

A REVIEW ON SEISMIC PERFORMANCE OF MASONRY STRUCTURE DURING PAST EARTHQUAKES

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Abstract — *The present work investigates the performance of masonry buildings during the most severe past earthquakes both national and international. The majority of the buildings in the affected region were built of masonry. The structure shows different types of damage pattern for low to severe earthquake conditions. Most of the masonry buildings were formed with random or coursed stone and mud brick walls without any reinforcement and confined masonry buildings. Many of these buildings were damaged or had collapsed. Generally three types of failure mechanism define the behaviour of masonry structures namely, sliding shear failure, diagonal shear failure and flexural failure. Confined and reinforced masonry buildings shows relatively good performance in comparison with other masonry buildings. The damages are due to several reasons such as poor construction quality and poor workmanship of the buildings. From the census in India majority (more than 80%) of the buildings is masonry. Thus the present study shows the need of retrofitting of masonry structures in India.*

Keywords— *Confine masonry, Diagonal shear failure, Failure mechanism, Flexural failure, Sliding shear failure.*

I. INTRODUCTION

One of the most frightening and destructive phenomena of nature is a severe earthquake and it's terrible after effects. Over 80% of the buildings in the India are built of masonry. Mainly three types of structural systems; reinforced concrete, unreinforced & reinforced masonry and confined masonry are commonly constructed in rural and urban region in India. Brick masonry construction is widely prevalent among the middle-class population in urban areas and has become popular in rural areas in the last 30 years. Brick masonry walls in cement mortar function as the main load-bearing element. If constructed without seismic features, buildings of this type are vulnerable to earthquake effects. They exhibited rather poor performance during the earthquakes in India.

Many masonry buildings subjected to destructive earthquakes collapsed and were severely damaged due to some unsuitable designs or some mistakes on projects or applications. Therefore sometimes the idea of unsuitable type of buildings was adduced for masonry buildings. However, sometimes many masonry buildings especially historical ones survived the earthquake with only slightly damaged or even undamaged. In spite of the fact that many new reinforced concrete structures built at the same location have been severely damaged or collapsed. Thus, if masonry buildings are designed to be resistant against earthquake and constructed with good quality materials, they would survive during the earthquakes. But in recent earthquake of Nepal (2015) most of the masonry buildings which comes under the category of monumental buildings performs worst. Although the structural type of masonry buildings varies in different earthquake zones, their damage resulting from earthquakes can be commonly classified. Many structural deficiencies by the earthquakes damages are large opening in load bearing walls, lack of especially vertical confining elements, poor quality mortar, heavy balconies and unconfined gable walls.

In this paper a review of past earthquake effect to masonry structures and issues responsible for poor performance, damages, and failures are presented.

II. PAST EARTHQUAKE DAMAGES TO MASONRY STRUCTURES FROM EARTHQUAKE REPORTS:

1. 1960 VALDIVIA EARTHQUAKE

The 1960 Valdivia earthquake or Great Chilean earthquake (Gran terremoto de Chile) of 22 May was the most powerful earthquake ever recorded. Various studies have placed it at 9.4–9.6 on the moment magnitude scale. It occurred in the afternoon (19:11 GMT, 15:11 local time), and lasted approximately 10 minutes. The death toll and monetary losses arising from this widespread disaster were not certain. Various estimates of the total number of fatalities from the

earthquake have been published, ranging between 1,000 and 6,000 killed. Different sources have estimated the monetary cost ranged from US\$400 million to 800 million.

The earthquake shaking caused a wide range of damage to buildings within the affected area. The region has a lots of old houses, churches, and other buildings built with adobe or unreinforced masonry shown in Fig. 1. Absence of reinforcement and connection between adjoining walls resulted in the collapse of about 80,000 houses. Falling debris was a cause to many human deaths. About 300,000 houses and 400 churches were partially collapsed and unsafe to occupy. One of the historical buildings, Intendencia Regional del Maule, was severely damaged during the earthquake. The building was a three-story public historical building located in Talcal, Chile. The damage consisted of cracked and heavily compromise unreinforced masonry walls as well as interior and exterior architectural details and finishes. This was expected since old buildings such as the Intendencia Regional del Maule was not designed for the current earthquake knowledge.



Fig. 1 Partially collapse of the building in Valdivia Earthquake.

2. 2004 SUMATRA EARTHQUAKE

The Mw 9.0 earthquake struck at 06:28 a.m. local time in Sri Lanka. Although initial estimates had put the worldwide death toll at over 275,000 with thousands of others missing, according to the U.S. Geological Survey a total of 227,898 people died. While damage in little Andaman island and all Nicobar island was predominantly tsunami related, that in the islands north of little Andaman was primarily due to earthquake shaking, though tsunami waves and high tides were also an issue. In general, the building stock consists of a large number of traditional and non-engineered. Many traditional structures were made of wood, and they performed well in the earthquake shaking. However, a number of new, poorly constructed masonry structures suffered severe damage or even collapse due to shaking as shown in Fig 2.

Most of buildings on the east coast of Sri Lanka are made of bricks. Damage to these buildings was most apparent in regions where part of the building was left standing. However, in most cases, the only indication of a pre existing building was a remnant of a foundation. In some areas, there was a zone near the coast where all structures were completely destroyed; however, the damage to structures varied over short stretches of coast.

In one part of Kalmunai, the zone of destruction extended about 0.5 km inland, but less than 2 km from there, most of the structures were standing and relatively undamaged at distances greater than 100m from the shoreline. This variability may have resulted from differences in both the tsunami heights and the quality of construction. Large scour was noted in most areas, which appeared to result from both the incoming and returning flow, undermining the foundations of many structures. In masonry load-bearing walls and light roof trusses made of either steel pipes or timber, walls were not tied together to create lateral resistance. Large movement of the flexible roofs from earthquake forces caused out-of-plane masonry wall collapse. Similar damage was observed at a much larger scale in many school buildings, where the long partition walls separating two classrooms were either badly damaged or had fallen due to out-of-plane instability.



Fig. 2 Total collapse of the building in Sumatra Earthquake

3. 2011 TOHOKU EARTHQUAKE

The 2011 earthquake off the Pacific coast of Tohoku was a magnitude 9.0-9.1 under sea mega thrust earthquake off the coast of Japan that occurred at 14:46 JST (05:46 UTC) on Friday 11 March 2011, with the epicenter approximately 70 kilometers east of Oshika Peninsula of Tohoku and the hypocenter at an underwater depth of approximately 29 km. The earthquake was often referred to in Japan as the Great East Japan Earthquake and was also known as the 2011 Tohoku earthquake.

Report confirmed 15,894 deaths, 6152 injured and 2,562 people missing across twenty prefectures, as well as 228,863 people living away from their home in either temporary housing or due to permanent relocation. An report listed 1,27,290 buildings totally collapsed, with a further 2,72,788 buildings "half collapsed", and another 7,47,989 buildings partially damaged.

Damage to the engineered constructions was limited to broken doors, windows, and masonry failures. Masonry walls suffered out of plane failures and were jettisoned in great distance, mainly in buildings constructed near the shoreline. Almost all of the damaged buildings were designed in accordance with the old building code and damaged due to lack of seismic strength, short column shear failure due to the source wall or the eccentricity of structural elements. In most cases masonry walls out of plane punching shear failures and pounding failure were observed as shown in Fig 3. Buildings with appropriate seismic reinforcement/retrofit were mostly free of damage, indicating that the seismic reinforcement/retrofit of buildings was effective. Even so, clear structural damage occurred due to the ground motion amplification. The 8 and 9 story buildings at Aobayama campus of Tohoku University were damaged due to ground motion amplification in the site. Many pile foundation buildings were damaged during the earthquake.



Fig.3 Pounding failure in Tohoku Earthquake

4. 1952 KAMCHATKA EARTHQUAKE

The Kamchatka Tsunami was generated by a magnitude 9.0 earthquake on November 4, 1952, in East Russia. The local tsunami, which generated waves as high as 50 feet, caused extensive damage to the Kamchatka Peninsula and the Kuril Islands, and left an estimated 10,000 to 15,000 people dead. Waves traveled as far as Peru, Chile and New Zealand, but the largest damage to other areas of the Pacific Ocean occurred in the Hawaiian Islands. Masonry structures were also widely distributed across this region even though their numbers are less than wooden buildings. Buildings built with tuff stone called nobirustone (shiogama-stone) produced in the Shiogama City region of Miyagi Prefecture were widely distributed across the Tohoku region and observed full collapse of the building in Fig 4.

In Shiogama City, the Takahashi family residence (1922) is in part a two-story stone building that uses local nobirustone. This building sustained significant damage such as horizontal cracking starting from the entrance due to ground motions. There was damage to many stone monuments such as stone lanterns. This damage included displaced stones and fallen top stones.

In Iwate Prefecture, there was no damage to the brick-constructed silos at Koiwai farm (1907-08), which is registered as tangible cultural property. Morioka City's "Former Covered Parade Ground" building (1909) is a brick structure that has been nominated as a modern heritage, but cracks appeared in the entrance area and emergency measures are being taken to prevent the building from collapsing.

In Sendai City, the 3-story brick architectural museum in the Tohoku University campus (before 1910) sustained damage such as cracks in brick walls. In Fukushima City, the brick-constructed and registered tangible cultural property, the United Church of Christ in Japan, was damaged by the disaster.

In North Kanto, there was no structural damage to the timber framed brick structure, the former Tomioka Silk Mill, which was registered as an important cultural property.



Fig.4 Total collapse of the building in Kamchatka Earthquake.

5. 2010 MAULE EARTHQUAKE

The 2010 Chile earthquake occurred off the coast of central Chile on Saturday, 27 February at 03:34 local time (06:34 UTC), having a magnitude of 8.8 on the moment magnitude scale, with intense shaking lasting for about three minutes. It was felt strongly in six Chilean regions that together make up about 80 percent of the country's population.

In Chile, 370,000 homes were damaged. The final death toll of 525 victims and 25 people missing was announced by authorities in January 2011. This is down from early reports on 3 March of 802 people dead. Earthquake's losses to the economy of Chile are estimated at US\$15–30 billion.

Museums, churches, and other historic masonry structures sustained out-of-plane failures in unreinforced masonry walls (Fig. 5), cladding damage, and parapet and other roof connection failures. For example, the Basilica Del Salvador in Santiago, constructed in the 1870s and previously damaged in the 1985 earthquake, was further compromised in the 2010 event. The building's façade lay in rubble at its base. Also in Santiago, large pieces of the façade on the west side of the museum of fine arts had fallen, damaging the stairs below. Throughout central Chile, historical churches were disproportionately impacted by the event, as most were unreinforced masonry or adobe structures and particularly susceptible to earthquake damage. In Curico, a church's tower had collapsed onto the roof, causing the roof to collapse as well. All that remained of a church in Peralillo were two stark white columns.

In Santa Cruz, the city's main abode church, constructed 165 years ago, was heavily damaged and scheduled for demolition.



Fig. 5 Out of plane failure in Maule Earthquake.

6. 1906 ECUADOR–COLOMBIA EARTHQUAKE

The 1906 Ecuador–Colombia earthquake occurred at 15:36 UTC on January 31, off the coast of Ecuador, near Esmeraldas. The earthquake had a moment magnitude of 8.8 and triggered a destructive tsunami that caused at least 500 casualties on the coast of Colombia.

The greatest damage from the tsunami occurred on the coast between Río Verde, Ecuador and Micay, Colombia. Estimates of the number of deaths caused by the tsunami vary between 500 and 1,500. The rupture zone for this earthquake was 500–600 km (310–370 mi) long, and encompassed those for the earthquake of 1958 (Mw=7.7) and 1979 (Mw=8.2). The lack of overlap between the three more recent events suggests the presence of minor barriers to rupture propagation along the plate boundary. The area of the burned district covered 4.7 square mile.

Wood buildings lost = 24,671

Brick buildings lost = 3,168

Total buildings lost = 28,188

Estimated property damage \$400,000,000 in 1906 dollars from earthquake and fire, \$80,000,000 from the earthquake alone. The town of Pedernale near the epicenter was reported to have suffered many building collapses and significant damage, with the mayor saying the entire town had “collapsed” as shown in Fig 6. Severe damage to buildings has also been reported in the city of Manta.



Fig. 6 Partially collapse of the building in Ecuador–Colombia Earthquake.

7. 1965 RAT ISLANDS EARTHQUAKE

The great $M_w=8.7$ Rat Islands under thrusting earthquake (larger star on the above map) of February 4, 1965, ruptured a 600-km segment of the western end of the Aleutian Islands (black solid line). The waveform analysis indicates unilateral rupture from east to west and three large pulses of moment release located along the fault (Beck and Christensen, 1991).

The Rat Islands event was closely followed by a large tensional outer-rise event of March 30, 1965 (M_s 7.5, smaller star), which was located ocean ward of the largest moment release associated with the Rat Islands main shock rupture. This event may have been triggered by the large displacement near the main shock epicenter. The overriding plate along the western Aleutian subduction zone was laterally segmented into a series of rigid tectonic blocks separated by fault controlled canyons and extensional basins. This earthquake generated a tsunami reported to be about 10.7 meters high on Shemya Island.

Loss caused by flooding on Amchitka Island was estimated at about \$10,000. Property damage was estimated at about \$311 million, collapse of building as shown in Fig 7.



Fig. 7 Total collapse of the building in Rat Islands

8. 1950 ASSAM–TIBET EARTHQUAKE

The 1950 Assam–Tibet earthquake, also known as the Assam earthquake, occurred on 15 August and had a moment magnitude of 8.6. The epicenter was located in the Mishmi hills, known in Chinese as the Qilinggong mountains, south the Kangri garpo and just east of the Himalayas in the North-East Frontier Agency part of Assam, India. This area, south of the McMahon Line and now known as Arunachal Pradesh. The earthquake was destructive in both Assam (India) and Tibet (China) and between 1,500 and 3,300 people were killed.

The buildings in the area around Shillong consisted of three types: stone buildings; ekrabuilt buildings which consisted of wooden framework with walls of san grass covered in plaster; and the timber plank buildings built on "log hut" principle, having a wooden framework covered with planks, and resting unattached on the ground and most of the structure observed was partially collapsed as shown in Fig 8. The plank buildings were in general undamaged. Damage caused by this earthquake led to the development and adoption of Assam-type houses.



Fig. 8 Partially collapsed of the building in Assam-Tibet Earthquake.

9. 1991 UTTARKASHI EARTHQUAKE

The magnitude of the earthquake was assigned as 6.1 by the Indian Meteorological Department (IMD) based on body wave data. The USGS assigned a surface wave magnitude of 7.1. There was confusion about epicenter of the earthquake, with preliminary estimates by IMD indicating its location close to Almora, about 170 km from Uttarkashi.

Uttarkashi has a number of three and four story reinforced concrete (RC) framed buildings which sustained damage. Shear-cracks developed in the ground floor columns of two stories Post Office Building in Uttarkashi built in 1985-86 by engineers of the department of post and telegraphs. The strong floor beams in the frame forced the yielding into ground-story columns. The weaker roof beams sustain flexural hairline cracks while the supporting second story columns were damaged. Most government buildings, both offices and residences, are one or two story buildings with load bearing walls and sloping roofs. Older construction was of unreinforced random rubble stone masonry which performed very poorly and observed full structures were collapse. The newer construction was of unreinforced concrete block masonry and usually includes a RC band at lintel level. The ITBP Paramilitary Campus at Mahidanda consists a large number of two story residential buildings with load bearing walls of concrete masonry. All have RC lintel bands, but no roof bands or gable bands. The construction was about 10 years old. The damage to buildings consisted of (i) diagonal cracks below window sills, (ii) damage at the connection between masonry walls and RC roof slabs, (iii) in buildings with corrugated iron sheet roofs, damage at seat of purlins on the gable end walls, and (iv) damage to walls supporting roofs at different heights at either end (Fig. 9).



Fig. 9 Damage to wall supporting Split Level roof - ITBP campus, Mahidanda, Uttarkashi Earthquake

10. 1993 KILLARI EARTHQUAKE

A very active swarm between August and October 1992 (125 felt events in Killari); the largest event on October 18, 1992 ($m_b=4.5$) caused damage to many stone/mud buildings in Killari. Centred near the village of Killari, Latur district, Maharashtra State, Central India (18.2N; 76.4E).

The collapse of traditional stone-and-mud buildings in the mesoseismal area was nearly total. The wood-plank roofs of these single-story dwellings typically are topped with a 30-60 cm thick layer of clay to provide protection from rain and heat. All such constructions behaved very poorly due to the heavy mass at the roof and the poor strength of the supporting rubble masonry walls; such houses were the main cause for the high number of casualties as shown in Fig 10.

Some houses were made of load-bearing walls of burnt-clay bricks in cement mortar supporting either a reinforced concrete slab or a corrugated sheet roof. In a residential colony at Killari, a house supporting heavy reinforced concrete roof sustained severe wall cracks, while the adjoining one supporting a light roof of corrugated asbestos sheets sustained only hairline cracks in the walls. Surprisingly, a few brick masonry houses in the area were found to have concrete lintel bands. Such houses performed very well with no damage.

The structures (buildings, public utilities, industrial facilities, etc.) behaved in expected way during earthquake. Non-engineered conventional buildings suffered complete collapse to very severe damage making them non-usable. Almost all the conventional buildings of stone wall with mud mortar collapsed in the epicentral area as their resistance against lateral force was very little. Though the stone wall buildings with sand cement mortar or those with wooden frame to support roof responded in a better way than the stone wall with mud mortar but they also became unusable. The engineered structures responded in expected way and suffered generally acceptable pattern of damage. Performance of reinforced structures, in general, was good except one water tank. It was reported that the reinforcement detailing of this tank might not be in accordance with the accepted practice.



Fig. 10 Collapse of brick masonry structure in Killari Earthquake

11. 1997 JABALPUR EARTHQUAKE

The earthquake occurred on May 22, 1997 at 04:22 am (local time) centered about 8 km southeast of the city of Jabalpur (epicenter 23.18°N 80.02°E) in the state of Madhya Pradesh in central India. USGS (United States Geological Survey) estimates the depth of focus at a default 33 km. It caused significant damage to structures in the districts of Jabalpur, Mandla, Sivni and Chhindwada in the state of Madhya Pradesh.

About 8546 houses collapsed and about 52,690 houses were badly damaged. In all, 887 villages (or equivalent) were affected. More than 90% of houses collapsed or were badly damaged in at least two of these villages with a population of about 500. During this earthquake, about 38 persons died and about 350 were injured and also observed most of the structure partially collapsed as shown in Fig 11. The affected area consists of both rural and urban environments. The predominant type of construction in the rural areas was earthen, while that in the urban areas was load-bearing brick masonry with mud or cement mortar. In Jabalpur, there was a good number of reinforced concrete (RC) moment resisting frame multi-story buildings with infill walls consisting of unreinforced brick masonry in cement mortar.

The rural dwellings were usually a single story with earthen walls (usually 10 to 12 feet high; about 30 inches wide at the base and about 12 inches at the top) supporting a pitched tile roof having wooden rafters and purlins. The rafters and purlins were circular posts up to 15 feet long made from locally available trees. In general, rafters and purlins were tied together with coir rope.



Fig. 11 Partially collapsed of the structure in Jabalpur Earthquake

12. 1999 CHAMOLI EARTHQUAKE

The earthquake occurred at 00:35:13.59 hours (local time) near the town of Chamoli in the state of Uttar Pradesh in northern India. The earthquake magnitude was mb 6.3, MS 6.6 as per USGS, and it was mb 6.8, MS 6.5 as per India Meteorological Department (IMD). The preliminary location of epicenters by different agencies was somewhat inconsistent; 30°49.2'N, 79°28.8'E as per USGS, and 30°17.82'N, 79°33.84'E.

Many of the villages were not connected by motorable roads and are accessible only after considerable trekking. The building stock in the affected area consists primarily of rural dwellings, with some urban houses and a few modern constructions for office or commercial purposes in towns. Load-bearing random rubble stone masonry in mud mortar formed the predominant wall system employed in the area. In most of the masonry structures, out-of-plane failure occurred as shown in Fig 12. Many constructions of the recent years have been in brick or concrete block masonry in cement mortar. The roofing system was usually thatch, tin sheets, slate tiles, or RC slabs.

Traditional stone dwellings in the area were usually of one or two storeys with a rather low storey height (about 1.65m). The walls were about 0.45-0.60m thick in stone masonry with mud mortar and are usually of two types: (a) Random rubble stone masonry using the undressed stones: The wall was made of two separate sections, the outer and inner wythes, so that both surfaces were smooth. The space between the two wythes was filled with stone rubble. (b) Masonry with slate wafers: Dressed stones and slate wafers were stacked tightly with very little or no mud mortar in between. In carefully done walls of this type, the dressed stones appear at intervals of about 0.5m along the length and about 0.3m along the height; else they appear at random locations. Unlike in case of random rubble masonry, the rubble of small stones is not dumped in the middle region of the wall. Since none of the slate wafers is wide enough, this type of wall also has a tendency to split and buckle into two separate wythes due to lack of interlocking. Most of the dwellings have wood rafter roof supported directly on the walls. Many very old constructions and a few new constructions have wood rafter roof supported on vertical wooden posts.



Fig.12 Out-of-plane failure in Chamoli Earthquake

13. 2010 BASYURT-KARAKOCAN (ELAZIG EARTHQUAKE)

An earthquake of magnitude $M_w=6.0$ occurred on March 8, 2010 at 04:32 local time, in Elazig province, Basyurt-Karakocan region of Turkey. Official number of houses with light, moderate and heavy damage is respectively: 3854, 1561 and 3007. The earthquake affected region consists of small villages with R/C frame and unreinforced brick, concrete block and adobe masonry. Most of the URM buildings were old and rather unmaintained.

Main reasons of dense damage within Basyurt-Kovancilar-Gokdere region are as following;

- Improper material and construction techniques have been used.
- Villages were located on steep and risky locations for landslides or on flat but saturated soil conditions.

The most common damage type was partial collapse of load bearing walls due to “out of plane” behaviour (Fig. 13). Even if load bearing walls could stand after earthquake without total or partial collapse, wide cracks prevents usability of the buildings. Building types will be classified in terms of construction material, although, most of the buildings were constructed with binary combination of different materials.

1) Masonry Houses with Sun-dried Soil Bricks:

Sun-dried soil brick (soil brick) was the most common construction material type especially for one storey houses and stalls.

Slabs were usually wooden, which were “simply supported” by stall floor. However, there was a lack of restraint on the slab boundaries; therefore it may be more convenient to consider them as “sliding support”. In other words, poorly constructed slabs and roofs were not capable to behave as a rigid diaphragm and transmit the lateral forces among the walls.

2) Masonry Houses with Stones:

Relatively new buildings, starting from 1980’s, are constructed with a kind of light, volcanic stone, coming from Güllüce, in that territory. This stone can be reshaped very easily; therefore, it was so common to see as outer walls of the buildings.

In two story masonry buildings, it is not easy to define a particular damage pattern, but it can be seen that, with a slightly more proper construction technique, they did not collapse totally, although they have suffered from heavy damage.



Fig.13 Partially collapsed structure in Basyurt-Karakocan (Elazig) Earthquake

14. 2016 PIDIE JAYA EARTHQUAKE INDONESIA

A M6.5 earthquake struck Pidie Jaya Regency of Aceh Province in Indonesia on December 7, 2016 at 5:03 AM. An information release from Badan Nasional Penanggulangan Bencana (BNPB), the Indonesian National Agency for Disaster Management, estimated the total economic loss from this earthquake at IDR 2.94 trillion. The provincial government declared a state of emergency for 14 days following the quake, which caused 104 deaths, injured hundreds more, and displaced about 50 percent of the district's population. BNPB reported damage to 19,130 residential homes, 306 schools, and more than 500 commercial and public buildings, religious establishments, and healthcare facilities.

While masonry buildings were popular in both cities and villages in Indonesia, very few were completely unreinforced buildings – instead it was common to observe partially confined or confined masonry buildings. The unconfined masonry portions of houses, such as kitchens, usually fell outside of the primary footprint. In most cases, these unreinforced masonry portions of the buildings collapsed in the earthquake as shown in Fig 14.

Confined masonry was one of the main building typologies encountered in the areas, especially for low-rise residential and single-story school buildings.

These were typically non-engineered buildings. The level of confinement varied between the houses and schools buildings were observed. It was common to see reinforced concrete columns, plinth, and ring beams, but the sides of openings, sill, or lintel beams were made of unreinforced concrete. The foundations were typically built of stone masonry with a plinth beam at the level between the foundation and wall. Typically, the walls were only one brick wide, with the brick oriented along the narrow dimension parallel with the wall (approximately 10 cm wide) and were up to 4m high. In many cases for both houses and schools, the walls spanned 4 m to 5 m or more between perpendicular walls.



Fig.14 Collapsed masonry building in Pidie Jaya Earthquake

15. 2015 AFGHANISTAN–PAKISTAN EARTHQUAKE

On the 26th October 2015 Afghanistan-Pakistan Mw 7.5 earthquake, in reference to the ground motions observed in KP Pakistan and preliminary reconnaissance surveys conducted on the behavior assessment of structures in KP Pakistan subjected to the event.

The ground motions acceleration was recorded in Peshawar by the National Center of Excellence in Geology, University of Peshawar, and KP. The buildings damage assessment is carried out by the structural expert team of the Earthquake Engineering Center of UET Peshawar in the most affected regions in KP Pakistan (Abbottabad, Chitral, Dir, Mohmand Agency, Peshawar, Shangla, Swat), to understand the performance of structures against the earthquake induced ground motions and derive lessons learned from the earthquake event.

Rubble stone masonry structures in dry condition or mud mortar and adobe/mud structures performed very poorly in this earthquake and have shown severe damages, partial and total collapses (Fig. 15). It was due to the low strength of materials and poor construction practice (not using any confining beam and column elements). Furthermore, due to

raining few days before the earthquake event, these structures were in wet condition when subjected to ground motion shaking, thus possesses less strength. Topographic effects at ridges have also played role in amplifying ground motions and increasing time duration of shaking, because of focusing of seismic waves. These observations were primarily made in the mountainous region of Dir, mohmand Agency, chitral and Swat. Brick masonry structures of very old construction, 70-80 years older, also performed very poorly in Peshawar, due to building materials deterioration because of aging. These buildings have shown severe damages and roof collapses. However, the same structures where timber-framing laces were used performed well and the structures remain intact. These observations were made in Peshawar, particularly in awqaf buildings. Brick masonry and brick masonry confined structures have performed poorly and have shown severe damages in case of ground motion amplification on alluvium soil due to local site effects or due to localized foundation settlement. Poor performance of confined masonry structures was also observed due to improper construction of these structures, particularly confining elements were built before 26th October 2015 Afghanistan-Pakistan Earthquake the masonry walls and no tooting of RC elements to masonry walls has been carried out. These observations have been made in Upper Dir and Malakand.



Fig.15 Partially collapsed structure in Afghanistan–Pakistan Earthquake

16. 2014 SOUTH NAPA EARTHQUAKE

The Mw 6.0 South Napa earthquake struck at 3:20 am (PDT) on August 24, 2014, just north of San Francisco, California. The cities of Napa, American Canyon, and Vallejo were located in the area of strongest ground shaking, and had the most damage. The epicentral area of the earthquake, with MMI shaking intensities overlaid on population density. The total population within MMI VI was estimated to have been about 200,000, with approximately 36,000 subjected to shaking at the level of MMI VIII. (Table 1)

The housing stock in Napa and Solano Counties comprises mostly single family homes. Of the 207,000 housing units in the region, over two-thirds were detached single family units (masonry structures). In Napa County, nearly 30% of the housing stock was built before 1959, while in Solano County only 20% of residences predate 1959. The median house price in Napa County is \$460,000; in Solano County it is \$290,000. Napa County also observed that many failures occurred in structure like out-of-plane, in-plane, and pounding etc. as shown in Fig 16.

Most single-family homes in the region were one- or two-story wood-frame structures with either wood or stucco exterior siding. Many homes built before 1950 have cripple wall foundations, where the first floor of the structure was elevated several feet off the ground on short perimeter walls that were vulnerable to collapse in earthquake ground shaking.

The area surrounding downtown Napa has a high concentration of such structures, and several cripple wall failures were observed. Many mobile homes in Napa County had extensive foundation damage as a result of earthquake ground shaking. Typical mobile home foundations comprise stacked concrete blocks that were vulnerable to collapse in an earthquake. An exterior survey of more than 80 mobile homes in the Salvador Mobile Estates community in Napa revealed that nearly a quarter of homes had either significant permanent displacement or partial foundation collapse.

Table 1. Estimated population with MMI isoseismal

≥ MMI	Population
VI	1,99,000
VII	90,000
VIII	36,000

In the Napa Valley Mobile Home Park, earthquake shaking ignited fires that destroyed four homes and damaged too. Several teams performed rapid visual inspections of unreinforced masonry buildings (URMs) in the downtown area of Napa. Most buildings with retrofits appeared to perform well with respect to global life safety or collapse prevention, but a number of localized life safety hazards were identified. Damage was variable, but over 30 retrofitted URM buildings generally outperformed the three remaining nearby un-retrofitted buildings. Because interior access was not available for most buildings, interior damage and the extent of retrofit was only partially documented.



Fig.16 Out-of-plane failure in South Napa Earthquake

17. 2002 MOLISE, ITALY, EARTHQUAKE

At 11:32 am (local time) on October 31, 2002, a magnitude Mw 5.7 earthquake struck the inland part of Molise, a small rural region in the southeastern part of the Italian peninsula. The epicenter was located about 220 km southeast of Rome, but the earthquake was felt as far away as Naples and the Italian capital. This earthquake caused widespread damage in 50 villages and killed 30 people, 27 of whom were children trapped in the collapse of the elementary school in San Giuliano di Puglia.

The Molise earthquake sequence damaged towns in the Campobasso Province in Molise and in the Foggia Province in Puglia. San Giuliano di Puglia, Bonefro, Santa Croce di Magliano, Ripabottoni, Castellino del Biferno, and Casalnuovo Monterotaro were the most affected towns. As of December 15, 2002, about 15,000 inspections had been made in Molise and about 2,000 in Puglia. In San Giuliano alone about 300 buildings have already been declared unsafe and will probably be demolished. The inspection survey considered six tagging conditions: A (usable with no restrictions), B (usable with conditions); C (partially usable); D (to be inspected again); E (not usable); F (not usable because of damage to adjacent buildings). The preliminary breakdown of the inspections in the six most affected towns are shown in Table 2.

Table 2. Post earthquake building inspection in the most damaged towns.

Comune	Total	A	B	C	D	E
S. Giuliano	590	160	55	11	21	298
S. Croce	1453	1073	123	48	19	170
Ripabottoni	895	428	75	55	56	232
Castellino	544	2720	29	16	18	166
Bonefro	1203	740	143	20	5	245

Better construction practices and, probably, lower ground shaking made older buildings perform relatively well, with many fewer collapses than more modern construction. Some significant examples of damage to older buildings include out-of-plane failures of walls and failure of the roof-supporting structure as shown in Fig 17.

Some interior damage, with partial detachment of the façade from the exterior wall, was also observed in the historical part of Casalnuovo Monterotaro. Some of the collapses in the older buildings occurred in buildings that were abandoned and in an acute state of disrepair. All the damage mechanisms typical of stone-wall and brick-wall buildings were observed in the relatively newer structures located in the developments outside the old town.



Fig.17 Out of plane failure of building in Molise Earthquake

18. 2005 KASHMIR EARTHQUAKE

On October 8, 2005, at 08:50 am local time, a Mw7.6 earthquake struck the Kashmiri region of Pakistan and India, causing widespread destruction in Pakistan's Azad Jammu and Kashmir (AJK) and North-west Frontier Provinces

(NWFP), & in India's western and southern Kashmir an area of 30,000 km². This was the deadliest earthquake in the recent history of the sub-continent, with more than 80,000 fatalities, 200,000 people injured, and more than 4 million people left homeless.

The majority of buildings in the affected region use the unreinforced masonry walls as bearing and enclosure walls. These masonry structures can be viewed as box-type structures in which the primary lateral resistance against the earthquake forces was provided by the membrane action of the diaphragms (floors and roofs) and bearing walls. The seismic performance of load bearing masonry structures depend heavily on the structural characteristics (strength, stiffness and ductility) of surrounding walls to resist in-plane and out-of-plane inertia forces and of the diaphragms (floors & roofs) to not only safely resist the shear forces but also to distribute the forces to vertical elements (walls) and maintain the integrity of the structure (Fig 18).

A significant number of casualties and injuries in the rural areas were associated with the total collapse of single-story unreinforced earthen wall stone masonry buildings.

The stone masonry walls consisted of irregularly placed un-dressed stones, mostly rounded, that were laid in cement sand, mud mortar, or even dry in some cases. A number of features seem to be responsible for widespread collapse of buildings. Stone masonry buildings were more common in the villages than in the cities. The quality of mortar and stones used and the level of workmanship were poor, due to the economic constraints on the people. Stone masonry set in plain earth (i.e., mud) is not unusual.

Brick masonry buildings were the most common form of masonry in towns, and performed better than the stone or concrete block masonry buildings. According to the Earthquake Engineering Center at NWFP UET Peshawar, unreinforced one and two story brick masonry buildings, with RC slabs as roofing, comprise 25% of the total building stock of the cities near the epicenter. About 30% of these buildings collapsed, while the rest suffered slight damage. Because the unit cost of brick masonry was higher than that of other forms of masonry, the owners were people with financial resources. Along with better workmanship, good quality mortar was used in the construction of brick masonry buildings. However, no evidence of either bond beams or other earthquake resistant improvement techniques was found in such buildings.



Fig.18 Out-of-plane collapse in Kashmir earthquake

19. 2013 LUSHAN EARTHQUAKE

A moment magnitude Mw 6.6 earthquake (USGS) struck Lushan County at 8:02 am local time on April 20, 2013. The county is about 130km west of the city of Chengdu in southwestern China. It has a population of over 110,000 and the main township has a population of about 20,000. There were more than 200 fatalities and over 11,000 injured.

According to UNICEF (2013), greater than 90% of the buildings were damaged, while in Baoxing County, to the northwest, greater than 60% of the buildings were damaged. Other seriously affected counties were Yucheng and Tianquan Counties.

From observations in Lushan, the damages appeared similar to those in the Wenchuan earthquake, although on a smaller scale and much more limited in area. It is reported that the damage in Baoxing, higher in the mountains than Lushan, was more severe. After the 2008 quake, a new town was constructed in Lushan and the damages there were far less severe than in the old town. In the old town and the mountain villages, the construction was largely brick and mortar, and it performed poorly and observed many failures are occurred in the structure and also many structures were partially and fully collapsed as shown in Fig 19. The government buildings in the new town, built according to modern code, generally sustained less damage.

The unreinforced masonry (URM) structures predominated in low-rise buildings and houses in rural areas throughout China, regardless of the seismic risk. In such structures, clay brick masonry walls were the primary load-bearing components, which were usually 120 mm to 360 mm thick, depending primarily on the economic condition of the owner rather than structural concerns. Precast concrete slabs were usually used as floor slabs due to its low cost, easy transportation and fast construction. As a result of the vast collapse of URM buildings and houses, especially those with precast concrete floor slabs, during the deadly earthquake, confinements such as reinforced concrete (RC) tie columns and tie beams were introduced to URM structures to enhance their integrity and thus the seismic performance.

In a masonry infilled timber frame house, two parts of very different mechanical properties were combined to form a dual structural system, in which the stiff masonry infill provide lateral resistance while the flexible timber frame carries

the vertical load. In such a dual system, the seismic damage can also be discussed in two parts, i.e., that of the masonry infills, and that of the timber frame itself. Cracking and collapse of masonry infills were the most commonly-seen damage to the masonry infilled timber frame houses. Such behaviour is substantially different from that of URM structures, in which the masonry walls provide the sole resistance for both the vertical loads and the earthquake lateral load. Severe shear cracking of the masonry walls due to lateral load would at the same time greatly degrade their vertical load-bearing capacity and may eventually lead to the collapse of the house.



Fig.19 Fully collapsed of the structure in Lushan Earthquake

20. 2001 NISQUALLY EARTHQUAKE

On Wednesday, 28 February 2001, a moment magnitude 6.8 earthquake occurred beneath the southern Puget Sound area of Washington State. The preliminary location by the University of Washington Seismological Laboratory places the earthquake at a depth of 52 km with an epicentral location of 47.149°N and 122.727°W. This location was near the Nisqually river delta about 18 km northeast of the city of Olympia and the earthquake has therefore been named the Nisqually earthquake. The epicenter is 24 km southwest of the city of Tacoma and 58 km southwest of the city of Seattle. The origin time was 18:54:32 UTC, or 10:54:32 a.m. local time.

Structures damaged included office buildings, residences, schools, hospitals, airport structures and churches. These structures and the surrounding areas were closed for various lengths of time following the earthquake. Structural damage was primarily concentrated in older unreinforced masonry buildings, with some damage reported to wood-frame structures and reinforced concrete structures. In general, new buildings and buildings that had recently been seismically upgraded typically displayed good structural performance, but many still sustained non-structural damage.

Structural and non-structural damage also resulted from geotechnical failures. In general, areas that sustained the most significant damage were built on fill or weak soils. Lateral spreading and settlement induced large deformations, which resulted in nonstructural and some structural damage. Landslides caused damage to houses. Unreinforced masonry (URM) buildings built before 1950 exhibited the poorest behaviour. The most common damage included shedding of brick from parapets and chimneys. Other URM buildings exhibited diagonal “stair-step” cracking in walls and piers, damage to walls in the upper stories, vertical cracking in walls, damage to masonry arches, and damage to walls as a result of pounding. In many cases, fallen brick resulted in damage to objects, such as cars and canopies, outside the building as shown in Fig 20.



Fig.20 Brick Parapet and Wall Failure in Nisqually Earthquake

21. NEPAL EARTHQUAKE 2015

The April 2015 Nepal earthquake (also known as the Gorkha earthquake). It occurred at 11:56 Nepal Standard Time on 25 April, with a magnitude of 7.8. During the earthquake 5, 01,201 building were collapsed and 2, 72,177 numbers of buildings were damaged. Most of the buildings damaged by the earthquake were masonry building.

During an earthquake when a structure is shaking, it gets damaged if it is not sufficiently strong and/or flexible. The extent and degree of damage depend on how weak and/or rigid it is. The type of damage depends on a number of factors including the type, direction and duration of the earthquake forces, the frequency of the ground motion, the natural

frequency of the building, the nature of the underground geology and soil deposits, the shape of the structure, the type of building technology, etc.

Several buildings, most of them were old, collapsed in the densely populated Kathmandu valley. Kathmandu's darbar square, a UNESCO world heritage site, was totally damaged in the quake. Harsh damage took place to the parts of the palace complex in Vasanthapura Square. The site of palaces and temples of the city was warren of narrow lanes and historic structure. Kathmandu residents ran onto the streets and other open spaces, throwing up clouds of dust and wide creaks opened on paved streets and the building's wall. At Langtang valley in Rasuwa district, a major tourist destination in Nepal, also famous for trekking, it is said that over 100 people were killed and 120 people were injured or missing following the massive avalanche which swept away the entire village in the wake of the powerful quake that hit Rasuwa district. April 25 quake left 8,699 people dead, 22,220 people injured and flattened thousands of buildings besides destroying whole villages in affected area. In Nepal, Over 5, 00,000 houses were destroyed and 2, 69,000 were damaged by the earthquakes and hundreds of thousands of people were still staying in temporary shelters. More than 8, 64,000 affected people, who lived in remote mountainous area, have lost their relatives and houses.

A number of old temples, pagodas and churches in the Kathmandu valley were razed. Several temples including Manakamana Temple at Gorkha, Janaki Mandir at Janakpur; Kasthamandap, Panchtale temple, Basantapur Durbar, the Dasa Avtar temple and the Shiva Parvati temple were demolished. The Kumari Temple and the Taleju Bhawani Temple partially collapsed. Some portion of the Jaya Bageshwari Temple at Gaushala, Pashupatinath Temple, Swyambhunath, Boudhanath Stupa, Ratna Mandir and Rani Pokhari had been destroyed.

The Char Narayan Mandir, the statue of Yog Narendra Malla, the Taleju Temple, the Hari Shankar, Uma Maheshwar Temple and the Machhindranath Temple in Bungamati were destroyed. In Tripureshwar, the Kal Mochan Ghat, a temple inspired by Mughal architecture, was completely destroyed and the nearby Tripura Sundari also suffered significant damage. In Bhaktapur, several monuments and Temples were totally destroyed.

Most of the damaged masonry structures were poorly constructed without following the design guidelines while minor or no structural damages were observed in well-constructed masonry buildings. Several structural deficiencies by the recent earthquake were assessed including: poor quality of materials and workmanship, pounding effect, weak storey, unconfined gable walls, missing confining elements, vertical and horizontal irregularities, lack of corner treatment, heavy balcony and poor anchorage for horizontal projections (Fig. 21). Lack of cyclic maintenance and unpreparedness for strong ground shaking. The major deficiencies indicating non-compliance with codal provisions should be noted and strengthening of existing building may increase the performance of the building on coming days.



Fig. 21 Quality of mortar and bricks used in building in Nepal Earthquake

III. CONCLUSIONS

The damage to the built environment, economic loss, and human casualties caused by earthquakes are increasing proportionally with the growth of settlements and population in the upper reaches of the region. Significant damage was observed in the prevailing stone masonry residential, community, and government buildings, particularly those of random-rubble, a type which is well-known for poor seismic performance. Much of the damage can be attributed to inferior construction materials, inadequate support of the roof and roof trusses, poor wall-to-wall connections, poor detailing work, a weak in-plane wall due to large openings, out-of-plane instability of the walls, a lack of integrity or robustness, asymmetric floor plans, and aging. Buildings should not only meet the functional requirements of occupants, but also the essential requirement for safety, based on sound earthquake resistant design and construction. Conventional unreinforced masonry laced with timber performed satisfactorily, as expected, since it arrests destructive cracking and evenly distributes the deformation, which adds to the energy dissipation capacity of the system, without jeopardizing its structural integrity and vertical load-carrying capacity. There is an urgent need to revive these traditional masonry practices, which have proven their ability to resist earthquake loads, in contrast to contemporary colonial-style masonry buildings.

- Many buildings of non-engineered (adobe & rubble masonry) and semi engineered (brick masonry & confined masonry) constructions have incurred severe damages and experienced partial and total collapses and performed poorly in case of ground motion amplification due to soft-soil conditions and topographic effects (ridges effects). This point to the importance of site-soil & site-topography consideration in the design and construction of structures. The poor performance of confined masonry buildings also attributed to the improper construction practice, no toothing was

observed between column and masonry i.e. confining columns was built first and masonry after. However proper confined masonry construction requires building the masonry wall first, after placing reinforcement skeleton for confining columns, and then pour concrete for columns later.

- Significant amount of medium to good quality constructions (brick masonry buildings) have performed very poorly in case of local differential settlement due to local soil failure, which was primarily due to improper drainage and blockage, causing water ponding, that kept the foundation soil wet for years and resulted in the foundation soil to lose its shear strength capacity for carrying vertical and lateral loads. This calls for attention to improve building drainage systems.
- Damages to infill walls have been observed, which calls for using soft (flexible) infill in the structures. Furthermore, pounding effects in the structures have been observed which calls for attention in future designs to use soft joint filler in expansion joints to minimize hammering effects during earthquake.
- Structures with timber laces and timber framing have performed better, even in case of using low strength infill materials. However, in case of large panels, masonry materials detachment and panel out-of-plane failure have been observed.
- From the above discussion it can be understand that there is an urgent need of retrofitting of existing masonry building in India as it contributes more than 75% of existing building stock and comes under the category of non-engineered building. Before retrofitting the performance of such building needed to be known.
- So a proper guideline for obtaining performance & than retrofitting of masonry building needed to be framed.

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