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State of Art Review: Structural Health Monitoring, Retrofitting and Rehabilitation of Masonry Structures

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Abstract: Brick masonry being an oldest material for construction is widely used worldwide. Its low tensile strength and brittle nature has made it vulnerable under various loading. As unreinforced brick masonry doesn't show any ductility and becomes highly unsafe during earthquakes and therefore, Structural health monitoring has become necessary for old brick masonry heritage buildings having cultural value. A brief review is carried out on ways proposed by researchers to retrofit and restore brick masonry buildings by some of the techniques like tying, jacketing, shotcreting, introduction of fibre reinforced polymers (FRP), inserting meshes, base isolation etc., are more durable, popular and convenient in terms of application.

Keywords: Brick masonry, structural health monitoring, retrofitting/ rehabilitation, Fibre reinforced polymer (FRP).

I. INTRODUCTION

Masonry buildings have shown severe damages and collapse worldwide in recent strong earthquakes. As it is known un-reinforced masonry (URM) walls has low tensile strength, and therefore they are susceptible to out-of- plane failure which leads to subsequent collapse of masonry buildings. The unreinforced masonry acts as a brittle material, hence if the stress state within the wall exceeds masonry strength, brittle failure occurs that followed by sometimes complete collapse of the wall and the building. In India and several other countries. Seismic strengthening of URM buildings often uses ferrocement (welded wire mesh with micro-concrete or cement mortar) hence, unreinforced masonry walls are susceptible to earthquakes and should be reinforced and/or confined whenever possible [1].

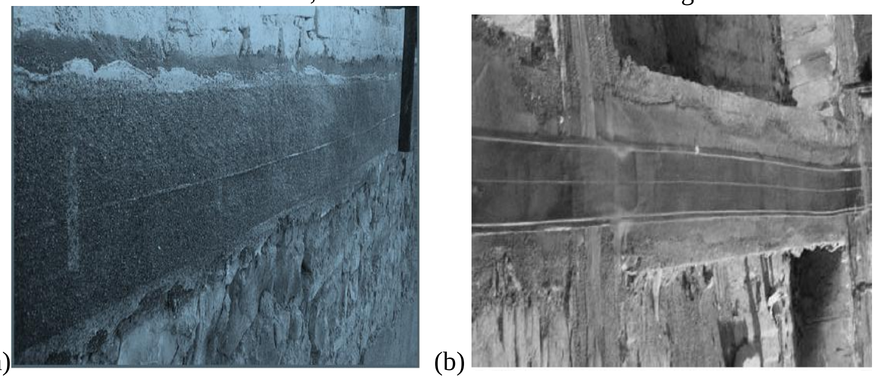
Historic buildings are substantial symbols of any culture's heritage, and it is therefore necessary to protect against such destructive forces as flooding, freeze/thaw cycles, earthquake loads and general ageing. Such heritage buildings are made open for public viewing and for tourists to visit them, hence often providing financial and community benefits to the authorities undertaken them. The natural phenomena stated above are not alone in imposing damage on the structural integrity of a building but also the effects of imposed loads and their resultant vibrations can also cause severe damage such as cracks, which in turn results in complete collapse of the structure. As some structural deterioration takes place below the ground level, visual inspection cannot offer a complete understanding of evaluating a structure's state of repair, which makes the application of non-destructive testing (NDT) highly desirable [2].

Strengthening of URM buildings based on the application of composites is gaining particular interest nowadays. Best application of Composites is developing connections between the structural elements of a masonry building, even under conditions that could cause a connection failure, such as a seismic load. Actually, their application is capable of improvement of tensile strength of masonry materials though only under the composite bond area. Main thrust is given to strengthen or retrofit these buildings so as to improve their safety under lateral loading as well as to preserve them as memory of the ancient art of builders [3].

II. STRUCTURAL HEALTH MONITORING

Heritage buildings and sites are important as they represent national cultural background. Most of the ancient historical and architectural heritage are made of ancient masonry construction, comprises of extremely extensive range of uncertainties due to various reasons like heterogenous nature, local inconsistency of the material strength and stiffness, non-uniformity in the internal masonry texture, where lack of material, empty volumes and rubble used to fill in the walls are usually hard to spot. There is a lack of international standards, but nowadays national guidelines have been adopted in some of the countries. Structural health monitoring (SHM) has emerged as a proper tool to integrate and support the conservation of these historical buildings [4].

There are many heritage and monumental structures worldwide who are under threat of seismic actions and therefore their vulnerability assessment is indispensable task [5]. In this study masonry structures are analysed by considering three historic masonry structures (San Torcato church, Qutub Minar and Gailerio buildings) and their analysis is done by using varied methods of structural analysis and comparison is also carried out between pushover methods and non-linear dynamic analysis with time integration. The results of these three case studies showed that modal pushover analysis is not in good agreement with the non-linear analysis or the experimental observation, because the non-linear behaviour has started at very early stage of loading and also due to absence of stiff floors, so called box-behaviour is missing in these historical building.



(a) (b)

Fig.1. a) Optical fibre for Brillouin sensing embedded into CFRP strengthening on the external masonry.
b) Smart CFRP sheet placed on vaults (Stefano *et al* 2016)

An Earthquake in 1997 had damaged an old historical building dated 1600 A.D. known as Plazzo-Elmi-Pandolfiin Foligno (Italy) [6]. This building was then repaired and retrofitted by using carbon FRP and effectiveness of this strengthening technique was then verified by non-destructive technique. Brillouin technology was used to assess effectiveness of the retrofitting by embedding a low-cost sensor (optical fibre) into CFRP strengthening on the external masonry (refer fig-1 (a) & (b)). This sensor monitored all critical areas and makes it easy to detect abnormality in load transfer between CFRP and the surface of the structure and detect the eventual cracking pattern.

Apart from conventional approach of seismic protection of historic building (retrofitting and repair) there is another method commonly known as passive control solution which involves structural intervention in the form of introduction of flexible interface (HDRE or FPS) between superstructure and the foundation of the building popularly known as base isolation techniques, which is used to bring down the transfer of forces acting on the superstructure during an earthquake event [7]. Another technique under this approach other than base isolation is the provision of dampers, which are need not required to be put between foundation and superstructure. These energy dissipating devices (dampers) like tuned mass dampers, friction dampers or sliding isolation elements now being used in large numbers of historic buildings like city halls of Oakland and San Francisco in California.

Some of the historical buildings in Italy were also inspected by using structural health monitoring (like The Verona Arena, Portoguaro Civic Tower, Gaudenzio Dome in Novara, Torre dell Aquila Trento etc) [8]. The dome of S. Gaudenzio church was also analysed using FEM. The mode shapes and frequencies of particular building was evaluated and the damages it may have experienced due to different earthquakes were hinted. As the mechanical properties of the material of the ancient building are very uncertain from one another, building a predictive numerical model requires enough collection of data from the different locations of the building and then putting the average value of the properties in FE model. It may not true that the all the sensors attached were able to give accurate values as the choice of resolution and accuracy depends on the specific requested performance with all these shortcomings. Old heritage structures health is still required to be checked by more and more advanced techniques so as to strengthen them as soon as possible with best techniques available.

III. RETROFITTING AND REHABILITATION

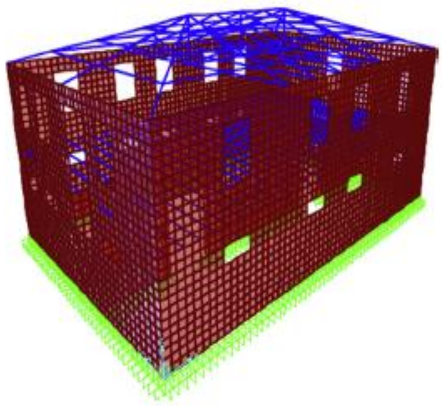
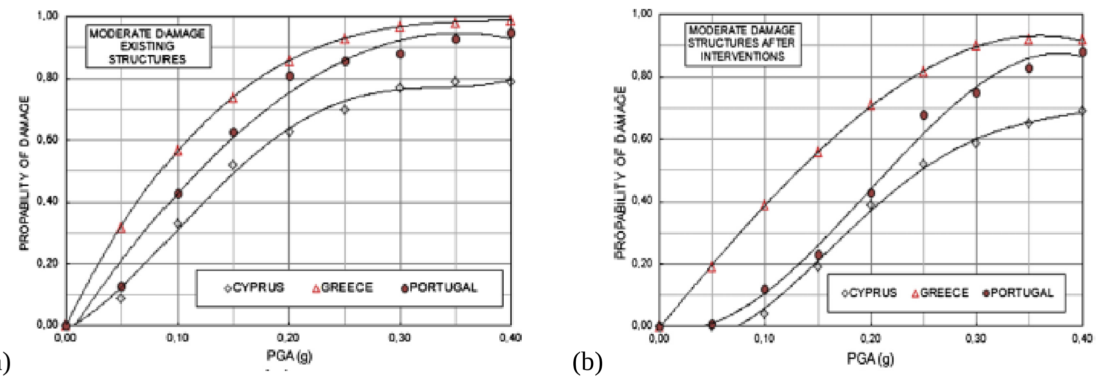


Fig.2. Numerical model created on SAP2000 of the adobe masonry building (Asteris et al 2014).

URM failures can be due to many reasons like structural weakness or overloading, dynamic vibrations, settlements, in-plane and out-of-plane deformations etc. It has been observed that URM buildings have features that can threaten human lives for cases like unbraced parapets, improper connections to the roof, and brittle nature of URM [9].Seismic rehabilitation of heritage masonry buildings has two major goals - life safety; and protection of historical and cultural value of the buildings [10]. Masonry structures are maximum in number among all types of constructions around the world. Past research has showed that most of the researchers have focused their studies on RC structures. However, seismic retrofitting of masonry structure is rare.

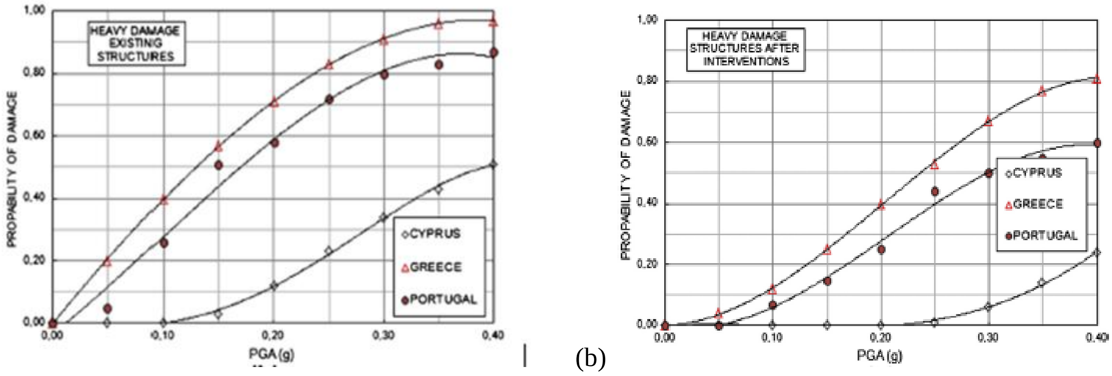


(a) (b)

Fig.3. Fragility curves for the existing structure (a) Case of moderate damage before interventions (b) Case of moderate damage after interventions (Asteris*et al* 2014).

Historical masonry monumental structure in crete, Greece; Averio, Portugal; Askas, Cyprus; were simulated and numerical study was carried out using SAP2000 v.14 software (see figure-2). Seismic vulnerability of these structures was assessed by plotting fragility curves for both existing and the repaired structures (refer figure-3 &4). This study pointed out the vulnerability of the assessed masonry building and required immediate restoration and strengthening. And the methodology followed to assess their actual health status proves helpful as per the results of analysis.

One of the strengthening technique known as “Reticolatus” which is implemented by inserting continuous mesh of stainless high strength steel cords, the ends of which are made connected to the other face of the wall by means of diagonal stainless-steel bars in a number of 5 per m2, in the mortar joints, stripped up to a depth of 50-60 mm (refer figure-5 & 6). These strips are used to make square meshes of the size of 300-500 mm wide normally, in vertical and horizontal directions [11].



(a) (b)

Fig.4. Fragility curves for the existing structures: (a) Case of heavy damage before interventions (b) Case of heavy damage after interventions (Asteris*et al* 2014).

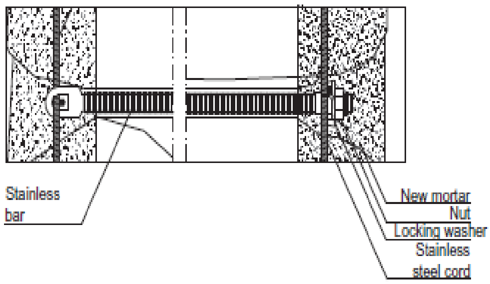


Fig. 5. Details of through connectors in a basement before repair (Borri*et al* 2014).

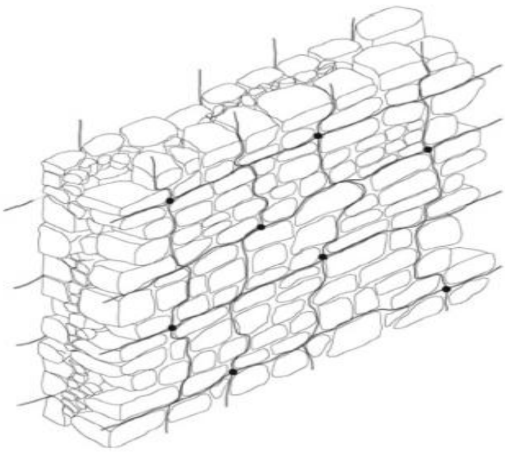


Fig.6. Wall strengthened with 'Reticolatus' (Borri*et al* 2014).

For URM strengthening and retrofitting can also be done by using GFRP (Glass Fibre Reinforced Polymer) refer fig-7. Number of panels were tested with different unit sizes of brick & stone and forms are carried out in the laboratory. The aim of this study was to find out improvement in the shear strength of URM by inclusion of these retrofitting techniques. The result of the tests showed the in-plane shear strength of the reinforced masonry wall/panel has increased significantly as compared to the URM Panel. Fibre reinforced polymers are high strength fibres embedded in a resin matrix. These fibres are usually carbon (CFRP's), Glass (GFRP's) and Aramid (AFRP's) [12]. These fibres are multiple times stronger than steel in the longitudinal direction and generally weak in lateral direction. FRP generally shows no ductility, so the stress-strain behaviour is taken linear elastic to the failure. The young modulus of CFRP is highest generally around 150-200 GPa.

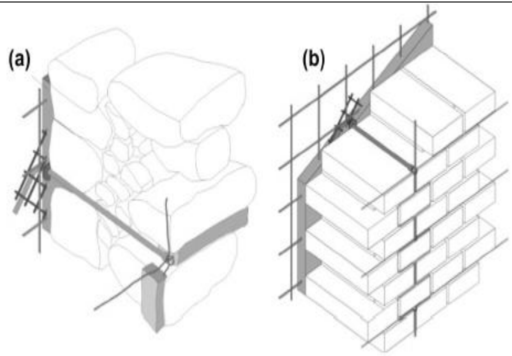


Fig.7. Hybrid strengthening with 'Reticolatus' and GFRP jacketing for (a) stone masonry panels and (b) brick-panels with GFRP mesh inside (Borri*et al* 2014).

Other than very high strength of FRP over other conventional materials available, it is highly durable and light weight. Due to its light weight, it's application is easy in a confined space and no heavy handling equipment is needed. FRP's are available in sheets, tendons, strips, reinforcing bars and meshes. FRP's are the one of the retrofitting technique used for rehabilitation of historic unreinforced masonry (HURM). The fibres like Carbon, Glass and Aramid the in-plane shear load carrying capacity of HURM. FRP's can be wrapped around masonry columns which increases its axial load carrying capacity as shown in figure-8. In this study, a test on HURM specimen strengthened with CFRPs strips laid parallel, normal to the mortar bed joints and diagonal to the bed joints (refer fig-9). This has been observed that in most of the historical masonry buildings arches present extensively and they are also subjected to damages caused by seismic forces during earthquakes.

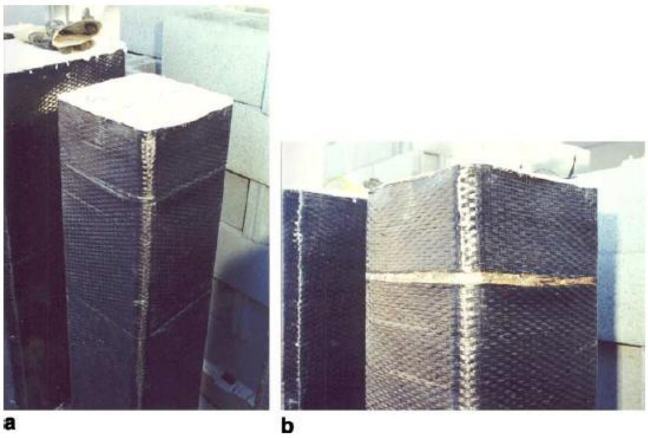


Fig.8. Jacketing of masonry columns with steel meshes (N G Shrive 2006)

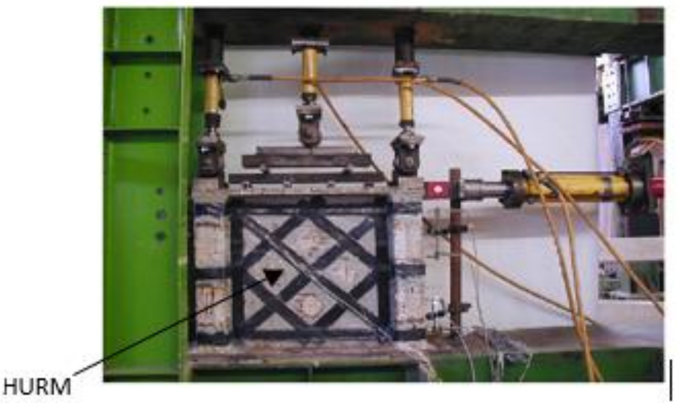


Fig.9. Setup for cyclic test of URM wall with diagonal CFRP strips (Roberto Capozucca 2011).

Fig.10. Shotcrete repair: (a) Concrete wall in factory; (b)Clay masonry walls (Augenti*et al* 2013).

Fibre Reinforced concrete (FRC) is considered as one of the oldest retrofitting material but most researched composite technology [13]. This technology is particularly most effective when substrate surface is rough after removal of loose and damaged portion or reinforcement is fully exposed and FRC is applied through shotcrete (see figure-10) and is made by adding randomly distributed fibres into a mortar or concrete. The effective application of FRC are such as tunnel lining, basement walls, slabs on grade etc.

[14] and [15] has carried out experiments on masonry arch by strengthening and retrofitting arch with sheets of CFRP's and GFRP's as shown in figure-11 & 12. The experimental work was then simulated the result of the numerical analysis validated the methodology adopted in this study. The result also confirmed that the applied retrofitting techniques significantly improved brick arch strengthened.

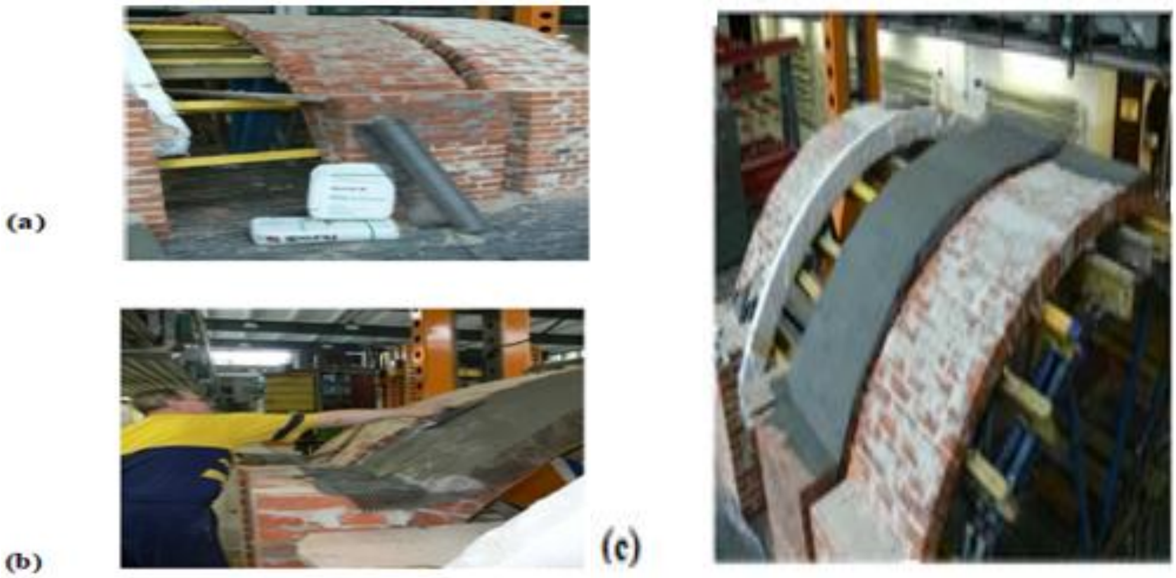


Fig.11.a) Arch $A_{2\,+}$ reinforcing material (carbon fibre mesh and cementitious matrix) b) Attaching (cementing) carbon fibre mesh on the A_2 arch c) General view of arch A_2 (central arch) with the attached carbon fibre mesh (Bednarz*et a*l 2011).

Fig.12. A_2 arch destruction scheme with marked hinging spots (Bednarz*et al* 2011).

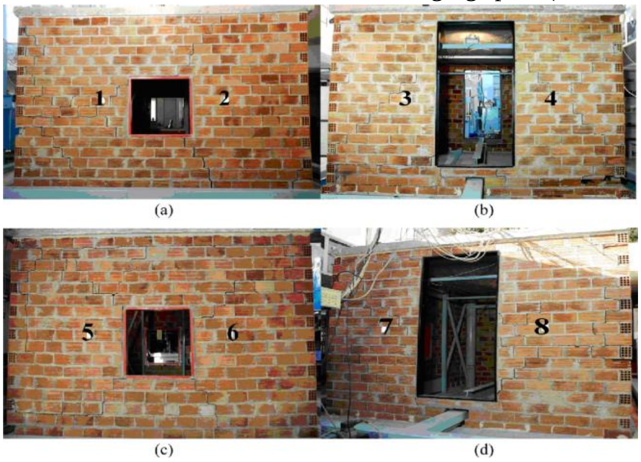


Fig.13. The sides of the masonry building damaged after the application of the sixth seismic event (Borri et al 2014).

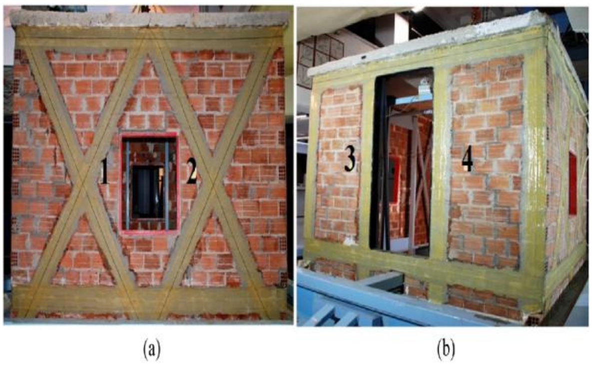


Fig.14. A picture of the repaired masonry building with reinforced GFRP strips: (a) sides 1-2 and (b) sides 3-4 (Borri*et al* 2014).

An un-reinforced and subsequently reinforced and retested masonry structures was tested by a series of graduallyncreased shake table seismic tests in order to evaluate its seismic vulnerability and to assess the effectiveness of reinforcement to withstand Earthquake [16]. The URM building was severely damaged with large visible crack openings visible at all masonry walls (fig-13). This severely damaged building was then repaired with specially designed GFRP bands (fig-14). In spite of the larger amplitude earthquake events applied on the repaired masonry building (covering around 20% of the wall surface) to bear earthquake events significantly higher in magnitude than the earthquake events applied to the un-reinforced masonry building caused severe damage to this wall.

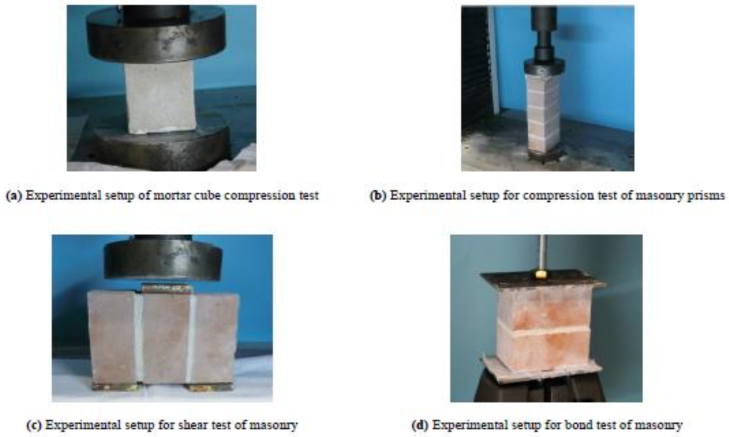


Fig.15. Experimental set-up for different types of tests used to determine material property of the masonry (Parisi*et al* 2013).

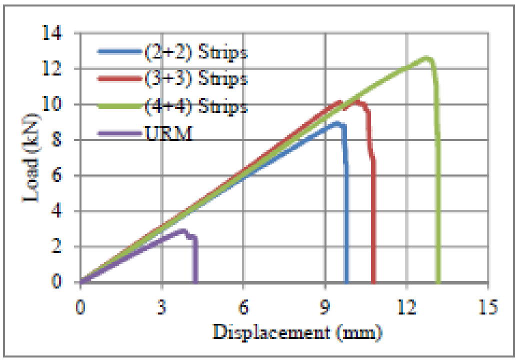


Fig.16. Load- displacement curve with volumetric ratio of 0.0072 of CFRP with varying number of strips (Parisi et al 2014).

[17] deals with the strengthening of masonry wall system carried out by using FRP (Fibre reinforced polymer). Aim of study was to find out the optimum quantity and placement of FRP for strengthening brick wall system which is done by testing ten masonry wallets under diagonal compression test (see fig-15). Response of masonry wallets with different volume and configuration of FRP strips were recorded. Carefully analysedresults of experiment showed that for higher volumetric ratios as 0.0072, increasing number of strips of FRC has good effect on the ultimate strength and failure displacement. Reducing CFRP volume below certain level may not fruitful /suitable attempts as the width of CFRP will be reduced resulting in lower surface area of an individual strips (see fig-16).

In [18] improvement of in-plane response of the walls with opening before and after external strengthening of spandrels with an inorganic matrix Grid (IMG) strengthening system has been studied. Recent seismic codes do not talk about assessment and strengthening of existing masonry spandrels panels by inorganic-matrix grid (IMG) composites. Experimental work was then simulated by using non-linear finite element analysis and micro-modelling technique of computation was adopted to verify the contribution of masonry constituents like masonry units, mortar, and IMG system constituents. The results of numerical as well as experimental analyses were compared for damage patterns and force-displacement curves (fig- 17&18).

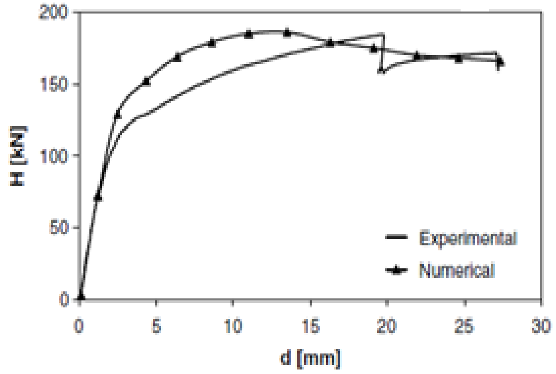


Fig.17. Numerical versus experimental force-displacement curves for as-built sub-assemblage(F. Parisi*et al* 2011).

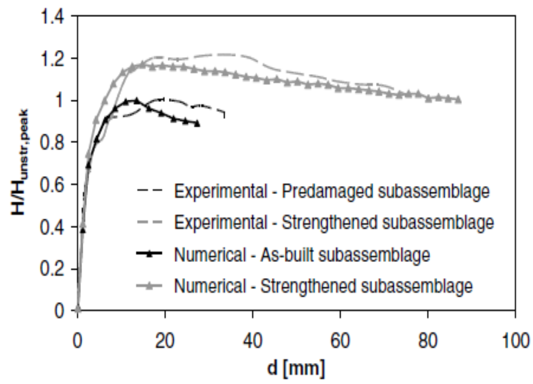


Fig.18. Comparison of numerical and experimental normalized curves (F Parisi*et al* 2011).

This paper aims on the application of natural rubber bearing base isolation technique for the seismic protection of masonry heritage buildings [19]. In this paper the opportunities which are available for the application of base isolation in case of seismic protection of unreinforced masonry (URM) structures which are important architectural heritage have been studied. A new methodology of URM buildings considering equivalent frame models (EFM) with plastic hinges is applied for the purpose of the study. Proper isolation devices are proposed on behalf of calculated approach for its selection which is based on Non-Linear static (pushover) analysis (fig-19) of such buildings and the desired level of protection, with reference to the code based damaged limit state.

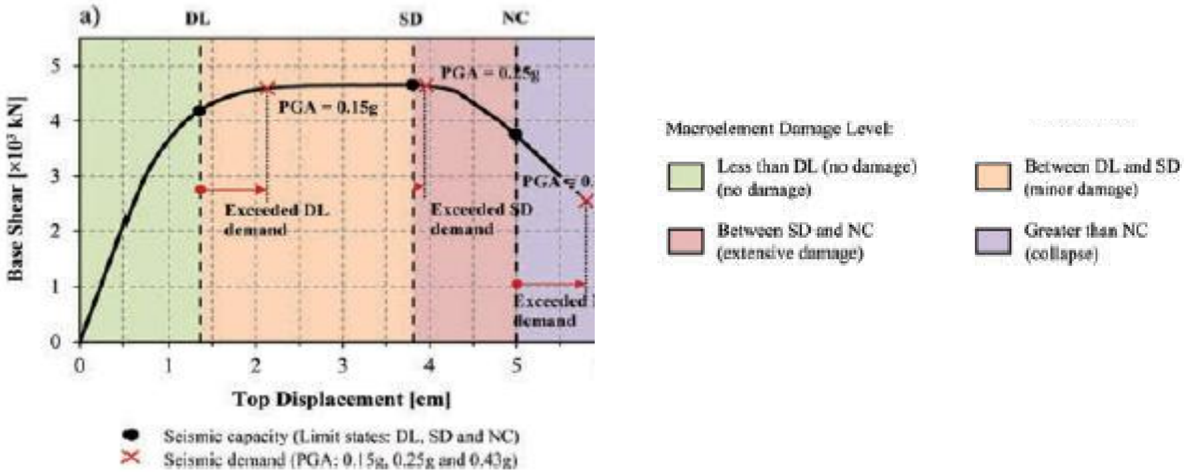


Fig.19. Capacity curve of the analysed building showing the corresponding limit states and the seismic demand displacements (khan *et al* 2017).

This paper deals with the strengthening of in-plane strength of masonry panel is with geosynthetics [20]. strengthening of clay brick masonry panels with non-woven geotextile so as to increase in-plane strength, and the panels were tested as well as simulated. The panels were subjected to diagonal compression. The results of the study show that geosynthetic increased the load carrying capacity, shear strength, in-plane strength and stiffness significantly with better performance in case of cross pattern.

IV. CONCLUSION

URM structures are heterogenous in nature with varied characteristics of every constituents in it, makes it complex building material and also its low ductility has lead to shift in researcher's interest to other more ductile materials. As nowadays, seismic activities are occurring more frequently, safety of the buildings having cultural heritage value or are among important buildings has become the first and foremost task to look at. The structural health monitoring of such structures can be carried out as discussed above with different techniques available and also their retrofitting is required at the same time to strengthen them.

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