AT RISK: The Seismic Performance of Reinforced Concrete Frame Buildings with Masonry Infill Walls

A tutorial developed by a committee of the World Housing Encyclopedia a project of the Earthquake Engineering Research Institute and the International Association for Earthquake Engineering





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Cover: Five story RC frame residential building with unreinforced masonry infills that collapsed about 50 km from the epicenter during the M7.7 2001 Bhuj (India) earthquake. The building had parking in half of the ground story, with apartments in the other half. Most residential buildings are currently constructed this way in India and many other countries, without formal design for gravity or seismic loading. The typical column size in such buildings is 230 mm by 450 mm with 90 degree hook ends in the ties. The same beam-slab reinforcement detail is repeated at all floor levels; the building in the photo shows a vertical split in the middle of the building due to this generic reinforcement detailing at all floor levels. Such poor detailing results in lapping of all beam and slab rebars at the same location in plan at all floors of the building. This is a dangerous practice that can result in building collapse in an earthquake. Photo: C.V.R. Murty

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World Housing Encyclopedia

Tutorial Reinforced Concrete Frame Buildings with Masonry Infill Walls

About the Tutorial

This document is written for building professionals with two key objectives: 1) to improve the understanding of the poor seismic performance of reinforced concrete frame buildings with masonry infill walls, and 2) to offer viable alternative construction technologies that can provide a higher level of seismic safety. Causes for the unsatisfactory seismic performance of these RC frame buildings lie in (a) the poor choice of a building site, (b) the inappropriate choice of building architectural forms that offer poor seismic performance, (c) the absence of structural design for expected earthquake behavior, (d) the lack of special seismic detailing of key structural elements, (e) inadequately skilled construction labor, (f) poor quality building materials, and (g) the absence of construction supervision. The problem is aggravated further by the use of unreinforced masonry infill walls, usually made of clay bricks or hollow clay tiles. The effect of infills is usually not accounted for in the design, however these walls may significantly affect the way in which the building responds to earthquake ground shaking and may even cause the building to collapse (as reported often after several major earthquakes worldwide).

In general, achieving satisfactory seismic performance of RC frame buildings subjected to several cycles of earthquake ground shaking is considered to be a challenge even in highly industrialized countries with advanced construction technology. Keeping these challenges in mind, this document proposes two alternative building technologies characterized by a higher level of seismic safety at a comparable cost and construction complexity to RC frame construction; these technologies are confined masonry construction and RC frame construction with RC shear walls .

Considering the enormous number of existing RC frame buildings with infills in regions of moderate to high seismic risk across the world, this document also discusses some generic seismic retrofit strategies for these structures that may reduce associated risks.

It is important that all those involved in the construction process understand how these buildings perform during earthquakes, what the key challenges are related to their earthquake safety, and what construction technology alternatives might be more appropriate. Authors of this document believe that better understanding of these critical issues will result in improved construction and retrofit practices for buildings of this type, reducing life and property losses in future earthquakes.

About the WHE

The World Housing Encyclopedia (WHE) is a project of the Earthquake Engineering Research Institute and the International Association for Earthquake Engineering. Volunteer earthquake engineers and housing experts from around the world participate in this web-based project by developing reports on housing construction practices in their countries. In addition, volunteers prepare tutorials on various construction technologies and donate time on various special projects, such as the creation of the World Adobe Forum and the collection of information on various temporary housing alternatives. All information provided by the volunteers is peer-reviewed. Visit www.worldhousing.net for more information.

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NOTE:

Throughout the document KEY POINTS and DESIGN TIPS have been placed in the margins--these points are targeted at the readers who may not be as interested in some of the technical details in the text. KEY POINTS are in gold ellipses; DESIGN TIPS are in blue hexagons.



1. Introduction

Reinforced concrete is one of the most widely used modern building materials. Concrete is an "artificial stone" obtained by mixing cement, sand, and aggregates with water. Fresh concrete can be molded into almost any shape, giving it an inherent advantage over other materials. It became very popular after the invention of Portland cement in the 19th century; however, its limited tension resistance initially prevented its wide use in building construction. To overcome poor tensile strength, steel bars are embedded in concrete to form a composite material called reinforced concrete (RC). The use of RC construction in the modern world stems from the wide availability of its ingredients - reinforcing steel as well as concrete. Except for the production of steel and cement, the production of concrete does not require expensive manufacturing mills. But, construction with concrete does require a certain level of technology, expertise and workmanship, particularly in the field during construction. Despite this need for sophistication and professional inputs, a large number of single-family houses or low-rise residential buildings across the world have been and are being constructed using RC without any engineering assistance. Such buildings, in seismic areas, are potential death traps. This is the motivation behind developing this tutorial.

A typical RC building (shown in Figure 1) is generally made of a number of plate-like horizontal elements (slabs), rib-like horizontal elements (beams) connected to the underside of slabs, slender vertical elements (columns), and flat vertical elements (walls). In most cases, all these elements are cast monolithically - that is, beams and columns are cast at the construction site in a single operation in order to act in unison. Fresh concrete is poured into wood or steel forms placed around the steel reinforcement for different elements in buildings. Such buildings are called monolithic (or cast-in-place) RC buildings, in contrast to precast RC buildings, wherein each of the elements is cast separately (often in a factory environment) and then assembled together at the building site. In monolithic RC buildings, the connection between the elements is achieved by providing continuous reinforcement bars that pass from one element to another. The intersection between a beam and a column, known as beam-column joint, plays a vital role in the capacity of these buildings to resist lateral loads.

In RC frames the integral action of beams, columns and slabs, provides resistance to both gravity and lateral loads through bending in beams and columns. RC frames built in earthquake-prone regions should possess ductility, or the ability to sustain significant deformations under extreme loading conditions; this aspect will be discussed in Chapter 3. Frames that are designed to resist mainly the effects of gravity loads most often are called non-ductile (or gravity) frames. The non-ductile RC frame with or without infill walls is a very common building construction technology practiced around the globe (Figure 2).

A large number of RC buildings are being built worldwide without engineering input



Of the 37 countries represented to date in the WHE database, 23 have submitted reports on seismically vulnerable concrete construction; this includes many of the most populous countries in the world These three-dimensional RC frames (i.e., beam-column-slab systems) are made functional for habitation by building walls called *infill walls*. These walls are built at desired locations throughout the building, usually in the vertical plane defined by adjoining pairs of beams and columns. One popular material used for making walls across the world is burnt clay brick masonry in cement mortar. Lately, the use of solid or hollow concrete blocks and hollow clay tiles is on the rise across the world. In some cases, the masonry infill walls are also reinforced with steel bars passing through them in the vertical and horizontal directions and anchoring these bars into the adjoining beams and columns.

With the rapid growth of urban population, RC frame construction has been widely used for residential construction in both the developing and industrialized countries. As of this writing (October 2006), the global database of housing construction in the World Housing Encyclopedia (WHE) contains more than 110 reports describing housing construction from 37 countries (see www.world-housing.net). Along with masonry, reinforced concrete seems to be the material of choice for housing construction -- the database currently contains 26 reports (approximately 25% of all reports) describing RC concrete frame construction in Algeria, Chile, Colombia, Cyprus, Greece, India, Italy, Kyrgyzstan, Malaysia, Mexico, Palestinian Territories, Syrian Arab Republic, Taiwan, Turkey, Uzbekistan, Venezuela, Serbia, Romania, and the USA.

This construction is extensively practiced in many parts of the world, especially in developing countries. At this time, 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. High-



Figure 1. A typical RC frame building with masonry infills and its components (source: C.V.R. Murty).



Figure 2. This Algiers, Algeria, cityscape has many reinforced concrete frame buildings, like many other cities around the world (photo: S. Brzev)

rise apartment buildings of this type have a rather high population density, in some cases a few hundred residents per building. Examples of RC frame construction from various countries are shown in Figures 3 and 4.

The extensive use of RC construction, especially in developing countries, is attributed to its relatively low initial cost compared to other materials such as steel. The cost of construction depends on the region and local construction practices. As an example, a unit area of a typical residential building made with RC costs approximately US\$100--\$400/ m² in India, US\$250/m² in Turkey and US\$500/m² in Italy (Yakut, 2004).

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 Ducze earthquakes in Turkey, the 2001 Bhuj earthquake in India, the 2001 Chi Chi earthquake in Taiwan, and the 2003 Boumerdes earthquake in Algeria, revealed major seismic deficiencies in these buildings, some of which led to catastrophic collapses causing a death toll measured in thousands. One of the major causes of seismic vulnerability associated with these buildings is that, in the developing countries, a large number of the existing RC frame buildings have been designed by architects and engineers without formal training in the seismic design and construction and have been built by inadequately skilled construction workers.

Construction with concrete requires an advanced level of technology, expertise and workmanship Unless careful attention is paid to many design and construction issues, these buildings can experience damage or collapse in major earthquakes

Engineers have used past earthquake failures to learn how to improve RC frame performance Because of the high occupancy associated with these buildings, as well as their ubiquitous presence throughout the world, significant fatalities and property losses can be associated with their potential poor earthquake performance. Thus, special care is required to understand the challenges that earthquakes pose and ensure that appropriate features are incorporated in the architectural and structural design and construction of RC frame buildings. Figure 5 depicts the construction of a modern RC frame building in Mexico. Key considerations related to the construction of RC frames will be discussed later in this document.

The estimated number of vulnerable RC frame buildings in seismic zones across the world is staggering, including both developing and highly industrialized countries. In industrialized countries, thousands of older RC frame buildings are considered to be at risk since the building codes did not include requirements for special seismic detailing of reinforced concrete structures until the 1970's when several earthquakes demonstrated the need for more ductile design. The WHE database documents the damage to older RC frame buildings in major earthquakes that shook the USA in the past 50 years, including the 1964 Anchorage, Alaska, the 1971 San Fernando, California, and the 1994 Northridge, California earthquakes. These earthquakes revealed the vulnerability of RC frame buildings, and prompted the development of modern seismic retrofitting technologies (Faison, Comartin and Elwood, 2004). In an ideal world, it would be best to strengthen all these buildings to protect them from the effects of future earthquakes and minimize fatalities and property losses. However, in a pre-earthquake situation, it is unlikely that funding



Figure 3. Low-to-midrise RC frame construction: Turkey (top left; from Gulkan et al.2002); Colombia (top right; from Mejia 2002); Taiwan (bottom left; from Yao and Sheu 2002); India (bottom right; from Jaiswal et al. 2002)





Figure 4. Examples of RC highrises in Canada (left; from Pao and Brzev 2002), and Chile (right; from Moroni and Gomez 2002). RC shear walls provide resistance to earthquake effects in these buildings while columns are designed to resist gravity loads.

is going to be available to retrofit a significant number of these buildings in any one community. Consequently, there is a need to develop strategies and policies for prioritizing buildings to be retrofitted according to their importance and funding resources. The WHE database contains several reports describing the retrofitting techniques for RC frame buildings in countries like the USA, Mexico, Algeria, India, Greece, Colombia, Chile, Italy, Romania, Taiwan, Turkey, etc. Some generic seismic retrofit strategies suitable for RC frame structures are discussed in this document (see Chapter 6).

Considering the high seismic vulnerability associated with the RC frame buildings, it is necessary to consider viable alternatives to RC frame construction, which provide a higher level of seismic safety at comparable costs and construction complexity; some alternatives will be proposed later on in this document (see Chapter 5).

Due to its high collapse risk, construction of RC frames should be avoided, unless designed by a qualified engineer



Figure 5. An example of RC frame construction from Mexico (source: Rodriguez and Jarque 2005): column reinforcement placement (left) and the completed frame with infills (right).

2. Conceptual Design and Planning Considerations

Building Shape

The behavior of a building during an earthquake depends on several factors, including whether its shape is simple and symmetric. Some buildings in past earthquakes have performed poorly due to highly irregular shapes (see Figure 6). Since the building shape is determined very early in the development of a project, it is crucial that architects and structural engineers work together during the planning stages to ensure that unfavorable features are avoided and a good building configuration is chosen. Key issues in understanding the role of building configuration are outlined below.

 Buildings with simple geometry in plan typically perform better during strong earthquakes than buildings with re-entrant corners from plans with U, V, H and + shapes (see Figure 7a). This is because buildings with simple geometry offer smooth and direct load paths for the inertia forces induced during earthquake shaking to flow to the foundation (see Figure 7b).

One way to reduce irregularity is to separate the building into simple blocks separated by air gaps (also known as separation joints). This type of design allows the simply configured buildings to act independently, thereby avoiding high stress concentrations at re-entrant corners that often lead to damage. For example, a building with an L-shaped plan can be divided into two rectangular plan buildings using a separation joint at the junction (see Figure 8). But, the consequence of this separation joint is that the two parts of the building may pound (or crush)

Buildings with simple shapes perform well in earthquakes



Figure 6. A building with a very irregular shape suffered extensive damage in the 2001 Bhuj, India earthquake (source: EERI 2001).

Avoid buildings with vertical setbacks and varying story heights



Figure 7. Influence of building shape: a) Buildings with simple shapes permit the shaking induced inertia forces to flow directly to the foundation and hence perform well in earthquakes; b) buildings with irregular shapes force the inertia forces to bend at each re-entrant corner, which results in damage at these corners and hence poor earthquake performance of the building as a whole (source: Murty 2005).



Figure 8. Separation joints help simplify building plans (source: Murty 2005).

during earthquakes if not separated with a sufficient gap.

Vertical irregularities may have a negative effect on building performance during an earthquake. Buildings with vertical setbacks (such as hotel buildings with a podium at the base) cause a sudden change in earthquake resistance at the level of discontinuity (see Figure 9a). Buildings that have fewer columns or walls in a particular story or with an unusually tall story (see Figure 9b) exhibit soft or weak story behavior and tend to incur damage or collapse

that is initiated in the irregular story. Buildings on sloping ground that have columns with unequal height along the slope, often exhibit damage in the short columns (see Figure 9c).

• Discontinuities in elements that are needed to transfer earthquake loads from the building to the ground are also of concern. For example, buildings are vulnerable if they have columns that hang or float on beams at an intermediate story and do not follow through all the way to the foundation (see Figure 9d). Also, buildings that have reinforced concrete walls designed to carry the earthquake



loads to the foundation but that are discontinuous in between are vulnerable (see Figure 9e). When these walls are discontinued at an upper level, the building is very likely to sustain severe damage during strong earthquake shaking.

Non-Symmetric Layout

Buildings with irregular shapes lack regularity/symmetry in plan, which may result in twisting under earthquake shaking (see Figure 10). For example, in a propped overhanging building (see Figure 11) the overhanging portion swings on the relatively slender columns under it. It is important to minimize twisting

Buildings with bent load paths perform poorly in earthquakes



Figure 9. Sudden changes in load path lead to poor performance of buildings in *earthquakes: a) setbacks; b) weak or flexible stories; c) sloping ground; d) hanging or* floating columns; e) discontinuous structural members (source: Murty 2005).



Figure 10. Examples of vertical irregularities (from Bangladesh) that can induce undesirable torsional effects (source: M. A. Noor).

Ensure that buildings have symmetry in plan and in elevation

Structural members (e.g. columns and walls) should not be discontinued at lower levels of the building

Ensure that architectural elements do not alter the structural response of the building

of a building during an earthquake. Twist in buildings, called *torsion* by engineers, causes structural elements (e.g. walls) at the same floor level to move horizontally by different amounts. As a result of torsion, columns and walls on the side that moves more experience more extensive damage (see Figure 12).

Many buildings have been severely affected by excessive torsional effects during past earthquakes. It is best to minimize (if not completely avoid) this twist by ensuring that buildings have symmetry in plan (*i.e.*, uniformly distributed mass and uniformly placed vertical members that resist horizontal earthquake loads). It is best to place earthquake resisting frames symmetrically along the exterior perimeter of a building; such a layout increases building

resistance to torsion/twisting.

It is, of course, important to pay attention to aesthetics during the design process. However, this should not be done at the expense of good building behavior and adequate earthquake safety. Architectural features that are detrimental to the earthquake performance of buildings must be avoided. When irregular architectural features are included, a considerably higher level of engineering effort is required in the structural design.

Masonry Infill Walls

In some parts of the world, especially in developing countries, masonry walls are used as infill walls in both the interior and exterior RC frames (see Figure 13). The material of the masonry infill is the main variant,



Figure 11. A building with ground floor open on one-side twists during earthquake shaking (source: Murty 2005).



Vertical members of buildings that move more horizontally sustain more damage (source: Murty 2005).

Provide earthquakeresisting frames symmetrically along exterior perimeter of building

ranging from cut natural stones (*e.g.*, granite, sandstone or laterite) to man-made bricks and blocks (*e.g.*, burnt clay bricks, solid & hollow concrete blocks, and hollow clay tiles), as shown in Figure 14.

It is particularly challenging to design these buildings to achieve satisfactory earthquake performance. Performance of such buildings in past earthquakes has revealed that the presence of masonry infill walls is typically detrimental for the seismic performance of the building. Masonry infill walls should not be used UNLESS they are specifically designed by an engineer to:

- Work in conjunction with the frame to resist the lateral loads, or
- Remain isolated from the frame.

Some builders mistakenly believe that the presence of masonry infill in the frame panels improves earthquake performance, however the evidence from past earthquakes proves that this statement is usually wrong (see Figure 15). It can only be true if the building has been carefully designed by an engineer so the infill walls provide the bracing without failing the frame. A bare frame (without infills) must be able to resist the earthquake effects (see Figure 16a). Infill walls must be uniformly distributed in the building (see Figure 16b). Masonry infills should not be discontinued at any intermediate story or the ground story level; this would have an undesirable effect on the load path (see Figure 16c).

The effects of infill walls must be considered in the structural design



Figure 13. Typical brick infill wall construction in Turkey: masonry infill walls are added after the frame construction is complete (source: Gulkan et al. 2002).



а



Figure 14.(*a*) Assortment of infill masonry units from Peru; (*b*) Typical hollow clay tile from Peru (photos: H. Faison).

In many parts of the world, masonry walls are used as infill walls



Figure 15. RC frame building with masonry infills in Algeria (after the 2003 Boumerdes earthquake): (a) masonry infill walls fail in both directions; (b) Masonry infill wall failure showing diagonal cracking due to compression strut action (photos: S. Brzev)

Masonry infill walls significantly affect the seismic performance of a frame building

Confined masonry is a viable alternative to RC frames with infills for low-rise buildings

> Infill walls must be uniformly distributed in a building

Infill walls act as diagonal struts and increase the stiffness of a RC frame building. The increase in the stiffness depends on the wall thickness and the number of frame panels with infills, and can be quite significant in some cases (up to 20 times that of the bare RC frame). The increased stiffness of the building due to the presence of infills reduces the ability of the frame to flex and deform. In ductile RC frames, masonry infills may prevent the primary frame elements (i.e., columns and beams) from responding in a ductile manner -instead, such structures may show a non-ductile (brittle) performance. This may culminate in a sudden and dramatic failure.

However, most RC frame buildings with masonry infill walls are not designed to account for the effect of the infill walls on building performance, which is why this tutorial recommends avoiding this construction altogether — either by confining the masonry or using RC shear walls (see the discussion in Chapter 5).

When ductile RC frames are designed to withstand large displacements without collapse, masonry infills should be isolated from the frame by a sufficient gap. In this manner, masonry infill walls do not affect the frame performance and frame displacements are not restrained. Another advantage of the isolated masonry infill is that the walls remain undamaged, thereby reducing post-earthquake repair costs.

From the point of view of controlling weather conditions inside the building, the gaps need to be sealed with an elastic material; these provisions may be expensive and require good construction details to be executed with precision.

Overall, based on the poor earthquake performance of non-ductile RC frame buildings and also load-bearing masonry buildings, confined masonry construction is emerging as a better alternative for low-rise buildings in developing countries (Brzev 2007, Blondet 2005). This type of construction is much easier to build than ductile frames with isolated infills.

Out-of-plane seismic resistance of masonry infills

The difficulty in isolating masonry infill walls from RC frames is that such walls become susceptible to collapse in the out-of-plane



Figure 16. Infill walls influence the behavior of a RC frame: (a) a bare frame; (b) infill walls must be uniformly distributed in the building; and (c) if the inflls are absent at the ground floor level this modifies the load path, which is detrimental to earthquake performance (source: C.V.R. Murty).

direction, that is, in the direction perpendicular to the wall surface. This is particularly pronounced when either the story height is large or when the column spacing is large. Once masonry walls crack, continued shaking can easily cause collapse in the heavy infill blocks and pose a serious life safety threat to building inhabitants.

Short and Captive Columns

Some columns in RC frames may be considerably shorter in height than other columns in the same story (see Figure 17). *Short columns* occur in buildings constructed on a slope or in buildings with mezzanine floors or loft slabs that are added in between two regular floors (see



Figure 18). In past earthquakes, RC frame buildings that have columns of different heights within one story suffered more damage in the shorter columns than in the taller columns located in the same story. Short columns are stiffer, and require a larger force to deform by the same amount than taller columns that are more flexible. This increased force generally incurs extensive damage on the short columns, as illustrated by earthquake damage photos (see Figure 19).

There is another special situation in buildings when the short-column effect occurs. Consider a *masonry* wall of partial height with a window above it (see Figure 20). The upper portion of the column next to the window behaves as a short column due to the presence of the infill

Figure 17. A building with short columns at the basement level in Cyprus (source: Levtchitch 2002).

Avoid building designs that have short or captive columns



Figure 18. Examples of common building types with short columns (source: Murty 2005).



Figure 19. Captive column damage from (a) 2003 Bourmerdes, Algeria earthquake (photo: M. Farsi), and (b) 2001 Bhuj earthquake in India. (source: EERI)

wall, which limits the movement of the lower portion of the column. These columns are called *captive columns* because they are partially restrained by walls. In many cases, other columns in the same story are of regular height, as there are no walls adjoining them. When the floor slab moves horizontally during an earthquake, the upper ends of all columns undergo the same displacement. However, the stiff walls restrict horizontal movement of the lower portion of the captive column, so the captive column displaces by the full amount over *the* short height adjacent to the window opening. On the other hand, regular columns displace over the full height. The effective height over which a short column can freely bend is

small, thus short columns attract a larger seismic forces as compared to regular columns. As a result, short columns sustain more damage. The damage in these short columns is often in the form of X-shaped cracks, which is characteristic for *shear failure*.

In new buildings, the *short column effect* should be avoided during the architectural design stage itself. In existing buildings, the infills in the short column region should be isolated from adjoining columns. Adequate gaps should be provided for the columns to swing back and forth without interfering with the infill masonry walls; this is essential because the columns may not have been designed to resist the large shear forces that these short columns will attract.

In past earthquakes, short columns in RC frame buildings with columns of different heights within one story, experienced significant damage



Figure 20. Captive columns are common in RC buildings when partial height walls adjoin columns and the walls are treated as non-structural elements (source: Murty 2005).

There may be a limited number of unavoidable design situations that require the use of short columns. Such buildings must be designed and built to minimize their vulnerability to increased seismic damage. These short columns should be recognized at the structural analysis stage itself; the problem of short columns becomes obvious when such members attract large shear forces.

Modifications of Existing Buildings

Alterations

Building alterations are common in RC frame buildings with infill walls. For example, in Algeria, India, and Turkey, typical modifications include enclosing of balconies to increase room sizes, or demolishing interior walls to expand existing apartments. In some cases, columns or bearing walls are removed in order to expand the apartment size; alternatively, new stairs are connected by perforating the slabs; in some cases, walls are perforated to create openings. When these alterations have not been accounted for in the original design and/or are undertaken without involvement of qualified professionals, there is an increased risk of earthquake damage.

Vertical Additions

In some cases, additional stories are added on top of the existing RC frame building without taking into account the load-bearing capacity of the existing structure. Building owners usually decide to build these additional stories when additional living space is needed and municipal ordinances are lax about height limits. In some cases, these extensions are performed without building permits. Unfortunately, the plans for future building additions do not always account for the additional loads on the foundations or the additional forces to be imposed on the existing RC frame.

In some countries, low-rise one- to three-story buildings are provided with the starter reinforcement bars projecting from the columns at the roof level for the future construction of additional stories. In general, unprotected starter bars usually become extensively corroded if the construction of the expanded building Building alterations can detrimentally affect its performance in an earthquake portion does not continue within a few years. Since the bottom portions of columns experience high stresses during earthquakes, a weak plane forms in the new story that makes it susceptible to collapse. An example of a vulnerable building addition in Cyprus is shown in Figure 21.

Adjacent Buildings: Pounding Effect

When two buildings are located too close to each other, they may collide during strong shaking; this effect is known as *pounding*. The pounding effect is more pronounced in taller buildings. When building heights do not match, the roof of the shorter building may pound at the mid-height of the columns in the taller building; this can be very dangerous, and can lead to story collapse (see Figure 22 and Figure 23).



Figure 21. An example of an existing *RC* frame building in Cyprus showing weak columns, incomplete frame and a heavy rigid parapet wall (source: Levtchitch 2002).



Figure 22. Pounding can occur in adjacent buildings located very close to each other due to earthquake-induced shaking (source: Murty 2005).



Figure 23. (a) Pounding between a six-story building and a two-story building in Golcuk, Turkey causing damage in the column of the six-story building during the 1999 earthquake; (b) Detail of pounding damage in a six-story building shown in figure (a). (source: Gulkan et al. 2002).

Soft and Weak Stories

The most common type of vertical irregularity occurs in buildings that have an *open* ground story. An open ground story building has both columns and masonry infill walls in the upper stories but only columns in the ground story (see Figure 24). Simply put, these buildings look as if they are supported by chopsticks! Open ground story buildings have consistently shown poor performance during past earthquakes across the world. For example, during the 1999 Turkey, 1999 Taiwan, 2001 India and 2003 Algeria earthquakes, a significant number of these buildings collapsed. In many instances, the upper portion of an open ground story building (above the ground story level) moves as a single rigid block; this makes the building behave like an inverted pendulum, with the ground story columns acting as the *pendulum rod* and the rest of the building acting as a rigid pendulum mass. As a consequence, large movements occur locally in the ground story alone, thereby inducing large damage in



Figure 24. Typical building with a soft ground story in India (source: EERI 2001).

the columns during an earthquake (see Figure 25). Soft stories can also occur in the intermediate floors of a building, and cause damage and collapse at those levels (see Figure 26).

The following two features are characteristic of open ground story buildings:

(a) Relatively *flexible* ground story in comparison to the stories

above, *i.e.*, the relative horizontal movement at the ground story level is much larger than the stories above. This flexible ground story is called a *soft story* (see Figure 24).

(b) Relatively *weak* ground story in comparison to the stories above, *i.e.*, the total horizontal earthquake force (load) resisted at the ground story level is significantly less than the stories



Figure 25. Excessive deformations in the ground story alone are not desirable since the columns in the ground story become stressed well beyond the level anticipated in the design (source: Murty 2005).

Ground story columns severely stressed





Figure 26. An example of a building collapse due to an intermediate soft story in the 2001 Bhuj, India earthquake. (source: EERI 2001)

above. Thus, the open ground story is a *weak story*.

Open ground story buildings are often called *soft story buildings*, even though their ground story may be both *soft* and *weak*. Generally, the soft or weak story usually exists at the ground story level (Figure 27), but it could exist at any other story level, too.

How to Avoid Soft Stories

Architects and structural designers can use the following conceptual design strategies to avoid undesirable performance of open ground story buildings in earthquakes:

• Provide some shear walls at the open story level: this should be possible even when the open ground story is being provided to offer car parking (see Figure 28b).





Figure 27. Building collapses due to the soft story effect: (a) A low-rise concrete building collapse in the 2003 Bourmerdes, Algeria earthquake (photo: S. Brzev); (b) A weak-story mechanism developed at the first floor of the building in a mixed-function building -- the ground floor was used for commercial purposes and lacked the stiffness provided by the infill walls at the upper floors (source: Gulkan et al. 2002); (c) Soft story collapse in the 1999 Chi Chi, Taiwan earthquake (source: Yao and Sheu 2002).



Figure 28. The building needs to be designed to take into account the effect of the open story on performance (a). This might include (b) providing walls in all possible panels in the open story, or (c) choosing an alternative structural system e.g. RC shear walls, to resist lateral earthquake loads (source: Murty et al. 2006)

Avoid completely open stories--use alternative design strategies Select an alternative structural system (e.g. RC shear walls) to provide earthquake resistance. When the number of panels in the ground story level that can be infilled with masonry walls is insufficient to offer adequate lateral stiffness and resistance in the ground story level, a ductile frame is not an adequate choice. In such cases, an alternative system, like a RC shear wall, is required to provide earthquake resistance (see Figure 28c).

Strong Beam—Weak Column Failure

In a reinforced concrete frame building subjected to earthquake ground shaking, seismic effects are transferred from beams to columns down to the foundations. Beam-tocolumn connections are also critical in ensuring satisfactory seismic performance of these buildings. The currently accepted approach for the seismic design of reinforced concrete frames is the so-called *strong columnweak beam* approach. The guiding design principles associated with this approach are summarized below:

- (a) Columns (which receive forces from beams) should be designed to be stronger in bending than the beams, and in turn foundations (which receive forces from columns) should be designed to be stronger than columns. Columns can be made stronger in bending than the beams by having a larger cross-sectional area and a large amount of longitudinal steel than the beam.
- (b) Connections between beams and columns as well as columns and foundations must be designed such that failure is

avoided, ensuring that forces can safely be transferred between these elements.

Reports from past earthquakes throughout the world have confirmed that buildings designed contrary to the strong column-weak beam approach often fail in earthquakes.

When the strong column-weak beam approach is followed in design, damage is expected to occur *first* in beams. When beams are detailed properly so that ductile behavior is ensured, the building frame is able to deform significantly, despite progressive damage caused by the consequent yielding of beam reinforcement. In a major earthquake, this type of damage takes place in several beams throughout the structure; however, this is considered to be "acceptable damage" because it is unlikely to cause sudden building collapse (see Figure 29a). In contrast, columns that are weaker in comparison to beams suffer severe localized damage at the top and bottom of a particular story (see Figure 29b); this can cause the collapse of an entire building, in spite of the columns at stories above remaining virtually undamaged.

These vulnerable structures are characterized by relatively small column dimensions compared to the beam dimensions and are known as "strong beam-weak column" structures (as shown in Figure 30 [right]). Failures of small, weak columns have been reported after earthquakes around the world (see Figure 31 and Figure 32). For example, several reinforced concrete buildings collapsed due to this effect in the 1999 Turkey earthquake (see Figure 32). Even when complete building collapse does not occur, damage is often too extensive, making repair unfeasible. Such buildings are usually demolished after an earthquake.

Properly designed RC frame buildings will experience damage in many beams during strong shaking, but this type of damage does not usually lead to collapse





Figure 29. Two distinct design approaches result in significantly different earthquake performances (source: Murty 2005).



Figure 30. The beams must be designed to act as the weak links in a RC frame building; this can be achieved by designing columns to be stronger than beams (source: C.V.R. Murty).





Figure 31. Collapse of a multistory RC frame building due to weak column-strong beam design in the 2001 Bhuj, India earthquake (photo: C. V. R. Murty).

Buildings with weak columns and strong beams experience damage in their columns first; this can lead to a building collapse



Figure 32. Multiple-story collapse in a six-story building due to strong beam-weak column design in the 1999 Turkey earthquake (source: Gulkan et al. 2002).

3. Detailing Considerations

On Ductility

Earthquake shaking causes vigorous movement underneath the building and thereby transmits energy to the building. The philosophy of earthquake-resistant design is to make the building absorb this energy by allowing the damage at desired locations of certain structural elements. This damage is associated with significant deformations, and extensive yielding (stretching) of steel reinforcement in reinforced concrete members. This behavior is known as ductile behavior. *Ductility* denotes an ability of a structure to sustain significant deformations under extreme loading conditions and thus absorb a significant amount of earthquake energy. Achieving ductility in RC members is particularly challenging due to the different behavior of concrete and steel: concrete is a brittle material, which crushes when subjected to compression and cracks when subjected to tension; on the other hand, steel shows ductile behavior when subjected to tension.

As a result, reinforced concrete structures can be made to behave in a ductile manner when designed to take advantage of ductile steel properties.

However, one of the key challenges associated with the earthquakeresistant design of reinforced concrete structures is to ensure that members behave in a ductile manner and that the damage occurs at predetermined locations. This can be achieved by applying the *Capacity Design Approach* which can be explained by using the chain analogy (see Figure 33). Consider a chain made of brittle links; when pulled, the failure of any of the links causes a brittle failure of the chain. However, when a ductile link is introduced in the chain, a ductile mode of failure can take place if the ductile link is made to be the weakest of all and fails first. In order for the ductile failure to take place in this kind of structure, the brittle links must be stronger in comparison to the ductile link.

Steel and concrete are combined to take advantage of each material's best attributes

Earthquakeresistant design aims to ensure that damage occurs at specific locations within a building



Figure 33. Capacity Design Method can ensure that the chain fails in a ductile manner (source: Murty 2005). Ductile structures absorb earthquake energy through localized damage, thereby preventing collapse The ductile behavior of RC frame buildings in earthquakes is desirable since it helps secure the safety of building inhabitants. Ductile behavior is ensured by carefully designing the beams, columns and joints, so that collapse is prevented even if a devastating earthquake takes place. Note that, in extreme cases, significant damage might take place in ductile buildings. The main strategy is to prevent the occurrence of brittle modes of failure before the desired ductile mode of failure has been initiated.

Ductile detailing is the process of ensuring that the above principles are employed while proportioning the RC frame members and providing the required reinforcement. This is achieved by choosing suitable dimensions and arrangement of reinforcement bars in the beams, columns, and joints, as discussed below.

Beams

Failure modes

Beams may experience one of the following two modes of failure:

- (a) Flexural failure (brittle or ductile); brittle failure occurs when there is too much horizontal reinforcement in the tension zone of the beam, while ductile failure occurs if beams are designed conversely with relatively less steel in the tension area.
- (b) Shear failure; this occurs when the amount (size and/ or spacing) of stirrups is not adequate. This failure, characterized by diagonal cracking in the end regions of

the beams, is always brittle and must be avoided by providing closely spaced closed-loop stirrups.

Brittle modes of failure are undesirable and must be avoided by skillful design and detailing of horizontal reinforcement and stirrups, as discussed in this section.

Location and amount of horizontal rebars

Horizontal rebars should be provided along the length of the beam to resist flexural cracking on the faces of the beam that are subjected to tension. Unlike the case of gravity loads where the load direction is always known, lateral forces change direction during earthquake ground shaking. As a result, both the top and bottom beam faces may be subjected to tension and require horizontal reinforcement (see Figure 34). The behavior of a beam is different under different loadings. The undeformed beam with no load has no tension at any face of the beam (condition A). However, under gravity loading when the direction does not change (condition B), the bottom face at the center of the beam is in tension (see the red polygon that is now larger than its original rectangle in (A), while the top face is in compression (see the blue polygon that is now smaller than its original rectangle in (A). On the other hand, for earthquake shaking in one direction (condition C), the top face at the one end of the beam is in tension and the bottom face at the same end is in compression (see red and blue polygons). At the same time, due to reverse bending at the other end, the top face is in tension while the bottom face is in compression.

Beams, columns and joints can be carefully designed so that collapse is prevented even in a devastating earthquake
When the direction of the load is reversed, the situation in the beam is just the opposite. Any portion of the beam that is expected to be in tension (red polygons) must have horizontal rebars to resist cracking of the concrete. Under earthquake loading, both beam faces require rebars, unlike gravity loading where the load direction does not change and tension develops only on one side. Thus, different sections of the beam need reinforcement depending on the loading condition.

In general, it is a good seismic design practice to provide a minimum of two bars (with the total area not less than the design area of steel obtained from calculations) at the top and bottom faces along the *full length* of the beam. At the beam ends, the amount of bottom steel shall be at least equal to half of that provided on the top. Since it is not practical to use very long rebars in construction, it is generally necessary to use smaller rebar lengths and join them so that they can span the full distances required. To ensure that the rebar is strong enough when it is joined with other pieces, the bars must overlap by a specified distance, depending on the bar diameter. This overlapping length is called a lap splice. Splicing must be avoided in regions where horizontal bars are expected to yield in tension. Top bars should be spliced in the middle one-third of the effective span (see Figure 35). Splicing should be done for an adequate length and the spliced length shall be enclosed by closely spaced stirrups. In general, seismic codes prescribe that no more than 50% of the bars shall be spliced at any section.

Brittle beam failure due to shear must be avoided



Condition B: gravity loading

Condition C: earthquake loading

Figure 34. Beam behavior under different loading conditions: (A) no loading; (B) gravity loading; (C) earthquake shaking in one direction; the reinforcement requirement at different locations of the beam depends on the loading condition (source: H. Faison).

Closely spaced stirrups should be provided near the beam ends and at the lap splices



Figure 35. Stirrups must be closely spaced at the beam ends and lap splices (source: Murty 2005).



Figure 36. RC beams must have stirrups with 135° hooks around the horizontal bars (source: Murty 2005).

Stirrups

Stirrups prevent brittle shear failure in RC beams by restraining diagonal shear cracks and by protecting the concrete from bulging outwards due to flexure; stirrups also provide confinement and prevent the buckling of the compressed horizontal bars.

All closed stirrups should have 135° hooks provided on alternate sides in adjacent stirrups. Such stirrups do not open during strong earthquake ground shaking (see Figure 36) since the stirrup ends are embedded in confined core. Simply put, these stirrups act like the metal straps around wooden water barrels. The water inside the barrel exerts a pressure that pushes the wooden slats of the barrel outwards. The metal straps that wrap around the barrel resist this pressure and prevent the barrel from bursting. Similarly, the stirrups in the beam resist the pressures from within the beam, and keep the concrete core intact. The stirrup spacing in any portion of the beam should be determined from design calculations. In general, seismic codes prescribe closely spaced stirrups provided near the column faces over a length equal to twice the beam depth.

Columns

Failure modes

RC columns can experience two failure modes, namely axial-flexural failure and shear failure. The column resistance due to axialflexural effects is ideally limited by making the columns stronger than the beams (as discussed in Chapter 2). As a result, the beams, rather than columns, absorb the earthquake energy and sustain damage in the process. This resistance is determined, amongst other factors, by the total cross-sectional area of vertical steel rebars. Shear failure is brittle and must be avoided in columns by providing closely spaced transverse ties that enclose all the vertical bars.

Tall and slender columns often tend to be weaker than the framing beams, particularly when the column width in the direction of framing is small. To prevent the undesirable "weak column-strong beam" effect (discussed in Chapter 2), seismic design codes require the columns to be stronger than the beams. Since columns are often wider than the beams framing into them and have a larger amount of steel reinforcement than beams, the column width in the direction of frame action should be generally equal to or greater than the width of beams framing into them. Also, circular columns with spiral reinforcement tend to show superior earthquake performance over rectangular columns of the same cross-sectional area. However, spiral reinforcement is not common in design practice, particularly in columns of rectangular or square shape. Further, the entire length of spiral must be made from a single bar. Also, the ends of the spiral need to be securely anchored into the beamcolumn joints or beam-slab system.

Vertical rebars

Vertical rebars resist axial loads and bending moments developed in the column due to gravity loading as well as due to earthquake shaking. Vertical bars should be distributed on all the sides of the column. It is preferred to use a larger number of smaller diameter bars instead of a fewer bars with large diameter, even if they have the same total cross-sectional area. Use square or circular columns rather than rectangular columns

Closedloop vertical stirrups should be provided throughout the beam length Extended column starter bars intended for future building extension will become extensively corroded after a few years and should be avoided Not more than 50% of bars should be spliced at any one location (see Figure 37). Lap splices shall be provided only in the middle half of the member length – it is not recommended to place lap splices in the top or bottom region of the column (see Figure 38).

Horizontal ties

While vertical loads and bending moments on columns are resisted by the vertical rebars, lateral earthquake forces are resisted by closely spaced closed-loop horizontal ties (see Figure 39). The horizontal ties should be designed to restrain the development of diagonal shear cracks. Furthermore, horizontal ties hold together the vertical rebars and prevent them from excessive buckling, and confine the concrete core within the column. The ties thus help prevent crushing of the column core so that it can continue to resist the vertical loads. Several earthquakes have revealed column failures due to ties

that are spaced too far apart, do not have 135° hooks, or are otherwise inadequately designed (see Figure 40).

The ties should be ended with a 135° hook with sufficient length extension at the end of the bar to ensure proper confinement of the concrete within the stirrup. These lengths are usually prescribed by relevant national standards. The hooks must be embedded within the concrete core so that the ties will not pop open during earthquake shaking and compromise the integrity of the concrete core. If the length of any side of column and hence the hoop is too large, then a cross tie should be added to prevent the hoop from bulging outwards (see Figure 41). Ties should be provided with closer spacing at the two ends of the column for at least the length prescribed by the relevant national standards.

Longitudinal rebar lap splices should only be provided at the column midheight



Figure 37. Inadequate splice length and location for future construction--100% splices at the bottom of the column base (source: Mejia 2002).



Figure 38. Ties must be closely spaced at the top and bottom ends of column and at lap splices (source: Murty 2005). Horizontal closed ties confine the concrete core in columns so that the building does not lose its vertical load carrying capacity



Figure 39. Steel reinforcement in columns must have ties with 135° *hooks around the vertical bars (source: Murty 2005).*

All column, joint, and beam ties must have 135° hooks



Figure 40. Examples of column failure in the 2001 Bhuj, India earthquake: (a) buckling of vertical column rebars due to inadequately spaced horizontal ties (source: EERI 2001); (b) severe damage of a ground-floor column due to improper confinement of concrete and lapping of large number of longitudinal bars (source: Jaiswal et al. 2002); (c) typical infrequent horizontal ties with 90° hooks, which were unable to confine the concrete core (135° hooks should have been used instead) (source: Jaiswal et al. 2002).





Figure 41. Additional cross-ties are required in the horizontal direction at regular intervals to keep the concrete in place and to prevent the vertical column rebars from buckling (source: Murty 2005).

Both beam and column longitudinal rebars must be enclosed by hoop ties in the joint region

Beam-Column Joints

Beam-column joints are the areas where the beams and columns intersect (see Figure 42a). During earthquake ground shaking, beamcolumn joints might sustain severe damage if due attention is not given to their design and detailing. Earthquake forces cause the beamcolumn joint to be pulled in one direction at the top rebar and in the opposite direction at the bottom rebar (see Figure 42b). These forces are resisted by bond between the concrete and steel in the joint region. When either the column is not wide enough or the concrete strength in the joint region is too low, there is insufficient grip of concrete on the steel rebars; this causes the rebars to slip and lose its capacity to carry load. If these opposing pull-push forces are too large for the joint to resist, geometric distortion may occur in the joint region resulting in the formation of diagonal shear cracks (see Figure 42c).

Significant stress demand posed on the steel bars and concrete in the



Figure 42. Beam-column joints: (a) intersection of beams and columns known as beam-column joints; (b) push-pull forces on joints cause compression and tension forces which result in irreparable damage in joints under strong earthquake shaking; c) distortion of joint causes diagonal cracking and crushing of concrete (source: C.V.R. Murty).

beam-column joint region mandates that special attention be paid to the design and detailing of these regions. When the beam-column joints are unable to transfer internal forces from beams to columns, they are likely to fail prematurely in a brittle fashion, thereby jeopardizing the safety of the entire building (see Figure 43).

Two important factors to be ensured in the beam-column joint design are:

- (a) The steel bars should not be discontinued in the joint region; this applies to both interior and exterior joints (see Figure 44); and
- (b) The vertical rebars in columns must be held together by means of closely spaced closed-loop transverse ties within the beamcolumn joint region (see Figure 45). Laboratory experiments have shown that the larger the

volume of the confined concrete in the beam-column joint region, the better the seismic performance of the beam-column joint.

In exterior joints wherein beams terminate at columns, horizontal beam bars need to be anchored into the column to ensure proper gripping of these bars in the joint region. This is typically done by bending the rebars into 90° hooks (see Figure 46). In interior joints, the beam bars should be continuous through the joint. Moreover, these bars must be placed on the inside of the column reinforcement cage (composed of vertical rebars and horizontal ties) and without any bends (see Figure 47).

Consider using cross ties to prevent vertical bar buckling when rectangular columns are necessary



Figure 43. Shear failure of a RC beamcolumn joint during the 1985 Mexico City Earthquake, due to beam bars placed outside the column cross-section (source: EERI 2000).



Figure 44. Improper reinforcement detailing of a beam-column joint in India: discontinuous beam rebars at the beam-column junction; these rebars are required to be continuous and provide confinement to the concrete in the joint region (note the absence of beam-column ties) (source: Jaiswal et al. 2002).



Portion of top

(a) Poor

beam bar below

soffit of the beam

Figure 45. Closely spaced closed-loop transverse ties must be provided within the beam-column region (source: Murty 2005).



Portion

column already

(b) Good

cast



Figure 47. Details of joint reinforcing showing the importance placing the horizontal beam rebars on the inside of the column reinforcement cage (source: Murty 2005).

Masonry Infill Walls

As discussed in Chapter 2, there are two distinct approaches related to masonry infill walls in RC frame buildings. These are:

- To isolate the infills from the frame (must be designed as ductile frames), and
- To integrate the infills into the frame (must be designed as infilled ductile frames).

Each of these approaches requires different detailing and design practices for masonry infill walls. When masonry infill walls are to be isolated from the adjoining frame, two simple ways of ensuring the out-of-plane stability of masonry infill walls that are separated from the RC frame are:

- (a) To break the large masonry infill wall panels into smaller ones; this can be accomplished by providing stiff members made of wood or lightly reinforced concrete in vertical, diagonal and/or horizontal directions, and
- (b) To provide reinforcement in the infill walls; the reinforcement should be provided at regular spacing in the vertical and horizontal direction. Design codes in some countries (*e.g.,* Indonesia) contain provisions on how to improve the out-of-

plane performance of masonry infills without interfering with the frame members. It is suggested to provide *practical columns*, that is, lightly reinforced RC columns of small cross-section with vertical steel bars loosely inserted into the beam at the top end, at regular intervals along the wall length and at the wall ends. This provision is illustrated in Figure 48. Isolating infills is not an easy task. It is difficult to maintain the gap between practical columns and the frame columns, and ensure that outside weather conditions do not affect the building interior.

When masonry infill walls are to be integrated with the adjoining frame, horizontal steel anchors (dowels) need to be provided to tie the wall to the framing columns; these anchors need to be provided at regular spacing in order to ensure force transfer between the wall and the frame (see Figure 49). When the wall panel length is large, a practical column should be provided to improve the outof-plane resistance of the masonry infill wall. Again, it is not easy to reinforce the masonry walls made of solid clay bricks. It has been observed that reinforcing bars tend to corrode, dilate in size and crack the masonry walls. In some projects, stainless steel bars are used to avoid this problem. But, in



Figure 48. Practical columns provided to isolate masonry infills in Indonesian practice: (a) partial height infills, (b) full height infills, (c) close-up details of a practical column, and (d) close-up details of anchoring practical columns into the beam above, but without offering any resistance to lateral deformation of the building frame (source: Murty et al.

general, no positive connection is provided between infills and the frame; they are simply built flush to the frame surface.

Non-Structural Elements

Parts of buildings that resist and transfer the forces generated by earthquake ground shaking are called structural elements (e.g., beams, columns, walls, and slabs), while building contents and some other elements are called nonstructural elements. Just as in the case of structural elements, nonstructural elements also need to be designed to resist the earthquake effects (induced forces and relative displacements). Further on, adequate connections are required to safely transfer all the forces generated in non-structural

elements to the structural elements (see Figure 50a). Sometimes, the forces are not as much a concern for the non-structural elements as are relative floor displacements. For instance, when the sewage pipes pass from one floor to another, they need to have the capability to move laterally by different amounts at the different floor levels and still remain in function (se Figure 50b).

The way non-structural elements are installed within the structural system could have significant - often detrimental - effect on the performance of a structural system. For instance, infill walls built integrally with the columns and beams are often treated as nonstructural elements, and not much attention is paid to their effect on the building. However, in reality, these walls are structural elements, as they foul with the lateral movement of

Many non-structural elements, like stairs, may alter the building response to an earthquake and incur excessive damage if not accounted for in the structural design



Figure 49. Details of anchors between infill and frame when the masonry wall needs to be integrated with the building frame (source: Murty et al. 2006).



Figure 50. Design of non-structural elements should account for the following: (a) lateral forces transferred to structural elements, and (b) relative lateral movements up the building height (source: C.V.R. Murty).

the columns and significantly alter the behavior of the building (see the discussion on infill walls in Chapter 2). In all cases, no addition, attachment, removal of material or alteration of any kind that would change the behavior of a structural element from its original design intent should be allowed. Design and installation of all non-structural elements must meet the applicable specifications and codes (see Figure 51). In some cases, very stiff and strong structural elements can be disconnected from the rest of the structural system of the building, and rendered non-structural. For example, in staircase areas of buildings, the inclined staircase slabs and beams offer large stiffness and interfere with the otherwise symmetric shaking of the building. In such cases, isolating the diagonal members to simply rest on and slide in the horizontal direction (see Figure 52) will significantly improve building performance.



Figure 51. Examples of poor construction practices: (a) unacceptable installation of pipes in column reinforcement cages, and (b) unacceptable installation of electrical conduits by damaging an existing RC beam (photos: A. Irfanogulu).



Figure 52. Diagonal slabs and beams in staircases attract large seismic forces, and thereby incur damage: the provision of a sliding support is effective in limiting the magnitude of seismic forces (source: C.V.R. Murty).

4. Construction Considerations

Construction quality has a significant bearing on ductile seismic performance of buildings – poor construction leads to poor earthquake performance. Therefore, a sound earthquake resistant structure requires the successful completion of all steps involved in the making of the building, namely:

- *Design*: conceptual development of a rational design based on prevalent codes of practice;
- *Construction*: physical construction, *i.e.*, implementation of the conceived design; and
- *Maintenance*: inspection, maintenance, monitoring, and remodeling over the building's lifetime.

The above process is like the making of a chain: to have a strong chain, all of the links must be sufficiently strong. Similarly, to build a good building, all steps in the *construction stage* also must be performed as per the minimum specifications laid out in the design. Issues associated with the *design* of a typical reinforced concrete frame building are covered earlier in this document, while the constructionrelated issues are summarized below: issues associated with the *maintenance* are not dealt with in this document.

The physical construction of a RC building can be considered successful only if:

 (a) The building is built according to the structural drawings produced during the *design stage;*

- (b) Appropriate and good quality materials, acceptable by the applicable material codes, are used in the construction;
- (c) The construction is carried out as per procedures laid out in the codes of practice, accompanied by competent, thorough, and honest inspection.

It is significantly easier and cheaper to build a quality construction the first time, than to build a poor construction and then bear the costs, inconvenience and delays related to replacing the poorly constructed or defective structural elements or systems. The following aspects of construction have well-established practices that are enumerated in relevant national standards and are summarized below:

- material quality,
- workmanship, and
- inspection.

For more in-depth discussion on this topic, readers are referred to the publication, *Built to Resist Earthquakes*, which addresses design and construction issues for architects, engineers and inspectors (ATC/ SEAOC 1999). The following sections summarize some of the major issues related to construction quality.

Material Quality

Selection and use of appropriate and good quality materials is a prerequisite for successful construction. Proper design, construction and maintenance are all critical to the good performance of a building in an earthquake

Material quality, workmanship and inspection--all are equally important for earthquake safety

Selection and control of materials

The elements used in the concrete mix, that is, cement, aggregate, water, and any additives to the mix, need to be properly selected and utilized. Several major points addressing material selection include:

- A competent civil or materials engineer must develop the concrete mix design or the proportioning of the ingredients comprising the concrete. It is important not to alter the proportions of the ingredients once the mix has been designed by an engineer.
- Code-specified cement must be used. Attention must be paid in choosing the cement and/or the aggregate to avoid any detrimental cement pasteaggregate reactions.
- Aggregate should be chosen to match the type and grain size distribution specified in the concrete mix design. Beach sand should never be used.
- Adherence between cement paste and aggregate is essential for concrete quality. To that

end, when necessary, aggregate should be washed with clean water and drained/dried to remove any dirt, dust, and organic material (see Figure 53).

 Clean water should be used in preparation of the concrete mix. Inadequate performance can result from using salt water, dirty or muddy water, or water with organic material in the preparation of the concrete mix. Inappropriate water could result in rapid deterioration of the concrete and corrosion of the steel reinforcement.

Preparation, handling, and curing of concrete

Concrete is prepared best in a concrete batch plant where it is easier to achieve a high level of quality control. On-site concrete mixers are the distant second preference if obtaining concrete from a batch plant is not an option. The least desirable option is to prepare concrete on-site manually. This last option should be avoided to the extent possible since it is almost impossible to prepare consistently good quality concrete batches manually (see Figure 54). Important considerations in the handling of concrete are discussed below:



Figure 53. Inappropriate aggregate size; note the highly porous poor quality concrete and rusted smooth bars (photo: A. Irfanoglu).

The concrete mix used for construction must be prepared by an engineer

Concrete should be prepared in batch plants



Figure 54. Manual mixing and preparation of concrete is the least preferred batch preparation option because of the inability to ensure consistent quality (photo: A. Irfanoglu).

Fresh concrete mix

Once the concrete mix is ready, it should be handled properly and used in construction as quickly as possible. Fresh concrete should never be allowed to dry or set before it is cast in forms. During the transport from its preparation site to the building site location, concrete may segregate or separate. In other words, the aggregate may group together forming aggregate anomalies, or water may accumulate at the surface or drain away from the fresh concrete. In such cases, the proper concrete mixture should be reestablished by thorough re-mixing. Water may need to be added to replace the drained away amount. However, it should be remembered that any such addition or increase in the water-to-cement ratio would lower the concrete strength.

Concrete setting

Once the fresh concrete is cast, proper care of the setting (hardening) stage should be taken. Wrapping or covering the concrete elements with plastic sheets often provides a good setting environment for the hardening stage. Once the concrete sets, which takes a few hours under normal conditions, the curing process begins. During curing, it is important to maintain the proper levels of moisture content and temperature in and around the cast element. It is usually sufficient to cover the cast elements in moist burlap and wrap plastic sheets over the burlap. Occasional wetting of the burlap is often the way to maintain proper moisture content. If wooden forms are used in the formwork, the moisture level should be monitored closely as wood used in the forms may absorb too much water from the concrete being cured.

Selection and control of steel

Steel reinforcement must match what is specified in the structural drawings. Specific considerations include:

- Only mill-certified steel of the type(s) allowed for use in earthquake-resistant construction of buildings should be used.
- Steel grades must match the specifications given in the structural drawings.

Proper moisture conditions should be ensured throughout the curing of the concrete

> Steel rebars used must be mill-certified

Steel grades different than those specified on construction drawings can be harmful to the building

Designers should ensure that the construction drawings are simple and constructible

Workmanship is the last, but vital, link in converting design to reality

- Whenever possible, smooth bars should be avoided (unless specified and properly accounted for in the structural design).
- Cold-formed steel, that is, steel re-formed from scrap steel, must be avoided. Such steel has widely varying quality and it is inappropriate for use in reinforced concrete construction.
- Inappropriately deformed bars should not be used in construction. Over-bent or over-stretched segments can form weak spots in the reinforcement (see Figure 55).
- Corroded bars should be avoided. This requires not only purchase of good quality steel reinforcement and its proper storage, but also sequencing the construction process to minimize the exposure of the reinforcement to corrosive



Figure 55. Smooth reinforcing steel delivered to a construction site in *Turkey, bent into a "U" shape (source: Gulkan et al. 2002).*

elements (water/moisture plus air being the all too natural ones). Loose particles need to be removed from the steel surface using hand-wire brushes. In all cases, the extent of corrosion must not be excessive to render reinforcing bars unacceptable by applicable material standards.

Workmanship

In reinforced concrete frame construction, it is very important to have qualified work crews with appropriate experience and competent workmanship. It is also very important to have a feasible and well-thought construction sequence to let the crews perform their tasks in a proper and timely manner. The construction crews are the last, but vital link, in the construction process.

The design engineer and the architect play important roles in ensuring that the design is feasible and can be understood by construction crews.

The design engineer should keep the structural configuration and detailing of the structural system and its sub-elements as simple and straightforward as possible. It is good practice to use standard or typical detailing as much as possible. Of course, it is the responsibility of the whole building team --from the architect and the design engineer to the field crews-- to build a good quality building.

The key processes where workmanship is critical in construction are:

1) *Steelwork*: the steelwork has to result in reinforcement layouts per the specifications given in the structural drawings. Reinforcing elements should be clean and should not have any dirt or oil on them (see Figure 56).

- 2) *Formwork*: to be able to cast reinforced concrete elements properly, good quality forms need to be built. This requires use of clean, leak-proof and tightly constructed formwork systems, characterized by adequate stiffness and strength. Where necessary, proper falsework may need to be incorporated into the formwork construction to support the forms.
- 3) *Proper placement of steelwork into the forms*: reinforcing steel assemblies need to be placed and secured within the forms in such a way that the design specifications (such as minimum concrete cover thickness) have been met. This would prevent future corrosion of the reinforcement and spalling of the concrete. The steelwork should not be displaced or distorted when fresh concrete is placed into the forms.
- 4) Concrete work: transportation, handling, placement and consolidation of fresh concrete should be done properly. Accumulation or loss of water, or segregation of aggregate in the concrete mix should be avoided as much as possible. If such alterations of the concrete matrix take place, the concrete mix should be reconstituted before placing the fresh concrete into forms.

Fresh concrete should be poured into the forms and properly distributed (consolidated) within and around the steel reinforcing elements. Use of vibrators or other instruments that enhance consolidation of the concrete within forms is recommended. It is extremely important to have good bond between concrete and the steel reinforcement. To that end, there should be no excessive voids or weak spots within the cast concrete. Improper consolidation of fresh concrete due to improper use of vibrators or other tools typically results in the accumulation of an excessive amount of water around the steel reinforcement. The outcome is very poor bond between the reinforcement and the concrete, resulting in poor bond strength.

5) *Non-structural elements*: the way in which non-structural elements are installed within the building may have significant -- and often detrimental -- effects on its seismic performance. The effect of infill walls, for example, is discussed elsewhere in this tutorial. In all cases, no addition, attachment, removal of material or alteration of any kind that would change the behavior of a structural element from its original design intent, should be allowed. Examples of improper installation of non-structural elements which may have dangerous consequences on the seismic performance of an entire building are shown in Figure 51. The design and installation of all non-structural work must meet the applicable specifications and codes.

Members of the building team, from the design engineer and the architect to the field crews and the engineer-in-charge, must have a clear understanding of their own and others' responsibilities and tasks. They must be aware of the chain-of-command and their position within this chain. This means, for example, never cutting Use of vibrators for consolidating fresh concrete is recommended

It is essential to properly place steel rebars into forms and ensure adequate concrete cover to prevent corrosion All parties involved in the construction process must have a clear understanding of their responsibilities



Figure 56. Poor workmanship: dirty groundwork and inappropriate column and bar anchorage (source: Mejia 2002).

corners or allowing subordinates to cut corners without rational consideration of the possible effects of such an act and without explicit approval of the engineer in charge of the construction. It should be remembered that once a defective element is built, it would take great amount of time and expense to remove and replace it with a proper one.

Inspection

The construction work should not only be monitored by an internal controller (often the site engineer), but also by a certified independent inspector. The inspection process should be rigorous and carried out by a competent inspector in an honest manner. Inspection is a critical task in the construction process--just a few missing column ties or the absence of 135° bends may lead to collapse of the entire building. Key considerations for the building inspector are listed below:

- The inspector should be free of any conflicts of interest (immediate or future) in carrying out the inspection.
- 2) The inspector should have unobstructed and free access to ongoing site activities and relevant construction documents at all times.
- 3) At a minimum, the inspector should be present whenever and wherever the applicable construction codes require that an independent inspection be carried out. Often times, once the concrete is cast, there is very little an inspector can do with regards to verification of the construction quality and adherence to the construction drawings, specifications and applicable codes.
- The inspector should document his/her observations diligently and keep the records.
- 5) The inspector should interact and, when necessary, give regular feedback to the site engineer about his/her observations.
- 6) The inspector should promptly bring to the attention of the engineer-in-charge any issues related to the quality of construction.

It is the duty of the inspector to be competent and thorough in the monitoring and inspection of the construction. And of course, it is the responsibility of the contractor and the construction crews to perform their tasks at a competence level not less than that set by the codes and construction documents and drawings.

Inspection should be performed by certified inspectors who have no conflict of interest in the task at hand

5. Alternatives to RC Frames with Masonry Infills in Regions of High Seismic Risk

Why are Alternatives Needed

Engineers across the world have been designing RC frame buildings for many decades now. Experiences from earthquakes across the world have made it amply clear that earthquake resistance cannot be guaranteed in a RC building when its seismic safety relies solely on moment resisting frames (unless these frames are specially detailed). The problem is aggravated further by the use of unreinforced masonry infills. While infill walls are required to define the functional spaces in a building, their presence may be detrimental for the satisfactory seismic performance. It is not easy to achieve ductile seismic performance in RC frame buildings; special seismic detailing performed with an advanced level of construction skills and quality control is required. Constructing a RC frame building is not an easy task, and it involves a high level of skills related to constructing beams, columns, and beam - column joints. Inadequately reinforced beam – column joints pose a serious threat to basic frame behavior and can lead to devastating consequences, including the collapse of the entire building. In general, achieving satisfactory seismic performance of RC frame buildings subjected to several cycles of earthquake ground shaking is

considered to be a challenge even in highly industrialized countries with advanced construction technology.

Notwithstanding the above limitations, designers and builders in many countries have embraced RC moment resisting frames as the dominant system for multi-story buildings, and construction with this system is on the rise throughout the world. The authors of this tutorial would like to emphasize that RC moment resisting frames with infills should not be relied upon as a system that provides a satisfactory level of safety for buildings in regions of high seismic risk. Consequently, the alternative building systems discussed in this chapter are expected to provide a better level of seismic safety than the currently practiced non-ductile RC frame building system with masonry infills.

The Alternatives

The two alternative building systems are confined masonry and RC frames with RC walls. The former system is intended for low-rise construction (up to 3 to 4 stories tall), while the latter can be used for a wide range of building heights, however it is considered to be most economically feasible for medium-to-high rise Infill walls tend to collapse during strong shaking and therefore are not reliable for earthquake resistance

Use alternative structural systems instead of RC frames construction. The salient aspects of these two schemes are described below.

Confined Masonry Buildings

Background

Confined masonry construction consists of masonry walls (made either of clay brick or concrete block units) and horizontal and vertical reinforced concrete confining members provided on all four sides of a masonry wall. Vertical members, called tie-columns, resemble columns in reinforced concrete frame construction. Horizontal elements, called tie-beams, resemble beams in reinforced concrete frame construction.

The structural components of a confined masonry building are: (a) *Masonry walls* – transmit the

a) Masonry walls – transmit the gravity load from the slab down to the foundation, and also resist seismic forces. The walls must be confined by concrete tie-beams and tiecolumns to ensure satisfactory earthquake performance.

- (b) Confining elements (tie-columns and tie-beams) – provide restraint to masonry walls and protect them from complete disintegration even in major earthquakes; these elements do not resist gravity loads.
- (c) *Floor and roof slabs* transmit both gravity and lateral loads to the walls. In an earthquake, slabs behave like horizontal beams and are called diaphragms.
- (d) *Plinth band* transmits the load from the walls down to the foundation. It also protects the ground floor walls from excessive settlement in soft soil conditions.
- (e) *Foundation* transmits the loads from the structure to the ground.

The components of a typical confined masonry building are shown in Figure 57.

The appearance of finished confined masonry construction and frame construction with masonry infills may look alike to lay persons. However, these two construction systems are substantially different. The main differences are related to the construction sequence, as well as the behavior under seismic conditions.



Figure 57. Typical confined masonry building (source: Blondet 2005)

Confined masonry buildings look similar to RC frame buildings with infills, but perform significantly better during earthquake shaking

Use confined masonry construction for buildings from 1 to 4 stories in height

Item	RC Frame Building	Confined Masonry Building
Gravity and lateral load- resisting system	RC frame resists both gravity and lateral loads through beams, columns, and their connections.	Masonry walls are the main load-bearing elements and are expected to carry both gravity and lateral loads. Lateral loads are resisted by diagonal compression struts forming in the walls and tension and compression forces in end columns.
Foundation construction	Isolated footing beneath each column.	Continuous strip footing beneath the wall with the RC plinth band.
Superstructure construction sequence	 The frame is constructed first. Masonry walls are constructed at a later stage. 	 Masonry walls are constructed first. Subsequently, tie-columns are cast in place. Finally, tie-beams are

Table 1: Comparison of RC Frame and confined masonry buildings

Reinforcement detailing for confined masonry construction is simple

These differences are summarized in Table 1 and are illustrated in Figure 58. In confined masonry construction, confining elements are not designed to act as a moment resisting frame; as a result, the detailing of reinforcement is simple. In general, confining elements have smaller cross sectional dimensions than the corresponding beams and columns in a RC frame. Confining elements require less reinforcement than beams and columns in RC frame construction.

Advantages

Confined masonry offers an alternative to both unreinforced masonry and RC frame construction. This construction practice has evolved though an informal process based on satisfactory performance in past earthquakes. The first reported use of confined masonry construction was in the reconstruction of buildings destroyed by the 1908 Messina, Italy earthquake (Magnitude 7.2), which killed over 70,000 people. Subsequently, in 1940s this construction technology was introduced in Chile and Mexico. Over the last 30 years, confined masonry construction has been practiced in the Mediterranean region of Europe (Italy, Slovenia, Serbia), Latin America (Mexico, Chile, Peru, Argentina, and other countries), the Middle East (Iran), and Asia (Indonesia, China). It is important to note that confined masonry construction is practiced in countries and regions of extremely

constructed on top of the walls, simultaneously with the floor/roof slab construction.



Confined masonry construction requires less reinforcement than RC frame construction

Figure 58. (a) RC frame building, and (b) confined masonry building during construction, before the masonry is constructed the full height of the wall (source: Brzev 2006).

RC shear walls reduce the lateral sway of the building which generally reduces both structural and nonstructural damage high seismic risk. Several examples of confined masonry construction around the world, from Argentina, Chile, Iran, Serbia and Slovenia, are featured in the WHE (EERI/IAEE 2000). More details on confined masonry construction are provided in publications by Blondet (2005), Brzev (2006) and Anthoine and Taucer (2006).

RC Frame Buildings with RC Shear Walls

Background

Reinforced concrete (RC) frame buildings can be provided with vertical plate-like RC walls (often called shear walls), in addition to the slabs, beams, columns and infill walls, as shown in Figure 59. These RC walls should be continuous throughout the building height starting at the foundation level. The thickness can range from 150 mm in low-rise buildings to 400 mm in high-rise buildings. These structural walls are usually provided along both length and width of buildings. They act like *vertically-oriented* beams that carry earthquake loads downwards to

the foundation. Thus, a RC frame building with *RC shear walls* has two systems to resist the effects of strong earthquake shaking, namely:

- (a) a three-dimensional RC moment resisting frame (with interconnected columns, beams and slabs) (see Figure 59a), and
- (b) RC shear walls oriented along one or both horizontal directions of a building (see Figure 59b).

The columns of RC frame buildings with RC shear walls primarily carry gravity loads (i.e., the loads due to self-weight and the contents of the building). RC shear walls provide large strength and stiffness to buildings in the direction of their orientation; this significantly reduces lateral sway of the building and thereby reduces damage to structural and nonstructural components. Since RC shear walls also carry large horizontal earthquake forces, the overturning effects on them are large. Thus, design of their foundations requires special attention. RC shear walls are preferably provided along both the length and the width of a building. However, when provided along only one direction, an earthquake-resistant momentresisting frame (*i.e.*, grid of beams



Figure 59. RC Frame Buildings: (a) with three-dimensional RC columnbeam-slab frame only, and (b) with three-dimensional RC column-beam-slab frame and RC shear walls (source: Murty 2005).

Use RC shear walls for mediumrise to high-rise buildings and columns) must be provided along the other direction to resist earthquake effects.

Door or window openings can be provided in RC walls, but their size must be limited to ensure minimal interruption to the force flow through the walls. Moreover, the openings should be symmetrically located. Special design checks are required to ensure that the area of a wall at an opening is sufficient to carry the horizontal earthquake force. RC walls in buildings must be symmetrically located in plan to reduce the ill-effects of twist in buildings (see Figure 60). They could be placed symmetrically along one or both directions in plan. RC walls are more effective when located along the exterior perimeter of the building: such a layout increases resistance of the building to twisting.

RC walls are oblong in cross-section, i.e., one dimension of the cross-section is much larger than the other. While rectangular cross-section is common, L- and U-shaped sections are also used (see Figure 61). Hollow RC shafts around the elevator core of buildings also act as shear walls.

RC shear walls need to be designed and constructed in a manner such that a ductile behavior is ensured. Overall geometric proportions of the wall, types and amount of reinforcement, and connection with remaining elements in the building also help in improving their ductility. Seismic provisions of building codes in various countries provide guidelines for ductile detailing of RC shear walls.

In a RC shear wall, steel reinforcing bars are to be provided in regularly spaced vertical and horizontal grids (see Figure 62a). The vertical and horizontal reinforcement in the wall can be placed in one or two parallel layers (also called curtains). Horizontal reinforcement needs to



Figure 60. RC wall layout must be symmetric to avoid undesirable twist effects: (a) Unsymmetric location of RC walls is not desirable, and (b) Symmetric layout of RC walls about both axes of the building and along the perimeter of the building is desirable (source: Murty 2005).



Symmetrical placement of shear walls along the building perimeter will ensure the best earthquake performance be anchored at the wall ends. This reinforcement should be distributed uniformly across the wall crosssection.

Under the large overturning effects caused by horizontal earthquake forces, end regions of shear walls experience high compressive and tensile stresses. To ensure that shear walls behave in a ductile manner, the wall end regions must be reinforced in a special manner to sustain these load reversals (see Figure 62b). End regions of a wall with increased confinement are called *boundary elements*. The special confining transverse reinforcement in boundary elements is similar to that provided in columns of RC frames. Sometimes, the thickness of the shear wall in these boundary elements is also increased. RC walls with boundary elements have substantially higher bending strength and horizontal shear force carrying capacity, and are therefore less susceptible to earthquake damage than walls without boundary elements. For more detail on RC shear walls, refer to Paulay & Priestley (1992).

Advantages

Properly designed and detailed buildings with RC shear walls have shown very good performance in past earthquakes. The 1985 Llolleo, Chile earthquake (M 7.8) exposed many RC buildings with shear walls to extremely severe ground shaking. Most of the buildings of this type suffered minor damage or remained undamaged (Moroni and Gomez, 2002). 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 (M 7.2) (Bostenaru and Sandu, 2002). RC shear wall buildings were exposed to the 1979 Montenegro earthquake (M 7.2) and the 1993 Boumerdes, Algeria earthquake (M 6.8). The buildings were damaged due to severe groundshaking, however collapse was avoided.



Figure 62. Layout of main reinforcement in shear walls as per IS:13920-1993 – detailing is the key to good seismic performance (source: Murty 2005).

Boundary elements = highly reinforced regions with closed loop ties at both ends of the shear wall RC shear walls in high seismic regions require special detailing. However, in past earthquakes, even buildings with sufficient amount of RC shear walls that were not specially detailed for seismic performance (but had enough well-distributed reinforcement) performed well.

RC frame buildings with shear walls are a popular choice in many earthquake prone countries, like Chile, New Zealand and USA, because of the following advantages:

- (a) RC shear walls are effective in providing earthquake safety and avoiding collapse.
- (b) Reinforcement detailing of RC shear walls is less complex than detailing of ductile RC frames.
- (c) The construction cost for a RC frame building with shear walls is generally less than that of an otherwise identical RC frame building without shear walls.

In major damaging earthquakes, buildings with RC shear walls suffered damage, however collapse was avoided

6. Retrofitting RC Frame Buildings

Introduction

Thus far, this document has focused on the problems associated with planning and design of new RC frame buildings with masonry infills. However, an enormous stock of RC frame buildings exists in countries and regions prone to moderate or major earthquakes. These buildings are mainly concentrated in rapidly growing urban areas. In many cases, the local population considers them as the construction type of choice for residential apartment buildings. Unfortunately, one of the major causes of seismic vulnerability associated with these buildings is that, in developing countries, a large number of existing RC frame buildings have been designed by architects and engineers who may not have formal training in seismic design and construction and/or they have been built by inadequately-trained construction workers.

The estimated number of vulnerable RC frame buildings in seismic zones across the world is staggering. In an ideal world, it would be great to strengthen all these buildings in order to protect them from the effects of future earthquakes and minimize fatalities and property losses. *Seismic strengthening* (also known as seismic retrofitting) represents a judicious modification of the structural components in a building with a purpose to improve its performance in future earthquakes. Seismic retrofit can take place

before an earthquake (as a preventive measure) or after an earthquake, when it is usually combined with the repair of earthquake-induced damage. It should be noted that seismic retrofitting is required not just for building structures (including foundations) but also for their nonstructural components, e.g., building finishes and contents. With the current costs of building finishes and contents soaring to over two-thirds of the total building cost, seismic retrofitting of the non-structural components needs to receive due attention to ensure that the loss of property is minimised during earthquakes.

In theory, it would be possible to retrofit the majority of existing RC frame buildings. However, in a preearthquake situation, it is unlikely that funding is going to be available to retrofit significant number of these buildings in any one community. Consequently, there is a need to develop strategies and policies for prioritising buildings to be retrofitted according to their importance and funding resources. This section discusses some generic seismic retrofit strategies suitable for RC frame structures.

In some countries, prescriptive retrofit schemes are being implemented. Here, no calculations are performed to understand the strength and ductility capacities of the existing building; generic prescriptions are made for all buildings. This is an unacceptable approach and can lead to making the existing buildings unsafe. Seismic retrofitting is a modification of the structural and nonstructural components in a building that aims to improve a building's performance in future earthquakes

Vulnerability Assessment

Seismic assessment procedures are well-established. Three tiers of seismic vulnerability assessment are practiced for buildings, namely Rapid Visual Screening, Quick Structural Evaluation, and Detailed Assessment. These assessments are performed in telescopic sequence; when the building fails at one tier, it is subject to the next tier of assessment. Rapid Visual Screening is a quick assessment made in order to designate vulnerable buildings. It typically consists of configuration-related checks based on *t*he building layout and configuration discussed in Chapter 2 of this document, including load path, weak story, soft story, geometry, effective mass, torsion, and pounding.

Once a building is identified to be vulnerable through Rapid Visual Screening, it is subjected to the second assessment procedure, namely the Quick Structural Evaluation. It involves general strength related checks based on structural design aspects like shear and axial stress checks of the vertical members resisting earthquake loads. Again, once a building is identified as vulnerable through a Quick Structural Evaluation, it is subjected to the third assessment procedure, namely a Detailed Assessment. This detailed assessment is a quantitative and rigorous evaluation of the vulnerability of the building.

Detailed Assessments include a detailed vulnerability assessment of the *structural system* that resists the earthquake loads, as well as the *non-structural elements (i.e.,* the contents, finishes and elements that do not resist earthquake loads). Generic retrofit provisions for

nonstructural elements are outlined in FEMA 274 (1994). A considerable amount of literature is available on this subject internationally, e.g. FEMA 154 (1988), ATC 20 (1989), FEMA 310 (1998), FEMA 356 (2000), and most recently ASCE (2003), ASCE (2006), and ICC (2006).

Ways to Strengthen Existing RC Frame Buildings

Usually, *engineers* lead the seismic retrofit effort of the structural system, and *architects* lead the effort for nonstructural elements. While strategies for retrofit of non-structural elements are generally uniform, this is not true for structural retrofitting. Seismic strengthening measures identified for one RC frame building may not be relevant for another. It is therefore very important to develop retrofit solutions for each building on a caseby-case basis.

Earthquake resistance in RC frame buildings can be enhanced either by:

- (a) increasing their seismic capacity
 increasing stiffness, strength
 & ductility, and reducing
 irregularity--this is a conventional
 approach to seismic retrofitting
 which has been followed in the
 past few decades, or;
- (b) reducing their seismic response-increasing damping by means of energy dissipation devices, reducing mass, or isolating the building from the ground.

Both of these sets of measures require an appreciation of the overall seismic response of the building, and not just of individual structural members (see Figure 63).

Seismic vulnerability assessments help to pinpoint expected earthquake failures and help determine if structural retrofitting is necessary

Performance of a building in an earthquake can be improved by increasing its seismic capacity or reducing its seismic response Seismic capacity of existing buildings is typically enhanced by increasing strength or ductility of individual *existing* structural members (*e.g.*, jacketing existing beams and columns with steel, concrete or fiber-wrap overlays) or by introducing *new* structural members (*e.g.*, shear walls). In any case, the purpose is to significantly increase the ability of a building structure to resist earthquake effects.

The alternative approach is to reduce seismic forces in the structure either by installing special devices which can increase damping in the structure (so-called *seismic dampers*), or isolate a building from the ground by means of *base isolation devices*. These emerging technologies can be used to retrofit existing RC frame structures; however, their high cost and the sophisticated expertise required to design and implement such projects represent impediments for broader application at this time.

The following retrofit strategies for RC buildings described in this document have been used after recent earthquakes in several countries, or have a promise of becoming widely used in the future:

- Installing *new* RC shear walls or steel braces and tying them to the existing frame.
- Strengthening of *existing* masonry infills with fiber reinforced composites.
- Jacketing of *existing* individual structural components, such as columns and beams, using concrete or steel jackets, or composite fiber-wrap overlays.

Installation of New RC Shear Walls or Steel Braces

The most common, and perhaps the most effective, method for strengthening reinforced concrete frame structures consists of the installation of new RC shear walls, as shown in Figure 64. These walls are usually either of reinforced concrete or (less frequently) of reinforced masonry construction.

New RC shear walls must be installed at strategic locations in order to minimize undesirable torsional effects. Also, these walls must be reinforced in such a way as to act together with the existing structure. Careful detailing and material



Figure 63. Seismic retrofitting strategies for lateral load resisting structural system (source: Durgesh C. Rai).

To increase the capacity of a structural system, the individual components may be strengthened and/or new structural members may be added

The most effective retrofit for RC frame structures is to install new RC shear walls at strategic locations



selection are required to ensure an effective connection between the new and existing structure. The addition of shear walls substantially alters the force distribution in the structure under lateral load, and thus normally requires strengthening of the foundations. This method was extensively used in Turkey after the 1999 earthquakes (Gulkan et al. 2002) and in Taiwan after the 2001 Chi Chi earthquake (Yao and Sheu 2002). Figure 65 shows a retrofit concept for RC frames based on the installation of new shear walls.

In some cases, installation of new reinforced concrete shear walls is combined with the column jacketing, as shown in Figure 66. Jacketing also has a beneficial effect of increasing the strength and ductility of existing reinforced concrete columns, as previously discussed. This technique is usually implemented when it is not possible to achieve an effective connection between the new and the existing structure using the steel dowels. (In some countries, the practice of using chemical anchors, which act as dowels, is not very well developed.)

As an alternative to installing the new RC or masonry shear walls, steel braces can be provided to increase earthquake resistance of these buildings. Figure 67 illustrates a retrofit example from a recent test in Japan.



Figure 64. Installation of new shear walls (source: C.V.R. Murty).





Figure 65. Installation of new RC shear walls in an existing RC frame building– note dowels provided to tie the new and the existing structure (source: C.V.R. Murty, adapted from Gulkan et al. 2002).

New shear walls must be reinforced in such a way to act in unison with the existing frame structure



Figure 66. Retrofit of existing RC building using new RC shear walls and jacketing of the existing columns after the 2003 Boumerdes (Algeria) earthquake (photo: M. Farsi; drawing courtesy of CTC Algiers).



Figure 67. Retrofit of RC frames with steel braces – shake-table testing at E-Defence, Japan: a) short column failure at the ground story level; b) retrofit using steel braces (source: C. Comartin).

b

а

Jacketing can increase strength and ductilty of columns

Fiber Reinforced Polymer (FRP) overlays can be used to strengthen existing masonry infills or to jacket columns

Retrofit using FRPs need to be performed carefully, considering their brittle behavior.

Jacketing

Jacketing consists of installing new steel reinforcement bars (lateral ties and vertical bars) in order to increase strength and ductility of existing concrete members (usually columns), as shown in Figure 68. As a result of the jacketing, the column cross section is also enlarged. When new ties are installed in the beam-column joint region, the existing concrete in the joint region must be carefully removed. Figures 69 and 70 show the jacketing of RC frames in Colombia.

Alternatively, jacketing can be accomplished by means of steel straps and angles, as shown in Figure 71. In this case, straps act as lateral reinforcement (ties), while angles act as vertical reinforcement. These components are welded to ensure the integrity of the retrofit scheme.

Jacketing of RC columns was used to retrofit RC frame buildings in India after the 2001 Bhuj earthquake, and previously in Romania after the 1977 Vrancea earthquake (Bostenaru 2004). Some of the observed implementation flaws are:

- In some cases, retrofit was limited to ground floor columns only, which may not be sufficient; in some cases, the longitudinal bars added in the concrete portion were left projecting out without any connection to the existing RC beam and column members above, as well as to the foundations below (see Figure 72).
- In most cases, the existing columns were *snugly* strapped with steel angles and straps (see Figure 72) before the concrete was poured. And, in many cases, the jacketing

was performed without any preparation of the existing concrete surface (the cover of the existing column should be chipped!).

- In most cases, the size of jacketed columns was inadequate even for gravity loads; however, in some cases column size became ridiculously large after the jacketing (see Figure 73).
- In some cases, jacketing of the columns discontinued at the ground floor level without extending into the foundations.

In recent years, use of composite fiber wraps to confine reinforced concrete columns has been increasingly common. This technology is simpler and ultimately less expensive than using steel bars. Fiber Reinforced Polymer (FRP) overlays can be applied circumferentially around reinforced concrete columns to provide confining reinforcement; this has been shown to increase both their strength and ductility. The fiber-wrap technology has been used worldwide for seismic retrofitting of reinforced concrete bridge piers and columns in buildings in the last decade. Detailed design procedures are outlined in publications developed by ISIS Canada (2001, 2003, and 2004).





Figure 68. Jacketing of existing RC columns using new RC encasement (source: NRC 1995).



Figure 69. Installation of reinforced concrete jackets from the foundation level up to the beam soffit; examples from Colombia (source: Mejia 2002).



Strengthening technique 3: New long-to-direk and transveriel veloperteente is added in beams and addresses



Figure 70. Jacketing of a beam-column joint region; an example from Colombia (source: Mejia, 2002).



Figure 71. Steel jacketing of existing RC columns (source: NRC 1995)

Jacketing consists of installing new steel reinforcement bars (lateral ties and vertical bars)that increase the column cross section



Figure 72. An example of improper steel-based jacketing: vertical steel angles battened with horizontal welded reinforcement bars, followed by the pouring of concrete; the battens do not continue into the upper floor beams nor do they start from the foundation level. The jacketing is limited to the ground floor level (photo: C.V.R. Murty).



Figure 73. An example of improper retrofit practice: jacketing of RC columns resulted in extremely large column sizes (note the absence of continuity with regards to upper floors and the foundation) (photo: C.V.R. Murty).

Strengthening Existing Masonry Infills

Installation of new RC shear walls in existing buildings is a timeconsuming effort. The application of this method is feasible in a post-earthquake situation, when a building is damaged and needs to be vacated. However, it may not be feasible to vacate an undamaged building. The need to perform retrofit in an inhabited building in a fast and effective manner has prompted research studies focused on the use of Fiber Reinforced Polymer (FRP) overlays to strengthen existing masonry infills. This emerging technology is being increasingly used to retrofit bridges and buildings in pre- and postearthquake situations. FRPs are light-weight materials characterized by significantly higher tensile strength when compared to steel reinforcement. Several types of fibers (including those made out of glass and carbon) embedded in epoxy-based resin are used to form sheets or bars. Another characteristic of FRPs is their brittle behavior; once their strength has been reached, these materials fail suddenly (similar to glass).

A major advantage of this retrofit scheme is its fast implementation, which can be performed within days or even hours (depending on the scope of work) and does not require relocation of building inhabitants. It should be noted, however, that a material cost for FRP sheets might be prohibitive for some building owners.

Extensive research on this subject was conducted at the Middle East Technical University (METU) in Turkey (Erdem et al 2004; Ozcebe et al. 2004). Carbon Fibre Reinforced Polymer (CFRP) sheets in the form of diagonal strips were used to strengthen existing masonry infills made of hollow clay tiles. The goal of the retrofit was to transform these nonstructural panels into shear walls capable of providing resistance to lateral earthquake forces. The strips were bonded to the RC frames by means of special dowels made from CFRP sheets. The results of the study showed that this method could be effectively used to increase strength and stiffness of RC frames; however, the effectiveness is strongly dependent on the extent of anchorage between the strips and the frame. It should be also noted that, due to the brittle nature of CFRP material and unreinforced masonry infills, this retrofit solution has only marginal influence upon the ductility of the existing structure. Figure 74 shows the test setup for the METU study.

Strengthening RC Frame Buildings with Open Ground Story

A large number of existing RC frame buildings across the world are those with open, flexible or weak ground stories; such buildings are extremely vulnerable to earthquakes, as discussed earlier in this document. Since this vulnerable building system is still constructed, practical retrofit schemes are discussed here. Generally, retrofitting of such buildings should ensure that a sudden and large decrease in the stiffness and/or strength is eliminated in any story of the building. There are a number of options for retrofitting existing open ground story buildings, as shown in Figure 75. It is often possible to retain the original function of the ground level (i.e. parking) while reducing the flexibility or weakness

Buildings with open, flexible or weak ground stories are *EXTREMELY* vulnerable in earthquakes
of the building. Developing detailed retrofit solutions is a timeconsuming task which requires an advanced level of expertise. Due to several constraints, including human and economic resources, it is not possible to retrofit all vulnerable buildings of this type located in high seismic risk areas. Therefore, the following two strategies are proposed to deal with this problem: a short-term goal (to prevent collapse), and a long-term goal (to ensure improved seismic performance as a result of the retrofit).

Short Term Goal = Prevent Collapse

Once the vulnerable building with open ground story has been identified, the foremost responsibility is to urgently improve the safety of open ground story buildings, before the next earthquake strikes and brings



Figure 74. Configuration of CFRP strips and anchor dowel locations (source: C.V.R. Murty, adapted from Erdem et al. 2004).



Figure 75. Options for seismic retrofitting of open ground story buildings: (a) infilling openings at the ground floor level; and (b) installation of continuous RC shear wall (source: C.V.R. Murty).

them down. One quick solution is to install masonry infill walls in the ground story between as many columns as possible (see Figures 75a and 76).

Long Term Goal = Improve Seismic Performance

For selected existing buildings and for all new buildings that have open ground stories, the stiffness and strength irregularity in the ground story should be minimized, if not eliminated. In the ground story, RC walls can be built in select bays but running continuously along the full height of the building (see Figures 75b and 77); the other bays can be infilled with masonry walls or left open. Of course, in the upper stories, the other bays will be infilled with masonry walls. Using these types of solutions (designed by a qualified engineer for each particular building), good earthquake behavior will be ensured.

How Seismic Retrofit Affects Structural Characteristics

The above retrofit methods, when properly implemented, influence one or more of the following structural characteristics:

- *Strength* it is desirable for a retrofit to increase the strength of an existing structure, that is, the level at which the structure or its components start to fail.
- *Stiffness* most retrofit methods also affect the stiffness of a structure, that is, its ability to deform (sway) when subjected to seismic forces – stiff structures sway less than flexible structures when subjected to same lateral forces.
- *Ductility* it is very desirable for a retrofit method to increase ductility of an existing structure, that is, its ability to deform substantially before the failure.



Figure 76. Short-term solution to the seismic vulnerability of an open ground story building after the 2001 Bhuj earthquake: note the open bays in the ground story infilled with new masonry walls (photo: C.V.R. Murty).

The stiffness and strength irregularity in the ground story should be minimized or eliminated altogether Usually, a retrofit method influences one or more structural characteristics. The effects of retrofit methods discussed in this document are summarized in Table 2.

Retrofitting RC Frames with Masonry Infills: Implementation Challenges

A few common retrofit methods suitable for RC frames with infills have been discussed in this section. The descriptions are meant to provide an insight into retrofit concepts rather than offer detailed solutions. Retrofit design must be done by qualified professionals before field implementation takes place. A thorough seismic analysis needs to be performed, wherein the analysis model for an existing structure is developed, and the effect of retrofit of each existing structural member is quantified. New structural members (e.g. RC shear walls) added to the existing structure must be incorporated in the structural model at the analysis stage. Several computer analysis software packages suitable for this purpose are commercially available. However, the key for success for building owners and implementing agencies is to engage knowledgeable engineers with a background in seismic design and retrofit and structural engineering in general.

In a post-earthquake situation, governments and private sector agencies are faced with a daunting task



Figure 77. Long-term solution for open ground story buildings: continuous RC shear walls provided along the building height to overcome the reduced stiffness and strength caused by the open ground story structure (source: Murty 2005).



	Results in the increase of		
Retrofit Method	Strength	Stiffness	Ductility
Installing new RC walls	YES	SIGNIFICANT	SIGNIFICANT
Strengthening existing masonry infills with CFRPs	YES	SIGNIFICANT	VERY SMALL
Jacketing	YES	MODERATE	MODERATE

associated with handling massive projects focused on rehabilitating hundreds or even thousands of buildings. However, it must be recognized that each building is unique and that seismic retrofit schemes identified for one RC frame building may not be relevant for another. Retrofit requirements depend on many factors, including the seismic hazard of the building site, local soil conditions, expected seismic performance, and type and age of the structure. Thus, mass retrofitting strategies are not meaningful in the case of RC frame buildings, unless the buildings have the same deficiencies and failure modes.

Another challenge associated with implementing retrofit of RC frame buildings with infills lies in the limited expertise related to both design and construction of seismic retrofit projects. Retrofitting is an advanced process and, in most cases, requires a higher level of expertise than that required for design and construction of new buildings. Developing countries are more significantly faced with this problem, particularly in a postearthquake situation. Some of the challenges which implementing agencies are faced with due to the lack of expertise and experience include:

- Finding out retrofit cost estimates for various types of structures (RC frames, masonry buildings, etc.);
- Identifying and using

equipment required for undertaking modifications/ enhancements of existing structural elements;

- Estimating the time required to complete the retrofit for a specific building depending on its size and construction type; and
- Finding the construction labor with the set of skills required for the retrofit implementation.

The above challenges highlight an urgent need for a dialog between all stakeholders within countries and regions at risk from earthquake disasters. Road maps are required to estimate the required human resources and equipment, and establish effective construction management systems for implementing seismic retrofitting projects of vulnerable RC frame buildings in pre- or post-earthquake situations across the world.

required for seismic retrofitting of vulnerable RC frame buildings in high seismic risk areas worldwide

Road maps

are required to

estimate the human resources and equipment

In most cases, retrofit design and construction of retrofit measures in existing buildings requires a higher level of expertise than that required for design and construction of new buildings

Table 2: Retrofit Methods and their Effect on Structural Characteristics

7. Conclusions

This document highlights the poor seismic performance of RC frame buildings with masonry infills, and documents the underlying design and construction factors causing such performance. There is a significant concern in the earthquake engineering community that many of these buildings, already built and standing throughout the world, are potential death traps in future earthquakes. And even the new ones being built can be potentially dangerous if attention is not paid to the critical design, construction and management issues.

Technical Challenges

The design and construction of RC frame buildings require many small but vital factors to make these buildings earthquake-resistant. As discussed in this document, the primary challenges in RC frame construction are to ensure:

- (a) that columns are stronger than the beams
- (b) that the rebars in the beamcolumn joints allow proper concreting 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 flexible in the horizontal direction, either in any one story or in the whole.

In general, it is very difficult to design, detail and construct RC frames to perform well in earthquakes, even though the required additional factors are only incremental in nature, including the costs. For instance, the column ties need to be provided with 135° bends at the ends of the hooks, as opposed to 90° bends in RC frames made in non-seismic areas. The additional effort and cost are nominal, but the consequences of not making this change can be catastrophic. When special attention cannot be paid to design, detailing and construction, RC frames alone should not be used to resist lateral loads. Alternative lateral load resisting systems are required.

This tutorial on RC frame buildings encourages the use of the following two alternative structural systems to resist lateral loads:

- (a) RC shear walls continuous from the foundation to the roof provided in medium-tohigh-rise RC frame buildings; and
- (b) Confined masonry construction, that is, a combination of RC confining elements (tie-beams and tie-columns) and masonry walls, is suitable for low-rise buildings (one-to-four stories high).

Stakeholders

There are several important players in drawing the needed attention to these issues. Readers of this document should evaluate how they can use their role in the construction process to encourage safe design and construction. This enormous problem can become more manageable if each individual with a role in the design and construction process Architects, building owners, construction managers, designers, engineers, and municipal agencies all play important roles in improving performance of RC frame buildings with masonry infills in earthquakes takes responsibility to learn how he or she can personally influence the process. The key stakeholders and their respective roles are summarized below:

- Architects need to understand that their designs can directly influence building performance in an earthquake, and should refrain from designing complex shapes causing potential torsional problems. They need to understand that masonry infills are not just architectural components, but rather, have fundamental influence on the structural performance of a building.
- **Building owners** must play an absolutely critical role by understanding the importance of earthquake resistance and insisting that seismic features become a part of new design and construction.
- Construction Managers can explicitly improve the earthquake resistance of new buildings by ensuring quality construction materials and quality workmanship.
- **Designers** must understand that their designs have important consequences on building performance in an earthquake. From simple issues such as the placement of a wall or a window, to more complex configuration issues, designers need to realize that every such decision has implications for earthquake performance.
- Engineers have a pivotal role in improving the performance of RC frame buildings in earthquakes and by paying careful attention to the design and construction issues outlined in this tutorial.

Municipal agencies such as building authorities, city planning departments, and municipal managers, need to enforce the use of building codes and seismic design standards in their communities. This role is essential. Without the enforcement and regulatory teeth that can be imposed by such authorities, earthquake-resistant design practices are not uniformly applied or enforced. An educated owner or a sophisticated engineer may incorporate such practices in a particular design, but government agencies have a opportunity, in fact a responsibility, to ensure that such practices are enforced throughout a community and not just on a building by building basis.

Closing Comments

As developing countries become more and more urbanized, seismic risks will rise dramatically unless fundamental changes in policy, design, and construction are implemented. The time for these changes is long overdue. It thus becomes the responsibility of all stakeholders involved in the design and construction process to advocate for safer building design and construction practices.

Ultimately, the problem of RC frame construction with masonry infills is not just an engineering problem. The authors of this document believe that the global community will benefit from the improved design and construction practices suggested here, and that fewer lives will be lost and less property significantly damaged in future earthquakes.

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