

## NON-DUCTILE RC FRAMES AND ALTERNATIVE IMPROVED CONSTRUCTION TECHNOLOGIES

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### ABSTRACT :

This paper provides an overview of the challenges related to the design and construction of reinforced concrete (RC) frame buildings in areas of high seismic risk, and discusses alternative improved construction technologies and related educational initiatives. RC frame construction is frequently used in regions of high seismic risk across the world. Recent earthquakes have revealed major seismic deficiencies in these buildings, some of which led to catastrophic collapses and significant death tolls. Causes for the unsatisfactory performance include the absence of special seismic detailing of key structural elements, inadequate material and construction quality, and/or inadequate design. The problem is aggravated further by the use of unreinforced masonry infill walls that significantly affect the way in which the building responds to earthquake ground shaking. The authors propose two alternative building technologies characterized by a higher level of seismic safety at a comparable cost and construction complexity. One alternative is to provide RC shear walls continuously along the building height at several strategic locations; this will result in an increased stiffness and lateral drift control. Another alternative is to use confined masonry construction, in which lateral load resistance relies on masonry walls “confined” by horizontal and vertical RC elements. Confined masonry construction requires a lower level of design expertise and construction skills. Recent international initiatives focused on educating both technical and non-technical audiences on the challenges associated with seismic performance of RC frame construction and alternative building technologies are also discussed in the paper.

### KEYWORDS:

Reinforced concrete, nonductile, frame with infill, confined masonry, earthquake risk mitigation, education

## 1. INTRODUCTION

The use of reinforced concrete (RC) construction in the modern world stems from the wide availability of its ingredients - reinforcing steel as well as concrete. The most common type of RC construction for housing is in the form of cast in-situ frames with concrete floor and roof systems. These three-dimensional RC frames are made functional for habitation by building walls called *infill walls*. These walls are built after the concrete frame construction has been completed; reinforcement and anchorage to the adjacent frame elements (beams and columns) is usually not provided. The infills can be constructed by using a variety of masonry units: clay bricks or hollow clay tiles, hollow or solid concrete blocks, etc.

With increasing urbanization, RC frame construction has been widely used for multi-family housing in both the developing and industrialized countries. RC frame construction comprises approximately 75% of the building stock in Turkey, about 80% in Mexico, and over 30% in Greece (Yakut, 2004). Design applications range from single-family dwellings in countries like Algeria and Colombia, to high-rise apartment buildings in Chile, Canada, Mexico, Turkey, India, and China. Detailed reports on RC frame construction practices in these countries are available in the World Housing Encyclopedia (WHE) (EERI/IAEE 2000).

RC frame construction is frequently used in regions of high seismic risk, such as Latin America, southern Europe, North Africa, Middle East and Southeast Asia. Recent earthquakes across the world, including the 1999 Izmit and Duzce earthquakes in Turkey, the 2001 Bhuj earthquake in India, the 2001 Chi Chi earthquake in Taiwan, the 2003 Boumerdes earthquake in Algeria, and the recent 2008 Sichuan, China earthquake revealed major seismic deficiencies in these buildings, some of which led to catastrophic collapses causing death tolls measured in thousands.

Causes for the unsatisfactory performance lie in the absence of special seismic detailing of key structural elements, inadequate material quality, absence of construction supervision, and/or inadequate design by architects and engineers without formal training in seismic design. The problem is aggravated further by the use of unreinforced masonry infill walls. In usual design practice, the effect of infills is not accounted for. But, these walls significantly affect the way in which the building responds to earthquake ground shaking and may cause significant torsional effects.

## 2. CHALLENGES

Special care is required to understand the challenges that earthquakes pose and to ensure that appropriate features are incorporated in the architectural and structural design and construction of RC frame buildings. This paper discusses the challenges and proposes alternative technologies that provide higher level of seismic safety at a comparable cost and construction safety. The material presented herein draws from the tutorial titled *At Risk: The Seismic Performance of Reinforced Concrete Frame Buildings with Masonry Infill Walls* published by the EERI (Murty et al. 2006).

The primary challenges in RC frame construction in seismic areas are to ensure:

- (a) that the beams are weaker than columns,
- (b) that the rebars in the beam-column joints allow proper concrete placement in the joint region,
- (c) that the beams are ductile, through the proper rebar detailing, and
- (d) that the frame is not too weak or too flexible in the horizontal direction, either in any one story or in the whole.

It is not easy to achieve ductile behavior in RC frame buildings - special seismic detailing requires an advanced level of construction skills and quality control. Inadequately reinforced beam-column joints pose a serious threat to basic frame behavior and can lead to devastating consequences, including the total building collapse. In general, achieving satisfactory seismic performance of RC frame buildings subjected to several cycles of

earthquake ground shaking can be a challenge even in highly industrialized countries with advanced construction technology.

### 3. ALTERNATIVE BUILDING TECHNOLOGIES

When special attention cannot be paid to design, detailing and construction, RC frames alone should not be used to resist lateral loads. There are at least two alternative lateral load resisting systems which are expected to ensure a higher level of seismic safety than the non-ductile RC frame building system with masonry infills; these are confined masonry and RC frames with shear walls. The former system is intended for low-rise construction, while the latter can be used for a wide range of building heights, however it is most economically feasible for medium- to high-rise construction.

#### 3.1. Confined Masonry Construction

Over the last 100 years, confined masonry construction has emerged as a building technology that offers an alternative to both unreinforced masonry and RC frame construction. In fact, confined masonry has features of both these technologies. Confined masonry construction consists of masonry walls (made either of clay bricks or concrete block units) and horizontal and vertical RC confining members built on all four sides of a masonry wall panel. Vertical members, called *tie-columns*, resemble columns in RC frame construction except that they tend to be of far smaller cross-sections. Horizontal elements, called *tie-beams*, resemble beams in RC frame construction. In worldwide applications, confined masonry is used for non-engineered low-rise construction (one- to two-storey buildings) and also for engineered construction such as medium-rise apartment buildings (up to six storeys high). For a detailed discussion on the basic concepts and global applications of confined masonry constructions refer to Brzev (2007).

The appearance of a finished confined masonry construction and a RC frame construction with masonry infills may look alike to lay people, however these two construction systems are substantially different. The main differences stem from the construction sequence and the manner in which these structures resist gravity and lateral loads. These differences are summarized in Table 1 and are illustrated by diagrams in Figure 1.

Table 1 A comparison between confined masonry and RC frame construction (Brzev, 2007)

| Gravity and lateral load-resisting system | Confined masonry construction   | RC frame construction   |
|---|---|---|
|   | Masonry walls are the main load bearing elements and are expected to resist both gravity and lateral loads. Confining elements (tie-beams and tie-columns) are significantly smaller in size than RC beams and columns. | RC frames resist both gravity and lateral loads through their relatively large beams, columns, and their connections. Masonry infills are <u>not</u> load-bearing walls.          |
| Foundation construction                   | Strip footing beneath the wall and the RC plinth band   | Isolated footing beneath each column  |
| Superstructure construction sequence      | Masonry walls are constructed first. Subsequently, tie-columns are cast in place. Finally, tie-beams are constructed on top of the walls, simultaneously with the construction of floor or roof slabs.                  | The frame is constructed first. Masonry walls are constructed at a later stage and are not bonded to the frame members; these are nonstructural, that is, non-load bearing walls. |

In confined masonry construction, confining elements are not designed to act as a moment-resisting frame; as a

result, detailing of the reinforcement is simple. In general, confining elements have smaller cross-sectional dimensions than the corresponding beams and columns in a RC frame building. It should be noted that the most important differences between confined masonry walls and infill walls is that infill walls are not load-bearing walls, while the walls in a confined masonry building are load-bearing walls. A transition from RC frame to confined masonry construction in most cases leads to savings related to concrete cost, since confining elements are smaller in size than the corresponding RC frame members. Also, less reinforcement and less intricate detailing is required for confined masonry construction than for RC frame construction. Therefore, in this case “less means more”. For practical design guidelines related to confined masonry construction refer to Blondet (2005).

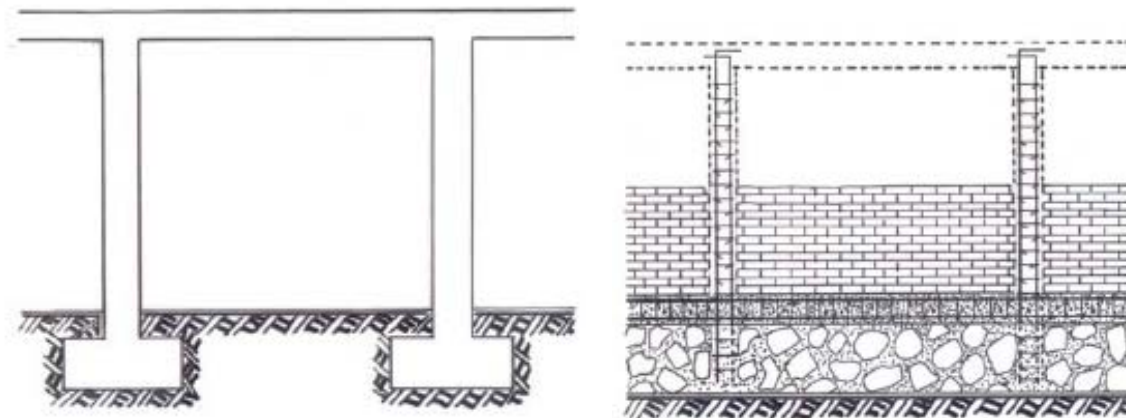


Figure 1. RC frame construction (left) and confined masonry construction (right) (Brzev, 2007).

Confined masonry buildings have demonstrated satisfactory performance in past earthquakes. In general, buildings of this type do experience some damage in earthquakes, however when properly designed and constructed they are able to sustain earthquake effects without collapse. Confined masonry construction has been exposed to several major earthquakes in Latin America: the 1985 Llole earthquake in Chile (magnitude 7.8) (Moroni et al. 2004); the 1985 Guerrero-Michoacan (magnitude 8.0) (Schultz, 1994) and the 2003 Tecoman (magnitude 7.6) earthquakes in Mexico (EERI, 2006); the 2001 El Salvador earthquakes (magnitude 7.6 and 6.6) (Dowling, 2004); the 1970 Chimbote (magnitude 7.0) and the 2007 Pisco (magnitude 8.0) earthquakes in Peru (EERI, 2007). The reconnaissance reports have confirmed that confined masonry buildings had performed very well in these earthquakes. It should be noted that this statement applies to buildings regular in plan and elevation, which are lightly loaded and have rather large wall density. In such cases, confined masonry tends to be quite forgiving of minor design and construction flaws, as well as material deficiencies. Poor seismic performance has been noted only when gross construction errors, design flaws, or material deficiencies have been introduced in the building design and construction process. Poor performance is usually associated with tie-column omissions, discontinuous tie-beams, inadequate diaphragm connections, and inappropriate structural configuration. Confined masonry has demonstrated similar seismic performance in a few other countries, including China, Indonesia, and Iran. For further information on the mechanisms of seismic load resistance and the seismic performance of confined masonry construction refer to Brzev (2007).

### 3.2. RC frames with shear walls

This dual system consists of RC shear walls provided at certain locations between the columns in a RC frame structure, as shown in Figure 2. In this system, shear walls are the main lateral load-resisting elements, while the columns are mainly resisting the effects of gravity loads. The walls should ideally be provided continuously along the building height to avoid a significant variation in the stiffness. The walls should be placed

symmetrically in plan to minimize the torsional effects in the building. Although the detailing requirements associated with RC shear wall construction are less complex compared to the detailing of RC frame members (and especially the area of beam-column joints), horizontal and vertical wall reinforcement must be installed and anchored by skilled construction labour. This construction is practiced in major urban centers of many countries worldwide. Examples from Chile and Canada are documented in the WHE reports by Moroni and Gomez (2002) and Pao and Brzev (2002). The mechanics of shear wall behaviour under seismic loads and the corresponding design approaches have been covered in several seismic engineering design references, e.g. Paulay and Priestley (1992).

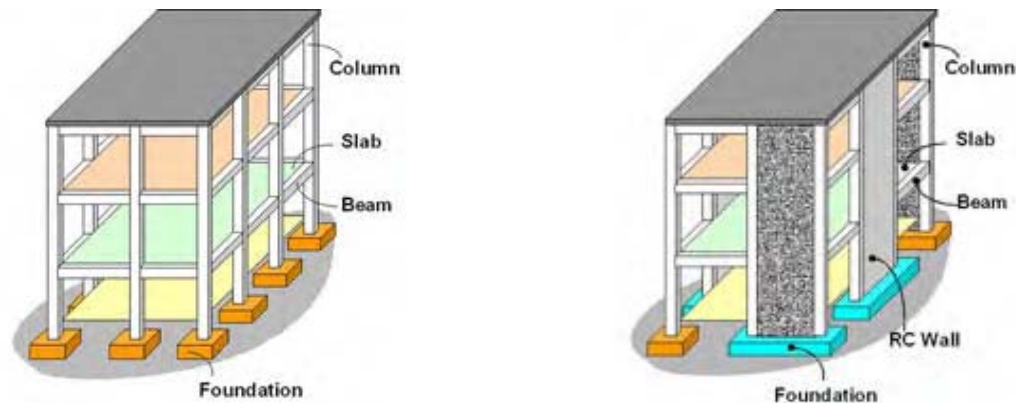


Figure 2. RC frame buildings: three-dimensional RC frame only (left), and three-dimensional RC frame with RC shear walls (source: Murty 2005).

The provision of RC shear walls results in an increase in the lateral stiffness and a decrease in the lateral deflections/drift under seismic load, thus leading to reduced damage to structural and nonstructural building components. Properly designed and detailed buildings with RC shear walls have shown very good performance in past earthquakes. The 1985 Llole, Chile earthquake (magnitude 7.8) exposed many RC buildings with shear walls to extremely severe ground shaking. Most of the shear wall buildings suffered minor damage or remained undamaged (Moroni and Gomez, 2002a). In the 1999 Izmit and the 2003 Bingol (Turkey) earthquakes, thousands of people died, many of them crushed under the ruins of collapsed RC frame buildings with infills. However, tunnel form buildings containing RC shear walls performed very well and no damage was reported (Yakut and Gulkan, 2003). The same was true for the “Fagure” type buildings in Romania after the 1977 Vrancea earthquake (magnitude 7.2) (Bostenaru and Sandu, 2002). RC shear wall buildings were exposed to the 1979 Montenegro earthquake (magnitude 7.2) and the 1993 Boumerdes, Algeria earthquake (magnitude 6.8). The buildings were damaged due to severe ground shaking, however their collapse was avoided.

#### 4. EDUCATIONAL INITIATIVES

Several organizations and individuals have made efforts to develop and share resources related to mitigating seismic hazard associated with vulnerable RC construction and promoting alternative construction technologies such as confined masonry. A few notable examples of global educational initiatives related to this topic are briefly outlined below.

At the 12<sup>th</sup> World Conference on Earthquake Engineering held in 2000 at Auckland, New Zealand, the Earthquake Engineering Research Institute (EERI) and the International Association for Earthquake Engineering (IAEE) inaugurated a web-based network called World Housing Encyclopedia (WHE). The WHE provides a platform for sharing information about housing construction practices worldwide, including both vulnerable housing that performed poorly in earthquakes and good practices that performed well in earthquakes

(EERI/IAEE 2000). The WHE web site ([www.world-housing.net](http://www.world-housing.net)) contains a searchable database of global housing information prepared by over 180 collaborators from 40 countries. In addition, the Tutorials section of the web site contains useful resources for seismic design, retrofit and construction intended to improve building construction practices in regions of high seismic risk. An example is the tutorial on reinforced concrete frames with masonry infills discussed in this paper, which was developed by a group of WHE network participants (Murty et al., 2006). The tutorial is a contribution towards understanding seismic risk and challenges associated with the RC frame construction and it is intended for use by both technical and non-technical audiences. An electronic version can be downloaded free of charge from the WHE web site (Tutorials section), and a printed version can be ordered from EERI. For a detailed overview of the WHE initiative refer to the paper at this conference by Greene et al. (2008).

The National Information Center of Earthquake Engineering (NICEE) at Indian Institute of Technology Kanpur, India, is a non-profit organization that maintains and disseminates resources on earthquake engineering. Over the years, NICEE has undertaken numerous community outreach activities including seminars, workshops, conferences, and published several publications that are either available free or charge or at a nominal fee ([www.nicee.org](http://www.nicee.org)). NICEE has co-sponsored the development of a set of 24 earthquake “tips”, each two pages long, which explain basic concepts of earthquake-resistant construction, ranging from a basic introduction to earthquakes to aspects of seismic design and detailing of reinforced concrete and masonry buildings (Murty, 2005). More recently, NICEE has published a monograph on confined masonry intended to sensitize and educate building professionals in India and other countries where this building technology is not being practiced (Brzev, 2007). The first part of the document outlines the main features of confined masonry construction, worldwide design applications, and the performance in past earthquakes, while the second part contains a generic guideline for the construction of low-rise confined masonry buildings.

Latin American earthquake engineers from countries like Peru, Colombia, and Mexico, have developed several excellent manuals and guidelines related to confined masonry construction. Blondet (2005) has developed a practical hands-on guide for builders of confined masonry buildings. The manual has been developed according to the Peruvian codes and practices, but could be adapted for the application in other countries. AIS (2001) has developed a graphical manual for the construction of confined masonry buildings which is mainly intended for use by skilled workers and technicians. The manual was developed according to the Colombian masonry standard, but general concepts could be used for the application in other countries. A few relevant confined masonry publications, both for technical and non-technical audiences, were developed in Mexico (Martinez-Pacheco, 2008). In Europe, City University of London (2005) published a web-based guideline for seismic design of various forms of masonry construction, including confined masonry, according to Eurocode 8.

Post-earthquake rebuilding efforts often provide opportunities for introducing new and/or improved building technologies. These efforts usually take place immediately after an earthquake has taken place, when the local population is extremely concerned about earthquake safety and is more receptive to changes in building technologies. Two recent examples related to the application of confined masonry construction are briefly described below. After the 2004 Great Sumatra earthquake and the Indian Ocean tsunami (magnitude around 9.0), a U.S.-based NGO Build Change undertook rebuilding of dwellings in Banda Aceh, one of the most severely disaster-stricken areas of Indonesia. Confined masonry was the building technology of choice for both the homeowners and Build Change, since it was practiced before the disaster and performed relatively well in past earthquakes in Indonesia. After assessing local construction practices, Build Change introduced improvements in the construction quality and detailing of reinforcement. A number of hands-on training programs for masons and other artisans took place and several training materials were developed (Hausler, 2006). Another example of a successful technology transfer in a post-earthquake rehabilitation effort is the work done in Mansehra, Pakistan after the 2005 Kashmir earthquake which killed 80,000 people in Pakistan and India. With the assistance from the Swiss Agency for Development and Cooperation, Schacher (2007) prepared several training materials for the local artisans in the affected area and provided technical assistance in the rebuilding effort. Before the earthquake, unreinforced masonry and RC frame construction were prevalent

construction practices in the area. Thus, in this case confined masonry was introduced as a new building technology, or a somewhat modified version of reinforced masonry construction which was introduced in the area affected by the 2001 Bhuj earthquake in the neighboring India (Schacher, 2008).

In January 2008, an International Strategic Workshop on the Promotion of Confined Masonry was organized at Kanpur, India, by the NICEE, EERI and the World Seismic Safety Initiative (WSSI). A group of international experts from India, the USA, Switzerland, Peru, Mexico, China, Indonesia, and Canada created a Confined Masonry Network (CM\_net) with two major objectives: to improve the design and construction quality of confined masonry where it is currently in use; and to introduce it in areas where it can reduce seismic risk. The web site [www.confinedmasonry.org](http://www.confinedmasonry.org) has been created as a growing repository of resources related to confined masonry construction, including training materials, guidelines, and research papers. Besides compiling the existing resources on confined masonry, this group is planning to develop a number of new resources, including an international norm for seismic design of confined masonry structures, state-of-the-art papers on confined masonry and research needs, structural and architectural design guidelines, etc. The network is also planning to organize awareness seminars for the design community, to write non-technical articles, and has already developed brochures that have been posted on the web site. The CM\_net provides a platform for discussion on issues related to confined masonry design and construction in seismic areas. Interested individuals are welcome to participate in the network activities by signing up on the web site [www.confinedmasonry.org](http://www.confinedmasonry.org).

## 5. CONCLUSIONS

The earthquake engineering community has the responsibility to reduce the earthquake risk associated with non-engineered or inadequately engineered construction in countries of high seismic risk and repeated high death tolls in earthquakes (Comartin et al., 2004). This paper has outlined some efforts made to date toward mitigating seismic risk associated with vulnerable nonductile RC frame construction with masonry infills through educational initiatives in several countries. We, the earthquake engineering community, need to move faster in this direction in order to prevent the recurrence of unacceptably high human losses in future earthquakes.

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