Structural Safety of Masonry Infills in Reinforced Concrete Buildings: A Case Study of Community Housing Resettlement Project in Dhading

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Abstract

Reinforced concrete (RC) frame buildings with unreinforced masonry (URM) infill walls are practised worldwide. Masonry infills in such frame structures can suffer damage in both in-plane (IP) and out-of-plane (OOP) direction during an earthquake and OOP collapse of infill walls is a big problem even in buildings designed to resist earthquake forces. To prevent OOP failure of such walls, design codes recommend some measures. However, they are found to be not adopted during construction due to practical difficulties. The aim of the paper is to highlight the issues of structural safety of masonry infills and provide practical strategies to achieve code recommendation to maintain OOP stability of infill wall. Besides, the paper discusses typical technical challenges during the construction of RC buildings, especially in connection to a reconstruction works after a major earthquake. For this, a case study of the community housing resettlement project in Dhola- Dhading, built for 55 families displaced by the 25th April 2015 Gorkha, Nepal earthquake, has been presented. Methodology of study comprised with review of literatures, analysis of data related to the project, investigation of construction sites and unstructured interviews with the concerned stakeholders. The paper shares the experiences of reconstruction which can be important to help increase construction quality of RC buildings considering the fact that such buildings are trending in Nepal. The recommendations can be useful to reduce human casualties and economic losses in case of future earthquakes.

Keywords: *Reinforced concrete buildings, Unreinforced Masonry infill, Earthquake, In-Plane failure, Out-of-Plane failure*

1. Introduction

Building with reinforced concrete (RC) frames are used all over the word and are also popular form of construction in Nepal. In these types of buildings, unreinforced masonry (URM) are used to construct infill walls. The performance of such buildings during an earthquake are dependent on performance of masonry infills and is largely dependent on the arrangement of the masonry infills. Presence of regularly distributed infills can contribute to their strength and stiffness and on the contrary, irregular arrangement of infills either in plan or elevation can have adverse effects. Post-earthquake damage surveys after 2009 L'Aquila, Italy earthquake (Ricci et al. 2011), 2011 Lorca, Spain earthquake (De Luca et al. 2014), have revealed failure of such structures related to the failure of infill wall and was also observed in 25th April 2015 Gorkha, Nepal earthquake (Hermanns et al. 2014, Gautam and Chaulagain 2016, Barbosa et al. 2017,

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Varum et al. 2017, Bhagat et al. 2018). A report published by the Government of Nepal estimated that about 6,613 RC frame buildings collapsed and about 16,971 were damaged due to the sequence of Gorkha earthquake (NPC 2015). However, most of the collapsed structures were non-engineered or built by following prescriptive design guidelines like NBC 201 (1994a) and NBC 205 (1994b), also known as mandatory rules of thumb (MRT) in Nepal. New RC buildings (low-rise to medium-rise), primarily with moment-resisting frame structures for residential, commercial and institutional uses (government offices, hospitals or university buildings), and some medium to high-rise (10 to 20 stories) apartment buildings in Kathmandu valley, suffered minimum structural damage but showed significant non-structural damage related to infills.

Masonry infills are intended to be non-structural, but since they are built in contact with the RC frame, they significantly affect the structural earthquake response of the infilled frames and ultimately the whole building. Past researches especially in-plane (IP) behaviour of infill walls, have established how they influence strength and stiffness of the infilled frame and how they can be the cause of brittle shear failures of the columns, which can lead to partial or total collapse of buildings during earthquakes. Considering this, seismic design criteria for safety of infilled frames have been recommended in design codes and guidelines (e.g. FEMA 306, NBC 201, CEN 2004). However, during earthquakes, infill walls are subjected to simultaneous IP and OOP loads, in which large inter-storey drifts are expected at lower stories while higher inertia forces are expected at the upper stories. This leads to failure of infills in both IP and OOP direction. Particularly, OOP collapse of infills is observed in the bottom to mid storeys and is a big problem even for buildings designed to withstand earthquake forces. It was also observed in Gorkha, Nepal earthquake and have been reported in some articles (e.g. Hermanns et al. 2014, Barbosa et al. 2017, Varum et al. 2017). Therefore, safety against the OOP failure of masonry infills which can result in human casualties (or death) and economic losses, is a huge concern for researchers.

Research on OOP behaviour of infill walls is still very limited. Studies have shown that masonry can have adequate lateral strength against OOP loads due to resistance derived from arching action (Dawe and Seah 1989, Angel 1994, Flanagan and Bennett 1999a, Furtado et al. 2016). But OOP resistance of infill wall can be influenced by several factors like boundary condition (Di Domenico et al. 2018, Butenweg et al. 2019), slenderness ratio (Flanagan and Bennett 1999a, Ricci et al. 2018, Koutas and Bournas 2019), aspect ratio (Varela-Rivera et al. 2012a, Moreno-Herera et al. 2016), openings (Dawe and Seah 1989, Akhoundi et al. 2016), gravity load (Varela-Rivera et al. 2012b, Furtado et al. 2016), IP damage (Angel 1994, Calvi and Bolognini 2001, Hak et al. 2014, Ricci et al. 2018) to name few. Analytical models have been proposed to estimate the OOP capacity of the URM infill walls (e.g. Dawe and Seah 1989, Angel 1994, Bashandy et al. 1995, Flanagan and Bennett 1999b) and some of them have been adopted by the design guidelines (e.g. FEMA 356). But reliability of analytical models is still an open question. Numerical modelling techniques to account for OOP behaviour of infill wall are in initial stages of development (Hashemi and Mosalam 2007, Mohyeddin et al. 2013, Furtado et al. 2015, Di Trapani et al. 2018, Anić et al. 2019, Nasiri and Liu 2019, Cavaleri et al. 2019). Besides, to reduce the OOP vulnerability seen in existing masonry infills, research are being conducted to replace them by new masonry infill systems (e.g. Petrus et al. 2015, Preti et al. 2015, Silva et al. 2016, Verlato et al. 2016, Vailati et al. 2017). However, they are not yet ready to be used in practise.

At this stage, there are no more than limited provisions set up by the design codes and guidelines to maintain OOP stability of URM masonry infill walls. There are recommendations from limiting the slenderness ratio of the infills to making RC bands (CEN 2004, FEMA 356, NBC 201). However, there are practical challenges in tying RC bands in infill wall with the columns. Following the devastating earthquake of 2015, the trend of constructing RC frame buildings have increased in Nepal. Inspection of some construction sites have revealed that the RC bands are not constructed properly. Additionally, there are other technical challenges for workers to construct RC buildings with seismic resistant features, especially in rural areas of Nepal where skilled manpower are in shortage (Sharma et al. 2018). The aim of the paper is to highlight the issue of the structural safety of masonry infills in new RC buildings and alongside present some technical challenges during the construction of RC buildings. A case study of community housing resettlement project in Dhola, Dhading where RC frame buildings were built for 55 families displaced by 25th April 2015 Gorkha, Nepal earthquake, has been presented to discuss on these challenges.

2. Methodology

The paper has been prepared based on review of available literatures in masonry infills. Design data and construction details of the project and visit of other similar constructions aid to develop the paper. Unstructured queries made with the engineers, contractors, masons and house owners further helps to understand the state of practise in RC constructions.

3. Description of the resettlement project

25th April 2015 Gokha, Nepal earthquake displaced a community of people making them homeless after their houses were completely destroyed. New buildings with masonry infilled RC frame technology were planned, designed and constructed for 55 families as a part of resettlement project in Dhola-7, Dhading. The project site was remotely connected to Dhading Besi, headquarter of Dhading district. The project was driven by the urgent need to provide shelter to the displaced community.

A sample of a house planned for the people affected by the earthquake is shown in Fig 1. It is a two storey residential building. This size of the building was planned for two families. Each family would have two rooms in the ground floor and two rooms in the top floor. Two houses otherwise would be separate, were joined together to minimise the cost of construction by sharing wall, footing and frame elements. In case of single family house wherever necessary (due to odd number of families, shape of land), half the size of this plan with two rooms at bottom and top floors and with the same design, were built separately. Most of the houses constructed belonged to first category planned for two families.

The overall height of the buildings to the top of the roof is 20 feet. Height of the ground floor is 9 feet. The building is covered with a double sloped lightweight roof. CGI sheets were used as a roof cover. The primary width of the building is 13.5 ft. and length is 44 ft (Fig 2). The building is regular in plan and elevation. Buildings were designed as Moment Resisting RC Frame structures. RC slab (100 mm thick) was provided in the ground floor while on the first floor there was no RC slab but only ring beams to tie the columns together (Fig 3).

a) Planned view   b) Constructed at site

Fig 1. 3D view of building

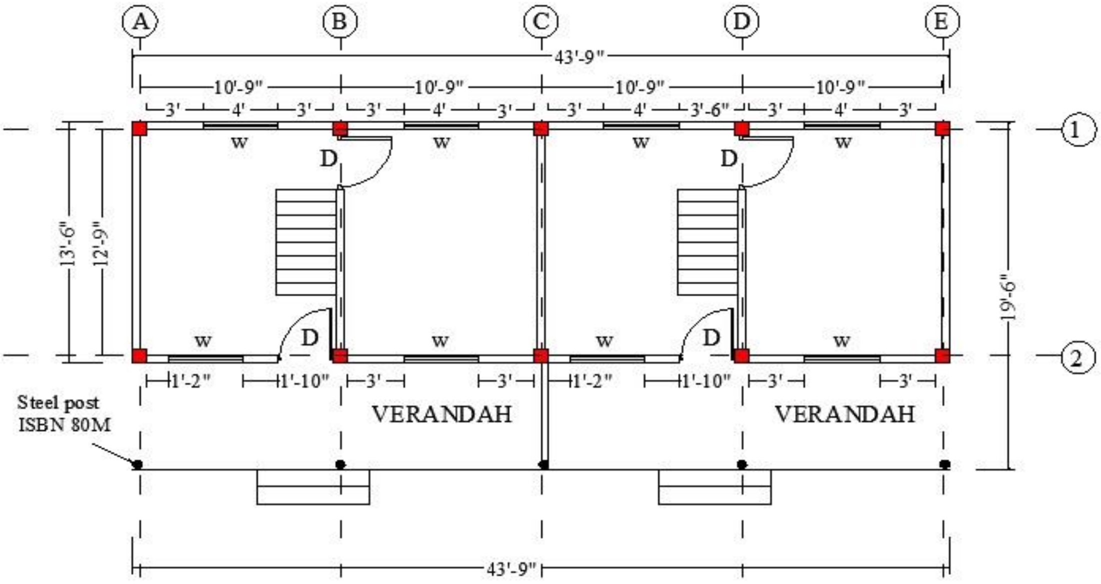

Fig 2. Ground Floor plan for building (dimension in feet-inch)

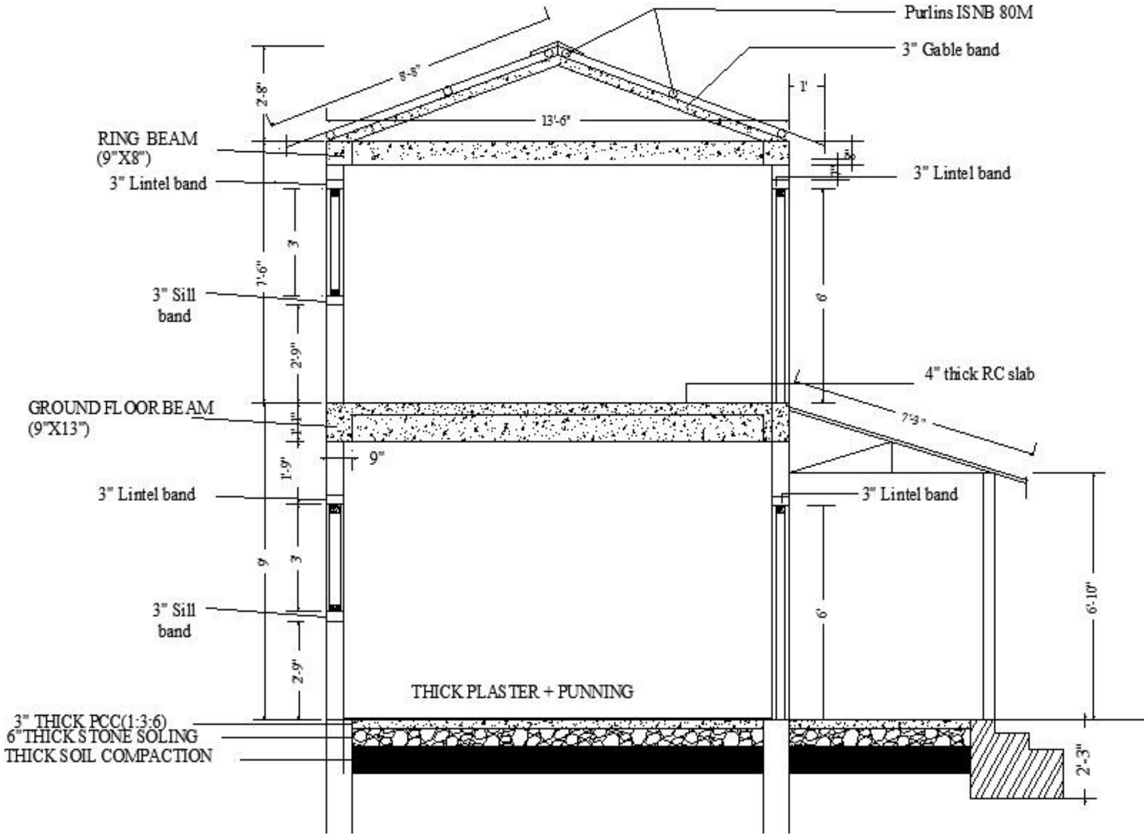

Fig 3. Sectional view of the planned building

Buildings were designed with a strong column-weak beam philosophy following the Nepal Building code (NBC 105) as well as Indian standard, IS 19893 (BIS 2002). The seismic zone considered for the design was zone V as per IS 1893 (BIS 2002) Tie beams were provided in the foundation and near the ground level. The tie beam provided was of size 230 mm x 230mm and three 12 mm bars were provided at the top and bottom as longitudinal reinforcement while 8 mm stirrups were provided at 150 mm c/c as transverse reinforcement. Square columns of size 300 mm x 300mm were used in all buildings and each columns had four 16 mm rebar and four 12 mm rebar as longitudinal reinforcement and 4-legged 8mm ties placed at spacing of 100 mm c/c as transverse reinforcement. Beams in ground floor had a width of 230 mm and depth of 330 mm. Longitudinal reinforcements for ground floor beams were composed of two 16 mm bars and one 12 mm bar, and 2-legged 8mm stirrups were provided as transverse reinforcements. The ring beam used in the first floor was 230 mm wide and 200 mm deep and three 12 mm bars were provided at top and bottom. Light tubular steel sections were provided to support the roof. M20 concrete and FE 500 (TMT) reinforcement bars with yield strength of 500 MPa were used.

Infill walls were distributed regularly in plan and in elevation. Masonry infills were built with solid clay brick with mortar made of cement and sand in the ratio of 1:4. The thickness of all external and internal infill walls was kept 115 mm (width of brick) which is smaller than recommended by Nepal building code (NBC 201) in case of external wall, which will be discussed in the following section. This was necessary in order to reduce the cost of each building. Plaster with cement sand ratio 1:4 was applied only on interior faces of infill walls. Buildings were not plastered from outside to minimise the cost of construction (Fig 1). RC bands of 75 mm thickness were recommended in design drawings at the level of sill and lintel of windows, to reduce OOP vulnerability of the slender (slenderness ratio of about 21) infill walls. RC bands were constructed although the community people were highly reluctant to the idea because of the technical difficulties associated with it and also due to the delay that it could create in constructing infill walls. People were living in the temporary shelter for long and they wanted to shift to new buildings as soon as possible. The project was therefore more need based and driven by the economic aspects rather than technical aspects and safety requirement.

3.1 Challenges during the construction of RC buildings with masonry infills

Constructions were done by utilising the manpower only from the community people for whom the buildings were being constructed, to lower the cost of construction. It was itself a big challenge for the consulting engineers. There were only few skilled workers available and they lacked many technical knowledge required for building a house. Many men and women who had very basic skills of construction were trained at the site. In the beginning, construction of one building was started so that those who had minimal idea could learn by observation and skills of the semi-skilled workers could be improved. The idea was replicated and eventually, the process was scaled up to construct other buildings of the community. This was crucial for the timely completion of all houses. Construction of the houses were completed in almost one and half year from the date of start. There were so many technical challenges during the reconstruction phase and some of them are highlighted below:

1. Levelling off the ground level and foundation pits (due to lack of mechanical tools)
2. Bar bending and making of stirrups
3. Executing reinforcement details in the beam column joint
4. Controlling quality of concrete mix (maintaining ratio of aggregates and water content)
5. Concrete casting in column (e.g. vibration and compaction issues)
6. Construction of RC bands

All these areas required special attention from supervising engineer. These problems were solved systematically during the construction period with the guidance from civil site engineer and by the instruction of structural engineers. Many of the above technical issues are often discussed in different forums. But rarely the problem in construction of RC bands and their connection with the columns gets the attention. Although it is common problem, it is special one and has been discussed in detail in this paper. RC bands are simple structural element, but their role for safety of the masonry infills is big and is therefore advised by the building codes to prevent their OOP failure. Though it might look simple to construct these elements, there are many things to consider. Several complexities have to be addressed to avoid any damage to the columns. The practical difficulties associated with the construction of RC bands way and the possible ways to address them have been discussed in the following section.

4. Current provisions in design codes and their practical challenges

Eurocode 8 (CEN 2004) recommends to restrict the slenderness ratio (height /thickness) of infill wall to 15 and in the cases with higher slenderness, special measures to prevent OOP collapse should be taken such as: application of light wire meshes well anchored on one face of the wall, wall ties tied to columns, concrete posts and belts across the panels. Similarly, US Federal recommendation FEMA 356 (2000) has the provision of calculation of OOP capacity and also the mid-height OOP deflection. Besides, it recommends to limit slenderness ratio to less than 10 in high seismic zones, for OOP collapse prevention of infill wall.

Nepal building code, NBC 201 (1994b) recommends minimum thickness of 115 mm for interior infill walls and 230 mm for exterior infill walls. Additionally, it suggests to provide horizontal RC bands of thickness 75 mm and width equal to thickness of wall shall on all infill walls - one at window-sill level, and the other at lintel-level, to reduce the OOP falling hazard. The RC band should be connected with the columns. The details of RC band as per NBC 201 (1994b) is shown in Fig. 4.

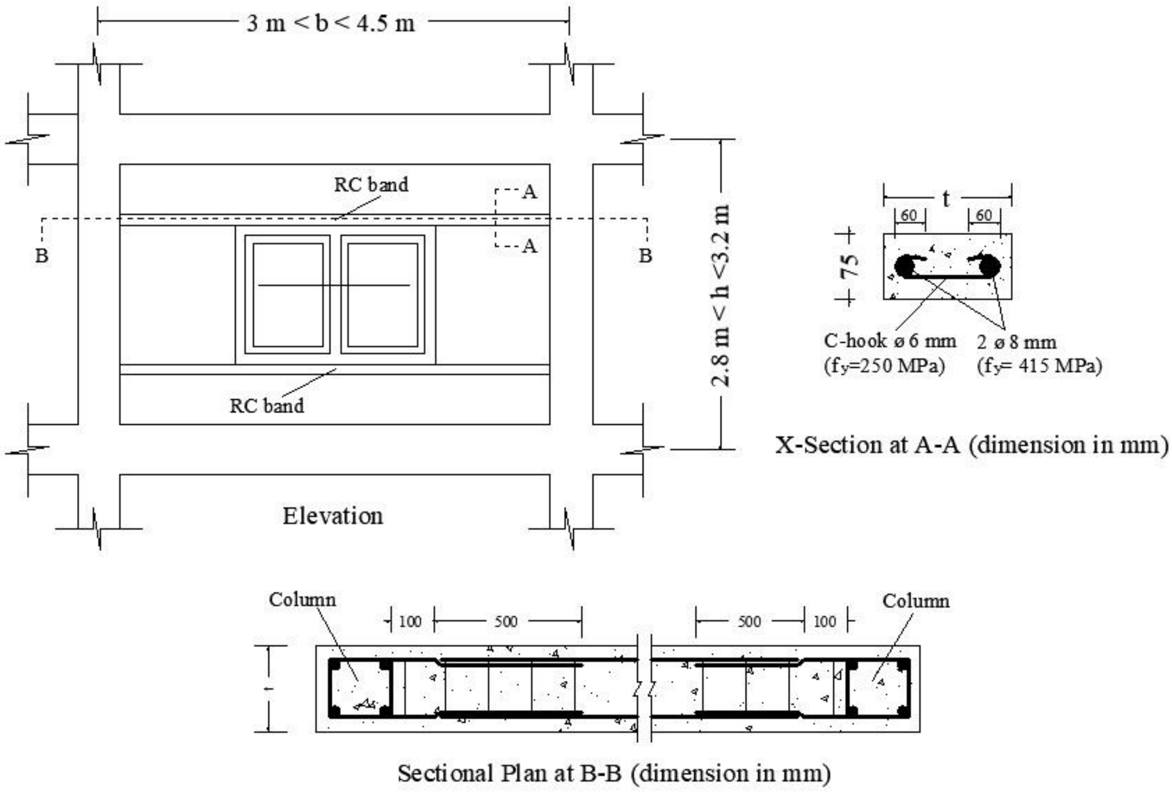

Fig 4. Detail of RC bands at lintel and sill level for infill wall (NBC 201, 1994b)

To construct such RC bands as shown in the above figure, is a big challenge for the construction workers. The main difficulty is in the connection of the RC bands with the columns. Infill walls are built after the frame is constructed. So, if the RC bands are to be connected to the columns, the extra anchor reinforcement has to be pre-inserted and fixed inside the columns at the level of RC bands, before casting the concrete. The code do not recommend any techniques to follow.

However, few approaches can be adopted. The difficulties and precautions to be taken with these approaches are described below:

a. Method 1: Two holes have to be drilled on the face of formwork from where the anchor bars can come out to the side where the RC band is necessary to be constructed. These two anchor reinforcements coming out from the holes can be later lapped with the longitudinal reinforcement of the RC bands. But this is not practical from several aspects. Firstly, these holes have to be carefully located so that there is no effect with any change in the position of the sill and lintel level. Secondly, drilling holes in the formwork needs other precautions during the concrete casting to avoid leakage of the cement sand slurry from the formwork. Also, applying vibration needle and compacting during concreting becomes a problem and they can have adverse effect on the quality of concrete.
b. Method 2: Reinforcement bars can be anchored to column directly by drilling to depth required for bonding. The bar should be grouted by epoxy based adhesive for significant strength. This method requires careful technical monitoring to not damage the column and also it adds extra cost to the construction.
c. Method 3: Alternative way of putting extra anchorage rebar inside the concrete column is shown in Fig 5. With this idea, U shaped rebar of required length is attached with the stirrups of the columns in such a way that the outer leg touches the inner face of the formwork. The concrete is casted as usual. After the removal of formwork, face of column where the U-bar sits, is scratched slowly and concrete is removed carefully. When the concrete gains strength, outer leg of U-bar is then stretched outside in right angle to the inner leg and is connected to the longitudinal reinforcement of the lintel or sill band. This method is also very sensitive. There are chances that the column strength is compromised. Especially while removing concrete, scour depth has to be controlled. This is a portion of the concrete cover in column and has important role. Later, removed concrete should be replaced by concrete of similar or higher strength and made with small sized aggregates. The replaced concrete is not like the original concrete, compaction of concrete is difficult to achieve, due care is necessary.

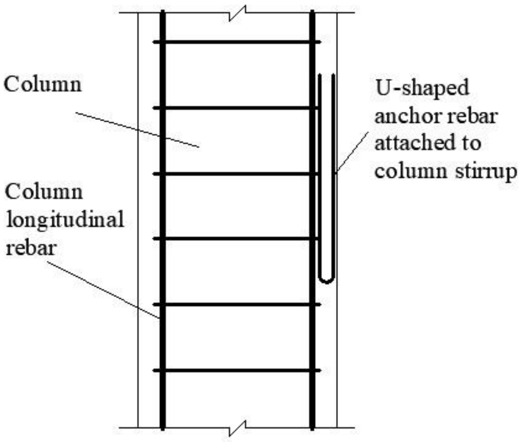

Fig 5. Arrangement of anchor rebar for RC band

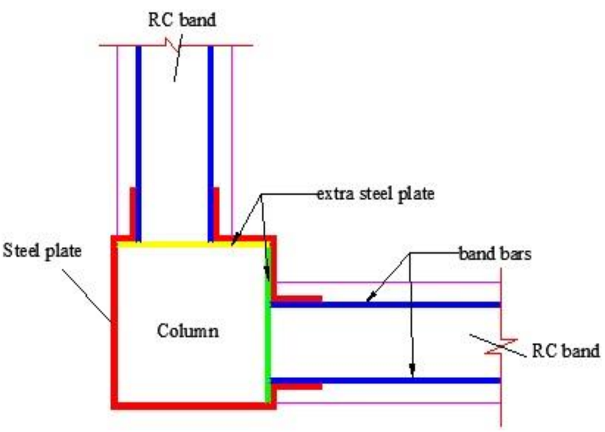

Fig 6. Steel plate as an anchor for RC band

As an alternative to the code idea, columns can be wrapped by steel plate of small width (e.g. 50 mm) and thickness (e.g. 5 mm) as shown in Fig 6. Steel plates is then welded to the reinforcement of the RC bands. Later, steel plate can be covered by high strength plaster. This technique is quite simple and there is no danger of any damage to columns. Reliability of this method is a question, considering that the welding between the steel plates and with the reinforcement of RC bands can be damaged by the cyclic nature of the earthquake loads. Nevertheless, infill wall will have higher OOP strength than when RC band is not connected with columns. It can be subject of future research.

Among these alternatives, Method 3 was adopted in the resettlement project in Dhola, Dhading. This approach was selected as it was comparatively easy, economical and applicable from different considerations. RC bands were installed in a way to have minimum impact on the columns.

5. Construction practise of RC bands in Nepal

Inspection of the construction sites in different areas of Nepal have showed different practises in construction of RC horizontal bands in masonry infill. Unstructured queries with the house owners, contractors, masons and engineers have revealed three different conditions: no band, bands but not connected to frame and bands connected to the frame.

1. No band – Some buildings were constructed without the RC bands in infill wall. House owners had no idea why the contractors have not built them. Few contractors defended saying that it delays their work. When RC bands have to be constructed, it requires to follow step-wise construction of infill-band-infill-band-infill. This takes extra time in comparison to constructing the infill wall without bands.

2. Bands but not connected to frame – Many houses were found to have RC bands at two levels i.e. sill and lintel, but they were not connected to the columns. Many contractors, masons and even engineers find practically difficult to connect the bands with columns.

3. Bands connected to frame – In some houses, RC bands were found to be connected to columns by following Method 3 as described earlier, by inserting U shaped rebar. In few cases, it was also observed that the removed concrete portion was later patched over by normal plaster instead of concrete.

   In many houses, RC bands were connected to the column partially by drilling the column to about 2 inch depth. Reinforcement of the bands were inserted to that depth and grouted by normal cement sand mix. Although these type of RC bands can be effective in IP load of earthquake to control diagonal cracking of infill wall, they have small contribution in OOP strength. This technique can be improved by the use of epoxy based grouting material as described in method 2 of previous section.

Based on the investigation of several new infilled frame RC building constructions, it can be understood that infill walls are still constructed without RC bands or without their proper connections to the frame. This makes infills in new RC houses vulnerable to OOP failure during the future earthquake. On one hand, it can be detrimental to the structural performance of whole building and on the other hand, failure of infill alone can result severe human casualties and economic losses.

6. Conclusions and Recommendations

RC buildings are popular form of construction and URM infill walls are important structural elements of such RC frame structures. Such infill walls are highly vulnerable during an earthquake. OOP failure of masonry infills is a big problem even for buildings designed to resist earthquake forces. However, there are still very limited provisions in the seismic design codes to prevent the OOP failure of masonry infill walls.

The trend of constructing RC buildings with URM infills have increased after 25th April 2015 Gorkha, Nepal earthquake. However, in many new RC constructions, code recommendation to provide horizontal RC bands in the infills, are not provided properly. This presents possibilities for OOP failure of such infill walls in future earthquake resulting in higher human casualties and economic losses.

There are many technical challenges in the construction of seismic resistant RC buildings, especially related to reinforcement detailing and one common challenge is the construction of RC bands in infill wall. In many cases, there are possibilities that they are being constructed by the non-trained workers. House owners need to be careful while assigning the job to local contractors. Construction of RC buildings has to be monitored possibly by an experienced civil/structural engineer.

New constructions are growing and so is the demand for the construction workers which will be even truer in case of reconstruction after a major disaster like earthquake. In this sense, 25th April 2015 Gorkha earthquake has become an opportunity for Nepal to prepare technical manpower required for future construction works. For quality works, construction workers are necessary to be frequently trained with new construction techniques and on uses of materials and tools. Systematic approach in handling the available manpower is a key for the timely completion of the reconstruction project.

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