Reconnaissance report on the Mw 7.5 Hindu Kush earthquake of 26th October 2015 and the subsequent aftershocks

Technical Report

by

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Abstract

The M7.5 Hindu Kush earthquake of 26th October, 2015 caused widespread damage in Afghanistan and northern region of Pakistan. The earthquake resulted due to reverse faulting at an intermediate depth of 210 km within the northeast-trending tabular zone underneath the Hindu Kush region of Afghanistan. The damage was mostly concentrated in Khyber Pakhtunkhwa, Federally Administered Tribal Areas and Gilgit-Baltistan. Immediately after the earthquake, a team of United Arab Emirates University (UAEU) academics visited earthquake affected areas of Pakistan to perform reconnaissance, who were facilitated by local team of academics and students at the University of Engineering and Technology (UET) Peshawar.

This report presents a synopsis of observations made by the UAEU reconnaissance team on the 2015 Hindu Kush earthquake and subsequent aftershocks. The report provides details on seismotectonics, strong motion characteristics, and an overview of damage statistics obtained by interrogating database compiled by local disaster management authority. The building inventory of the earthquake affected areas was characterised into key building typologies and typical details of each of the building typology were discussed. Typical damage patterns and failure modes observed for each typology were discussed, and critical building deficiencies were identified. In general, the nature of damage was more severe than what could have been expected for an earthquake of such intensity. The observed damage was mostly concentrated in unreinforced rural buildings and old urban URM buildings, both being built with no or minimal consideration for earthquake loading and having been constructed employing poor construction practices. Typical damage patterns included complete or partial out of plane collapse of walls, collapse of roofs due to loss of seating, shear cracking in masonry walls/panels, damage in unreinforced masonry spandrels, cracking at masonry-frame interface, damage at corners of adobe buildings, pounding damage, and toppled URM Minarets.
Acknowledgement

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1 Introduction

On the afternoon of 26th October, 2015 the Hindu Kush earthquake was felt across South Asia, causing widespread damage in Afghanistan and Pakistan. The earthquake resulted from reverse faulting at an intermediate depth of 210 km in the Hindu Kush region of Afghanistan, with its epicentre located 45 km south-west of Jarm and about 67 km north-west of Chitral district in Pakistan. The earthquake was initially given a magnitude of 7.7, which was later revised to 7.5 by US Geological Survey (USGS) [1]. On the contrary, the Meteorological Department of Pakistan (PMD) reported a magnitude of 8.1 for the earthquake based on the records of their installed seismic instrumentation network [2]. As being typical for earthquakes of such medium depth, the earthquake was comparatively less damaging than the one of same magnitude but shallow focal depth and was felt as far as Nepal. The earthquake caused widespread damage to buildings, infrastructure, and human life in northern areas of Afghanistan and Pakistan. Office of the President of Afghanistan (ARG) in an official media release reported 115 fatalities and damage to 7679 buildings in nine different provinces [3]. In Pakistan, the damage was mostly concentrated in Gilgit-Baltistan (GB), Khyber Pakhtunkhwa (KPK) and Federally Administered Tribal Areas (FATA) . Of these, KPK and FATA represent are larger in size and population when compared to GB and were therefore focused in the study herein. KPK, formerly known as North West Frontier Province (NWFP), is located in the north-western region of Pakistan and borders with Afghanistan.

![Figure 1. The 2015 Hindu Kush earthquake and subsequent aftershocks: a). epicentre location, shaking intensity, recorded PGA, building population, and damage level; and b). aftershocks since 26th October until 20th December, 2015 with magnitude four and above.](image)
Figure 1a shows the location of epicentre, with felt intensity overlay and contours representing peak ground acceleration (PGA). The PGA contours were generated by using recorded strong motion data and attenuation relationships appropriately selected based on source mechanism, magnitude, geological and soil conditions. The building population of affected KPK districts and resulting damage level are shown with circles of varying size and colour, where the size represents the building population obtained from census data collected in 1998 [5] and the fill colour represents level of damage reported by the Provincial Disaster Management Authority of KPK [6]. A damage level colour coding was used to represent percentage of total building population damaged during the earthquake (%BD), where red colour denotes more than 10 %BD, orange colour denotes 5-10 %BD damaged, yellow colour denotes 1-5 %BD, and light green shows less than 1 %BD. A direct correlation between the damage level and distance from the epicentre was noted as well as the type of prevalent construction type. Figure 1b shows the location, magnitude and focal depth of these aftershocks. As per USGS a total of 59 aftershocks with a magnitude of 4 or more have been recorded until 26th December, 2015, of these the shallow M4.9 aftershock of 27th November 2015 with its epicentre located in northern Pakistan has been reported by KPK locals during interviews to cause some minor subsequent building damage in eastern region of the province. The most notable aftershock since the earthquake is the M6.3 aftershock of 26th December 2015 located 48 km south east of Jarm. The aftershock resulted in further building damage and injuries to more than 67 people. The earthquake sequence not only resulted in building damage but also resulted in several fatalities. An overview of reported building damage, fatalities and injuries directly resulting from the earthquake as of 20 December, 2015 (prior to 26th December aftershock) in different districts of KPK province is presented in Figure 2. It was noticed that the majority of fatalities and injuries were reported in hilly and comparatively under developed districts of Dir, Shangla, Chitral and Swat, having large population of vulnerable buildings.
2 Seismicity of the region

The Mountainous ranges of Himalaya, Karakoram, and Hindu Kush are amongst the most seismically active regions in the world. The high seismicity of the region is attributed to the convergence between the Eurasia and the India plates, with the latter slipping northwards underneath the first at a rate of 37-48 mm/year [7]. Numerous oblique strike slip and reverse faults exist in Hindu Kush and Pamirs region, which have resulted in moderate to severe and often to devastating earthquakes in the past [8]. Frequent mantle earthquakes (on average five Mw 5+ earthquakes per year) occurred due to remnant lithospheric subduction within the steeply dipping, northeast-trending tabular zone underneath the Hindu Kush region, which is 700 km long and extends nearly to 300 km depth [9]. Other notable past damaging earthquakes in this region include the M7.6 earthquake of 2002 centred 20 km towards the west of the 2015 earthquake, and the M7.4 earthquake of 1983 centred 8 km towards the south of the 2015 earthquake. Seismicity of northern Pakistan is attributed to north-western segment of Karakoram fault system, whereas southern Pakistan reflects a complex plate boundary where the India plate slides northward relative to the Eurasia plate in the east, and the Arabia plate subducts northward beneath the Eurasia plate in far south at a rate of 17mm/year [10]. Figure 3 shows the plate boundary and epicentre locations of all historic earthquakes with magnitude 6+ that had occurred in the region since 1900, with notable damaging earthquakes coloured red. The data of historic earthquakes was retrieved from ANSS Comprehensive Catalog (ComCat) [11]. The 2015 Hindu Kush earthquake was seventh earthquake of 6+ magnitude since 1970 to hit Pakistan, of these two notable recent earthquakes are 2013 Baluchistan earthquake (Mw 7.7) and 2005 Kashmir earthquake (Mw 7.6).

Figure 3. Historical earthquakes in the region
The 2013 Baluchistan earthquake resulted due to oblique strike slip type motion at shallow crustal depths (15 km) at the southern fault systems in Pakistan, with epicentre located 75 km from Awaran. The earthquake caused at least 825 fatalities and damage to numerous rural houses [10]. The 2005 Kashmir earthquake is believed to be the most devastating earthquake to occur in the history of Pakistan that had caused 86,000 fatalities and damage to some 600,000 buildings (including 6298 schools and 782 health facilities) [12, 13]. The earthquake occurred at a depth of 26 km and was therefore was classified as a shallow focus earthquake. The epicentre of the earthquake was located at 19 km northeast of Muzaffarabad, resulting a shaking intensity as high as IX-X on Modified Mercalli Intensity (MMI) scale in some densely populated areas such as Balakot and Muzaffarabad. Pakistan has also witnessed massive destruction in 1945 due to tsunami, a result of a M8.1 earthquake centred at 100 km south of Karachi in Arabian Sea. The earthquake and associated tsunami claimed 4000 lives [14].

3 Strong motion records

It is noted that numerous seismometers have been installed throughout Pakistan to record strong motion records (SMRs) but are of proprietary nature and were not made available to authors. The SMRs shown in Figure 4a from two seismometers installed at Nilore (NIL) were obtained from Incorporated Research Institutions for Seismology (IRIS) and key characteristics for 11 other stations shown in Figure 4b were retrieved from the USGS event page. The SMR imply that the earthquake resulted from slip on a north-trending reverse fault and resulting string motion lasted for about 50 seconds. The Hindu Kush-Pamirs region is laced with faults, of these several have orientation similar to the fault that caused the earthquake. However, due to uncertainties inherent in focal depth estimation the earthquake could not be associated to a specific mapped fault.

Figure 4. Strong motion records and seismometer locations
a). pseudo-acceleration response spectra ($\zeta = 5\%$)          
b). pseudo-velocity response spectrum

Figure 5. Response spectra for the recorded strong motion data

SMRs from NIL were analysed and used to calculate pseudo-spectral acceleration values to construct a response spectra for SMRs (see Figure 5a) along with the median and absolute maximum curve. In order to identify the linear segments of the response spectrum, corresponding to acceleration dominated and velocity dominated natural time period ranges, pseudo-velocity spectra was drawn for Nilore (see Figure 5b). It was observed that the response spectrum can be delineated into four main linear segments to cover the range of natural periods of interest i.e., up to 5s. Peak ground acceleration ($u_{go}$), peak ground velocity ($\dot{u}_{go}$), and spectral pseudo-acceleration values corresponding to 0.3s, 1.0s and 3.0s available from other stations, shown in Figure 4b with circles, are given in Table 1, along with their distance from the epicentre and name of the closest main city.

Table 1. PGA, PGV, and spectral acceleration values recorded at

<table>
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<tr>
<th>City name</th>
<th>$d_e$ (km)</th>
<th>$u_{go}$ (% g)</th>
<th>$\dot{u}_{go}$ (cm/s)</th>
<th>$u_{0.3}$ (% g)</th>
<th>$u_{1.0}$ (% g)</th>
<th>$u_{3.0}$ (% g)</th>
<th>$\alpha_a$</th>
<th>$\alpha_v$</th>
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<tr>
<td>Peshawar</td>
<td>338.8</td>
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<td>5.85</td>
<td>8.02</td>
<td>9.88</td>
<td>2.08</td>
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<td>9.74</td>
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<td>1.66</td>
<td>1.4</td>
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<tr>
<td>Wah Cantt</td>
<td>390.5</td>
<td>14.13</td>
<td>21.71</td>
<td>33.4</td>
<td>41.26</td>
<td>8.26</td>
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<tr>
<td>Abbotabad</td>
<td>392.6</td>
<td>11.01</td>
<td>16.22</td>
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<td>4.15</td>
<td>2.5</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Where $d_e$ = distance from epicenter; $u_{go}$ = peak ground acceleration; $\dot{u}_{go}$ = peak ground velocity; $u_{0.3}$ = spectral acceleration for 0.3s time period; $u_{1.0}$ = spectral acceleration for 1.0s time period; $u_{3.0}$ = spectral acceleration for 3.0s time period; $\alpha_a$ = amplification factor for acceleration dominated range; and $\alpha_v$ = amplification factor for velocity dominated range
4 Building inventory of earthquake affected region

KPK districts closer to the Afghanistan border are not particularly economically privileged and are comparatively under developed than other parts of central Pakistan. Figure 6 presents an overview of housing construction types in KPK province, which is based on the census data conducted in 1998 by Pakistan Consensus Organization [5]. It can be noted that almost 90% of the building population in KPK has been constructed without any reinforcement. Seismic vulnerability of the building stock proliferate due to the fact that the majority of rural buildings are poorly constructed using mud or a very weak cement based mortar, with exception of few government and outlier type good quality buildings. Given said that, the majority of rural buildings in the earthquake affected region of KPK can be considered extremely vulnerable to earthquake damage, being non-engineered and built with no considerations for seismic loading. Rural building population of KPK comprise of mostly single-storey high dwellings, which have been constructed by unskilled house owners themselves. The following main construction types are prevalent in KPK’s rural building stock, listed is the order of their prevalence in the region.

- Unreinforced earthen (Adobe)
- Unreinforced undressed stone masonry (USM)
- Unreinforced brick or concrete block masonry (URM)
- Confined masonry with either clay brick or concrete block (CON-URM)
- Timber laced masonry and Dajji Diwari (TLM)

Urban building population of the earthquake affected region is less vulnerable than the rural building stock and can be categorised into the following four main building typologies, also listed is the order of their prevalence in the region.

- URM buildings
- Reinforced cement concrete (RCC) buildings
- Steel frame (SF) buildings
- CON-URM buildings
5 Characterisation of building diaphragms

Based on the field observations and several years of authors’ experience, the diaphragms of buildings in the region were categorised into three main types. These types are cast in-situ rigid RC diaphragms (CIRD), prefabricated rigid RC diaphragms (PRERD), and non-engineered flexible mud-timber diaphragms (NEFD). CIRD vary in thickness from 100 to 150 mm and are reinforced with a single fabricated mesh of 12 mm diameter deformed steel bars placed at an on centre spacing of 200 mm in both ways placed near the tension face with a concrete cover of 20-40 mm. In rural areas, broken brick pieces are placed at certain intervals before pouring concrete (example shown in Figure 7a) to reduce construction cost. For longer spans and to span openings concealed and dropped RC beams are also used, which are casted in-situ monolithic with the diaphragm. On roof a 75-125 mm thick mud layer is used as insulating layer, which are overlain by brick tiles or any other type of floor finish. PRERD consist of precast RC slab panels with precast RC beams or steel beams (see Fig 7b). This type of diaphragm is prevalent in all non-engineered buildings but with no or minimal wall to diaphragm and wall to foundation connections. NEFD consist of dressed or undressed wooden joists pocketed into load bearing walls over which a 50-100 mm mud layer is placed (see Figure 7c). Pitched galvanised iron cladded timber or steel truss roofs (referred to as pitched roof hereafter) are also prevalent in areas with frequent snowfall, which represent a very small proportion of the building stock of the earthquake affected region. One of the alarming observation was the absence of a load path continuity. The absence of wall to diaphragm connection is one example of this critical structural weakness, with diaphragms simply resting on top of load bearing walls and only the dead weight resisting the outwards movement of walls from underneath the diaphragms.

6 Building typologies and associated damage patterns

In general, the majority of engineered or semi engineered buildings performed satisfactorily, with only minor repairable damage observed in these. The majority of earthquake damage in urban buildings was limited to old URM buildings, which had been minimally maintained and had no form of reinforcement. At a couple of instances, the roof collapsed due to loss of seating in few poorly constructed and ill-maintained old urban URM buildings. Other than that newer engineered buildings exhibited no signs of damage. In contrast, a large number of rural buildings partially or completely collapsed owing to these being built with no engineering consideration employing poor workmanship.

Figure 7. Photos of typical diaphragms; a) CIRD; b) PRERD; and c) NEFD
Figure 8. Typical observed failure modes in adobe buildings; a). reconstructed OOP collapsed boundary wall; b). corner damage; c). evidence of pier rocking; d). vertical spandrel flexural cracking; e). vertical crack in OOP wall; and f). OOP wall separation.

The majority of fatalities and injuries resulted due to collapse of unreinforced rural buildings and in particular due to damaged Adobe and USM buildings. Typical characteristics of each building typology and associated damage patterns observed during the building performance inspections undertaken following the earthquake are discussed in the following sections. The building typologies are discussed in ascending order of their observed seismic resistance i.e., the worst discussed first and the best discussed last.

6.1 Adobe buildings

Adobe is arguably the oldest and the most widely used natural building material, especially in developing countries [15]. It has been a material of choice for low income rural population of Pakistan due to its low cost, and better thermal performance but it is also extremely earthquake prone and vulnerable to collapse during an earthquake. Typical construction starts by making adobe bricks by sun drying moulded wet mix of farm soil and straw bale, which are then laid in mud mortar to create load bearing walls. NEFD are commonly used in adobe buildings, which rest on load bearing adobe walls without any positive load path continuity or anchorage. These single storey adobe houses usually have an isolated block of two square rooms (roughly 3 m × 3m in size), about 5 m × 5 m open yard, and a kitchen and toilet at the corner opposite to the rooms. Typical adobe wall thickness range from 200 to 600 mm, with these sitting in a very shallow trench without any foundation detail.

Typical damage patterns observed in adobe buildings are shown in Figure 8 and discussed in the order of their occurrence. Out-of-plane (OOP) collapse of boundary walls (see Figure 8a) and load bearing
walls was amongst the most frequent damages observed in the surveyed buildings, with the latter often resulting in partial or complete collapse of diaphragm/roof. A NEFD is used in this building typology, which is supported by only a small bearing on the load bearing Adobe walls. At several instances, it was evident that the diaphragm collapsed due to outward movement of the supporting wall. Observed also was extensive damage at buildings corners, which was attributed to lack of confinement at building corners. Spandrel damage in perforated in-plane loaded Adobe walls was observed at several instances, with vertical cracks initiating from opening corners and/or horizontal crack at the top end of piers (see Figures 8c and 8d). Other less frequent observed damage patterns include vertical cracks in walls (see Figure 8e), and separation of OOP walls from perpend in-plane walls (see Figure 8f).

6.2 USM buildings

A large population of single story high USM dwellings prevails in the northern region of Pakistan, where stone is readily available in abundance. A typical USM dwelling consists of two rooms at the rear end of the building and a 1.5 m wide veranda, kitchen, and bath room located at the front of the house. A flat NEFD and pitched roof are both used in USM buildings, where the latter is mainly used in areas located up on hills expecting frequent snowfalls. The load bearing USM walls of these buildings are constructed using mostly undressed stones irregularly laid in a cement-sand or mud mortar, with mud mortar being more common. Sometimes, horizontal wooden planks spaced at equal vertical intervals were also observed. The thickness of USM walls vary depending upon building location but generally range between 300mm to 600mm. USM walls are plastered with a 30-60mm thick mud plaster on both faces.

At numerous instances, examples of poor workmanship was also evident. In general, government USM buildings were built to much higher quality standards using cement-sand mortar when compared to private dwellings, which performed satisfactorily with minor damages observed. USM buildings are extremely vulnerable to collapse during an earthquake, which has previously been witnessed during the 2005 Kashmir earthquake when numerous USM buildings collapsed and resulted in thousands of fatalities [16].

Typical damage patterns observed in USM buildings (see Figure 9) included, OOP collapse of load bearing walls, OOP failure of gable ends, partial OOP collapse of rock fragments, cracks near and around openings in in-plane loaded walls and separation of OOP walls. The majority of rural USM buildings had suffered some form of structural damage, with the majority partially or completely collapsed. It was observed during building performance inspection surveys that poor workmanship, absence of load path continuity i.e., absence of wall to diaphragm anchorage, and extremely low strength of mortar used during construction had largely contributed to the large damage observed for this type of construction. USM buildings constructed of dressed stones and cement-based binder performed better than undressed USM, with these undergoing only localised minor OOP damage in gable ends and cracking in narrow piers.
Figure 9. Typical observed failure modes in USM buildings; a) roof collapse due to OOP wall failure; b) diagonally cracked USM wall at the verge of OOP collapse, which was possibly due to combined in-plane and out of plane loading; c) partially collapsed OOP wall still supporting roof; d) OOP failure of USM wall with intact pitched roof; e) localised OOP collapse of rock fragments; f) extensive in-plane diagonal shear cracks in squat USM wall; g) diagonal shear cracking in perforated USM wall; g) gable end damage in good quality USM buildings; and f) vertical crack due to differential ground settlement.

6.3 URM buildings

URM buildings are by far the most common typology in both urban and rural areas of Pakistan, which are typically one to three story high. Burnt clay bricks, being $75 \times 115 \times 225$ mm with a compressive strength of about 5-10 MPa, are laid following an English bond pattern using a cement-sand mortar with a volumetric mix ratio of 1:3. Thickness of load bearing URM walls is typically a multiple of one brick width (also referred to as wythe). Two wythe (220 mm) thick and three wythe (330 mm) thick URM walls are typically used for load bearing walls and one wythe thick URM walls are used as non-
structural partition walls. Typically, a 12-25 mm thick cement-sand (1:6) plaster is also applied over both faces of URM walls to create smooth surface for consecutive painting. The thickness of URM walls is doubled at its base in steps, with each step being one course high and half brick length wider than the step above. URM walls with this stepped detail are founded on a 50 mm thick layer of levelling concrete strip overlying compacted earth at a depth of 1-2 m below natural surface level. Urban and rural URM buildings were distinctly different in their structural form. As a general trend, CIRD was used in urban URM buildings and NEFD was the mostly adopted roof in rural URM buildings. As discussed earlier, damage in URM buildings was mainly observed in old URM buildings of significant age.

Figure 10. Performance of URM buildings; a). OOP collapsed URM boundary wall; b). extensive diagonal cracks through bricks in old URM college building located in Swat; c). spandrel shear cracking and pounding damage in old URM building with lime based mortar; d-f). spandrel damage and cracking around window openings in old URM buildings; g). OOP deflected wall in a rural URM building; h). veneer collapsed out of plane; and i). undamaged URM building with severely damaged USM part.
The newly constructed URM buildings had no visible structural damage and only had some localised plaster cracking and OOP failure of boundary walls (see Figure 10a). OOP collapse of solid load bearing URM walls was not observed in any of the inspected URM buildings. However, there were few examples where the bricks and masonry fragments fell over outwards from URM buildings, URM walls deflected OOP in isolated rural URM buildings (see Figure 10g). The absence of OOP failure mode in solid load bearing URM walls is partially attributed to the large thickness (being typically three to four wythe thick) used in old URM buildings and partially to arching effect resulting due to adhesion and friction at URM-concrete interface. Cavity URM construction is not very common in Pakistan, and if used then wall ties are installed typically. Out of several URM buildings visited as part of this reconnaissance only one example was identified where the outer veneer of the cavity URM wall collapsed outwards (see Figure 10h). The most frequent damage pattern observed was the diagonal shear cracking of spandrels and piers (see Figures 10c-10f), evidencing the rocking of piers in perforated URM walls. Vertical flexural cracks at corners of openings were also observed at some instances.

The old URM buildings were mainly located in densely populated older parts of Peshawar, where buildings were built next to each other without any gap left in between. Therefore, the buildings act as row of buildings and in some instances pounding damage was also observed when a URM building was situated next to new stiffer RCC building. As a general trend, URM mosques were built to higher quality standards utilising better quality materials and stronger cement rich mortar. While no or minimal damage was observed in the load bearing walls of URM mosques, at very few instances the Minarets were observed to undergo severe damage. Figures 11a and 11b show photos of a minaret damaged due to pounding with adjacent RCC building. In Figure 11c shown is a minaret of a mosque located in Swat. The top slender part of the minaret above the marked red line in the diagram was built using RC, which was rested on RC support beams. The support beams were tied into a band RC beam running all around and this beam was simply placed on top of URM columns without any load path continuity. The upper part slid sideways along the interface of the band beams and URM columns as one rigid body for some 50 mm but fortunately did not collapse. Should that minaret had collapsed, it could have resulted in sizeable collateral damage to the lower URM building.
6.4 UCM buildings

UCM building construction is a relatively new in Pakistan compared to URM and USM but is gaining wider acceptance in both urban and rural areas of Pakistan. UCM construction is perceived as more economical and faster than URM due to its bigger size and more uniform strength characteristics. In rural areas, low strength locally made solid concrete blocks are used, having a size of $150 \times 200 \times 300$ mm and a compressive strength of 5-8 MPa. UCM buildings are typically single story high in rural areas and up to two story and rarely three story high in urban areas. The concrete blocks are laid in staggered stack bond pattern using a cement-sand mortar, with typical volumetric mix ratio of 1:3 or 1:6 in urban areas and 1:8 in rural areas. The UCM walls were mostly not plastered, with fewer exceptions where a mud or cement-sand plaster was used to render both faces of the wall. UCM walls usually rest on roughly 600 mm wide RC strip foundation constructed using concrete with volumetric mix ratio of 1:2:4 (cement:sand:aggregate), with a layer of underlying lean concrete laid over compacted earth.

Typical damage patterns observed in rural UCM buildings built using mud were out of plane failure of walls, collapse of roof due to loss of seating, diagonal shear cracking, cracks near openings, corners failures, and vertical cracks in walls. UCM built using mud was quite common in Federally Administered Tribal Areas (FATA) however rural buildings built with a cement mortar performed better with no to minimal damage.

![Figure 12. Some examples of damaged rural UCM buildings: a). photo of a rural UCM house; b). example of out-of-plane failure; c). example of diagonal cracking; d). example of vertical cracking in piers, where blocks were not staggered; e). extensive in-plane damage to UCM wall; and f). example of vertical crack where blocks were not staggered.](image-url)
Figure 13. Photo of TLM building located in Peshawar

6.5 TLM buildings

TLM is similar to a local traditional timber construction type called Daji Diwari (DD). TLM has been rarely used in side walls of old buildings located in the older parts of Peshawar city, which consisted of vertical timber studs roughly spaced every 900 mm and equally spaced horizontal timber blockings creating box-like openings that had been in-filled with URM (see Figure 13a). Whilst DD has mostly been used in northern hilly areas of Pakistan (i.e., Chitral and Kashmir) where stone and timber both are locally available in abundance. The use of DD is not common in earthquake affected region of KPK, with Chitral being the only KPK district where this building typology prevail. A typical DD wall is constructed by first constructing diagonally braced timber frames on top of USM foundation, which are then in-filled with undressed stones laid in mud or cement-sand mortar as a binding material for acoustic and thermal insulation. Timber frames of DD are connected to the USM foundation using nuts and mechanical anchor bolts. The constructed DD walls are then plastered on both faces using mud mortar. Hand sawn timber floor boards resting over timber joists are used as floors and a pitched roof. Many DD buildings also have a flat NEFD. A recent experimental study [17] investigated seismic performance of DD buildings, which suggested that DD buildings are capable of sustaining substantially large earthquake forces. USM infill was observed to increase the energy dissipation capacity of the system but had minimal contribution towards the lateral load capacity of the structure. Authors did not visit the areas with DD building population but news reports and residents of that area suggest that DD buildings had generally performed well during the earthquake.

6.6 CON-URM Buildings

This building typology was prevalent in both urban and rural areas of Pakistan in relatively new one to three storey high buildings. Typically, a continuous minimally RC strip foundations running under all masonry walls are used in CON-URM buildings. Minimal reinforcement for confining vertical members stems from the same foundation strip and is left until the masonry walls are constructed around these. Masonry units (either concrete blocks or clay bricks) create teething at locations where confining vertical RC members would be built at a later stage. The left space is then minimally reinforced with deformed steels bars and concrete is casted in-situ using a concrete mix with volumetric ratio of 1:2:4 (cement:sand:aggregate) with no fixed w/c ratio that yield in a concrete compressive strength of 15-30 MPa. Afterwards RC horizontal confining elements (often referred to as band beams) and a CIRD are concurrently constructed. The same procedure is repeated for constructing upper storeys.
CON-URM buildings generally performed better than URM buildings, with no or minimal damage observed in any of these buildings. The damage was limited to few cracks at several instances. Photos of typical CON-URM buildings are shown in Figure 14.

6.7 RCC buildings

RCC construction has been used in buildings with four or more storeys for last few decades, with pre-1970 RCC buildings mainly relying on a RCC frame structure designed to take gravity loading only. The majority of these RCC buildings lack seismic detailing and can be categorised as earthquake-prone. The design and construction practices evolved over time and most of the recently constructed structures have been built with some form of earthquake resisting lateral load resisting system. The majority of RCC buildings in earthquake affected areas have been constructed after 1990, with these being mostly used to construct four and more story buildings in urban areas. Provision of shear walls is not common in buildings built prior to 2005, when the 2005 Kashmir earthquake resulted in damage to a large number of RCC frame buildings and major changes were adopted in response to lessons learnt in Pakistan Building Code [18] and overall in civil engineering practice. This can be marked as a major shift in RCC design and construction practices.

RCC building stock in earthquake affected areas can be categorised into three main types, being non-engineered, semi-engineered, and engineered. Non-engineered RCC buildings are mainly low-rise up to three story height and are typically construed relying on experience of non-qualified building practitioners. These buildings often contain design defects, and low quality of construction. Semi-engineered RCC buildings have some form of design calculations and minimal quality control, typically design drawings and specifications are developed but employing minimal engineering consideration. The buildings, often lack in seismic detailing and may contain some design/construction defects. The majority of pre-2005 RCC buildings also lies in this category because many high seismic risk regions were given a relatively lower seismic rating in Pakistan building code of that time [19]. The concrete compressive strength ranges from 20-35 MPa in non-engineered or semi engineered RCC buildings, with no or minimal quality control. Whilst engineered RCC construction is typically designed and supervised by qualified engineering professionals and mostly comply with international standards.
A typical under construction engineered RCC building with dual load resisting system is shown in Figure 15a, whereas a semi-engineered RCC frame building is shown in Figure 15b. In this section, the discussion is limited to non-engineered and semi-engineered RCC construction because engineered RCC construction does not follow specific trends and most of the times are unique in terms structural characteristics. Lateral load resisting system of these RCC buildings mainly consisted of RCC moment frames with non-structural brick masonry or concrete block masonry infill panels. In almost all RCC buildings, a CIRD has been used. Partition walls are one wythe (115 mm) thick URM or UCM walls with a thickness of 150-200 mm, without any anchorage with the diaphragms. The infill masonry panels in modern engineered RCC buildings are constructed by leaving a gap around the panel, with panel tied to column using mild steel plates bent casted with one end embedded in concrete column and straightened afterwards to align with bend joints in infill masonry panels. Deformed reinforcement steel bars are locally available in two main grades, being Grade 40 (with a nominally specified yield strength, $f_y = 275$ MPa) and Grade 60 (with $f_y = 415$ MPa). The Grade 40 steel bars are used in the construction of CIRD, whereas the Grade 60 steel bars are used to construct foundations and frame members. Typical story height in RCC buildings is 3.0 - 3.7 m. The foundation are designed to carry the anticipated loading and the use of isolated column footing with tie beams or a mat foundation both are common.

**Figure 15.** Photos of RCC buildings after the earthquake: a). under construction engineered RCC building; b). semi-engineered RCC frame building; c). infill-frame interface damage in non-engineered RCC building; d). infill-frame interface damage in semi-engineered RCC building; e). diagonal crack in perforated infill masonry wall; and f). damage at seismic joint location.
In low-rise RCC buildings, columns are often constructed to flush with infill masonry wall and therefore column width is often equal to the thickness of infill masonry panel, being 200 mm for UCM and 220 mm for URM. This results in a rectangular column, with typical column length of 400-600 mm. However, the majority of newly constructed buildings had square columns having a width of 375-600 mm. RCC beams are mostly rectangular in shape having a width of 200-400 mm and depth ranging from 300 to 600 mm.

The new RCC buildings with four and more storeys are mostly engineered and often consist of a dual lateral load resisting system, being seismically detailed RCC frame supplemented by RCC shear walls (dual). Amongst typical damage patterns were damage at infill masonry panel-column interface (Figure 15c and 15d) diagonal shear cracking in infilled masonry panels, diagonal cracks near opening corners when a perforated infill masonry panel was used (Figure 15e), minor diagonal shear cracks in the masonry infill panels, and with very few column failure examples. By far cracking at the interface of panel and surrounding frame was the most commonly observed damage pattern. At some instances, damage at seismic joint location was also observed in modern row type RCC buildings (see Figure 15f).

6.8 SF buildings

Steel construction is not very common in Pakistan and only few shed type industrial buildings were observed in mainly the industrial zones like Hattar. These buildings can be classed semi-engineered and typically have a galvanised iron sheet cladded roof, with sheets resting over purlins connected to hot rolled steel trusses or portal frames. Welded connections are common. These buildings are mostly single storey, with large spans and storey height. Typically, 1-1.5 m high reinforced concrete masonry walls resting on RCC foundation strip are built on exterior periphery with GI cladding in upper part of exterior walls. An interior view of a typical industrial steel building is shown in Figure 16. No damage has been reported or observed in steel buildings.

7 Concluding remarks

An overview of observations made on the 2015 Hindu Kush Earthquake and the subsequent aftershock series was presented, which includes an account of seismotectonics, strong motion characteristics, and the seismicity of the region. The resulting damaging effects on human life and building infrastructure
was quantitatively commented on by interrogating the statistical data collected as part of disaster management activities. To assess the performance of different types of buildings a reconnaissance was undertaken soon after the main earthquake. The survey was carried out in the majority of affected regions of KPK. It was observed that the majority of fatalities and injuries occurred primarily due to collapsed rural unreinforced single storey houses, constructed by local un-experienced masons using locally available materials such as stone, adobe, clay bricks and low strength concrete blocks. The large portion of the damaged houses, mostly constructed using rubble masonry laid in mud mortar, were situated on the slopes of mountains/hills at high altitude of the northern region of Pakistan accessible only by walk. It was observed during building performance inspections that despite of loss of lives and massive destruction of houses, the same material and construction techniques were being used by locals for reconstruction of houses because of winter arrival and economic condition of the locals. While the provincial and national disaster management authorities of Pakistan are very active in response and recovery efforts, there still are challenges to overcome resource challenges. A large campaign (door to door) needs to be initiated by local authorities to assess the houses of low income families, specially living in the hilly areas. A program to educate local building owners and non-qualified builders about low cost techniques for repairing/seismic improvement of existing vulnerable houses, and about basic seismic safety provisions for simple local type structures would also help reduce future risk of experiencing similar or perhaps more severe consequences that could result from a shallow earthquake in the region. The following are some key findings of the study.

• The perceived shaking intensity in Pakistan was reported to be moderate-strong based but the damage level observed was between strong to very strong, being much larger than expected for such instrumented shake intensity.

• Partial or complete collapse of buildings was mostly observed for non-engineered rural building stock and in some cases in old urban URM buildings.

• The findings from interrogation of damage statistics, damage assessment surveys, and interviews with building practitioners and occupants of earthquake damaged houses suggested that the majority of the detrimental effects on human life and building infrastructure were associated to partial or complete collapse of vulnerable buildings.

• At several instances, building components were at the verge of collapse or were extensively damaged suggesting substantially reduced residual strength thus posing significant seismic hazard to their occupants and/or users. The local building control authorities may consider earthquake had no tagging restriction on use by as earthquake/aftershock of same magnitude is expected to occur in the nearby future and may collapse these buildings.

• The semi-engineered (confined masonry) performed satisfactorily compared to completely unreinforced building stock. Authors believe that more research is warranted to develop seismic resistant details suitable for local use, considering the socio-economic situation of the areas.

• One of the key observations on masonry infilled RCC framed buildings was the frequently noticed damage at the interface of infills and surrounding frame. At several other instances shear damage in non-structural masonry infills was also observed. A substantial amount of research
has be undertaken on minimising such damage and inclusion of such literature in civil engineering curricula would be advantageous.

- The damage statistics shows that a large number of remotely located schools have also been damaged, with extent of damage not known to authors. If the damage is of structural nature and then the residual strength of these buildings may have been compromised. These school buildings should be assessed as priority by competent engineers and should the need arise restriction on their use be enforced. Attempts should be made at government level to evaluate these buildings in detail to identify risk of future collapse.

- Finally, Authors believe that there is a need of more collaboration between local and as well as international stake holders i.e. practicing engineers, academics, and other involved in studying and reporting earthquakes. Even though a large number of seismometers have been installed as part of Pakistan, yet recorded data is not made available to wider community of engineers and academic for further analysis and research.

8 References


3. ARG. 115 killed, 538 injured; 7,630 homes, 12 schools, 17 mosques, 20 office buildings have been damaged in 9 provinces. 2015 [cited 2015 27 October]; Available from: www.president.gov.af.


