11 WCEE

Copyright © 1996 Elsevier Science Ltd
Paper No. 1389. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

SEISMIC RETROFITTING OF MASONRY BUILDINGS DAMAGED IN THE SEPTEMBER 1993 EARTHQUAKE IN INDIA

S.S. MOMIN[1], S. NIKOLIC-BRZEV[2] and K.M. BAJORIA[3]

1- Earthquake Rehabilitation Project, Government of Maharashtra, Bandhkam Bhavan, Solapur-413 003, India

2- Sandwell Inc., 1190 Hornby Street, Vancouver, B.C., V6Z 2H6, Canada

3- Department of Civil Engineering, Indian Institute of Technology, Bombay-400 076, India

ABSTRACT

A strong earthquake of magnitude 6.4 on the Richter scale struck Maharashtra State in Central India on September 30, 1993. The earthquake caused a large human loss - over 8,000 people were killed and other 16,000 were injured; more than one million of local population was rendered homeless. Over 200,000 private dwellings in the affected area, mainly non-engineered masonry buildings, were damaged or entirely collapsed in the earthquake. Repair and seismic retrofitting of damaged buildings is a part of an ongoing rehabilitation project initiated by the Government of Maharashtra, India and sponsored by the World Bank. The aim of massive retrofitting programme is to enhance seismic safety of existing vulnerable building stock with large inventory of stone masonry buildings. With due consideration to the local socio-economic conditions, a number of seismic upgrading provisions were proposed for a practical application. Reinforced concrete ring beams (bands) were introduced at the eaves level to ensure integral action of wall enclosures, and to reduce the effective wall height. Concrete wall anchors i.e. through-stones were installed in the existing stone walls in order to prevent delamination and buckling of the wall wythes. To enhance bonding between the adjoining walls, wall corners were strengthened externally with reinforced cement plaster wherever required. Steel tie bars were introduced at the roof level in order to keep the walls together and to increase lateral rigidity of roof diaphragm. Lateral movements of timber frame structures were restricted by installing knee bracing elements.

KEYWORDS

Post-earthquake rehabilitation; non-engineered structures; seismic retrofitting; stone masonry; low-rise buildings.

INTRODUCTION

A strong earthquake of magnitude 6.4 on the Richter scale struck Marathwada region of Maharashtra State in Central India on September 30, 1993. The earthquake caused a large human loss - around 8,000 people were killed and other 16,000 were injured; over one million of local population was rendered homeless. Devastating effects of the earthquake were mainly due to a large vulnerable housing stock, shallow focus causing widespread damage, early morning time of the event, and high population density in the area. Based on the historical records, Marathwada was supposed to be an area of scarce seismic activity and therefore no special design provisions were required for residential buildings. Moreover, the affected area consists mainly of rural settlements, and building construction is entirely in hands of local artisans with limited technical skills. Majority of dwellings damaged in the earthquake were non-engineered masonry structures. A detailed post-earthquake reconnaissance report was prepared by Kagami *et al.* (1994).

Repair and seismic retrofitting of over 200,000 privately-owned rural buildings damaged in the September 1993 earthquake is a part of an ongoing rehabilitation project initiated by the Government of Maharashtra and sponsored by the World Bank. Technical part of the programme consists of the following components: i) assessment and categorization of building damage; ii) identification of repair and retrofitting operations for typical building structures, and iii) execution of construction work, as reported by Nikolic-Brzev and Anicic (1994). Experience from the previous earthquakes world-wide and observations made during the field studies served as a background for the assessment of typical damage patterns and classifications. The second phase of the programme was aimed at prescribing appropriate remedial provisions for damaged houses. The final repair and retrofitting methodology was proposed as a joint effort of seismic engineering consultants and the Government of Maharashtra, as outlined in the GOM (1994). Basic elements of the proposed retrofitting methodology are summarized in this paper.

STONE MASONRY BUILDING PRACTICE IN MARATHWADA

Majority of traditional rural houses in the area are single-storeyed. Room spans are moderate, with small door openings and typically without window openings. Being a durable and abundantly available material, stone was used for wall construction in the Marathwada region since long ago. According to the 1991 Census of India, around 85% of houses in the region were constructed in stone masonry. Typical stone masonry walls observed in the area are load-bearing structures supporting the flat timber roofs with heavy earthen overlays. Climatic conditions in Marathwada are characterized with low rainfall and extremely hot summer months with outside temperatures exceeding 40C. Most likely, this is a reason for a rather large thickness of stone walls observed in traditional rural houses, ranging from 50 to as much as 200 cm. Traditionally, the walls were constructed in a random uncoursed manner, using simply piled stones binded with mud mortar. Round stone boulders were usually randomly picked up in the field and used without any additional shaping; less frequently, stones were cut with hammers and chisels in wedge-shaped blocks. Sometimes, lime or cement/sand mortar was used as a binding agent, particularly so in the recently constructed dwellings. Space in-between the external wall wythes was filled with loose stone rubble and mud mortar. As a result of degradation in rural construction practice, through-stones were not provided for tying the wall wythes together. Absence of header stones at the wall corners is another drawback in the traditional stone masonry construction. Also, vertical separation joints at the wall corners were observed in many instances, indicating a loose connection between the adjoining walls.

A traditional roof structure consists of timber planks and joists supported either directly by the walls or by a secondary structural system - timber frame structure known in the local language as "khan". In order to improve thermal comfort, local population used to cover a roof top by a 40 to 80 cm thick earthen overlay. Layout of a typical Marathwada house is illustrated in Fig. 1.

OBSERVED PATTERNS OF EARTHQUAKE PERFORMANCE AND DAMAGE

Excessive damage of stone masonry buildings in Marathwada is mainly due to loose connections between the critical structural elements, in particular walls and roofs. A traditional stone masonry wall comprises of three wythes; exterior wythes are constructed using large stone boulders whereas the middle one consists of stone rubbles binded with mud mortar. In the course of an earthquake, such a wall is subjected to simultaneous effects of gravitational and lateral loads. Lateral resistance of masonry structures subjected to vertical compressive stresses is provided by a frictional mechanism activated in bed joints. Due to a small contact area between the adjacent wedge-shaped stones binded with a weak mud mortar, frictional mechanism of lateral resistance was hardly effective in traditional stone masonry walls. As a consequence, numerous incidences of lateral instability and collapse of stone walls were reported in the September 30, 1993 earthquake. Overall performance of stone masonry walls in the affected area would have been certainly better even without a mortar (like in the case of "dry" stone masonry), provided that dressed stone boulders were used in construction. However, basalt stone that is abundantly available in Marathwada is rather hard for shaping with the traditional stone-cutting tools.

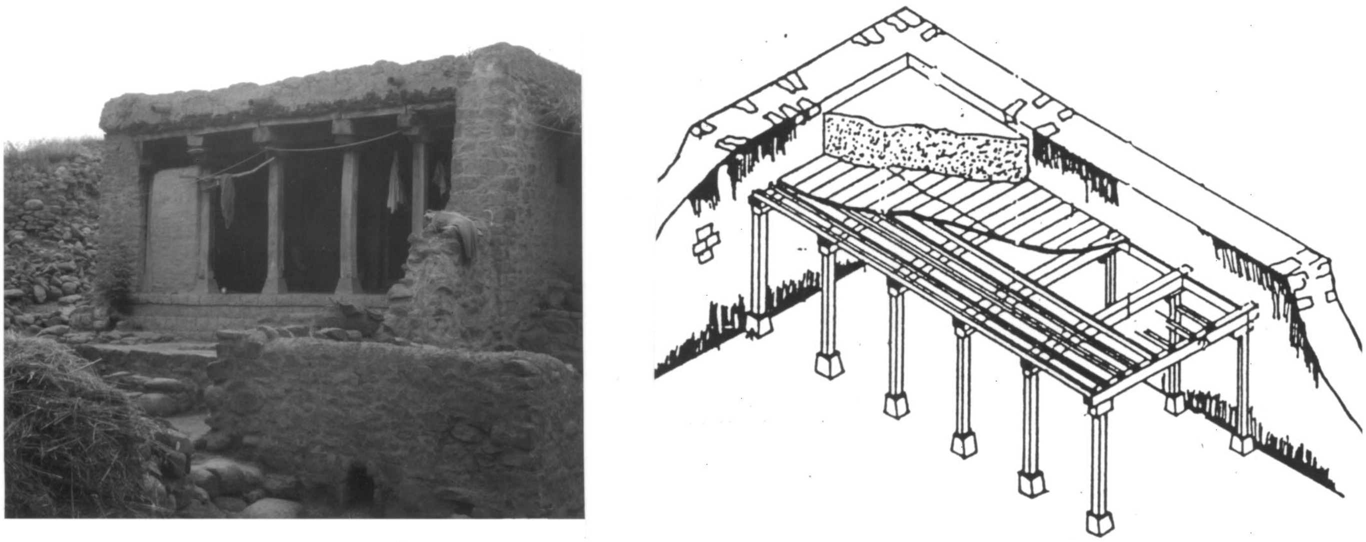

Fig. 1. A traditional stone masonry house with timber frame in a Marathwada village.

Typical patterns of earthquake damage to stone masonry buildings observed in the Marathwada area after the September 1993 earthquake were:

- Separation of adjoining walls at the corners and junctions as a result of out-of-plane action of seismic forces;
- Separation (delamination) of the wall wythes, due to the absence of through-stones (Fig. 2);
- Out-of-plane wall failure as a result of inadequate flexural resistance;
- Instability of timber frames due to excessive lateral drifts at the roof level, and
- Partial/total collapse of roofs induced by the failure of load-bearing walls.

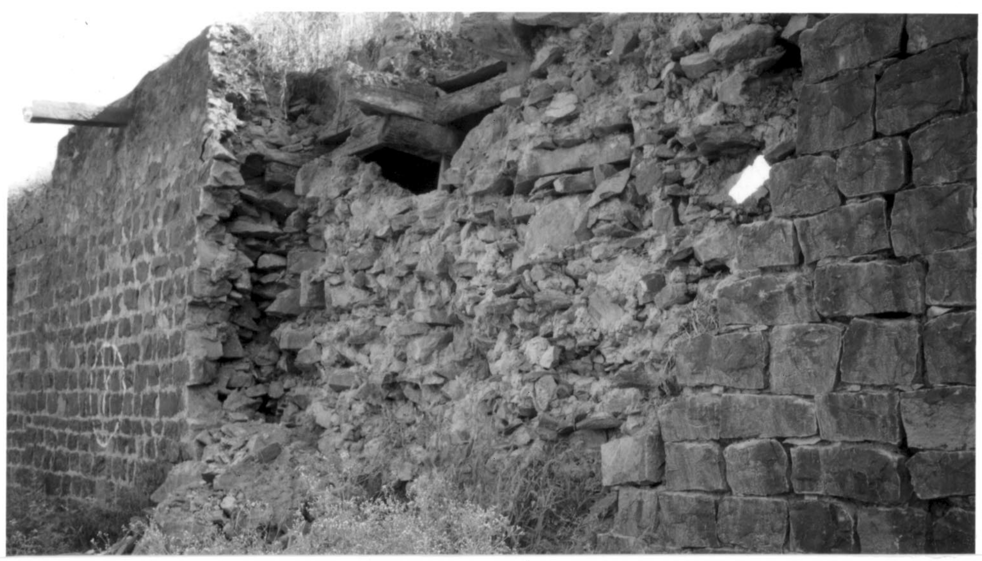

Fig. 2. Delamination and failure of a multi-wythe stone masonry wall in Marathwada.

Based on the field survey of stone masonry buildings damaged in the September 30, 1993 earthquake, the following progressive failure mechanism was identified for this type of structures:

1. Cracking of walls at the corners is an initial sign of structural distress. Vertical cracks propagate throughout the wall height as a result of progressive seismic action. Consequently, corner portions of the walls are getting crushed, stone boulders are falling out, etc. This pattern of earthquake damage has been

reported mainly in stone masonry buildings located in the areas away from the epicenter;
2. As a result of progressive earthquake action and a loose connection between the adjoining structural walls, each wall commences to resist seismic action as a free-standing wall structure;
3. Eventually, stability of the building gets endangered; the process culminates in the overall structural failure. In case of a roof structure supported entirely by the walls, failure of even a single wall might induce collapse of the roof structure. In the buildings with a secondary load-bearing structure (timber frame), however, failure of stone walls does not necessarily trigger a roof collapse.

SEISMIC RETROFITTING METHODOLOGY FOR STONE MASONRY BUILDINGS

One of the main aims of massive retrofitting programme undertaken by the Government of Maharashtra was to enhance seismic safety of existing buildings for future earthquake events. Considering drawbacks in the traditional stone masonry construction reported after the September 30, 1993 earthquake, the following major objectives of seismic retrofitting programme were identified:

- To enhance structural integrity of existing buildings;
- To reduce vulnerability of stone walls, and
- To upgrade lateral stability of timber frames.

The following important considerations had to be accounted for while meeting the above objectives: limited financial resources, low level of locally available artisan skills and tools, and scarcity of building materials. Having in mind the above constraints, some of the commonly used effective methods for repair of stone masonry walls such as injection grouting could not be recommended in this project; use of power-supplied tools and equipment (e.g. electric drills) was restricted; injection of epoxy-based grouts in the walls was not feasible. Due to the financial constraints, use of building materials such as cement and steel was restricted to the minimum. Unfortunately, quality of locally available lime, that could be a feasible component of masonry mortar and could serve as a partial substitute for cement in wall reconstruction, was not satisfactory. In the past, timber was traditionally used for house construction in the Marathwada area. However, wider use of timber in this project was restricted due to environmental concerns and financial constraints.

The above outlined socio-economic constraints aggravated efforts of meeting the programme objectives. Nevertheless, a number of feasible and cost-effective provisions for upgrading seismic stability of the existing stone masonry buildings were proposed for the field application, such as:

- Reinforced concrete ring beams introduced at the eaves level;
- Seismic upgrading of stone masonry walls;
- Horizontal steel ties installed at the roof level;
- External binding of wall corners, and
- Lateral bracing of timber frames.

Reinforced concrete ring beams (bands) fall in the category of fundamental seismic strengthening provisions related to masonry building construction (IS:4326, 1993). Placed at the critical elevations in the structure, such as plinth, lintel and/or roof level, the bands are tying walls together and imparting the required flexural strength to them. In the case of existing stone masonry buildings, however, introduction of bands at an elevation below the roof level was not considered feasible. Moreover, having in mind vulnerability of existing stone walls, such an operation could even have a destructive effect. Consequently, introduction of a ring beam at the eaves level of a building just below the roof joists was recommended, as illustrated in Fig. 3. A ring beam is typically constructed in lean concrete (15 MPa compressive strength), reinforced with two longitudinal deformed steel bars 8 mm diameter and steel links 6 mm diameter spaced at 300 mm on centre. Note that burnt clay bricks were used here as a substitute for formwork, as illustrated in Figs. 3 and 4.

In order to introduce a ring beam at the eaves level of an existing structure, parapet wall had to be dismantled. Evidence from the previous earthquakes reveals that parapet walls frequently get crumpled and fail in the earthquakes. This pattern of damage was particularly pronounced in case of loosely binded stone masonry walls in mud mortar typical for the Marathwada region. Therefore, reconstruction of parapet walls in an improved manner was recommended as an additional seismic upgrade, as illustrated in Fig. 4. Also shown in Fig. 4 are other seismic retrofitting provisions, such as through-stones installed in an existing stone wall and also reconstruction of parapet walls.

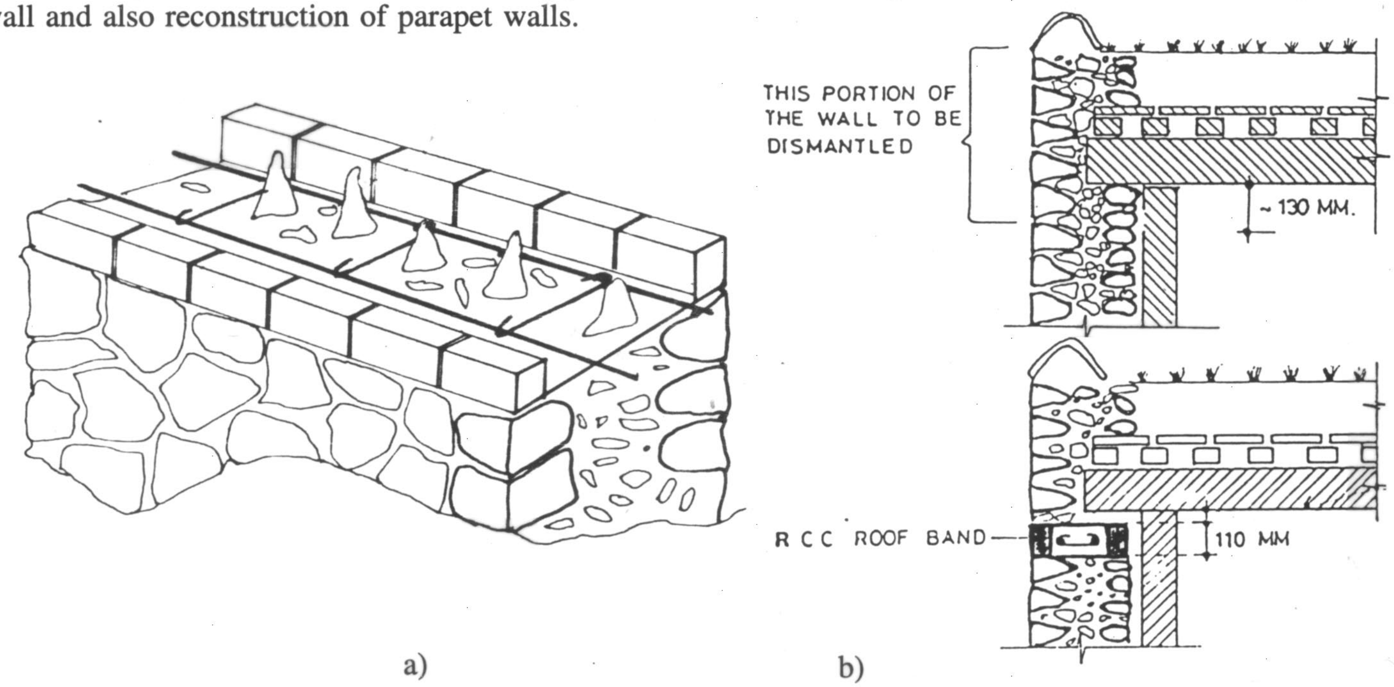

Fig. 3. Installation of reinforced concrete ring beam at the eaves level: a) Layout of a band, and b) Vertical section of a top portion of an existing wall with a ring beam.

Due to above outlined constraints, it was not possible to use majority of known technologies for upgrading mechanical strength of stone masonry walls. Introduction of through-stones (i.e. transverse wall ties) was recommended in order to prevent lateral instability of multi-wythe stone masonry walls (Arya, 1994). This is a simplified alternative to the commonly used wall anchors. Installation of through-stones consists of the following steps: i) one stone at each of the exterior wall wythes is removed manually using a small crowbar; ii) rubble filling in-between the wythes is removed and wedge-shaped hole of approximately 75 mm diameter is made in the wall; iii) one hooked steel bar 8 mm diameter is then placed in the hole, and iv) the hole is finally filled with concrete to match the original condition. Nominal spacing of through-stones at about 100 cm apart with 50 cm horizontal stagger has been recommended. An illustrative example related to field application of through-stones is presented in Fig. 4.

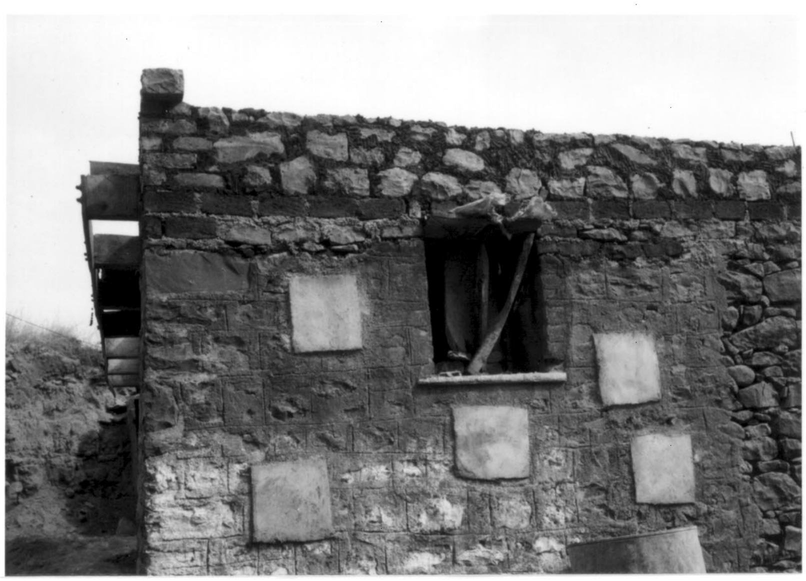

Fig. 4. A field application of retrofitting methodology showing ring beam installed at the eaves level including reconstruction of parapet walls, and through-stones installed in a stone wall (Kharosa village, Marathwada).

Having in mind a pronounced vulnerability of stone masonry walls, it was recommended to minimize gravitational load imposed to them, in order to reduce intensity of earthquake-induced inertia forces. Installation of a reinforced concrete ring beam at the eaves level, typically at 2.0 m above the ground level, leads to a reduction of effective wall height and of out-of-plane bending effects.

External binding of stone walls by applying reinforced cement plaster was recommended wherever improper bonding of walls at the corners and junctions was reported. Binding was installed by fixing welded wire mesh to external wall faces and then tying the coated surfaces with 8 mm diameter mild steel anchor bars embedded in concrete pockets. The anchors were spaced at 300 and 900 mm on centre in horizontal and vertical directions respectively. Welded wire mesh is covered with a 40 mm thick overlay of 1:3 cement/sand plaster.

In the majority of existing houses, timber roof structure was not capable of acting as a horizontal diaphragm that is suppose to transfer seismic lateral forces to a supporting wall structure. Moreover, the roof was not capable of providing support to the walls subjected to out-of-plane bending. In case of roof structures supported directly by the walls, roof joists were simply supported by the walls without any hold-down provisions. Earthquake-induced roof movements were thus restricted only by means of a frictional forces developed between the timber joists and the wall bearing area, typical width being only 10 to 15 cm. To enhance lateral rigidity of a roof diaphragm, installation of horizontal steel tie rods at the roof level was recommended. Mild steel bars 12 mm diameter were recommended here as an alternative to post-tensioned steel rods commonly used for the same purpose. The ties were anchored in concrete ring beams at the eaves level.

In general, heavy-weight timber roofs with thick earthen overlays obviously represents elements of high seismic risk in traditional Marathwada houses. Earthen overlay represents a concentrated heavy mass on the top of the building that attracts high seismic forces in the structure during an earthquake. Heavy-weight roofs are especially jeopardizing lateral stability of stone buildings without timber frames. Local failure in stone walls below the roof joists caused instability and failure of entire roof structures in many buildings located in the epicentral area. In the roof structures supported by timber frames, inertia forces at the roof top induced excessive deflections of the frame. The frames were in turn pushing outward stone walls, eventually leading to their out-of-plane failure. Earthquake-induced inertial forces imparted to traditional timber and mud roofs could be reduced at a rather low cost by removing the excessive earth mass from the roof top, as recommended by the GOM (1994). As a result of earthquake-induced fear, however, a part of the local population in Marathwada preferred an option of removing the existing timber roof altogether and installing light-weight corrugated iron sheet roofing instead.

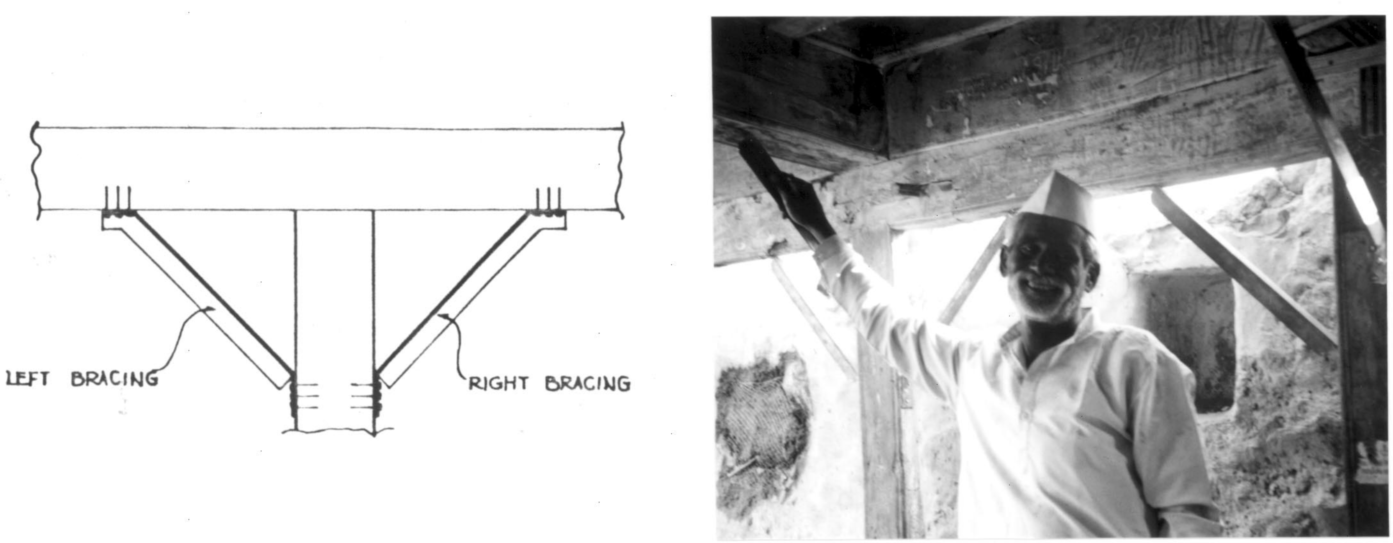

Fig. 5. Knee-bracing of a timber frame: a) Detail of a rolled steel angle bracing, and b) Field application in a rural house, Marathwada.

By and large, performance of timber frame structures (khans) in the September 30, 1993 earthquake was found satisfactory. Moreover, confinement action of khan structures prevented an inward failure of stone masonry walls and saved many human lives. However, considering the absence of provisions for restricting earthquake-induced lateral movements of timber frames, knee-bracing of frames has been recommended as one of the seismic upgrade provisions (GOI, 1993). Several simple and cost-effective alternatives of steel/timber knee-bracing have been worked out. Field experience revealed that installation of knee-bracing was found feasible for a practical application in majority of the affected rural dwellings. Details of a knee-bracing along with an example of field application are illustrated in Fig. 5.

CONCLUSIONS

Poor performance of stone masonry structures in the September 30, 1993 earthquake in Central India was mainly due to the faults observed in traditional construction practice as well as the brittle seismic response of these vulnerable structures. In the framework of massive earthquake rehabilitation project, over 200,000 rural dwellings in the earthquake-affected area needs to be repaired and retrofitted for anticipated recurrence of similar earthquake events in the future.

The basic aim of retrofitting methodology, as outlined in this paper, was to protect human lives and enhance seismic safety of existing buildings in the Marathwada area. Reinforced concrete ring beams (bands) were introduced at the eaves level to ensure integral action of wall enclosures, and to reduce effective wall height. Concrete wall anchors i.e. through-stones were installed in the existing stone walls in order to prevent delamination and buckling of the wall wythes. In order to enhance bonding between the adjoining walls, wall corners were strengthened externally by means of reinforced plaster wherever required. Steel tie bars were introduced at the roof level in order to tie the walls together and increase lateral rigidity of a roof diaphragm. Lateral movements of timber frames were restricted by introducing knee bracing elements.

REFERENCES

Arya, A.S. (1994). *Retrofitting of stone houses in Marathwada area of Maharashtra.* Building Materials and Technology Promotion Council, Ministry of Urban Development, Government of India, New Delhi.

GOI (1993). *Report of the Advisory Committee for reconstruction of houses damaged in Maharashtra and Karnataka during the earthquake on September 30, 1993.* Ministry of Urban Development, Government of India, New Delhi.

GOM (1994). *Guidelines for repair, strengthening and reconstruction of houses damaged in September 30, 1993 earthquake in Maharashtra, India for Marathwada and Solapur District.* Project Management Unit, Maharashtra Emergency Earthquake Rehabilitation Project, Government of Maharashtra (Nikolic-Brzev, S. and Anicic, D., *ed.*), Mantralaya, Bombay.

IS 4326 (1993). *Earthquake resistant design and construction of buildings.* Bureau of Indian Standards, New Delhi.

Kagami, H., Kuge, K., Bhartia, B.,K. and Sakai, S. (1994). *Reconnaissance report on the 30 September 1993 earthquake in the State of Maharashtra, India.* Research Report on Natural Disasters, The Japanese Ministry of Education, Science and Culture.

Nikolic-Brzev, S. and Anicic, D. (1994). *Strategy for reconstruction, repair and strengthening.* Project Management Unit, Maharashtra Emergency Earthquake Rehabilitation Project, Government of Maharashtra, Mantralaya, Bombay.