REINFORCED CONCRETE FRAME CONSTRUCTION

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BACKGROUND

Reinforced concrete is one of the most widely used modern building materials. Concrete is “artificial stone” obtained by mixing cement, sand, and aggregates with water. Fresh concrete can be molded into almost any shape, which is an inherent advantage over other materials. Concrete became very popular after the invention of Portland cement in 19th century; however, its limited tension resistance prevented its wide use in building construction. To overcome this weakness, steel bars are embedded in concrete to form a composite material called *reinforced concrete*. Developments in the modern reinforced concrete design and construction practice were pioneered by European engineers in the late 19th century. At the present time, reinforced concrete is extensively used in a wide variety of engineering applications (e.g., buildings, bridges, dams).

The worldwide use of reinforced concrete construction stems from the wide availability of reinforcing steel as well as the concrete ingredients. Unlike steel, concrete production does not require expensive manufacturing mills. Concrete construction, does, however, require a certain level of technology, expertise, and workmanship, particularly in the field during construction. In some cases, single-family houses or simple low-rise residential buildings are constructed without any engineering assistance.

The extensive use of reinforced concrete construction, especially in developing countries, is due to its relatively low cost compared to other materials such as steel. The cost of construction changes with the region and strongly depends on the local practice. As an example, a unit area of a typical residential building made with reinforced concrete costs approximately US\$100 /m^2 in India, US\$250/m^2 in Turkey, and US\$500/m^2 in Italy.

With the rapid growth of urban population in both the developing and the industrialized countries, reinforced concrete has become a material of choice for residential construction. Unfortunately, in many cases there is not the necessary level of expertise in design and construction. Design applications range from single-family buildings in countries like Algeria and Colombia to high-rises in Chile, Canada, Turkey, and China (Figure 1). Frequently, reinforced concrete construction is used in regions of high seismic

Figure 1: Typical residential RC frame building in Turkey (WHE Report 64, Turkey)

risk, such as Latin America, southern Europe, North Africa, the Middle East, and Southeast Asia.

REINFORCED CONCRETE FRAME BUILDINGS

Reinforced concrete (RC) frames consist of horizontal elements (beams) and vertical elements (columns) connected by rigid joints. These structures are cast monolithically—that is, beams and columns are cast in a single operation in order to act in unison. RC frames provide resistance to both gravity and lateral loads through bending in beams and columns (Figure 2). There are several subtypes of RC frame construction:

- Nonductile RC frames with/without infill walls
- Nonductile RC frames with reinforced infill walls
- Ductile RC frames with/without infill walls

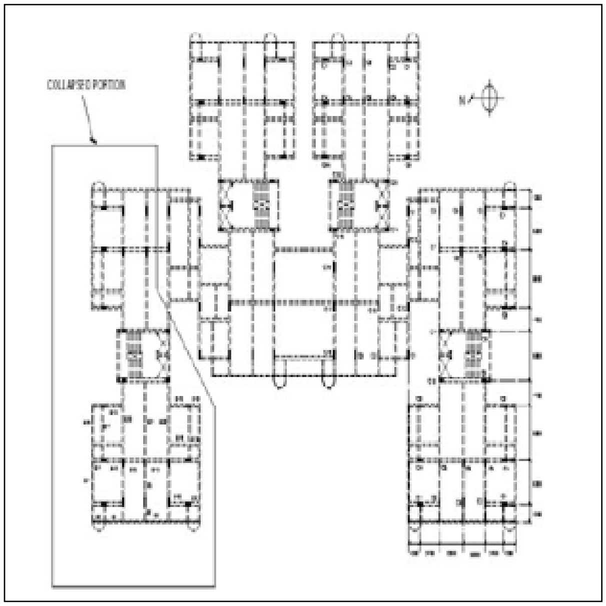

Figure 2: A plan of a typical RC frame building in Ahmedabad, India; note the portion that collapsed in the 2001 Bhuj earthquake (WHE Report 19, India)

The current WHE database includes over twenty reports describing RC frame construction. The most prevalent type is RC frame with masonry infill walls (Figure 3). This construction is still practiced extensively in many parts of the world, especially in developing countries. This construction comprises approximately 75% of the building stock in Turkey, about 60% in Colombia, and over 30% in Greece. Details of this construction type including regional variations are contained in the WHE reports from Cyprus (WHE Report 13), India (WHE Report 19), Palestinian Territories (WHE Report 48), Turkey (WHE Report 64), and Romania (WHE Report 71). RC frames with concrete infill walls, also known as dual systems, are very common in earthquake-prone areas. The WHE reports from Chile (Report 6) and Syria (Report 59) describe details of this construction type.

Code requirements related to design and detailing of RC frame buildings in seismic zones were significantly changed in the early 1970s. Earlier codes focused on the strength requirements—that is, on providing adequate strength in structural members to resist the lateral seismic forces. However, based on research evidence and lessons learned from earthquakes in the early 1970s, code requirements have become more focused on the proportioning and detailing of beams, columns, and joints with the objective to achieve a certain amount of ductility in addition to the required strength. *Ductility* is one of the key features required for desirable seismic behavior of building structures. It can be defined as the ability of a material to stretch (deform) significantly before failure. Steel (and some other metals) exhibit ductile behavior. For example, a metal paper clip can be bent back and forth without breaking. However, other materials are brittle (the opposite of ductile). A piece of chalk will break as soon as we try to bend it. In reinforced concrete, concrete behaves like chalk, whereas steel reinforcement behaves like a paper clip. Therefore, steel reinforcement has a key role in ensuring ductile behavior of reinforced concrete structures in earthquakes. Earthquake engineers spend a considerable amount of time trying to ensure that the amount and distribution of steel reinforcement are adequate for a specific design. That part of seismic design is called *seismic detailing*, or sometimes *the art of detailing*. The principles and rules of seismic detailing of reinforced concrete structures have been emerging over time and are mainly reflected in seismic provisions of building codes.

Thus, pre-1970 nonductile concrete frames, although often designed to resist lateral forces, did not incorporate modern ductile seismic detailing provisions. As a result, the main seismic deficiencies of the pre-1970s concrete frame construction include (ATC-40[1]):

- Inadequate column detailing. The two main detailing problems include inadequate column lap splices for main flexural reinforcement and a lack of adequate transverse reinforcement (ties) within the column (Figure 4). As an example, column lap splices were typically placed just above the floor level in the zone of high stresses. In addition, the column lap splices were generally too short, often in the order of 30-bar diameters, or less, and were typically not confined with closely spaced column ties (as required by modern codes).

- Lack of strong column/weak beam design approach. A capacity design approach was not followed in the design of the beam flexural reinforcement, as the beams were generally designed for the code level forces. The effects of post-yield behavior were not considered, thus increasing the chances for undesirable shear failure in either the beams or columns. Shear failure is rather brittle and sudden, and should be avoided in reinforced concrete structures located in seismic zones.

- Inadequate anchorage of beam reinforcement. The top reinforcing bars in beams were often terminated 6 to 8 feet away from the column face, whereas the bottom bars were typically discontinued at the face of the supporting column or provided with only a short lap-splice centered on the column.

- Excessive tie-spacing. Spacing of ties in beams and columns was excessively large by today's standards. Column ties often consisted of a single hoop with 90 degree hooks spaced at 12 to 18 inches on center. Today's ties generally require 135 degree hooks to ensure adequate confinement. Beam ties, often sized only for gravity shear loads, were spaced closely near the column face but were widely spaced or even discontinued throughout the mid-span region of the beam.

- Inadequate beam/column joint ties. The lack of ties in the beam/column joint created a weak zone and likely failure mechanism within the joint.

Figure 3: RC frame construction with hollow-clay tile masonry infill in Algeria (Credit: S. Brzev)

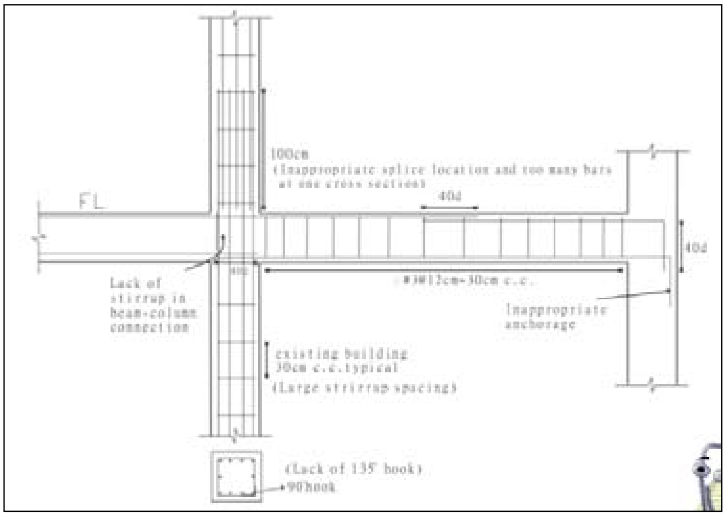

Figure 4: Features of nonductile RC frame construction in Taiwan (WHE Report 61)

SEISMIC PERFORMANCE

Earthquake performance of RC frame construction has been well documented. Damage patterns in reinforced concrete frames during the 1971 San Fernando (California) earthquake have been extensively studied. More recently, several destructive earthquakes of the last decade, including the 1999 Athens (Greece) earthquake, the 1999 İzmit and Düzce earthquakes (Turkey), 1999 Chi Chi (Taiwan) earthquake, 2001 Bhuj (India) earthquake, and the 2003 Boumerdes (Algeria) earthquake, have caused substantial damage to RC frame construction. These earthquakes have revealed the following patterns of damages and failures in RC frame construction:

- Shear failure and concrete crushing failure in concrete columns. These are the most undesirable nonductile modes of failure (Figure 5). This behavior can lead to the loss of gravity load-bearing capacity in the columns and potentially a total building collapse.

Figure 5: Shear failure of a reinforced concrete column in the 2001 Bhuj earthquake (WHE Report 19, India)

- Partial ductile design and detailing. Systems that exhibit some (limited) yielding behavior can eventually form dangerous collapse mechanisms as a result of stiffness or strength degradation at sections without ductile detailing.

- Conceptual design deficiencies. This includes such deficiencies as incomplete load path and architectural planning deficiencies such as vertical and/or horizontal irregularities. Architectural features play an important role in the performance of RC frame buildings.

- Inappropriate column/beam relative strengths. This can lead to failure of individual members and connections when the "weak column-strong beam" mechanism develops.

- Inadequate detailing of reinforcement.

- Soft-story effects. In many applications, architectural considerations result in a taller first story, which causes a soft-story formation due to drastic change in the stiffness between adjacent stories (Figure 6). The presence of a soft story results in a localized excessive drift that causes heavy damage or collapse of the story during a severe earthquake (Figure 7). Another typical case of soft story arises when the first floor is left open (that is, no infills) to serve a commercial function (stores) or as a parking garage (very common in Turkey, India, and Cyprus), while upper floors are infilled with unreinforced masonry walls. A relatively rare case results when the strength of the two adjacent stories is significantly different (weak story) leading to localized deformations similar to the soft-story mechanism.

- Short-column effects. The short- or captive-column failure occurs due to partial restraining of the columns that are, in turn, subjected to high shear stresses and fail in shear if unable to resist these stresses.

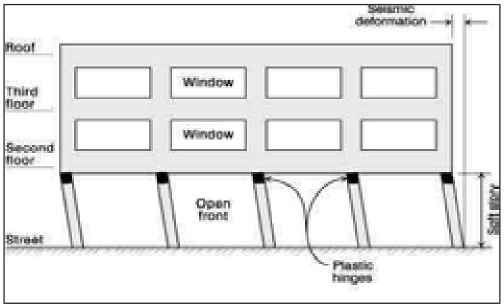

Figure 6: Soft-story mechanism
(WHE Report 61, Taiwan)

Figure 7: Building collapse due to soft-story mechanism in the 2003 Boumerdes earthquake (WHE Report 103, Algeria)

In several instances, seismic performance of RC frame buildings has been quite poor, even when subjected to earthquakes below the design level prescribed by code. One of the underlying reasons is the absence of an effective mechanism for code enforcement in some countries. This deficiency in governmental oversight is linked to several related factors, such as the lack of technical control and supervision, problems with the legal framework, low engineering fees, and improper regional construction practices. When one or more such factors are present during construction, the built structure does not comply with many aspects of the design. As a result, its seismic resistance becomes inadequate, with the consequence that unpredictable damage or failure results when subjected to loads below the code-prescribed levels. The key deficiencies identified in the RC frame construction practice include the following:

- Alteration of the member sizes during the construction phase from specifications in the design drawings
- Noncompliance of the detailing work with the design drawings
- Inferior quality of building materials and improper concrete-mix design
- Modifications in the structural system performed by adding/removing components without engineering input
- Reduction in the amount of steel reinforcement as compared to the design specifications
- Poor construction practice

SEISMIC REHABILITATION AND RETROFIT

With the enormous experience and available data on the earthquake performance of RC frame structures, their deficiencies are well known and can be identified with reasonable accuracy in some cases. Seismic assessment procedures are well established at the present time. In many areas with high seismic risk, existing reinforced concrete structures are being evaluated and retrofitted if found inadequate. A comprehensive amount of research has been directed towards developing seismic retrofit techniques applicable to RC frame structures.

Earthquake resistance in RC frame structures can be enhanced by either of the following approaches:

- Strengthening the components, such as columns and beams, by jacketing with concrete, steel, or fiber wrap overlays (see Figure 8)
- Increasing the overall capacity of the structural system by installing new concrete infill walls or steel bracings.

The most common rehabilitation measure is installation of new reinforced concrete infill walls (Figure 9) along with jacketing the columns to increase the strength of the existing structure. These new walls are reinforced in such a way as to act in unison with the existing structure. However, careful detailing and material selection is required to ensure that bonding between the new and the existing structure under earthquake loads is effective.

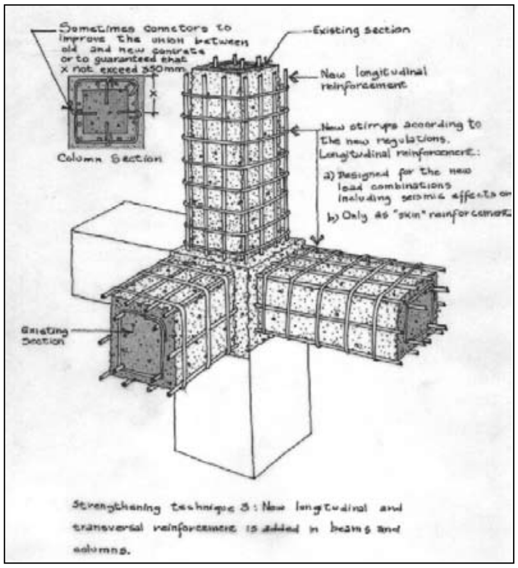

Figure 8: Jacketing of RC frame members (WHE Report 11, Colombia)

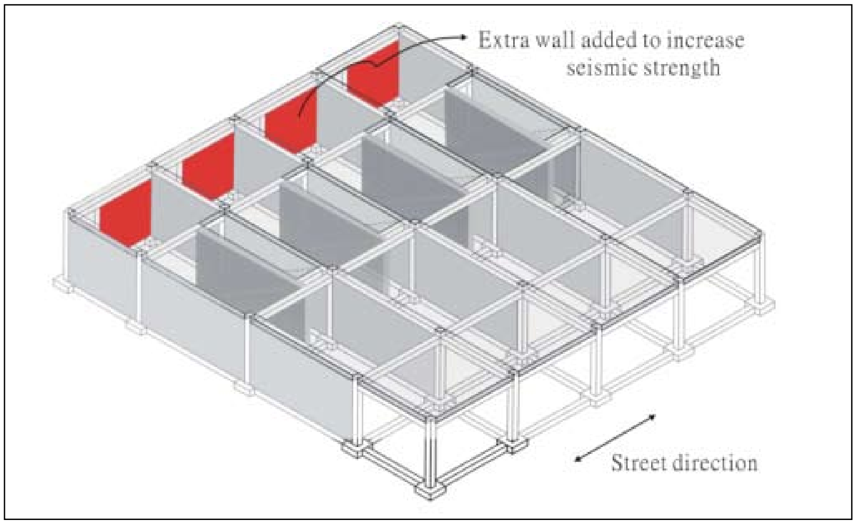

Figure 9: Illustration of seismic strengthening with addition of RC infill walls (WHE Report 62, Taiwan)

An alternative procedure which has been recently developed for RC frames with unreinforced masonry infill walls proposes the use of carbon-fiber, reinforced polymers (CFRP) applied on existing unreinforced masonry infill walls (Figure 10) to increase the overall lateral load capacity. Although its cost is higher, this method is easy to apply and much faster when compared to the installation of new concrete infill walls (Ozcebe et al.[2]).

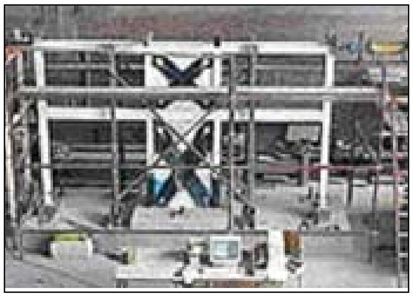

Figure 10: Strengthening of brick-infilled RC frame with CFRP

ENDNOTES

[1] Applied Technology Council (ATC), 1996. *Seismic Evaluation and Retrofit of Concrete Buildings.* Vol.1, Report No. SSC 96-01, (ATC-40).

[2] Ozcebe, G., Ersoy, U., Tankut, T,, Akyuz, U., and Erduran, E., 2004. Rehabilitation of existing RC structures using CFRP fabrics. *Proceedings of the 13th World Conference on Earthquake Engineering,* Vancouver, Canada, Paper No. 1393.