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Tilting table tests on strengthened masonry houses

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ABSTRACT

Turkey is located in a highly seismic zone, and large parts of the country are under earthquake risk. Moreover, about half of the building stock in Turkey is composed of masonry type houses, most of which were unreinforced and not designed in accordance with the modern codes. The roofs of masonry houses are usually composed of wooden beams placed on parallel opposing (reciprocal) walls in the short direction. Diaphragm action is not formed and longer walls are pushed in both in-plane and out-of-plane directions during an earthquake resulting in heavy structural damage. A post-tensioning was applied on the walls in vertical direction using recycled material of scrap tires and the performance of the technique was tested on a tilting table using full scale brick masonry house. The masonry house was first tested on the tilting table without any strengthening and then the same test was repeated using a strengthened new house model. The results indicate that the test house's lateral load carrying capacity was improved more than 60% as compared to the original test.

Keywords: Seismic, masonry, tilting table, test, recycle.

1. INTRODUCTION

This paper introduces and discusses the results of a proposed project about earthquake strengthening of masonry houses. The project targets to develop cost efficient earthquake resistance improvements to traditional masonry construction techniques so that poor people might effort. In order to improve the lateral load and energy dissipation capacities with respect to the original masonry wall, an alternative post tensioning technique is proposed, tests and analytical studies are conducted. The post-tensioning strap materials are intended to be obtained from recycled materials such as scrap tires. If the cost-efficient methods of seismic improvement is widely accepted and implemented in poor neighborhoods, actions can be taken by the own residents of houses to mitigate destructive results of earthquakes.

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Developing countries, that have active faults, also commonly have poor population living in self-constructed masonry houses. The poor economic and social background of the residents also means that masonry constructions do not receive any engineering services and, therefore, are susceptible to heavy damage or total collapse during earthquakes. Masonry houses are composed of building blocks with weak inter-binding action which have low tension capacity. The corner connection of the walls experiences higher stresses during earthquake action. At ground motion, all the structure is set in motion and different parts of the structure attempt to vibrate with different characteristics. The stiff structural system of the load-bearing walls and roof and the flexible characteristics of the non-load-bearing walls vibrate in perpendicular directions and the corners of the walls, being the junction between them are the areas of highest stress. Corner separations are the most observed type of failures after earthquakes. Once the corners have failed, the adjacent walls are more likely to fail out-of-plane and overturn. The disintegration of masonry constructions built from adobe, brick, or stone is very quick and it leads to a total collapse of the roof which is traditionally composed of very heavy earth (Fig. 1).

About half of the building stock in Turkey is masonry type and one fourth of the building stock is one-storey brick type buildings (Korkmaz 2006). Majority of these houses are built without engineering services using adobe, brick, and stone type materials and are not capable of dissipating energy during an earthquake due to their brittle characteristics under flexural loading. In general, strengthening studies are concentrated on modern engineered structures and relatively fewer studies exist about the seismic problems of rural masonry houses. Since the occupants of the rural houses are poor, the strengthening technique must be economical, effective and simple so that the owner can apply by himself. Scrap tires can be used for strengthening purposes of rural masonry houses.

Scrap tires are a major problem on an international scale (Adel 1999). For example, more than 270 million scrap tires are produced in United States each year and more than 300 million tires are currently stockpiled (Siddique 2004). Stockpiling of scrap tires is undesirable because of potential fire hazard, environmental damage and for disease-carrying insects, rats, mice, vermines and mosquitoes. (Youwai 2004). However scrap tires are abundant and may be utilized economically as a civil engineering material, if the mechanical properties of the material are found to be of adequate quality for the application involved. Scrap tire chips and their granular counterpart, crumb rubber, have been successfully used in a number of civil engineering applications (Piercea 2003). They can also be used as lightweight fill for retaining walls, highway crash barriers, insulated layers in roadways, drainage material, road subgrade, reinforcement for slopes, sound barriers, and rubberized asphalt. Adel, 1999 used scrap tires for column confinement. This study indicated that the columns behaved in a ductile manner when confined with steel-belted scrap tires, developing lateral drifts comparable to those expected in columns confined with conventional transverse steel reinforcement.

Fig. 1 Common modes of failure of rural masonry structures
(Pictures from Van Earthquake -2011-Turkey, Source: Korkmaz S. Z.)

Scrap tires are non-biodegradable and are durable (Shalaby 2004). The deterioration of an old tire is usually caused by the effects of ultraviolet in the sunlight, oxygen, and water. However, recent tires contains antioxidants and other additives to prevent deterioration. When tires are not used for their original intended use (i.e., transportation purposes), their life would be of at least 100 years (O'shaughnessy 1997). AB-Malek and Stevenson (1968) studied a rubber submerged in 24 m of sea water for a period of 42 years and no serious deterioration of the rubber had occurred.

2. MATERIAL AND METHOD

In the target strengthening scheme, the main material used is scrap tires, which are available almost at no cost. Tire is formed from four main parts which are tread, shoulder, sidewall and bead (Turer 2005). The tread contains a number of strong cords coated with rubber. The high-tensile steel wires are embedded in the tread and bead parts of tires, making these parts stronger than the other parts (Fig. 2).

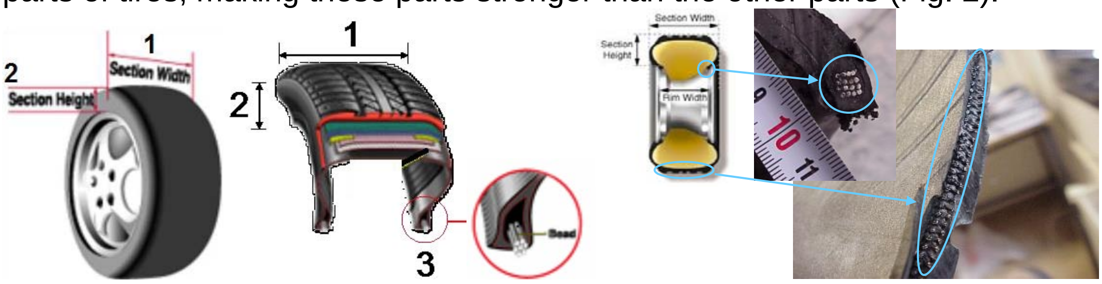


Fig. 2 Section of tire

In this study, only tread (sidewalls removed) are used. Therefore, firstly, the tensile strength capacities of these parts were investigated. Two sidewalls of scrap tires are cut out using a sharp utility knife and ring-shaped section of a tire "Scrap Tire Ring-STR" is obtained (Fig. 3).

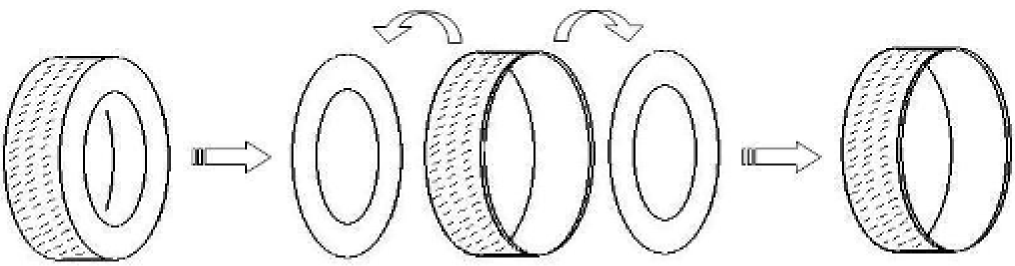


Fig. 3 Obtaining scrap tire rings (Korkmaz 2006 and Turer 2007)

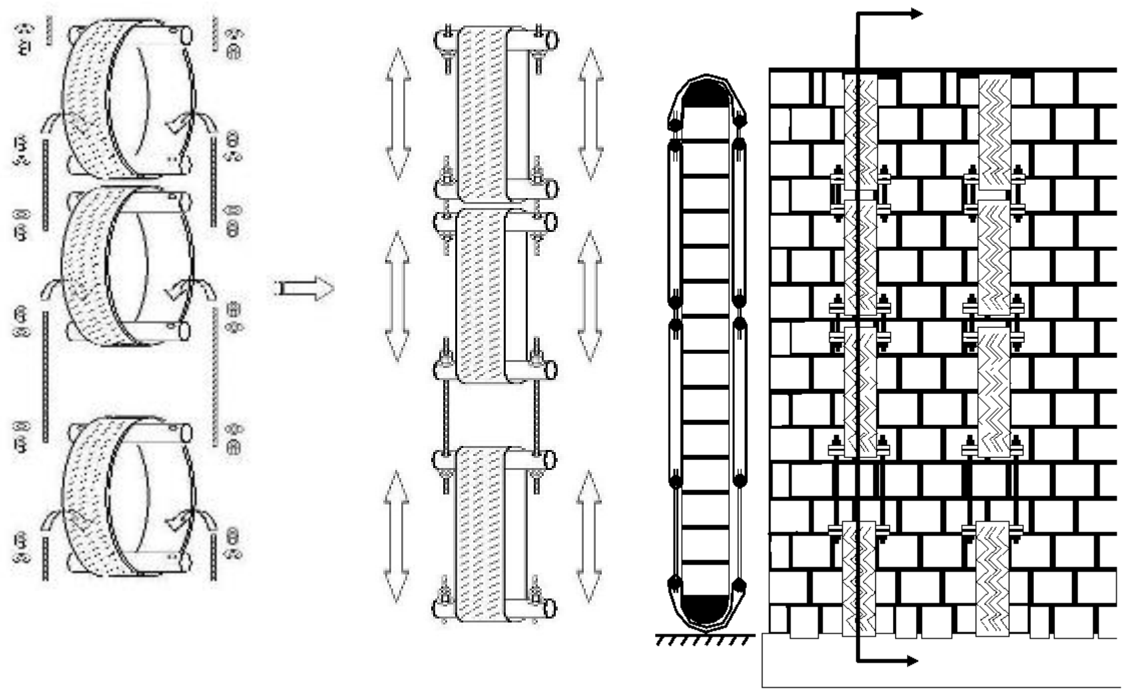
A series of tests were conducted to measure tensile strengths and load-deflection behavior of scrap tire tread-rings (STR). Connection details were designed and developed for production of scrap tire chains (STC) which were used in post-tensioning studies on masonry walls. The scrap tire band was clamped to the testing machine at each end using two-plated connectors with three bolts. A premature failure occurred before reaching the expected strength. This failure occurred due to tearing and slipping of bolts of the scrap tire band. Additional tension tests remained unsuccessful since the bolts continued to tear the tire. These results showed that tire bands cannot be successfully connected to each other using clamps and bolts. Therefore, it was decided to keep the ring shape of tires unchanged, i.e., in the form of a scrap tire thread-ring (STR).

Turer 2008 and Golalmis 2005 conducted a series of tests to measure tensile strengths and load-deflection behavior of Scrap Tire Rings (STR). A test setup is designed and constructed in the laboratory (Fig. 4).The testing scrap tire parts was conducted directly pulling it apart. More than 40single-STRs, which belong to different trademarks are tested in direct tension. The minimum and maximum tensile strengths among the tested specimens are 90 kN and 190 kN, respectively. The shapes of the load-deflection curves are similar and show linear-like slopes after an initial load of about 50 kN is applied.

Fig. 4 Single-STR test set-up (Turer 2005)

3. VERTICAL AND HORIZANTAL POST TENSIONING APPLICATION

Walls of masonry type houses are generally weak in out-of-plane bending direction (for forces induced during an earthquake) which can be improved by post-tensioning. The STRs are planned to be used for post-tensioning of masonry walls and the maximum tensile force foreseen to be used is about 25 kN to 50 kNs not exceeding capacity. The STR chains are wrapped around the masonry wall as shown in Fig. 5-a. By turning the bolts, the STRs are pulled together while adjustable tensile force is applied on the STR chains (Fig. 5-b). The scrap tire rings are passed through the holes opened at the bottom of the wall, just above the ground. On the top, it wrapped around the top roof girder. Semi-circular wooden logs are placed between the wall and STR chain (Fig. 5-c) in order to avoid stress concentrations on the wall application points and evenly distribute the post-tensioning forces on the wall.



a) b) c)

Fig. 5 Application of vertical strips (Korkmaz 2006)

Shear walls commonly fail in diagonal direction due to the formation of principle tensile stresses. Masonry walls loaded in their strong axis in shear show a similar failure pattern as the low tensile capacity is reached on a diagonal plane. The effect of post-tensioning on the shear capacity can be explained and illustrated using Mohr Circles as shown in Fig. 6. The horizontal in-plane load of F_{cr} generates shear stresses (τ). The failure of the wall is assumed to be governed by the tensile stress capacity of $\sigma^{t}_{cut\text{-}off}$, as shown in Fig. 7. The vertical load (W) is generated by the heavy dead load of the earth fill roof causing the vertical stress value of σ_w (Turer and Korkmaz 2007).

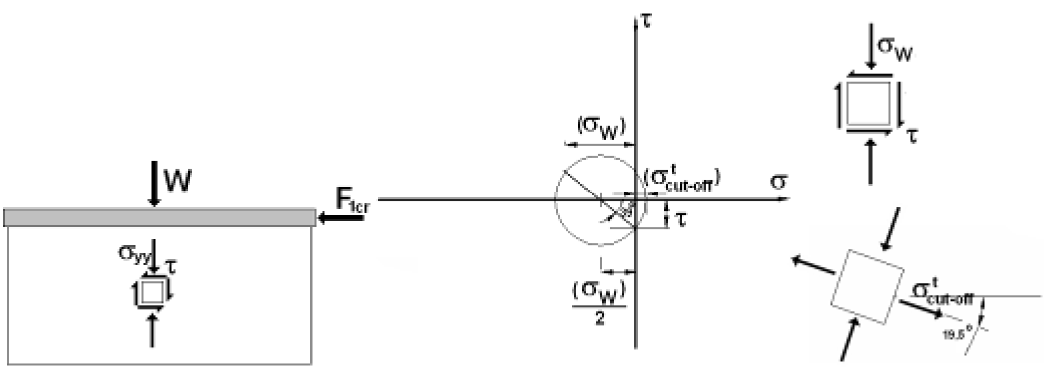


Fig. 6 Explanation of the failure mechanism with Mohr Circle (Turer and Korkmaz 2007)

The effect of vertical post-tensioning on shear load carrying capacity is simulated in Fig. 7 as additional vertical compressive stress (σ_v) is generated by the STR chains.

The centroid of the Mohr-Circle is shifted towards the compressive region of the stress axis by an amount of $\sigma_V/2$. Although the radius of the Mohr-Circle increases significantly, the useful shear capacity increase in τ_v remains low (Fig. 7) since the shear stress plane orientation for F_{cr}^V integration remains flat and refers to a relatively small τ_v value (Turer and Korkmaz 2007).

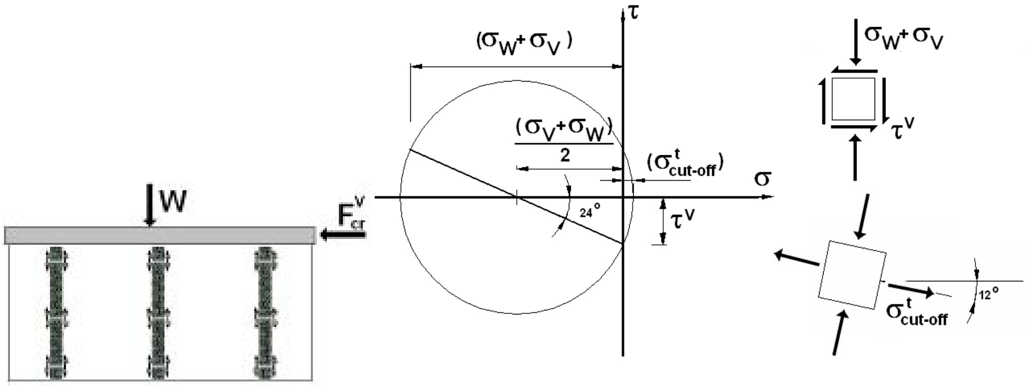
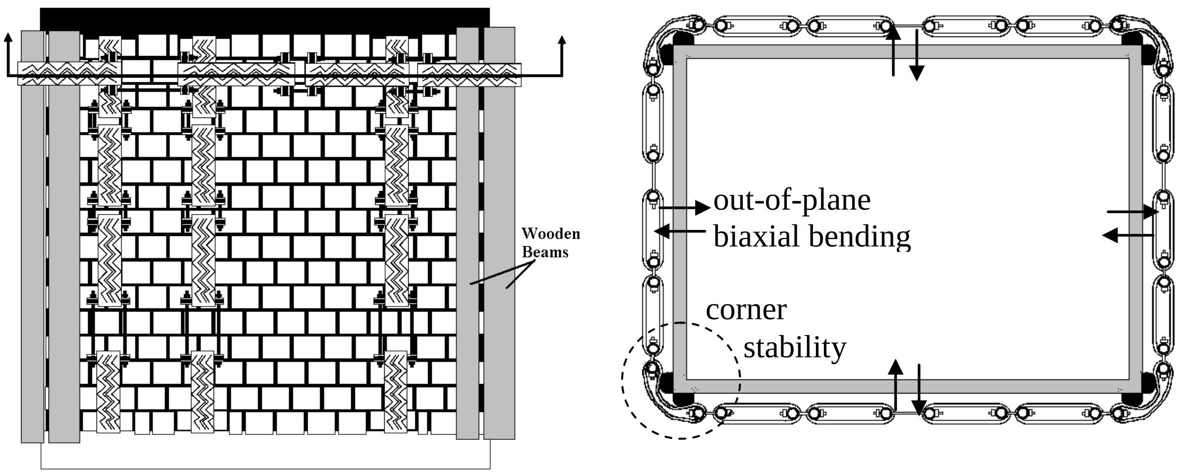


Fig. 7 Explanation of the capacity improvement under vertical wrapping (Korkmaz 2006)

As explained before, corner separation is the most frequently observed failure characteristics of masonry houses. In order to supply confinement effect on the masonry structure it is proposed to wrap STR chains around the house in the horizontal direction. Eight semi-circular wooden beams are placed at four corners of the structure and STR chains are placed and stretched around the perimeter of the building (Fig. 8). The horizontal wrapping under the roof level is considered to supply additional confinement effect in transverse direction while keeping the corners together and delaying the corner connection separation of the walls. The transverse direction post-tensioning also increases the walls' out-of-plane bending capacity in a bidirectional effect.



a) b)

Fig. 8 Application of horizontal wrapping (Korkmaz 2006)

The most pronounced increase in shear load capacity (F_{cr}^{V+H}) is achieved when the wall is post-tensioned in vertical and horizontal directions (Fig. 9). The optimum performance would be obtained when horizontally applied stress (σ_H) is equal to the vertically applied total stress (σ_w or $\sigma_w+\sigma_v$).

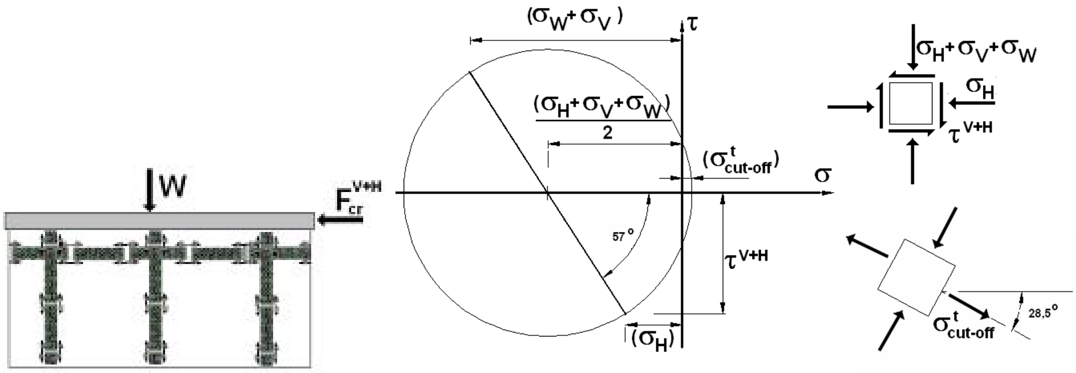


Fig. 9 Capacity improvements due to horizontal and vertical wrapping (Turer and Korkmaz 2007).

4. TILTING TABLE TEST OF FULL SCALE MASONRY HOUSE

In this part of the study, two, full-scale (1/1) traditional one-storey masonries, were tested. Since construction of a shaking table that has a capacity to test full scaled specimen is very expensive and time consuming, an alternative testing method was prepared. For that aim a tilting table is designed (Fig. 10). The aim of this test was to simulate the earthquake acceleration on masonry houses which acts at all points rather than just the roof or slab level that common static loading setups assume. The horizontal load is applied by making use of the gravitational acceleration as the test house is inclined. The mass of the masonry house walls is considerably large and should not be ignored during testing. The mass of the walls play an important role especially in out-of-plane bending direction. The effect is exacerbated if the roof supports are also acting on that wall which receives earthquake acceleration orthogonal to the supporting wall's plane. Tilting test models enabled application of acceleration at all points of the test house in proportion to the mass of its members. A lateral load, which is equal to weight of the structure multiplied by the sinus of the angle, is applied on specimen laterally.

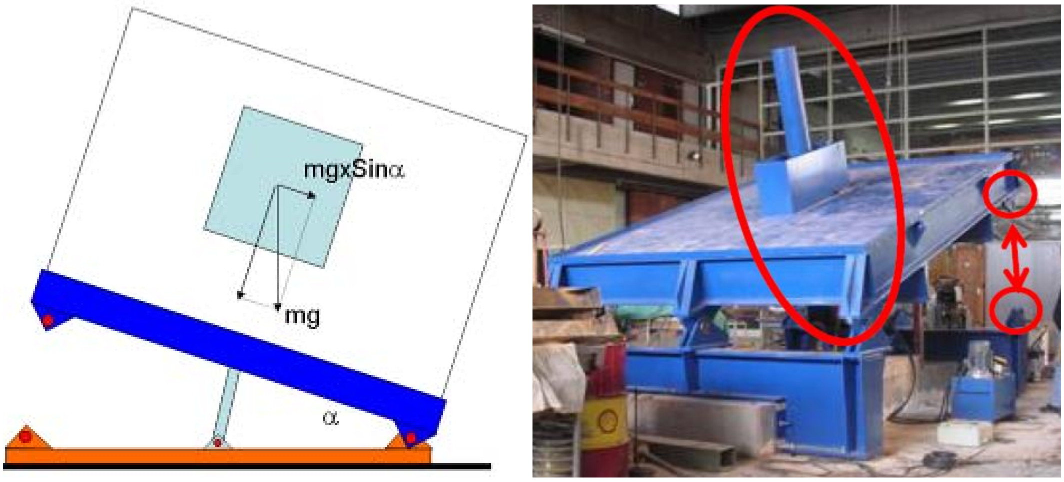


Fig. 10 Lateral load on tilting table

Two full scale houses were tested; the first house was tested without strengthening, and the second one was tested after applying post-tensioning with STR chains (STCs). Two full scale one-storey masonries with dimensions of 3m × 4m × 2.40 m width, length, and height, respectively, were identically constructed on the tilting table by an experienced mason. Full scale prototype test specimens had same geometrical properties with the 1/10 model house. Both models were identical and had a single room with two windows and one door (Fig. 11).

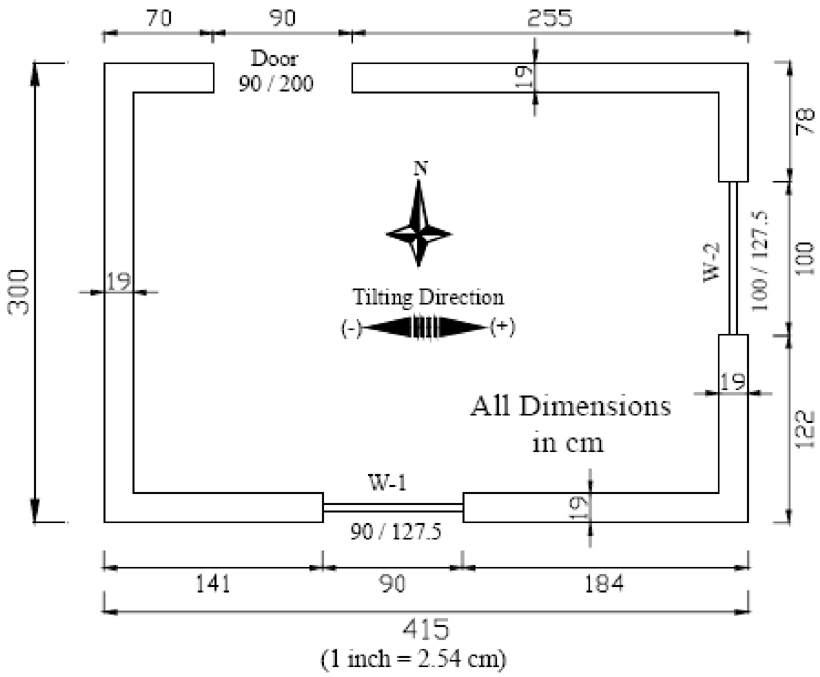


Fig. 11 Plan view of full scale masonry house

In order to simulate the weight of the roofs found in practice, both models were subjected to 55 kN roof weight (4. 7 kN/m^2) carried by five wooden logs placed in tilting direction onto reciprocal walls. The second specimen was post-tensioned by applying

STCs in two directions (9 STCs in vertical and 1 peripheral STC in horizontal directions). The strengthening operation in both directions was applied. First, 1.5 bricks were extracted from the bottom end of the wall, in order to reduce stress concentration on the tire and wall, semi-cylindrical logs were placed in the created gap at the bottom and top ends of the wall. Both wooden logs were bonded to the wall with cement paste for even load distribution. The STCs were then passed through the gap below the bottom wooden log and above the top wooden log, thus wrapping the wall. The post-tensioning load of 50 kN imposed on the walls was applied by turning the bolts of the STR connectors. 8 semi-cylindrical logs were placed on the upper sides of each corner of the walls underneath the horizontal STC (Fig. 12). The STC was then stretched, up to 25 kN, horizontally along the periphery of the model under the roof level. The lateral compression capacity of the bricks are smaller compared to the vertical compression load capacity. Furthermore, there were only two layers of bricks above the windows while a larger number of bricks were available in the vertical direction. Although the capacity of each brick was about 300 kN the load was kept smaller due to the tensile strength and time dependent behavior of scrap tires. Additional vertical load applied by the heavy roof was also taken into account.

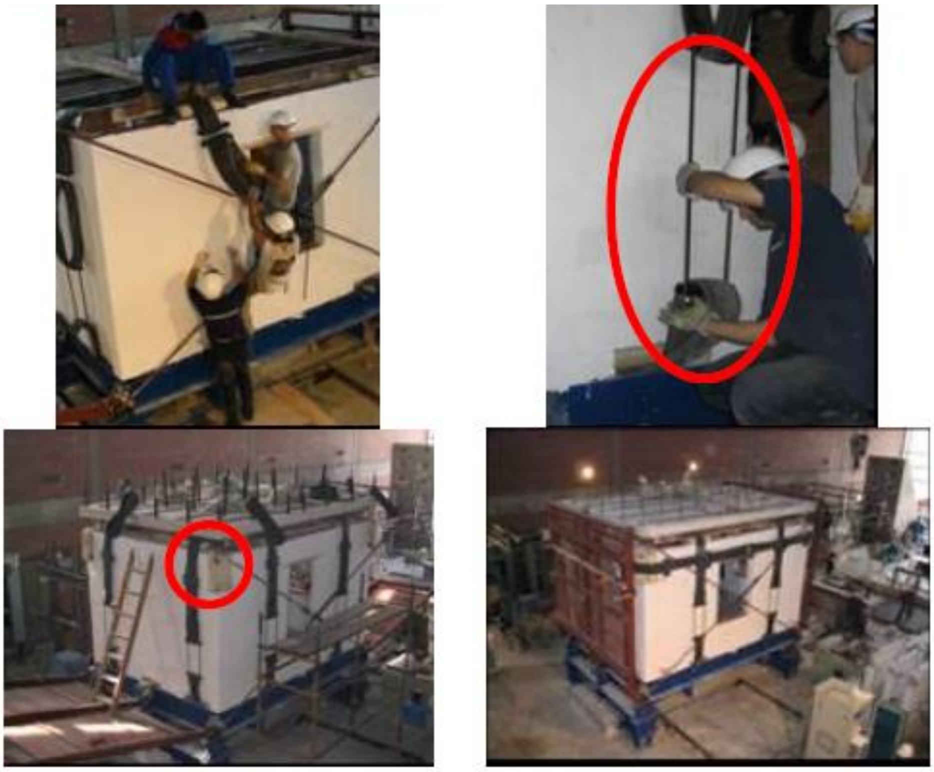


Fig. 12 Strengthening operation of the test specimen

The tilting table can be inclined in two directions via a hydraulic piston, located at the centre of the table. The direction of the tilting is controlled by six pins of the table support joints which permits cyclic static reversal loading. In order to measure the deflections of the walls in the out-of-plane direction, six displacements transducers (LVDTs) were used on either side of the specimen in groups of three. On the other hand, the deflections in in-plane directions were measured by four LVDTs placed diagonally over the walls parallel to the loading direction. Two LVDTs were placed on the narrow pin corners to measure the slope values.

The test of the first model was conducted with the aim of investigating the behavior of un-strengthened full-scale masonry building and determine its capacity for comparison against strengthened model results. The test building was exposed to simulated static cyclic reversal earthquake acceleration. Measured displacement values of walls in out-of-plane directions are given in Fig.13. During the tilting table experiment, the lateral load from the roof was transferred onto the walls in out-of-plane direction as a sinus function of the tilting slope. The load was further transferred from out-of-plane to in-plane direction walls through the bricks and mortar of the walls that supports the beams. During this transfer of load, the shear stress concentration increased, especially around the corners of the walls, doors, and windows. The walls showed linear behavior until the model collapsed suddenly at 18.8 degrees of tilting under the lateral acceleration force of 0.31g in positive tilting direction (Fig. 14). No clear crack formation was observed on the surface of masonry walls prior to the sudden collapse. With the increase of the value of the applied earthquake force, the wall displacements increased linearly up to the collapse of the structure showing brittle behavior due to the characteristics of the used material in the construction of the model. The loading was force controlled, therefore, the response beyond the cracking immediately led to mechanism formation and total collapse. Most probably the collapse mechanism would have been the same during an earthquake. The responses obtained from un-strengthened 1/10 scale lab specimens also supported the brittle behavior of un-strengthened masonry.

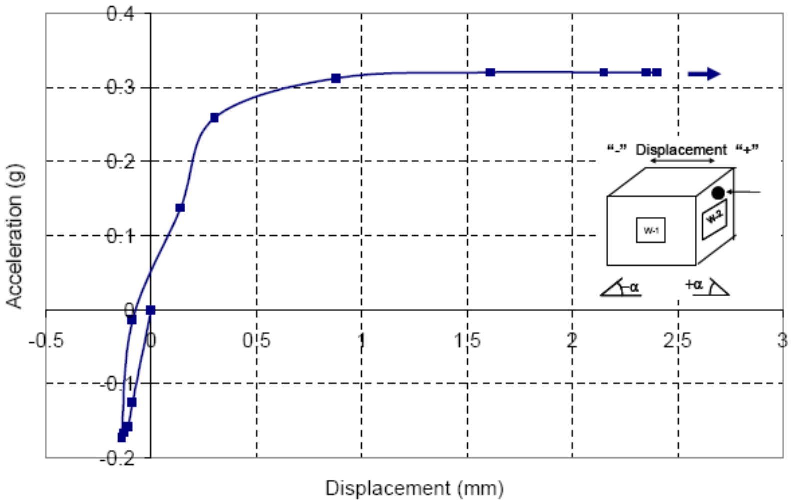


Fig. 13 Out-of-Plane displacement vs load graph of un-strengthened model

Fig. 14 Failure of original masonry house at an angle of 18^o

The crack formations initiated around the corners of the window and the door when the level of the shear stress reached the limits of the walls in in-plane direction (see Fig. 14) and continued diagonally. The failure of the in-plane walls, exposed the out-of-plane walls to an increased load beyond their capacity in that direction considering second order nonlinear effects, thus leading to mechanism formation and a sudden total collapse of the structural system. Contrary to the general expectations, the walls in out-of-plane direction did not fail at the base level but followed a semi-circular inverted path or a flat line at the 1/3rd of the height. The wall was not only supported at the base but also at the two edges along the corner joints with the perpendicular walls. Therefore, the post-tensioning was expected to greatly improve the out-of-bending behavior of the walls that are loaded in their orthogonal direction.

The location and direction of the cracks formed during the first full scale test were helpful in deciding the location of the post-tensioning STCs on the walls for the second model. 50 kN and 25 kN post-tensioning forces were applied on the walls in vertical and in horizontal directions, respectively. The magnitudes of post-tensioning forces were determined according to the strength properties of scrap tires and building materials. The second model (strengthened with scrap tires) was subject to quasi-static earthquake simulation acceleration by the tilting of the table. The model resisted tilting up to 34.4 degrees which was equivalent to 56% of the gravitational acceleration (i.e., 0.56 g). The measured diagonal displacement values of the out-of-plane are given in Fig. 15. The crack patterns of shear and out-of-plane walls are illustrated in Fig. 16.

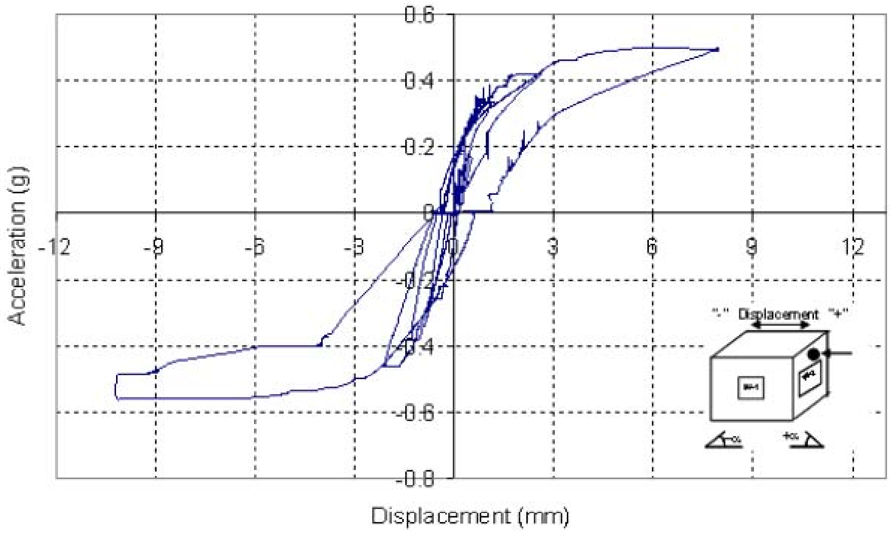


Fig. 15 Out-of-Plane displacement load graph of strengthened model

The formation characteristics of cracks, location of cracks, ductile behaviour of the strengthened building were similar to the specimen S2 in 1/10 model structure. Both 1/10 scaled and full scale prototype structures horizontally cracked at the bottom which was an indication of rigid body translation.


Fig. 16 Cracks of strengthened full scale specimen

The first model, subjected to 0.32 g lateral acceleration, collapsed suddenly, whereas the second model did not collapse and endured lateral acceleration level of

0.56g. In other words, the strength of the masonry walls, pre-stressed by STCs in vertical and horizontal directions, was enhanced by 75%. The second test was stopped since the house leaned on the safety shields. The model could have carried additional load in the nonlinear range. However, tilting the building towards large angles reduces the "weight" of the house as a function of 1-cos(α) in its vertical direction while applying lateral acceleration as a function of sin(α). The test house had a relatively short width and length and a heavy elevated roof which caused significant overturning forces. Reduction of the self weight of the house due to tilting aggravates the over-turning condition. The strength improvement of the test specimen was in fact larger than 75% since the self weight was reduced more at 34 degrees inclination and the failure was governed by tension crack at the base level indicating over-turning behavior.

The condition of the strengthened house after 34 degrees inclination showed that the applied post-tensioning forces had altered the directions of the cracks . Moreover, the cracks were much smaller in numbers and size compared to the first model. They were mostly concentrated at the base and under the windows while in the first model the wall cracks were very large and located at all levels, especially in diagonal direction around the corners of the window and the door. It is also important to note that, when the table was brought back to its original flat position, all cracks were closed and the strengthened model returned to its original shape due to the elastic behavior of scrap tires. Furthermore, the crack pattern of the strengthened model nicely matches with the crack pattern observed in 1/10 scale models.

During the experiment, the first model showed brittle behavior. In other words, when the system exceeded the linear range sudden collapse occurred. Applying posttensioning force on the walls, on the other hand, also improved their ductility capacities. In this way, the energy dissipation capacity of the walls of the strengthened model was enhanced.

4. CONCLUSIONS

The aim of this study was to make masonry houses safer which are, in general, belong to people with low-income group and are commonly undereducated. Masonry construction in rural areas is traditional and same inferior construction is repeated. In Turkey, the problem of finding an efficient solution to strengthening masonry houses is further exacerbated by the fact that about half of the building stock in the country is of masonry type. In addition to making masonry houses safer, this study has another benefit: it uses disposed materials suitable for strengthening houses by post-tensioning, namely, scrap tires. This in turn makes the implementation of the project economically affordable and environment-friendly. Scrap tires have steel mesh inside with high tensile strength that makes them suitable reinforcement material. Except for the low cost of transportation, scrap tires can be obtained free of charge rendering them as low-cost (strengthening) materials. Tires can be prepared using simple tools (e.g., a utility knife). Disposed tires is a threat to environment and human life; scrap tires are difficult to decay generating large waste yards which would catch fires from time to time polluting the atmosphere. Water collecting inside the tires causes mosquitoes to breed which would spread disease. Finally, the application of scrap tires on walls is simple and easy, and does not require complicated tools and practices.

According to the tilting table test results following conclusions can be drawn. The first model collapsed suddenly when subjected to (18^o inclination) 0.32g lateral acceleration; whereas, after wrapping the walls by pre-stressed STCs in the vertical and horizontal direction, the strength of the masonry was increased to (34^o inclination) 0.56g representing 75% percent improvement. Big cracks were formed around the corners of the windows and doors during the first test due to stress concentrations and principal tensile stresses. However, after applying the post-tensioning force on the walls in horizontal and vertical directions, the size of these cracks decreased or disappeared and the distribution of the cracks also changed. They were localized under windows where post-tensioning force was not applied and showed a well-distributed pattern. The energy dissipation capacity of the house was increased after applying post-tensioning force on the walls. Applied post-tensioning force provided both stiffness and improved ductility capacity of the house walls (about 3 times increase in in-plane direction with respect to the unstrengthened masonry house).

To sum up, the use of post-tensioning on masonry walls is a theoretically sound and experimentally proven method for strengthening of masonry walls. Moreover, the use of STR for post-tensioning of masonry walls is a low-cost alternative to using steel or FRP for strengthening low-economy class masonry houses in regions prone to earthquakes. Viscoelastic behavior of scrap tires which are reinforced by built-in steel mesh wires is also superior to steel or carbon fiber (FRP) since upon removal of the force, the tire returns back to its original shape closing the cracks and gaps that might have formed during the earthquake loading. The post-tensioning force is not lost during loadings in the non-linear range. The post-tensioning force on the STC's continues to increase until failure even if the load is reversed and applied in cycles, while steel based post tensioning might be lost due to yielding or FRP's may snap in a brittle way. Residual deformations remain in steel members beyond their yielding point, while STCs recover their inelastic deformations.

The outcomes of scrap tire usage are not only limited by access to cost-efficient easy to access strengthening material but also have positive effects on environmental concerns by recycling. Recycling of scrap tires on a global scale can drastically reduce waste yards and atmospheric contamination during large scale tire fires.

The study results and techniques can be easily implemented in other under developed countries with active seismic faults. The conventional rural masonry building construction techniques used by poor people show similarities in different countries. The positive results of seismic performance improvement can be repeated and implemented in many countries around the world.

Recycling otherwise useless scrap tire material for seismic performance improvement of masonry houses is not only a low cost remedy for poor residents but also an environment friendly approach by reducing waste material and protecting atmosphere from scrap tire dump area fires. Scrap tire usage for masonry house strengthening can be sustainable due to its low cost nature for low-income residents, availability of vast amounts of scrap tire around the globe, provided that the benefits and application techniques are properly documented and disseminated.

STR usage for post-tensioning of masonry walls is a low-cost alternative to using steel or FRP for strengthening low-economy class masonry houses in earthquake prone regions.

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