An analysis of the seismic vulnerability of the architectural heritage in Bhuj, Gujarat, India

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ABSTRACT: The 2001 Bhuj earthquake caused widespread damage to the architectural heritage in the state of Gujarat, especially in the Kutch district where the epicentre was located. Therefore, the present study was carried out to appraise the ills in the construction of the masonry historic buildings and in turn propose appropriate retrofitting strategies. The city of Bhuj was chosen as the area of study since it exhibits the highest density of architectural heritage in the region. A detailed on-site reconnaissance of the damage suffered by the selected historic masonry buildings was then carried out. This was followed by a thorough analysis of the collected data which led to the identification of the failure mechanisms that might have caused damage during the earthquake. A numerical procedure called FAMIVE, previously used to assess the occurrence of collapse mechanisms in other seismic regions, was used to corroborate the findings. Thus, the deficiencies in the structure of these buildings were recognised and relevant strengthening measures proposed.

1 INTRODUCTION

The state of Gujarat was struck by an earthquake of magnitude 7.7 on 26th January, 2001, which caused extensive damage to the architectural heritage. The Kutch region and its capital Bhuj, were worst affected in terms of heritage loss and damage. Detailed reconnaissance missions aimed at recording the distribution and level of damage were performed by teams from various organisations among which: Earthquake Engineering Research Institute (EERI), National Science Foundation, Washington D.C. (NSF), UNESCO, ICOMOS-UK, Indian Institute of Technology, Kanpur (IIT), Indian National Trust for Art and Cultural Heritage, New Delhi (INTACH), and Environmental Planning Collaborative, Bhuj (EPC). However, the seismic behaviour of the heritage buildings in the Kutch region with respect to their constructional details has not been discussed specifically, to date. Therefore, the present study was carried out to investigate the specific construction techniques employed in this region, appraise their seismic vulnerability or resilience, and in turn propose appropriate retrofitting strategies.

The heritage buildings in Bhuj were chosen as the area of study due to their proximal location to the epicentre and the highest incidence of historic buildings in the region as compared to the neighbouring urban developments. The safety of these historic masonry structures against earthquake-induced damage is a subject of highest priority in view of the fact that they testify the cultural and historical aspects of the region and add to its identity.

But for few exceptions (Lagomasino, 1999 and Augusti et al, 2001) parametric studies of monumental buildings are relatively rare. Usually studies and projects are conducted on a one to one basis, with the risk that knowledge gained in one case is not necessarily transferred to another. When, as it is the case in Bhuj, but also in Italy and elsewhere, there is a high density of valuable historic heritage, and relatively modest resources to be allocated for the prevention of loss, then it is essential to gain a more holistic picture of the performance of this heritage, so as to best inform the allocation of funds. Moreover the comparative study might highlight traditional and historic constructional solution and feature which are seismic resilient and that can be extended to other buildings of the same period lacking them. These would provide intervention strategies that are more compatible with the traditional structure and have already been proven.

Monumental buildings were chosen in preference to ordinary historic buildings for a number of reasons, among which, greater initial documentation available,
easier access for the surveys, interest on the part of the local and national authorities in view of possible repair and strengthening activities. From a structural point of view, the aim of the study was to identify specific construction techniques and assemblies that showed particularly high vulnerability and can be identified as primary causes of damage. One important criterion of choice of the building sample was the associated level of damage, which allowed the identification of developed collapse mechanisms and crack patterns. This means that only partially collapsed buildings were included in the sample.

Highly complex buildings such as the royal palaces were disregarded as unsuitable for this type of study.

2 ARCHITECTURAL HERITAGE OF BHUJ

The Kutch region has about 250 historic towns and villages. These hold approximately 15,000 heritage structures, out of which about 1,500 are Heritage Structure Type I, about 3,500 Heritage Structure Type II, and remaining 10,000 are Heritage Structure Type III. (Types I, II, III are classified by INTACH as heritage structure of exceptional quality, of some merit, and buildings with group values like bazaars and historic housing stock, respectively). The capital of the Kutch district is the walled city of Bhuj, which is known for its unique architectural heritage consisting of magnificent palaces, temples, mosques, decorated havelis, and gateways. According to a recent survey by Bhuj Area Development Authority, more than 300 heritage sites are contained within the walled city of Bhuj.

The architectural style of the historic monuments in Bhuj corresponds with the development of various traditions in the Kutch region, spanning from the Hindu and Jain cultures, through the Islamic tradition, up to the Portuguese (present in Gujarat since 1509) and British (1816–1947) colonial influence.

3 CONSTRUCTION PRACTICES IN BHUJ

In order to identify the most relevant structural typologies and constructional details, the study is conducted in two phases. The first phase consists of in situ qualitative inspections aimed at the reconnaissance of specific masonry fabrics and floor structures. A large number of buildings were inspected at this stage in order to assess whether a given typology is common and representative of a certain building tradition and style. The second phase consisted of choosing a certain number of buildings representative of the most common typologies identified and carry out a quantitative survey leading to the application of a numerical assessment procedure (FAMIVE).

Figure 1. (a) Three-leaf masonry wall in Jubilee Hospital, with dressed stone faces and thinner central infill; (b) Three-leaf masonry wall in Sirpat Gate, with semi-dressed stone faces and thick central infill; and (c) Sketch of single-leaf masonry wall in Vegetable Market.

The preliminary analysis of the masonry fabric in Bhuj has identified four typologies of decreasing structural quality:

A1 – Solid squared masonry with sufficient level of connection in the wall thickness

A2 – Three-leaf solid masonry with insufficient level of connection in the wall thickness

B – Mixed masonry made of squared stones and sun dried bricks

C – Rubble masonry with insufficient level of connection in the wall thickness.

Masonry walls in the historic buildings of Bhuj are mostly multilayered with dressed stone faces and a central infill of random rubble stones bound with mortar (Fig. 1 (a & b)). The stonework is, generally, of good quality but the infill of rubble masonry was observed to be of a low quality and the layers in these walls were not adequately connected. The thickness of these multileaf walls varied from 0.54 to 0.95 metres, with each face about 0.2–0.3 metres thick. Another system of constructing structural walls, found in a minority of buildings, is the single leaf stone masonry wall, built with either uncoursed random rubble masonry or semi-dressed or dressed masonry (Fig. 1 (c)). The average wall thickness in this case is about 0.65 metres. Mud mortar is used extensively in these walls, despite its poor shear strength. Currently no literature is available on the mechanical characteristics of either component of the masonry used.
In the surveyed set of buildings, the range of horizontal structures was more extensive, often with different typologies found in the same building:

A1 – Iron I-sections with stone jack arches and concrete slab on top
A2 – Iron I-sections with stones
A3 – Iron truss with iron members as purlins and timber battens and roofing tiles
B – Timber joists with wooden purlins and wooden floor boards
C – Stone slabs with concrete infill on top
D – Timber truss with timber purlins and timber battens and roofing tiles.

Timber members of size 0.3 × 0.25 metres are predominantly used for roofing and intermediate floors spanning on an average 5.5–6 metres and placed at a distance of about 2 metres from each other (Fig. 2 (a & b)). Iron I-sections (about 0.065 × 0.2 metres) spanning generally 6 metres, with dressed stone slabs placed in-between, are the second most common typology. The average distance between these members is 1.3 metres, centre to centre, resulting in a rather heavy structure (Fig. 2 (c)). Most commonly, wall plates or pad-stones are absent and the wooden and iron horizontal members sit directly on the masonry walls.

In the 19th century, iron trusses were also introduced in the region (Fig. 2 (d)). They are placed at a distance of about 2.8 metres from each other, span an average distance of 16 metres and are supported by cast iron brackets, bolted in the masonry walls.

The use of ornamental projected balconies called *jharokhas* is commonly found in the historic buildings in Bhuj (Fig. 3 (a)). Most of the openings have individual lintels, made of stone slabs. Presence of lintel bands in the early construction practice is not evident. Wooden lintel can only be seen in earlier heritage buildings, like the 16th century Rani Vaas palace, and seems to be lost later. Horizontal stone bands are also found in certain buildings at plinth, floor, and roof level (Fig. 3 (b)). They are present along the external face of the masonry walls and appear to be added simply for ornamental purposes. Besides these, other non-structural elements commonly used in the historic buildings of Bhuj include decorative parapets which form an important aspect of the building’s elevation.

Although these buildings rarely exhibit the incorporation of any earthquake-resistant feature in their construction, some buildings survived the recent earthquake forces and suffered little or no damage. According to a survey carried out jointly by INTACH and UNESCO teams, buildings within the Old Walled city of Ahmedabad were found to be built with timber lacing in the walls and in spite of the collapse of a large number of reinforced concrete high-rise buildings in the city, these timber-framed buildings suffered minor damage. Similarly, the best examples of buildings with less seismic damage in Bhuj are the Rani Vaas in the Palace Complex with timber-framed structure and the Old Vegetable Market with lightweight steel truss.

### 4 IN-SITU SURVEY

For the second phase of the study eight buildings, of different size, age of construction, geometry and fabric, were chosen as distinct examples of recurring typologies. Isolated buildings were taken in preference so that the influence of adjacent buildings could be disregarded. The number and choice of surveyed buildings was limited by the time available but also by the possibility of safe inspection. Moreover only buildings for which collapse was limited were surveyed, so that the mechanisms could be recognised in their incipient state. Unfortunately, some of the buildings initially chosen could not be included in the study as, following the earthquake, access was denied. Hence the eight
case studies are: Jubilee Hospital (1849 AD, Grade I), Alfred High School (1870 AD, Grade I), Kutch Museum (1877 AD, Grade I), Naniba Pathshala (1860–75 AD, Grade I), Old Vegetable Market (1882 AD, Grade I), Police Chavdi (Late 18th century, Grade II), Sirpat Gate (1723 AD, Grade II), Mahadev Gate (1723 AD, Grade II).

4.1 Site investigations
The data was collected on site by use of a purposely developed form and preparation of drawings (plans and elevations) for representing the seismic damage in terms of cracks, collapsed portions and deformations (Fig. 4 (a & b)). The symbolic representation used for a vulnerability assessment of churches after the Friuli earthquake of 1976 (Doglioni et al, 1994) was referred while developing the representation of the observed damage in these drawings. The documentation was developed on site by the author through measurements and photographic survey.

The parameters covered by the form concentrated mainly on the structural aspects of the buildings, required for analysing their seismic behaviour. Besides the geometric data, the data set included: building configuration, typology of the vertical and horizontal structures, structural integrity of the masonry walls, corner connections between two orthogonal walls, size and placement of openings, interface between the vertical load bearing walls and the horizontal roofing and flooring members, and the presence/absence of tying elements. However, the foundations and the ground conditions have not been recorded in the present study due to the difficulty in accessing the associated data within the time available. Superficial strip foundations made of roughly cut stone with weak mortar are assumed throughout.

4.2 Summary of observations
The condition assessment of these historic masonry buildings demonstrates their seismic vulnerability and puts forth the fact amongst them certain comparatively successful examples of construction methods also exist. This is further confirmed by the observed variation in the extent of damage is these buildings, ranging from 5% for the Old Vegetable Market, a rectangular plan, one storey building, with light roof structure, to 75% damage for the Jubilee Hospital, a two storey building with complex plan shape and heavy floor structure (Fig. 4).

As far as the masonry fabric is concerned, it would appear that the single-leaf dressed stone masonry walls in Old Vegetable Market performed better as compared to the thick three-leaf masonry walls in other buildings. This is mainly to be ascribed to the lack of adequate through thickness connection between the layers of the masonry walls, thus preventing them to behave as a monolithic structure. The poor quality of mud mortar could have been another reason for their poor performance. Furthermore, except for the case of Alfred High School, where the presence of quoins was observed throughout, orthogonal walls in the rest of the sample were also not properly keyed together.

Regularity of plan shape and elevation was also analysed. While in general the plan layouts are substantially rectangular, two of the buildings are L-shaped, (Kutch Museum, Naniba Pathshala) while others, such as Jubilee Hospital, and Alfred High School have irregular projections. Indeed are the projecting blocks that suffered highest damage. In Naniba Pathshala and Police Chavdi, the irregular vertical distribution of mass, with more concentration towards the upper levels, also resulted in substantial amount of damage in some facades.

In Jubilee Hospital, Alfred High School, Kutch Museum, Naniba Pathshala and Old Vegetable Market, horizontal bands made of stone were found running all around the building at plinth, floor and roof level. Though they were present along the external face of the masonry walls, it is difficult to specify their depth within the thickness of the wall as they were not seen along the internal face of the wall. A series of similar bands were also found along the north and south facades of Mahadev Gate and along the three exposed facades of Police Chavdi. From the external observation the stones did not seem to have been locked together and cracks were observed running through them although without extending the whole thickness of the walls. Their structural role is hence deemed rather limited.

In the 18th century buildings, Police Chavdi, Sirpat Gate and Mahadev Gate, the horizontal structure consisted of arches used to divide the space into smaller spans covered by stone slabs (Fig. 5). In Naniba Pathshala and in part of Jubilee Hospital, built in the earlier part of the second half of the 19th century wooden members are used while in the remaining buildings, the horizontal members used are iron I-sections with stone slabs or jack-arches (Jubilee Hospital, Alfred High School, Kutch Museum). The intermediate flooring was found to be unaffected by the earthquake in all the surveyed buildings, except for the partial collapse of the jack arch ceiling in the rear portion of Jubilee Hospital and the stone slab ceiling in Police Chavdi. Except for the two gates and the Old Vegetable Market, all other buildings have wooden trusses, in part or whole of their plan area. The wooden trusses in general performed very badly, possibly due to the absence of sufficient bracing and anchorage to the walls.

Except for the Old Vegetable Market and Sirpat Gate, there is no use of wall plates in the sample. The
Figure 4. (a & b). Examples of the drawings prepared for representing seismic damage in Jubilee Hospital.
horizontal members were seen resting either directly on the top of the wall or in pockets of modest depth into the walls. This resulted in a weak connection between the walls and these members, leading to serious damage or collapse of flooring and roofing in more than 50% of the sample. In Naniba Pathshala, wooden members spanning in both orthogonal directions helped to hold the building structure together, thus resulting in very little damage. Similarly, the roofing of Old Vegetable Market, made of lightweight iron trusses, suffered no damage.

The walls supporting the internal staircases in Jubilee Hospital, Alfred High School and Naniba Pathshala were subjected to greater damage compared to the other walls which were tied together to some extent by the intermediate flooring.

Structural stone columns, surveyed in Jubilee Hospital, Alfred High School, Police Chavdi, Sirpat Gate and Mahadev Gate, were made by vertically superimposed stone drums or blocks. In Naniba Pathshala, monolithic timber columns were found in the front portico. Not much damage was observed to either typology, whilst the ornamental columns, surveyed in Alfred High School, Kutch Museum and Old Vegetable Market, supporting only the decorative fascia, appeared to have systematically detached from the structural walls in the absence of adequate anchoring. Vaulted porticoes are an important feature of 3 of the surveyed buildings. The arches behaved considerably well, with damage only in the form of loosening of keystones or minor cracks. No collapse at the portico edge was observed. It was also observed that the non-structural elements like ornamentation features, parapets, jharokhas and roofing clay tiles were not adequately anchored to the building, resulting in their collapse or dislocation. Though, any damage to these features does not exhibit any danger to the building structure directly, their detachment caused damage to the other building parts as well as risk to human life.

4.3 Comparative study of structural systems

For each building surveyed, the extent and type of damage was recorded on plan and elevation drawings. This preliminary synthesis allowed establishing a qualitative judgement of the seismic behaviour of the individual elements in the building. This also helped to identify weak areas of the building fabric and the omission of structural details required for resilient seismic performance. The extent of damage was quantified according to the five categories used by the Gujarat State Disaster Management Authority. These are:

- **G1** Cracks of ½ inches width
- **G2** 10% or less damage
- **G3** 25% damage
- **G4** Above 25% damage (Due to the less precise definition of damage in this category, the facades with considerable amount of partial collapse have been considered in the G4 category for the present analysis)
- **G5** Totally Collapsed.

The distribution of damage within the sample, according to this classification is shown in Figure 12, where each building has been divided in a number of subunit and independent facades, as explained later. This shows that the majority of facades experienced more than 25% of damage or were partially collapsed. This proportion correlates well with the damage distribution presented by INTACH and UNESCO, for a much larger sample of buildings in the region, and hence indirectly proves the validity of the sample chosen for this study. It was also observed that the major part of the damage was concentrated in the upper parts of the surveyed buildings.

Further to the survey of damage extension, in order to quantify the severity of the damage the following weighting system was used:

a) Within the damaged area, the portion of the wall having cracks is given weight between 20–50%, depending on the depth of the cracks within the wall thickness.

b) The collapsed areas are assigned 100% weighting.

In order to compare the performance of different structural assemblies, for each group of facades having same configurational characteristics, given the relatively modest occurrence in the sample, the worst performance, i.e. the one with the worst damage index (expressed as a percentage of total damage) was chosen. The results of this analysis are shown in the graphs in (Figs. 6 to 12). The parameters that are considered relevant in terms of their influence on failure are building configuration, type of masonry fabric, typology of vertical structures, floor structures and roof structures, and presence of wall plates.

For each type the number of homogeneous facades with that characteristic and the maximum
Figure 6. Extent of damage in the building facades.

Figure 7. Effect of building configuration.

Figure 8. Effect of masonry wall typology.

Figure 9. Effect of structural type.

Figure 10. Effect of presence/absence of wall plate.

Figure 11. Effect of flooring typologies. (Two points to be considered while reading this graph: (a) Only 5 buildings have more than one storey, and (b) Jubilee Hospital has two types of flooring, jack arches and wooden rafters and purlins. Therefore, it is considered twice in this graph).
the size of the present sample, it will not be of great validity, as combinations and correlated occurrence of the various structural elements is limited. It is however worth noticing that the most common structural typologies, three-leaf walls with Iron I-section with stones floors and wooden trussed roofs, are also the highest damaged.

A second form of analysis was carried out, using the damage patterns to identify the failure mechanism/s for each portion of the facades surveyed. Given the complexity of the individual buildings, each building has been divided into smaller blocks, which are homogeneous for geometry, construction typologies and materials. Also other aspects, such as direction of horizontal flooring and roofing members, opening sizes and layout, etc. were taken into consideration, in creating the subsections. This led to a total of 54 facades being analysed. To each of these facades, one or two “most likely” mechanisms were attributed. The indexing of the failure mechanisms was established according to the nomenclature used by a numerical procedure called FaMIVE (Failure Mechanisms Identification and Vulnerability Evaluation) (Fig. 13). This had been developed and used to assess the occurrence of collapse mechanisms in historic centres in seismic regions (D’Ayala & Speranza, 2002). This analytical procedure returns a critical collapse load factor and associated failure mechanism for masonry facades, when the geometry and structural constraints are known. The results of the analysis where hence compared with the field observations.

Besides the quality of masonry fabric and workmanship, the major difference between the ordinary buildings, for which the procedure was initially developed, and the monumental buildings considered here, relates to the substantially greater slenderess of the external walls of the latter. This occurs both in elevation, as the average storey height is about 5–6 metres, but also horizontally as the distance between internal structural partitions can be quite substantial. These will of course influence the type of mechanisms most commonly observed.

On comparing the observed failure mechanisms in the surveyed facades with the feasible collapse mechanisms chosen automatically by the FaMIVE procedure, in 50% of the cases there is coincidence (Fig. 14). However if for the ones that do not coincide the mechanism yielding the second lowest collapse load factor is chosen among the calculated ones, then the correlation between the 2 classes increases to 76%.

![Figure 12. Roofing typologies. (The total number of buildings is more than 8 as some buildings have two types of roofing).](image)

![Figure 13. Collapse mechanisms identified by FaMIVE (D’Ayala and Speranza, 2002).](image)
observed failure mech.  
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\text{Figure 14. Comparison of observed and calculated collapse mechanisms.}
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calculated failure mech.

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\text{Figure 15. Occurrence of mechanisms.}
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Further more it can be noted from (Fig. 15) that the biggest differences between observed and calculated, occur for mechanisms G and A or D. But what is observed as a mechanism G can easily be interpreted as a collapse A or D occurring only at the upper storey, rather than over the whole height of the façade.

With respect to the occurrence of mechanisms, about 30% of façades are expected to develop horizontal arch failure (Mechanism G). Also amongst them, about 4% and 13% are seismically vulnerable due to the vertical overturning of the walls with (Mechanism B) and without (Mechanism A) the party/orthogonal walls, respectively, and about 10% by the columned wall failure (Mechanism M). (Fig. 14 & 15).

Mechanism G could have been caused due to the wide span of the façades and their insufficient connection with the orthogonal walls, as has been commonly observed in other samples (D’Ayala & Speranza, 2003). The overturning of the entire façade without involving the party walls, causing failure mechanism A, can be due to the lack of any connection at the corner or insufficient connections. However, when the level of connections at the corner is sufficient enough to restrain the overturning façade, the façade may also involve one or both the orthogonal walls and diagonal cracks appear along the party walls (Mechanism B). According to the observations and the analysis carried by D’Ayala (2003), the failure of the columned walls (Mechanism M) is caused due to the lateral movement of the columns, similar to a soft storey mechanism in concrete frames.

5 REPAIR GUIDELINES AND CONCLUSIONS

The architectural heritage of Gujarat was severely affected during the January 26, 2001 earthquake. A detailed investigation of the seismic vulnerability of some historic masonry buildings in Bhuj has established that the main damage to the masonry walls was due to the inadequate structural connections in these buildings, especially, at corners. The collapse of the roof in many cases was also associated with the absence of proper tying of horizontal members to the supporting walls.

The seismic upgrading of these buildings will require to meet at the same time two possibly conflicting criteria: life safety and minimum alteration of their historic fabric.

The traditional materials and construction techniques should be used as far as possible. However,
in certain cases the use of modern materials may be recommended in order to save larger portions of the original fabric. These interventions should be sympathetic and well-integrated with the character of the building. (Feilden, 2001).

The analysis has also highlighted few existing features which have played a significant role in preventing damage propagation. One such feature is the presence of horizontal bands present along the external face of the masonry walls. Although this cannot perform as ring-beam, they limit the progression of cracks both through the thickness and from storey to storey, hence limiting the damage extension and possibly preventing the out of plane collapse to affect the whole height of the façade. Their seismic effectiveness can be improved by connecting the individual stone blocks with each other.

Wall plates, preventing the horizontal flooring and roofing members from sliding out of the structural walls, have also proven effective. Although they do not prevent damage they limit its extension by providing lateral constraint. The insertion of wall plates in partially damaged buildings needing replacement of floors structures would be a very cost effective intervention.

The introduction of steel ties into the masonry can also be proposed for strengthening and connecting orthogonal the walls. Though successful examples of this seismic strengthening can be found in Europe’s historic town centres (D’Ayala et al, 1997), it is not part of the local traditional lexicon. Also, the implementation of this strategy would require the authorities to provide some basic training to local craftsmen. Similarly, in cases where it is difficult to insert wall plates, the horizontal members in floors and roof can also be anchored firmly to the walls using steel connectors.

During site reconnaissance, it was also observed that the presence of L-shaped quoins in Alfred High School restricted the outward movement of the wall edges. Where possible similar L-shaped stones can be introduced during rebuilding. Alternatively stone stitching can be employed (Tomažević, 2000). Though such methods are time consuming, they are more traditional and authentic to the historic fabric and can be implemented easily by local craftsmen.

Another recurring defect was the separation of the leaves in the multi-layer masonry walls. This can be prevented by inserting header stones at regular intervals along the length of the walls. In walls with thick central core this would not be feasible, and it is therefore recommended to use stainless steel anchors and where appropriate grouting. The injection of epoxy resins to consolidate the weak or cracked masonry is another strategy that could be adopted (Tomažević, 2000). However, it should be used only as a last resort due to its lack of reversibility and knowledge of long-term performance.

The collapse of parapets, ornamental details, jharokhas, projected cornices etc. can be controlled by providing stainless steel ties and appropriate anchorage to the rest of the masonry.

The reconnaissance survey of a number of damaged buildings together with the application of an analytical procedure for identifying collapse mechanisms has proven effective to highlight both resilient and vulnerable features in the Bhuj heritage. In turns this has led to the formulation of a strengthening strategy that can be effective in both repair and upgrading of these buildings. The cost effectiveness of such strategy remains to be assessed.

Similar investigations of the failure mechanisms can also be carried out in other parts of Gujarat to enhance the knowledge about the seismic capacity of the heritage structures in the state. This could lead to the preparation of a set of guidelines for retrofitting historic masonry buildings whose condition is deteriorating due to the lack of awareness amongst the local people regarding the availability of simple and effective solutions for seismic safety.

REFERENCES


