On Structural Systems and Details
Adopted in R/C Residential Buildings
Damaged Severely
during the 1999 Chi-chi Earthquake in Taiwan

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Based on the field investigation results conducted against the severely damaged reinforced concrete (R/C) building structures, which were caused by the 1999 Chi-chi earthquake in Taiwan, some of the principal causes to the extensive earthquake damage are discussed here, mainly focusing on the typical structural systems and details adopted in the ordinary R/C residential buildings in Taiwan.

Key words: Chi-chi earthquake, structural damage, R/C residential buildings, structural systems, soft-lower story, role of structural walls

1. INTRODUCTION

On September 21, 1999, an earthquake of Richter Magnitude of 7.7 occurred at the central district of Taiwan, the Republic of China, and considerable amount of human and structural damage were caused by this earthquake. Death toll was more than 2,400 and 11,300 people were injured during this earthquake [Source: http://www.roc-taiwan.or.jp/menu.html], and approximately 10,000 dwelling and non-dwelling building structures were totally collapsed [http://921.ncree.gov.tw/chi-main.php3].

In order to investigate the structural damage to the building structures caused by this earthquake, field investigation was conducted by authors during the period from the 6th through 11th of October in 1999, and a total of 285 different buildings with extensive earthquake damage were investigated in the damaged areas located in the central districts of Taiwan.

As the results of this field investigation, it was understood that most of the severe structural damage was concentrated in the first stories of low-rise and medium-rise R/C residential buildings with commercial spaces in their first stories [Reference 1].

Herein, based on the field investigation results on those damaged buildings which are introduced in Reference (1), the effects of typical structural systems adopted in Taiwan’s R/C moment resisting frames on those extensive earthquake damage are discussed.

Since those extensive earthquake damage were concentrated in the lower-stories of the low- and medium-rise R/C moment resisting frames where unreinforced brick or block masonry infill wall panels were provided in the openings enclosed by the cast-in-place R/C column- and beam-members with poor structural details, it is concluded that, if the adequate amounts of reinforced structural walls were provided in both vertical and horizontal directions of the buildings, then those walls would be able to play an effective role to prevent or reduce such a severe structural damage to the R/C building structures during this earthquake.
2. TYPICAL DAMAGE TO LOW- AND MEDIUM-RISE R/C RESIDENTIAL BUILDINGS

During this earthquake, there were a large number of low- and medium-rise residential buildings damaged severely in their first stories. Structural systems adopted in those buildings were R/C moment resisting frames with a soft or weak first-story. In most of the cases, those buildings were located and faced very closely to the roadway or wide streets. In the first-stories of those types of buildings in Taiwan, there are generally walkway(s) (or sidewalk(s)) provided along the roadway or along the corner of the street-crossing. In addition, commercial spaces such as stores and/or shops are provided in their first-stories, while in the upper stories of the buildings, there are residential spaces with much more structural and non-structural walls in both longitudinal and transverse directions of the buildings in plan. Those buildings with extensive earthquake damage in their first-stories can be classified into the following two types according to the structural systems being adopted:

2.1 R/C Moment Resisting Frames with Soft First-story in One Direction Only:

A large number of severe structural damage to the buildings with a soft first-story have been reported during the recent destructive earthquakes in earthquake countries. One of the typical structural damage in the case of Taiwan earthquake can be observed also in the R/C moment resisting frames with a soft (or weak) first-story in only one direction of the buildings. Figure 1 shows an illustrative example of this type of popular R/C residential building with commercial spaces in its first story. Herein, it can be noted that this type of building in Taiwan is usually located very closely to the adjacent street, and in the first story of the building,
there is generally a walkway provided along the roadway as being observed in Figure 1 and Photos 1 and 2. In addition to these walkways, openings (or entrances in many cases) for commercial spaces are usually located facing to the walkway. As the result, there are numerous independent R/C long columns without any attached wall panels located in the first-story roadside of the building. On the contrary, there are infill walls provided in both of the extreme edges of the building and column lines perpendicular to the walkway as shown in Figure 1. Since second through upper stories of this type of buildings are usually used as the residential spaces with much more amount of structural and non-structural walls provided in both longitudinal and transverse directions in plan, most of those buildings become to have a soft first-story in only one (longitudinal, or parallel to the road) direction, which resulted in the typical soft first-story failure of the R/C buildings as being observed in Photos 3 through 6.

2.2 R/C Moment Resisting Frames with Weak Rotational Resistance in First-story:
Another type of the typical structural damage in low- and medium-rise complexes having residential and commercial spaces is observed also in the R/C moment resisting frames with poor rotational rigidity and strength in the first-story of the buildings. Figure 2 shows an illustrative example of this type of popular R/C residential building with commercial spaces in its first story. Again, it is worthy of note that this type of building in Taiwan is usually located very closely to the corner of the adjacent road crossing, and in the first story of the building, there is generally one walkway provided along the corner of the road-intersection as shown in Figure 2 and Photo 7. In addition to this walkway, window-openings and entrance(s) for the first-story store(s) are usually located facing to this walkway. As the result, there are numerous independent R/C long columns without any attached wall panels located in the first-story roadside of the building. On the contrary, there are infill walls provided in
both of the opposite extreme edges of the building forming an L-shaped wall arrangement in plan as shown in Figure 2. Since second through upper stories of this type of buildings are usually used as the residential spaces with much more amount of structural and non-structural walls in both directions of the buildings in plan, most of those buildings become to be a weak first-story in the rotational direction, which resulted in the typical soft first-story failure of the R/C buildings as being observed in Photos 8 through 12.

Photo 8 Damage to a Building with Poor Rotational Resistance in First-story

Photo 9 Damage to First-story Long Columns in Building Shown in Photo 8
3. TYPICAL DAMAGE TO HIGH-RISE R/C RESIDENTIAL BUILDINGS

In addition to the earthquake damage to the low- and medium-rise residential and commercial complexes which had soft or weak first-stories as mentioned above, there were a number of high-rise residential buildings damaged severely in their lower stories during this earthquake. As mentioned later in Discussions of the present paper, most of those earthquake damage were caused by the total or partial collapse of R/C long- and/or short-columns located in the lower-stories of those buildings. Due to those structural damage to the principal R/C members, some of the buildings leaned and/or overturned as shown in Photos 13 through 15.
4. DISCUSSIONS ON SEVERE STRUCTURAL DAMAGE

4.1 Design Earthquake Forces for Building Structures in Taiwan

Based on the Uniform Building Code (UBC) and SEAOC Code in the United States (US), the modern seismic resistant design code for building structures was firstly established in 1974, where base shear ($V$) was given by the product of zoning factor ($Z=0.75~1.25$), horizontal factor for buildings ($K=0.67~1.33$), base-shear coefficient ($C=0.1$) and a total weight of the building ($W$). In 1982, occupancy importance factor ($I=1.0~1.5$) was newly introduced for determining the base-shear so as that $V=ZKICW$, and at the same time, higher value of ($C$) was revised as ($C=0.15$). Although a small correction for $C$-values in Taipei District was made in 1989, those seismic design forces have been used for ordinary building designs until 1997, when the current design standards was published [Reference 2]. As the results, it can be understood that most of the building structures which were damaged severely during this earthquake had been designed based on the relatively smaller design seismic forces. This fact seems to be one of the principal causes to the severe structural damage to the buildings which were subjected to high earthquake ground motion during the earthquake.

4.2 Structural Systems

As mentioned in Sections 2.1 and 2.2 of the present paper, it seems that many of the severe structural damage in their first-stories of the low- and medium-rise R/C residential buildings were mainly caused by the inadequate structural system adopted in their R/C moment resisting frames, such as:

1. The soft (or weak) first-story in one direction only, especially in the buildings located along the roadway, and
2. The weak rotational resistance in first-story, especially in the buildings located at the corner of the road-crossing.

In addition to those low- and medium-rise residential building damage as described above, some of the extensive damage to the first-story R/C short- and long-columns occurred in high-rise residential buildings (Photos 16, 17, 18 and 19) are seemed to be coming from;

3. The insufficient amount of structural walls provided in both longitudinal and transverse directions in plan especially in lower stories of the buildings,
4. The insufficient amount of structural walls provided along the height (or vertical direction) of the buildings, and
5. Irregular arrangement of structural walls provided within the whole building.
4.3 Important Role of Structural Walls
Since most of the extensive earthquake damage to the R/C buildings was concentrated in the lower-stories of R/C moment resisting frames, where insufficient amount of unreinforced brick or block masonry infill wall panels were provided in the openings enclosed by the cast-in-place R/C column- and beam-members with poor structural details, it can be understood that, if the adequate amounts of the high quality reinforced structural walls which were provided in both vertical and horizontal directions of the buildings with reasonable wall arrangement system, then these walls would be able to play a very important and effective role to prevent (or reduce) such a severe structural damage to the R/C building structures during this earthquake. This is because adequate amount of structural walls especially in lower-stories of the building can resist not only to the lateral earthquake forces but also to the vertical gravity loads of the building even after little crushing or failure occurs in the lower-story independent R/C columns. It is important to remember that there were almost no severe structural damage observed in a tremendously large amount of medium-rise R/C boxed-wall residential buildings during the 1995 Kobe earthquake in Japan.

4.4 Structural Details and Material Properties
In many of the low- and medium-rise R/C moment resisting frames which had extensive earthquake damage in their first-story independent columns, inadequate structural details as shown in Photos 21 and 22 were frequently observed, where vinyl plastic pipe(s) for water exhausting was buried within the core of the R/C column-section enclosed by the transverse hoop reinforcement. This kind of R/C column cross-sectional details seems to be popular in Taiwan because other examples were observed even in some R/C columns in the new building construction-site during the field investigation. This must be avoided because of the important role of the core concrete confined by the transverse reinforcement in R/C column-sections. Also poor concrete quality and construction management were observed in numerous damaged concrete members in building structures (Photo 22).

5. CONCLUDING REMARKS
Although considerable amounts of structural damage to the building structures were caused by the 1999 Taiwan
earthquake, some of the typical damage to the R/C residential buildings having soft or weak lower-stories were introduced first, and then principal causes to those severe structural damage were discussed. Special emphasis in discussion was placed on the structural systems adopted in many of the low- and medium-rise R/C residential buildings with commercial spaces in their first-stories. Finally it is concluded that the adequate amounts of reinforced structural walls, which are provided in both horizontal directions in plan, as well as vertical direction along the height of the buildings, play an important role to prevent or reduce such a severe structural damage to the R/C building structures in earthquake countries.

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7. REFERENCES
