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Seismic strengthening of infill walls with perforated steel plates

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A B S T R A C T

Brick infill walls are mostly used in reinforced concrete (RC) structures. It is a known fact that the use of these walls inside RC frames composed of columns and beams improves the strength and stiffness of the structure under seismic loadings. Since the brick wall is a rather brittle material, it only improves the strength for a small lateral drift range and this contribution is frequently neglected in the design process. In this work, the aim is to strengthen existing infill walls using perforated steel plates and so to improve the seismic performance. Totally 13 specimens, one being a reference and the remaining 12 strengthened, were manufactured and tested under reversed cyclic loading. The results showed that the strengthened specimens were extremely ductile and no significant loss in strength was observed up to 10% drift ratio. In addition to this ductile behavior, an increase of strength up to twice the reference value was observed. It is concluded that in the near future, by using this easy to apply technique, most RC structures with brick infill walls can be strengthened against earthquakes without discomforting the people within the structure, or at least more safety can be provided.

1. Introduction

Due to architectural concerns, frames in structures consisting of columns and beams are often infilled with brick walls. These walls complicate the behavior of RC frames under earthquake loads. For this reason, the researchers focused on this topic and conducted experimental [1–5], analytic [6–9] and numerical [10–12] studies. In general, brick walls built in this way may provide more stiffness and strength to frames under seismic forces, as presented in earlier studies. However, when the brick infill walls are subjected to a small lateral drift, they suffer significant damage, and therefore their contributions to the frame are lost. As a result of this brittle behavior, brick infill walls are for the most part not accepted as a load-bearing member of the structure and are not recommended to be included in calculations. There are many studies relating to the strengthening of these brick walls, which contributes partly against the seismic forces, by using different methods and materials to make them behave similarly to a ductile RC wall system. Generally, in these studies the strengthening is achieved by using carbon fiber reinforced polymers (CFRP) [13–22], various polymer materials [23–30], precast concrete panels [31–34], structural steel elements [35–38], and reinforced mortar [39–42]. In recent years, studies have focused on strengthening with CFRPs because this material is high-tech, lightweight, thin, relatively easy to implement, and has high tensile strength. However, all these studies agree that even though methods for improving the strength and stiffness of the structure under seismic loadings have been identified, the enhancement of the ductility is limited. To analyze the problem more clearly, load–displacement graphs of the specimens are presented in similar studies [13–20], which show the best strength performance investigated. For a common evaluation, by plotting the envelope curves under the deformations without any significant decrease (15%) of the maximum strength, the story drift ratios are calculated. The drift ratios are obtained from the lateral displacement values divided by the height of the story. The aspect ratios of the analyzed infill walls are between 0.5 and 2. The results showed that the carbon fiber laminates used for strengthening either rupture, tear or debond when the story drift ratios are over 2% at best possibility.

Furthermore, CFRP materials that require epoxy during application have some negative properties which are most often not taken into consideration by researchers. Being very sensitive to the effects of fire can be considered the most unfavorable property. All these polymer composite materials are flammable when a sufficient amount of heat is given. Furthermore, the polyester, vinylester, and epoxy that commonly exist in polymer composites are known to support the flammability and release dense black smoke. Studies have indicated that this smoke consists of extremely hazardous toxic chemicals (carbon monoxide, hydrogen fluoride,

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hydrogen chloride, hydrogen sulfide, and hydrogen cyanide) [43]. The negative effects of temperature on the epoxy strength occur at lower than the burning temperature. Studies have shown that, depending on the characteristics of the epoxy, at between 60 °C and 82 °C the adhesion between the CFRP and concrete is completely lost. A committee report of the American Concrete Institute (ACI) stated that the maximum service temperature of these composite applications should be 15 °C lower than the critical temperature [44].

In addition, there is a warning that the temperature of the application surface should be higher than 10 °C. In the same report, it is stated that CFRP is conductive and that therefore, to prevent corrosion, contact with the steel reinforcement inside the concrete members should be avoided. The fact that epoxy is affected negatively by ultraviolet light with time is another problem that must be solved [44].

Even if the strength and stiffness are improved partially by the other aforementioned methods, a sufficient level of ductility and energy dissipation capacity is not obtained as in CFRP applications.

Apart from this, demolishing the existing brick wall and building a new RC wall that transfers force to the frame is a common and successfully proven method [45–48]. But this method is difficult, time-consuming, and expensive. Besides, the residents are also required to evacuate the buildings for the months-long construction period, which indirectly increases the cost of strengthening the building.

It is observed that none of the methods mentioned in previous studies involve sufficient ductility, low cost, and easy to use criteria at the same time. To fulfill this need for an alternative strengthening method or at least to provide safety, this study aims to use perforated steel plates. Perforated steel plates are materials that can be provided easily, are more ductile than plain steel plates thanks to their holes, and are favorable for easy and quick application without using epoxy. Moreover, their advantages include: applicability without causing any damage to installations on the walls, completely dismountable if necessary, lower fire sensitivity, concealable with plaster, 100% recyclable, containing non-toxic and non-carcinogenic chemicals, and 50% lighter than plain steel plates.

The effectiveness of perforated steel plates was first investigated in studies on strengthening beams against flexure. Beams strengthened using this method not only reached the required theoretical strength but were also able to exceed the ductility level of the reference specimens [49]. In a later experimental study, plastered brick walls were strengthened with perforated steel plates and their behavior under monotonic loading was studied. In this research, 12 strengthened brick walls were tested against an unstrengthened reference wall. The results showed that the strength can be improved approximately 1.6 times and the dissipated energy can be increased to approximately 14 times its initial value. Moreover, when the brick walls which normally have quite brittle behavior are strengthened with the suggested method it is observed that they behave in a surprisingly ductile way comparable to an under-reinforced beam. Even under these high deformations, the brick wall's integrity is not lost under any of the strengthened specimens, and until the end of the experiment they continued to recline to the steel frame hinged from four corners [50]. The ductile behavior and promising result obtained in this pioneer study laid the foundation for the present study.

As it is known, the behavior of brick walls under monotonic loading is quite different from that under seismic loadings especially when the damage exceeds the elastic limits. During monotonic loading, when the damage develops as cracks and crushing, most of the small particles detached from the walls continue to transfer load with the effect of reclining. However, under seismic loads these particles disintegrate and fall off the wall. The gaps and stress concentration due to this behavior may cause the walls to lose their strength and collapse under smaller amounts of drift. Therefore, unlike the earlier study, in this research the plan is that the brick walls strengthened using the method developed will be tested under reversed cyclic lateral loads to simulate the seismic action.

In this study, perforated plates are placed at each side of the existing brick walls and they are fastened by bolts. Therefore it is expected to have a confining pressure on the brick walls and an increase in the strength of the system. Additionally, it is expected that the plates can also contribute to the wall strength by resisting the tensile stresses. It is claimed that the confinement method formed in this way can prevent the infill wall from being crushed and collapsing under the seismic forces, and that the ductility can be improved while keeping its integrity.

The present study was carried out in two stages. At the first stage, a systematic experimental study was performed by changing the thickness of perforated plates connected to the wall and the bolt spacing. The second stage consists of a series of tests carried out using the experience gained from the first stage to improve the behavior, determine the minimum perforated plate thickness, and test possible implementation problems that might occur in reality.

2. Experimental study

2.1. Test specimens

In this research, one reference (a brick wall consisting only of plaster) and 12 strengthened, half-scaled specimens were manufactured and tested. The geometry and details of the prepared specimens used for strengthening are shown in Fig. 1. Plastered walls having 1500 mm width and 1180 mm height were manufactured by considering the laboratory conditions. The wall thickness is nearly 135 mm with a 25 mm plaster thickness applied to both sides (Fig. 1a). The walls were manufactured using $85 \times 190 \times 190$ mm hollow clay bricks (Fig. 1b). These hollow bricks are used for masonry infill and placed in a way that their holes are in horizontal direction according to Turkish Standards [51]. All joints between the bricks are approximately 10 mm and filled with plaster mortar. As it is known that the most unfavorable behavior observed during an earthquake is at the upper corners, half broken bricks were placed with the direction of the hollows upward [52].

As mentioned earlier, the study was composed of two experimental stages. At the first stage including systematic experiments, the thickness of the perforated plates (0.5, 1.0 mm) and the bolt spacing (100, 150, 200 mm) were defined as parameters and a total of seven brick walls were tested by changing only one parameter in each experiment. Then, the test results were analyzed and the optimum spacing between the bolts was decided, and at the second stage the same standard bolt spacing was used for all the specimens. Brick walls strengthened using 0.3 mm thick perforated plates were also tested since it was thought that the lower limits at the plate thickness were not pushed enough. The experimental parameters in the second stage, where the feedback method was preferred, were based on: the plate thicknesses (0.3, 0.5 mm), additional reinforcement applied at the wall corners (bolt densification, L-shaped flat steels placement, creating concrete blocks) and application of the perforated plate (single cut or with a lap splice). The characteristics of the specimens are presented in Table 1.

The names of the test specimens are selected in a way that summarizes the experimental parameters. "S" is for "Specimen". The number following "S" (0.3, 0.5, and 1.0) represents the thickness of the perforated plate. At the end, either the numbers for bolt