Investigating Concrete Shear Wall Construction

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Abstract: Buildings with cast-in-situ reinforced concrete shear walls are widespread in many earthquake-prone countries and regions, such as Canada, Chile, Romania, Iran, Turkey, Colombia, the republics of the former Soviet Union, etc. This type of construction has been practiced since the 1960s in urban regions for medium- to high-rise buildings (4 to 35 stories high). Shear wall buildings are usually regular in plan and in elevation. However, in some buildings, lower floors are used for commercial purposes and the buildings are characterized with larger plan dimensions at those floors. In other cases, there are setbacks at higher floor levels. Shear wall buildings are commonly used for residential purposes and can house from 100 to 500 inhabitants per building. This type of construction has been described in the WHE reports from Chile (Report 4), Kyrgyzstan (Report 40), Canada (Report 79), Iran (Reports 78 and 87), Turkey (Report 101), and Colombia (Report 109).

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1. Introduction

The lateral and gravity load-resisting system consists of reinforced concrete walls and reinforced concrete slabs. Shear walls are the main vertical structural elements with a dual role of resisting both the gravity and lateral loads. Wall thickness varies from 140 mm to 500 mm, depending on the number of stories, building age, and thermal insulation requirements. In general, these walls are continuous throughout the building height; however, some walls are discontinued at the street front or basement level to allow for commercial or parking spaces. Usually the wall layout is symmetrical with respect to at least one axis of symmetry in the plan (Figure 1). Floor slabs are either cast-in-situ flat slabs, or, less often, precast hollow-core slabs. Slab thickness varies from 120 mm in the republics of the former Soviet Union, to 220 mm (the latter value corresponds to hollow-core slab used in Kyrgyzstan and other parts of the former Soviet Union). Buildings are supported by concrete strip or mat foundations; the latter type is common for buildings with basements. Structural modifications are not very common in this type of construction.

Code requirements, related to the seismic forces the shear wall buildings are designed for, depend on the seismicity of the building site, the method of analysis used, and the country specific seismic design provisions. For example, the Iranian seismic code prescribes a base shear coefficient for shear wall buildings of 5 to 6.7%, depending on the seismic zone. The maximum allowed lateral-story drift is limited to 0.002 according to both the Iranian and Canadian seismic requirements for regular buildings and to 0.005 according to the Colombian seismic code (NSR-98).

Reinforcement requirements are based on building code requirements specific for each country. In general, the wall reinforcement consists of two layers of distributed reinforcement (horizontal and vertical) throughout the wall length (Figure 2). In addition, vertical reinforcement bars are provided close to the door and window openings, as well as at the wall end zones (also known as boundary elements or barbells).

Table 1: H/T vs damage relation, shear wall buildings (MMI VIII Intensity)

H/T (m/sec)	Indicates what?	Reported damage
> 70	Very rigid building	None
50 – 70		Non-structural damage
40 – 50		Light structural damage
30 – 40	Very flexible building	Moderate structural damage

In Canada, the National Building Code (1995 edition) classifies shear wall buildings into the nominally ductile and ductile wall systems, with the corresponding force modification factor (R) values of 2 and 3.5, respectively. Horizontal and vertical distributed reinforcement (ratio 0.25%) is required for all shear walls. In instances of ductile shear walls, at least 4 bars (0.25% of the wall area) are required at each end zone.

Shear wall buildings in Romania (WHE Report 78) have lightly reinforced walls, with one layer of 12-mm-diameter vertical bars and 8-mm horizontal bars. The reinforcement spacing varies from 150 mm to 250 mm for walls in the longitudinal and transverse direction, respectively. Transverse shear walls have boundary elements at the façade end.

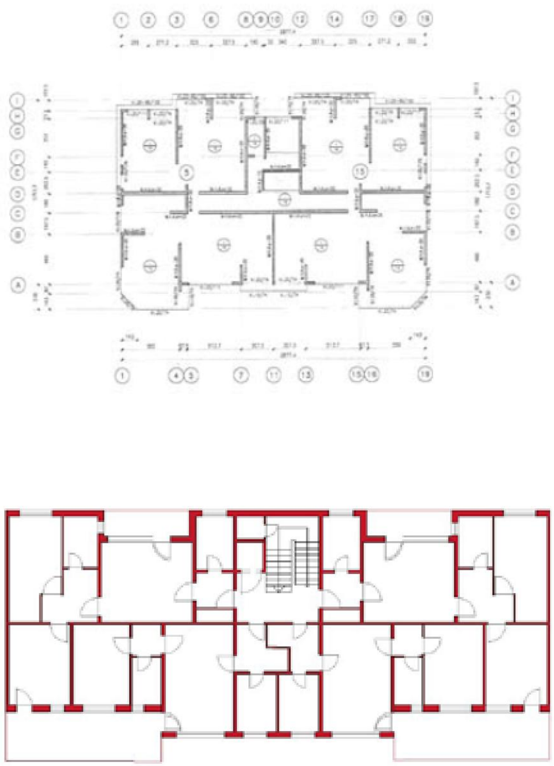

Figure 1: Plan of a typical shear wall building: (up) Iranian (WHE Report 4); (down) Romania (WHE Report 78)

In Iran, design of reinforced concrete structures is performed according to the ACI318- 95 Code. The shear wall design does not need to follow clauses 21.6.6.1 to 21.6.6.4 that refers to the design of boundary elements of the structural walls. Confinement reinforcement for vertical bars at wall ends or diagonal bars in coupling beams are rarely used. A reduced reinforcement cover is allowed.

In Colombia, the NRS-98 seismic code is also based on ACI318-95 and sub-chapter 21.6 is mandatory for shear walls located in moderate- or high-seismic areas.

Shear walls that are perforated with openings are called coupled walls. These walls act as isolated cantilevered walls connected by coupling beams (also called spandrel beams or lintels) designed for bending and shear effects. When designed in a ductile manner, these beams may act as fuses and are used to dissipate seismic energy. In Canada, the coupling beams are designed with diagonal reinforcement provided to ensure ductile seismic response. Reinforcement bars are joined together by welding or lap splices.

Exterior shear walls are clad in stucco backed by cold-form steel framing or masonry veneer, steel/glazing panels, or precast panels.

2. Material and Methods

2.1. CONSTRUCTION PROCESS

Usually, the pace of construction allows for the completion of approximately one floor/week. It is worth mentioning the tunnel-form construction method used in Turkey (WHE Report 101). In this case, the walls and the slab are cast in a single operation using specially designed half-tunnel-steel forms (upside down “U” shape), thereby cutting the construction time significantly.

The average unit construction cost including only structural parts (US$140-160/m2) is very similar in the countries with shear wall construction contained in the WHE, whereas the unit cost including finishes and land varies from US$500 to 1200/m2.

2.2. EARTHQUAKE PERFORMANCE

This building type is considered to be earthquake-resistant. Several reports indicate its good behavior in past earthquakes. On March 3, 1985, a magnitude 7.8 earthquake hit the central zone of Iran where most of the reinforced concrete buildings were located. Reconnaissance reports indicated extremely good seismic performance of these buildings, with very minor damage or no damage at all (Figure 4, Iran, and WHE Report 4).

Tunnel-form buildings have been exposed to the two major earthquakes in Turkey (the 1999 Izmit earthquake and the 2003 Bingol earthquake). These buildings performed extremely well, and no damage was reported. The same is true for the *Fagure* type buildings in Romania after the 1977, 1986, and 1990 earthquakes.

Unfavorable earthquake performance of these buildings in some earthquakes is related to inadequate construction quality, as was the case in Kichinev, Moldova (Kyrgyzstan, WHE Report 40). OD-type buildings suffered damage of various extents in the 1977 Vrancea (Romania) earthquake. According to the reports, damage was due to inadequate wall density in the longitudinal direction, inadequate amount and detailing of wall reinforcement, and the lack of lateral confinement in the walls and the boundary elements.

In Colombia, at least four moderate earthquakes (magnitudes 5.5–6.7) in the last 20 years have stricken the areas where shear walls buildings were located, and only minor nonstructural damages were reported.

Possible deficiencies that might adversely affect the seismic performance of this type of construction include: reduced wall density, soft-story mechanism, and torsional effects. In Iran, thinner walls are used in recent years and buildings are characterized with a smaller wall density. Also, some shear walls are reduced in length at the street or basement level to accommodate a commercial or a parking space. In Colombia, there is a tendency to use very thin walls with only one layer of reinforcement in new buildings; this can generate stability problems and cause buckling failure at the wall compression zone. Additionally, the most likely locations of possible earthquake damage are the end regions of spandrel beams that generally experience large shear stresses.

2.3. SEISMIC-STRENGTHENING TECHNOLOGIES

Due to their satisfactory seismic performance, there is a very limited experience related to seismic strengthening of shear wall buildings. Some strengthening strategies used in Romania include the following:

• Jacketing of boundary elements using cast-in-situ reinforced concrete (for walls with inadequate thickness and reinforcement)

• Crack injection with epoxy resin, grout, or mortar (for repairing the cracks in shear walls and coupling beams)

• Addition of new reinforced concrete shear walls (used in buildings with inadequate amount of shear walls in one direction)

3. Results

Qualifiers (indicators) that can be used to characterize shear wall buildings include the stiffness or mass distribution in plan or elevation (regular or irregular). Also, some additional quantitative parameters have been used, such as the ratio of the total building height over the fundamental period (H/T), story drift, P-Δ effect, top floor displacement, coupling index, redundancy index, and ductility capacity. All these parameters have been derived from a modal spectral analysis or a pushover analysis.

Wall density indicates the magnitude of lateral stiffness of shear wall buildings. It can be determined as a ratio of the wall area in each principal direction to the floor plan area. In general, wall density in shear wall buildings is rather high and the walls are rather uniformly distributed in the two principal directions. As a consequence, such buildings are rather stiff, lateral displacements or drifts are limited and the damage to nonstructural elements is minimized. For example, the total wall density in both directions in shear wall buildings in Kyrgyzstan is on the order of 15%, and the wall density in one direction is equal to 70–80% of the wall density in the other direction. The typical wall density in Turkish buildings is 4% in each direction (varies between 2–6%), whereas a large majority (95%) of buildings in Iran built in the period from 1960 to 2000 have wall density in one direction larger than 1.5% with an average of 2.8%1, (Figure 6). In Romania, the wall density in "Fagure" type buildings is 6.6–7.2% in each direction. However, the OD-type buildings in Romania are characterized with a single, centrally located wall in the longitudinal direction and eight walls in the transverse direction, thus resulting in a significantly smaller wall density in the longitudinal direction (1.4%) as compared to the transverse direction (4.8%). The wall density in Colombia is 3–5%, and the wall density in one direction is equal to 70–80% of the wall density in the other direction.

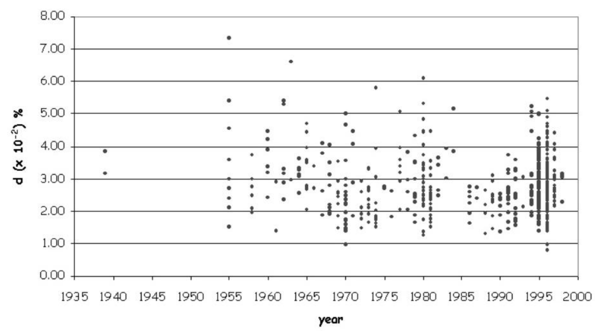

Figure 2: Wall density variation over time (WHE Report 4, Iran)

4. Discussions

H/T ratio also indicates the rigidity of a building. For example, buildings with H/T < 40 m/sec are considered to be flexible, whereas rigid buildings are characterized with H/T > 70 m/sec. From the observed structural performance in past earthquakes in Iran, the relation between H/T and the type of damage has been developed (see Table 1 below). (WHE Report 4, Iran).

The wall density per floor (*d/n*), indicates the building resistance in case of predominant shear behavior (note that *d* denotes wall density whereas *n* denotes number of stories in a building). Empirical rules indicate that when *d/n* in each direction is equal to 0.001, shear stresses developed in the walls are on the order of 0.6 MPa. This level of shear stresses can be easily resisted by regular reinforced concrete walls. This estimate is based on the following assumption: base shear force is equal to 0.06 times the total building weight and the floor weight is 1 *t/m2*; it should be noted that the above assumption is based on the Iranian conditions; however, it can be changed for other countries/conditions.

Table 2: H/T vs damage relation, shear wall buildings (MMI VIII Intensity)

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