFRP.

(2) The elastic stiffness of URM wall was largely modified by the use of FRPs, externally bonded over the surface of the walls but it was observed that stiffness value beyond some specific range does not increase the in-plane shear strength of masonry and it will only increase the cost of strengthening works.

(3) As masonry is quite fragile against lateral movement with a low lateral stiffness, diagonal bracing with PET-FRP sheet can be one of the options, if the cost of the material is not compromised. If seeking for a low-cost strengthening material, Nylon-FRP, Jute-FRP and Cotton-FRP could be one of the variable alternatives, where not only capacity is enhanced but, at the same time, the wall is made quite ductile, reversing a catastrophic mode of failure to a ductile one. Moreover, unlike synthetic FRP such as CFRP, PET-FRP and Nylon-FRP, Jute and Cotton are bio-degradable materials, and they do not pose any threat to the ambient environment. For low cost strengthening work, Jute, Cotton or Nylon can be good alternatives to PET and Carbon.

(4) Another interesting point that is manifest from this experimental study is that the FRP strengthening of the masonry can have only marginal effect on the structural performance at the service load condition but contribute a lot at some accidental overloading such as earthquake, where the seismic demand is high.

(5) The in-plane shear strengths observed in this experimental study are almost equal to each other for the cases where the amount of FRP was greater than a certain limit. This information has assisted to some extent to develop an analytical model for FRP strengthened wall based on effective strain in FRP.

At the end, a simplified model for evaluating shear strength of FRP retrofitted masonry wall is proposed and validated with the experimental results of this research and results from other sources. This can be a good source of guideline in developing design standards for performance based design of strengthening masonry structures for in-plane shear strength. Although the numerical models proposed in this study were not extensively verified for full scale walls, yet they can be an efficient tool to implement in any general purpose FEA program and furthering the simulation works of FRP strengthened masonry walls in future.