

Overview of Building Damages in 921 Chi-Chi Earthquake

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ABSTRACT

The 921 Chi-Chi earthquake caused approximately 9,000 buildings collapses or damages of various degrees. A large percentage of buildings that collapsed are un-reinforced clay block masonry cottages and non-engineered and one-to-three stories reinforced concrete frame structures constructed with brick in-fill partitions and exterior walls. Many collapsed buildings had a pedestrian corridor and open front at the ground floor. More than two dozen modern reinforced concrete moment resisting high-rise apartment buildings overturned or collapsed. The observed damages on reinforced concrete structures suggested a large effect of masonry and lightly reinforced concrete nonstructural components. The observed damages also suggest that only ductile details be used in all new constructions and in the repair of damaged structures, and buildings having "soft-story" characteristics should not be allowed in new constructions.

INTRODUCTION

On 1:47a.m. of September 21, 1999, a magnitude $M_L = 7.3$ earthquake struck the central region of Taiwan. Following the 921 Chi-Chi earthquake, two after shocks of $M_L = 6.8$ occurred about 30 hours and 127 hours after the main shock. Preliminary data indicates that approximately 3,000 buildings totally collapsed as a result of the earthquakes,

with more than 6,000 others partially collapsed and countless others damaged to various degrees. While it will take considerable effort and time to inventory that damage to a level of refinement that will allow formulation of a reliable critique of current building codes and practices, preliminary observations indicate that buildings that collapsed typically exhibited non-ductile reinforcing details compounded by detrimental building

configurations. A large percentage of buildings that collapsed due to the main shock or strong aftershocks are old unreinforced clay block masonry cottages and non-engineered and one-to-three stories reinforced concrete frame structures constructed with brick in-fill partitions and exterior walls. Many collapsed buildings had a pedestrian corridor and open front at the ground floor, and only one wall at the back of the building along the street direction (Photo 1). This type of building damage



Photo 1 Collapse of the typical building having pedestrian corridor

However, in the affected area, more than two dozen modern 10-to-20 stories apartment buildings overturned or collapsed. These were reinforced concrete moment resisting frames, most of them constructed with cast-in-place 15cm thick exterior wall and 12cm thick partition walls (Photo 3). The observed damages on reinforced concrete structures suggested a large effect of masonry and lightly reinforced concrete non-structural components. These buildings were typically designed following requirements for moment resisting frames identical to the Uniform Building Code

accounts for the majority of the complete building collapses near the epicenter due to severe ground shakings. Many school buildings suffered extensive and severe damages. The "short-column" type of damage in these reinforced concrete structures is rather common in the direction parallel to the exterior corridor outside the classrooms where windows above half-height in-fill shortened the effective length of almost all the columns (Photo 2).



Photo 2 Shear failure of RC columns due to the short column effect

(UBC) used in the United States, albeit generally one edition behind the latest published. Seismic force requirements of building designs in Taiwan for the past 25 years are given in Table 1. The seismic zonation maps in 1974, 1982 and 1997 editions of Taiwan Building Standards (BTS, 1974, 1982 and 1997) are given in Fig. 1 through Fig. 3, respectively. In the Nanto county, where most of the damage occurred, the specified peak-ground-acceleration to consider for design was 0.23g (for the 475 years return-period earthquake), which translates into a design coefficient of

approximately 0.11g for short period structures. Incidentally, that coefficient was 0.05g from 1974 to 1982, and 0.08g from 1982 to 1996, before the higher aforementioned value was adopted in 1997. Note that Nanto was located in Taiwan's Seismic Zone 2, and that design force 22% and 43% higher were mandated in Seismic Zones 1A and 1B, respectively (Fig. 3). Alternatively, the code permits the use of a slightly larger seismic force to size members with some relaxation on the ductile detailing of the reinforcement, following what is prescribed in the UBC. Surprisingly, many of the buildings that collapsed were engineered and constructed in the last decade. However, none exhibited evidence of ductile detailing.

Many of them appear to have tall floor and open plaza features in the ground level. Commonly encountered were failed columns with widely spaced stirrups (unconfined plastic hinge zone), splices with inadequate development length or located in the hinge region, light or in-existent joint transverse reinforcement, stirrups with 90°, etc. Strong-beam weak-columns systems apparently common, might have resulted in numerous story collapses following excessive column damage. This was particularly frequent in the first story of buildings, as the larger openings and higher story height there translate into a lower structural stiffness and strength, leading to "soft-story" mechanisms (photo 4).



Photo 3 Collapse of a apartment building in Fengyuan



Photo 4 Collapse of a high-rise apartment building in Dali

Table 1 Seismic Force Requirements in Taiwan

Year	Seismic Base Shear	Remarks
1974	$V_w = Z K C W$	$Z = 1.25, 1.0, 0.75$ $K = 0.67, 0.8, 1.0, 1.33$ $C_{max} = 0.10, W = D + 0.25 L$
1982	$V_w = Z K C I W$	$Z = 1.0, 0.8, 0.6$ $K = 0.67, 0.8, 1.0, 1.33$ $I = 1.0, 1.25, 1.5$ $C_{max} = 0.15, W = D$
1997	$V = \frac{Z I C W}{1.4 \alpha_y F_u}$	$Z = 0.33, 0.28, 0.23, 0.18$ $I = 1.0, 1.25, 1.5$ $C_{max} = 2.5, W = D$ $\alpha_y = 1.2$ (WSD), $\alpha_y = 1.5$ (USD) $F_u \approx 2.9, 2.5, 2.1$

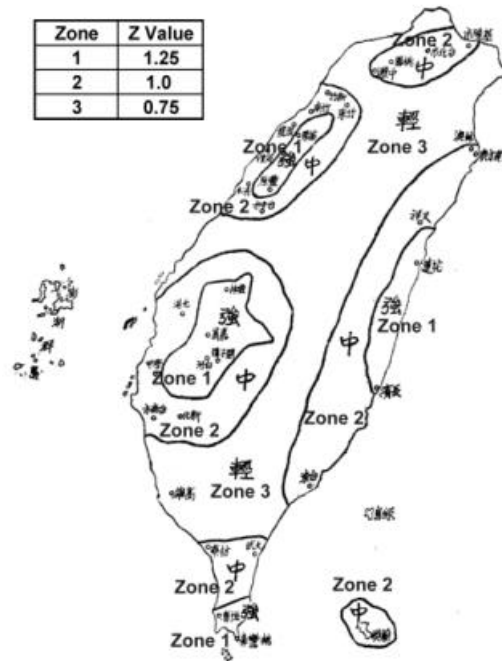


Fig. 1 Seismic zonation map in 1974 Taiwan Building Codes

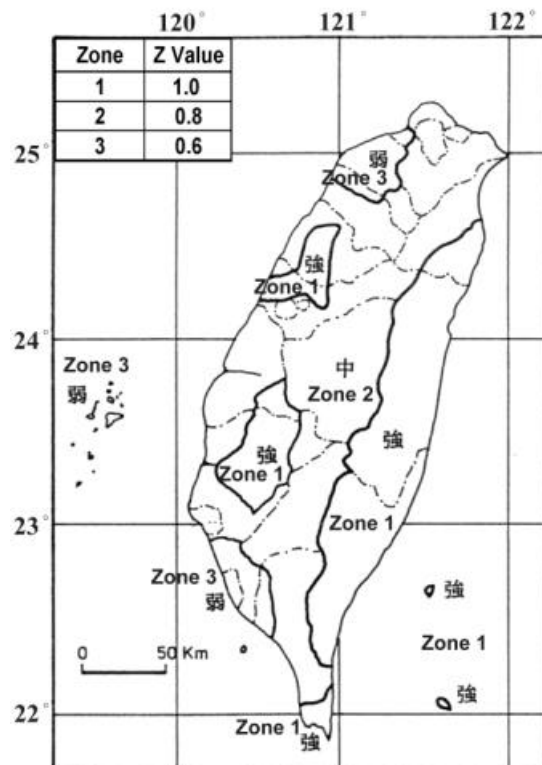


Fig. 2 Seismic zonation map in 1982 Taiwan Building Codes

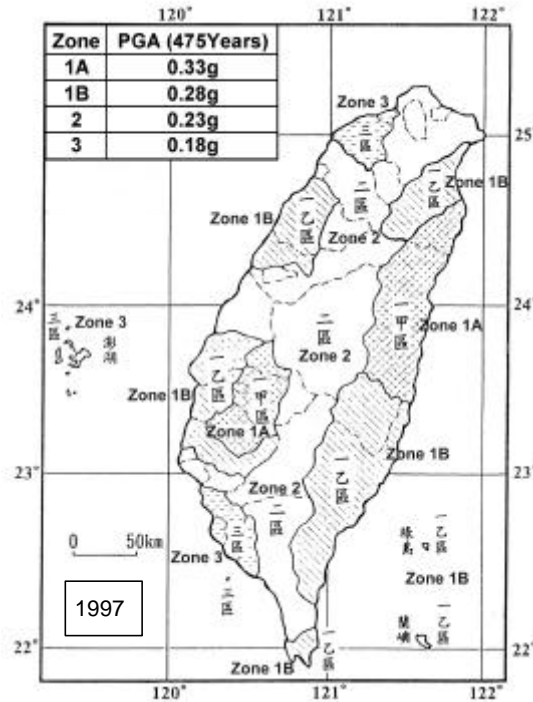


Fig. 3 Seismic zonation map in 1997 Taiwan Building Codes

BUILDING DAMAGE STATISTIC BY GEOGRAPHIC REGION

Overview of Building Damage Statistic

Shortly after the occurrence of the 921 earthquake, the National Center for Research on Earthquake Engineering (NCREE), the Architecture and Building Research Institute (ABRI) and the private organizations had quickly formed the reconnaissance team to investigate the island-wide building damages. There were 8,773 structural damages recorded using the Building Damage Survey Form [1]. Each damage report was filed for either an individual structure or a consecutively connected building block; therefore, the number of the actual damages had exceeded the reporting figure noted above.

Island-wide

The 921 earthquake has resulted in a tremendous amount of damages in the central part of Taiwan. Figure 4 indicates that approximately 90% of the 8,773 damages are concentrated in Nantou County and its adjacent Taichung County. Over 300 damaged buildings are also observed in the Miaoli County, as well as in the Taipei County. The detail damages of Nantou County, Taichung County, and Taipei County are described below.

Nantou County

Nantou County was severely impacted by this earthquake due to its epicenter location and the surface faulting. More than 4,500 structures, which equivalent to 53% of the island-wide damages, were surveyed in Nantou. Figure 5 illustrates

that Nantou City, Tsautuen Village, and Jungliau Village are the top three most damaged areas in this county; and their damaged building figures are 937, 846 and 823 respectively. The survey indicates that Nantou City, Tsautuen Village, Jushan Village, and Mingjian Village received substantial damages, because of the direct impact of the Chelungpu Fault.

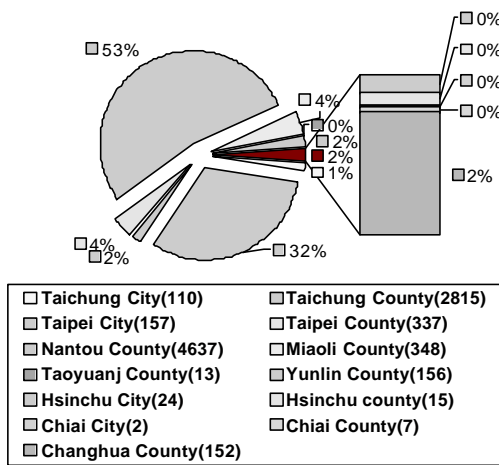


Fig. 4 Distribution of damaged buildings in Taiwan (number and percentage)

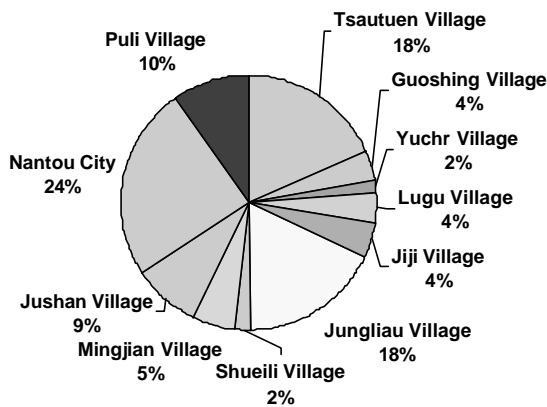


Fig. 5 Distribution of damaged buildings in Nantou County

Taichung County

Being a highly populated county adjacent to Nantou, Taichung County also experienced significant damages of 3,200 building failures. It is observed from Fig. 6 that these damages in the Taichung County were concentrated at Dungshr Village, Shrgang Village, Fengyuan City, and Shinshe Village. The regional damage ratios of these four areas are 28%, 24%, 19% and 14% respectively.

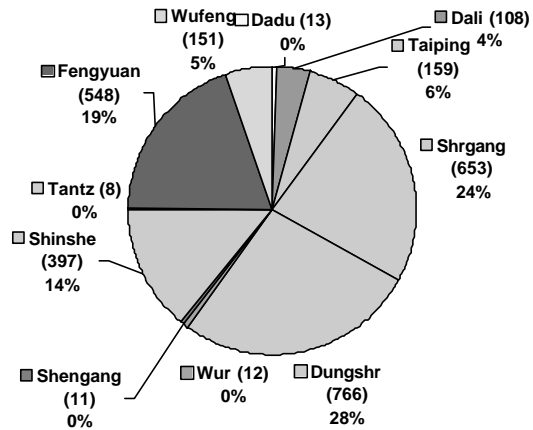


Fig. 6 Distribution of damaged buildings in Taichung County (number and percentage)

Taipei County

Taipei County, a special seismic zone in the north region, is applicable to a different earthquake design requirement because of the Taipei basin location. Under a normal circumstance, the earthquake damage should be less significant since the Taipei County is so distant away from the epicenter. However, as the assessment indicates that the level of damage in Taipei County was greater than most of the counties in the northern region. Figure 7 indicate that the earthquake damages were concentrated at the Shinjuan City and the Junghe City, and their damaged building numbers are 122 and 66 respectively.

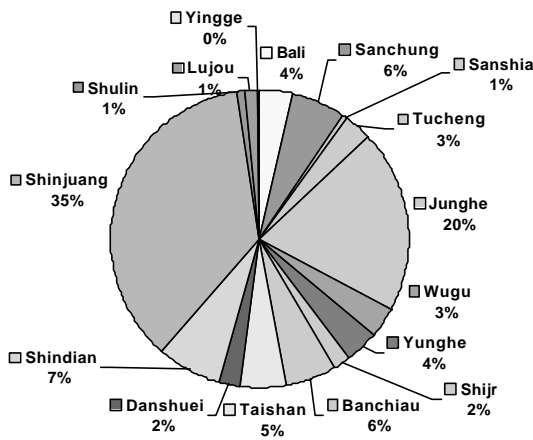


Fig. 7 Distribution of damaged buildings in Taipei County

Chelungpu Fault Area Building Damage Statistic

The tectonic movement of the Chelungpu faults causes the 921 earthquake.

The epicenter location, Chi-Chi Village is located near southeast portion of the Chelungpu fault. The rupture length of the Chelungpu fault in this earthquake is over 100km long in the north-south direction, and its impacts are enormous. According to the post-earthquake geological investigation, the earthquake caused many permanent landslides and surface faulting in Miaoli County, Taichung County, Taichung City and Nantou County. Twelve areas are directly impacted: Juolan Village, Dungsht Village, Shrgang Village, Fengyuan City, Tantz Village, Beituen Village, Taiping City, Wufeng Village, Tsautuen Village, Nantou City, Mingjian Village, and Jushan Village. Figure 8 illustrates that 5,088 damages were reported, which is equivalent to 58% of the island-wide damages.

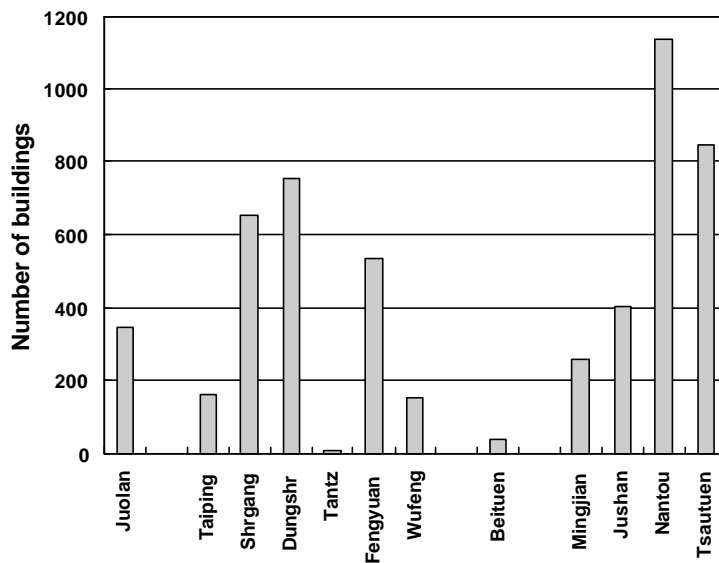


Fig. 8 Number of damaged buildings in cities near Chelungpu Fault

Overview of Observed Building Damages

To further the study of the earthquake damages, the observed data has been analyzed in seven aspects: (1)Structural

Damage Level, (2) Structural Height, (3) Structural Type, (4) Structural Construction Period, (5) Structural Usage, (6) Structural Plan Configuration, and (7) Structural Vertical Configuration. The

assessment presented here is based on the visual inspection of the exterior damage only. Prior to the completion of the report [1], some minor adjustments maybe applicable to the investigated data; however, these small adjustments can be considered to have negligible affect on the overall result of the analysis.

Structural Damage Level

To facilitate the damage study, five Damage Classification Indexes are used to assess the damage level. The five indexes are: (1)Collapse, (2)Tilt, (3)Severe Damage, (4)Moderate Damage, and (5)Minor Damage. A collapsed or tilted building is considered to be a total structural failure. Nantou County and Taichung County are the top two most severely damaged area in Taiwan, and most of their damages are classified as collapse or severe damage. In Taipei County and Miaoli County, most of the building failures are classified as minor damages.

Structural Height

Five categories are used to classify the building height in this damage survey; they are: 1 to 3-story height, 4 to 6-story height, 7 to 11-story height, 12 to 15-story height, and over15-story height. The survey indicates that 85% of the reported damages are less than 4-story height. Among these low-rise building damages, the un-reinforced brick or the un-reinforced clay block buildings represent a large portion. In the urbanized area, such as Taipei City and Taipei County, the majorities of the damaged buildings are 4 to 6-stories height [1].

Structural Material

Damaged structures have been classified into seven categories: (1)Reinforced Concrete Building, (2)Un-reinforced Brick Building, (3) Un-reinforced Clay Block

Building, (4)Structural Steel Building, (5) Light Metal Building, (6)Timber Building, (7)Steel Reinforced Concrete Building. It is important to note that unless the building is taller than 25 stories, the most popular material for building construction in Taiwan is reinforced concrete. The top three damaged structural types are the reinforced concrete structures, the un-reinforced brick structures and the un-reinforced clay block buildings. The reinforced concrete failures in this earthquake is significant amount; however, compared to the total amount of reinforced concrete buildings in Taiwan, it should be just a small percentage. On the other hand, the poor seismic resistance of the un-reinforced brick buildings and the un-reinforced clay block cottages are observed during this earthquake. Since these two construction materials were commonly used in the early age, most of these damages were occurred in the rural areas in Nantou County and Taichung County. Lack of a well seismic design and ductility is the major cause of the great failure of the un-reinforced brick and clay buildings.

BUILDING DAMAGE ANALYSIS BY CONSTRUCTION TYPES

Analyzing the seismic performance of the RC buildings, the un-reinforced brick buildings, the un-reinforced clay block buildings, and the structural steel buildings, their damage profiles are discussed in this section.

Damage of the Reinforced Concrete (RC) Building

Damage Level Analysis

Due to the improvement of the construction technique in Taiwan, reinforced

concrete structures become commonly constructed and represent a large portion of buildings. As the 921-earthquake damage survey indicates that the total number of the damaged reinforced concrete buildings has reached 4,325. Figure 9 indicates that 15% of the RC damaged buildings are the collapsed type, 10% of the damaged buildings are the tilted type, and 23% of the failures are the severely damaged type. The result indicates that over 48% of the RC damaged

structures are surveyed as sever damaged or more seriously damaged.

Building Height Analysis

The 921 earthquake created a tremendous amount of damages in both Nantou and Taichung County. Since many low-rise single family houses are constructed and widely spread over these two areas; therefore, large numbers of low-rise buildings failures are recorded in this assessment. Figure 10 shows that about 75% of the damaged RC buildings are the 1 to 3-story buildings, and 52% of these damaged low-rise buildings are classified as the severely damaged. It was observed that 17% of the damaged structures are the 4 to 6-story height, and the lesser damages were observed for the higher buildings. Although only five percent of the total damages is the high-rise failures, but each accident has an immediate impact on the safety of dozens of residents and families. The unsatisfied seismic performance of these 200 modern high-rise building are unexpected and needs to be carefully investigated.

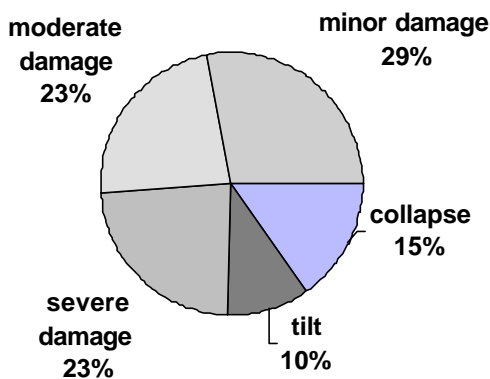


Fig. 9 Damaged percentage of RC structure

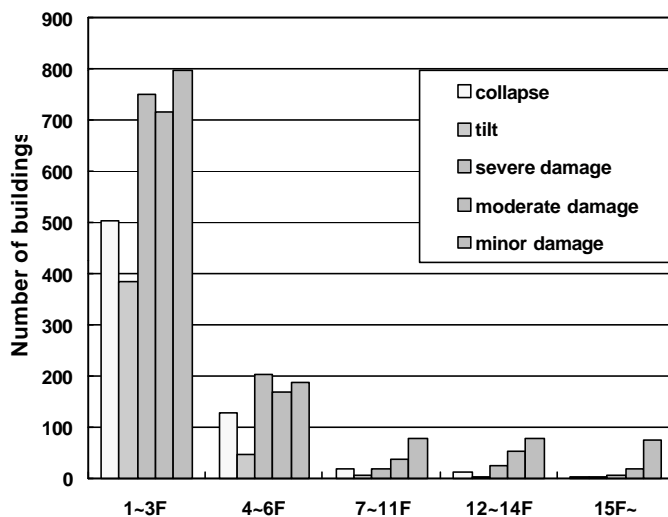


Fig. 10 Number of damaged RC structures with different number of stories

Construction Period Analysis

In order to find out the correlation between the structural damage level and the construction period, five construction periods are used in this survey: before 1974, 1975 to 1982, 1983 to 1989, 1990 to 1997, and after 1997. This breakdown can reflect the level of seismic design requirements prescribed by different versions of the design code. Figure 11 illustrates the damage level and the construction period of the damaged RC buildings. Since limited RC structures were constructed prior to 1974; therefore, roughly 7% of the total RC failures are constructed at that time. In

general, it was observed that the newly constructed buildings suffered a fewer damages. Approximately 30% of the RC damages were constructed between 1975 to 1982, and approximately 20% of damages were constructed between 1983 to 1989, and from 1990 to 1997. One exception is observed that the number of damaged buildings constructed during 1990 to 1997 is higher than the number of damaged buildings constructed during 1983 to 1989. In order to find out reasons, further investigations on the total number of buildings constructed in these two periods of time are required.

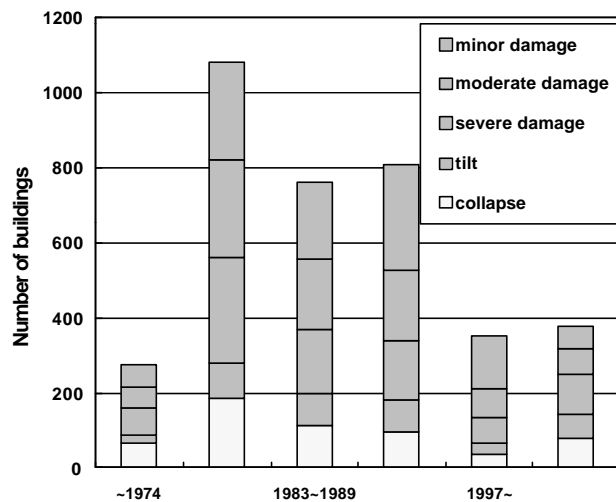


Fig. 11 Number of damaged RC structures with respect to construction periods

Usage Analysis

In Taiwan, most of the buildings are constructed for the residential purpose, and a certain percentage of the buildings are the retail stores and the residential/commercial mixed buildings. In comparison, the historical buildings, the hospitals, and the offices are the minority. Figure 12 indicates that about 65% of the RC damages are the residential buildings, this high percentage of damages is related to their large constructed amount.

However, approximately half of these damaged residential structures are described as severely damaged or worse, which has caused a significant impact on the human life. It was also observed that 20% of the RC damages are the residential/commercial mixed buildings. The school buildings also suffered significant damages, over 60% of the failed buildings were classified as severely damaged or worse. Since the factory, the offices, the hospitals, and the historical buildings are

less common, therefore, the number of damages reported is also lesser.

Vertical Configuration Analysis

Due to the long raining season in Taiwan, the Taiwanese developers commonly construct the buildings with the pedestrian corridor, and this popular style becomes a local practice and is prescribed in the building codes. Thus, the pedestrian corridor buildings represent a large portion of the failed structures, and experienced different level of damages.

Figure 13 indicates that approximately 84% of the RC damaged structures are the pedestrian corridor buildings, and roughly 45% of the pedestrian corridor buildings are classified as severely damaged or worse. The damage ratios of the other vertical configurations are relatively lesser. Approximately 7% of the damages are the buildings with a tall floor on ground level, 6% of the damages are the buildings with an overhang on the 2nd floor, and 1.5% of the damages are building with setback on the 2nd floor.

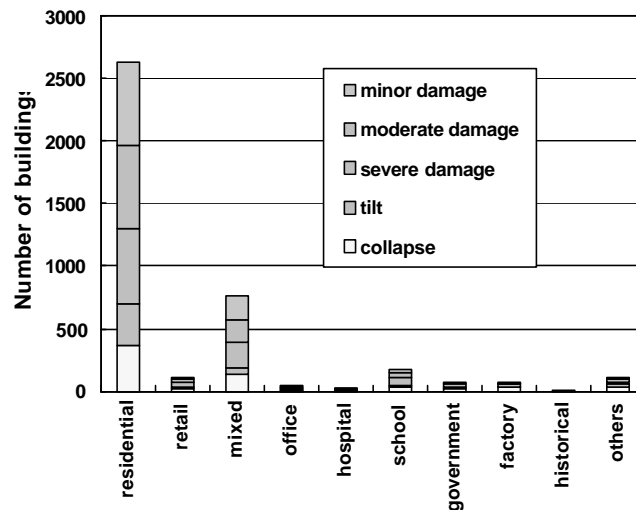


Fig. 12 Number of damaged RC structures with respect to building usage

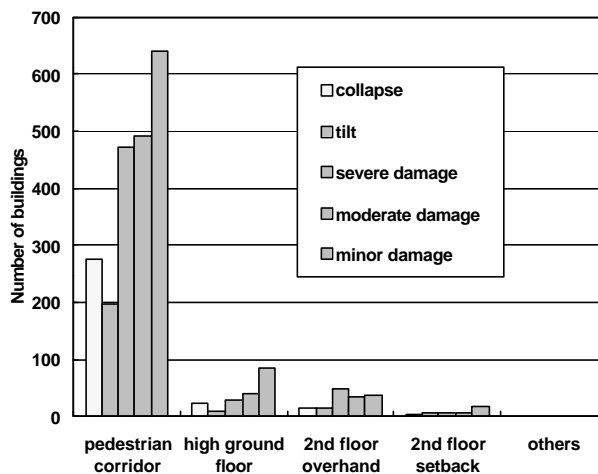


Fig. 13 Number of damaged RC structures with respect to vertical configuration

Damage of the Un-reinforced Brick Building

Damage Level Analysis

In the early agricultural age, the un-reinforced brick buildings were commonly constructed due to its low cost and simple manufactory. Because the un-reinforced brick block has a low seismic resistance, 2,014 un-reinforced brick building damages were recorded during this earthquake. The un-reinforced brick damaged buildings represent the second large group of the damaged structures. Figure 14 indicates that 1,428 damaged buildings, approximately 70% of the total damage, were classified as severely damaged or worse. The percentages of the damages for the collapsed buildings, the tilted buildings, and the severely damaged buildings are 38%, 7%, and 25% respectively. The poor seismic response and the brittle failure of the brick buildings had clearly illustrated during this earthquake.

Plan Configuration Analysis

The typical plan configuration for a un-reinforced brick buildings is rectangular shape, and the U shape floor plan is

Damage level of brick structures
(Data:4325 records)

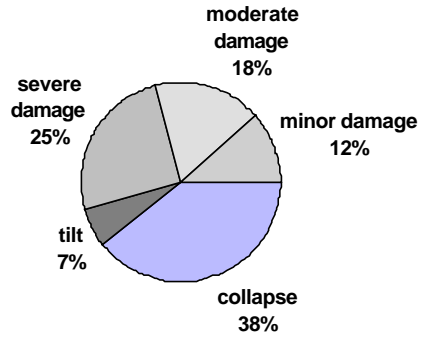


Fig. 14 Damaged percentage of brick structure

also used in some rural area. Figure 15 shows that the majorities of the damaged structures are either rectangular shape or U shape floor plans. There are 1,615 damaged buildings with rectangular floor plan, which are equivalent to 84% of the total failures. And the buildings with the U shape plan configurations are another 10% of the failed structures. The remaining 6% of the damaged building are either cross shape, H shape, or other plan configurations.

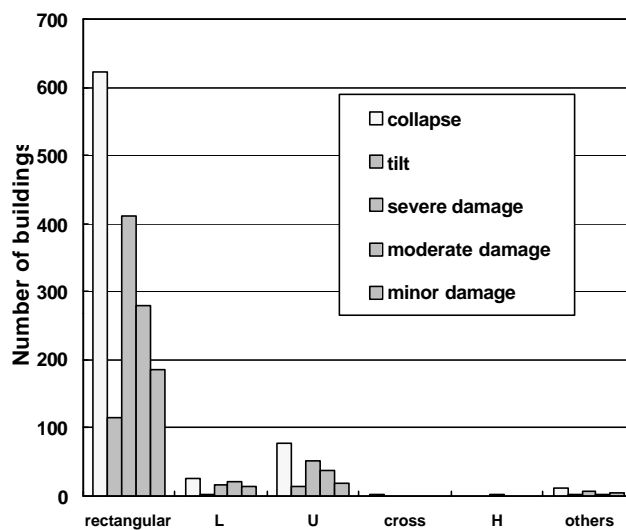


Fig. 15 Number of damaged brick structures with respect to plan configuration

Vertical Configuration Analysis

It was observed from Fig. 16 that the majorities of the damages are the build-

ings with pedestrian corridors. Other types of vertical configurations are the minorities.

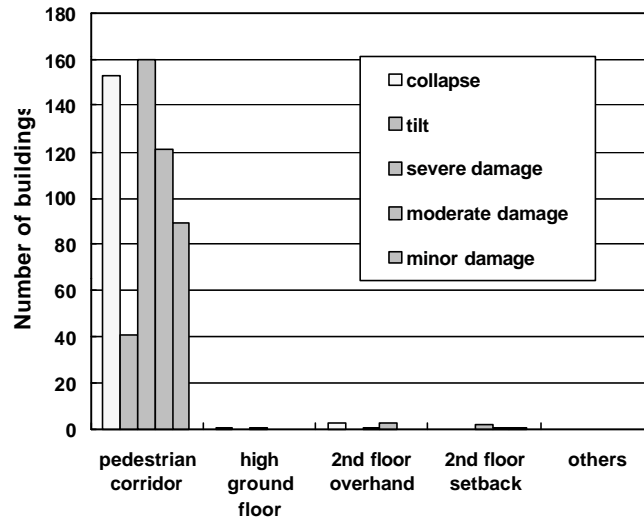


Fig. 16 Number of damaged brick structures with respect to plan configuration

Damage of the Un-reinforced Clay Block Building

Damage Level Analysis

In the early agricultural age, prior to the introduction of the seismic design, the un-reinforced clay block is simple for the manufacture and the common usage for one story cottage construction. Lacking the seismic design concept, these buildings were constructed as a shelter for the weather protection only. Under the strong earthquake shaking, the severe damages were observed. In this report, total 1,099 un-reinforced clay block cottages were damaged, which represent the third large group of the structural failures. Figure 17 indicates that over 75% of the failed cottages are collapsed, 5% of the damaged buildings are tilted, and 12% of the failed structures are severely damaged. The poor seismic resistance of this brittle material is shown, such that over 93% of these damaged cottages are recorded as severely damaged or worse.

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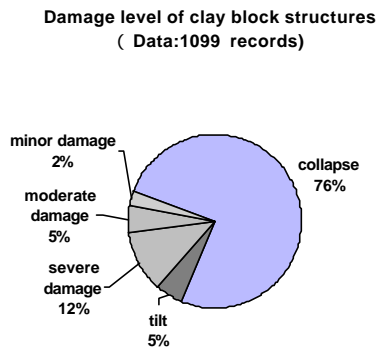


Fig. 17 Damaged percentnage of clay block structure

Damage of the Structural Steel Buildings

In Taiwan, most of the steel buildings are constructed in the last ten years. Steel frame structural systems are quite common for buildings taller than 25 stories. In order to cost-effectively satisfy the seismic and wind forces requirements, moment resisting frames (MRFs) coupled with concentrically or eccentrically braced frame (EBF) dual system are rather popular. In these steel buildings, most of the beams are built-up wide flange sections using the A36 or A572 grade 50 steel while the columns are built-up box sections using the A572 grade 50 steel. In most of the cases, moment connections were made for each beam-to-column joint. Most of the beam-to-column connections adopt bolted web and welded flanges details in which run off tabs and backings are left in place after the flange welds. In some of these connections, the beam web was welded to the shear tab. The most common welding procedures adopted in the field practice are SMAW using E7016 electrode. In some cases, FCAW procedures have been employed in the field using E70T-7 NR311 electrodes.

In Taichung City, about 50km north-west of the epicenter where the recorded

peak ground accelerations obtained from the main shock range between 0.2 and 0.3g. Several tall steel buildings have been constructed in the past decade. During the 921 Chi-Chi earthquake, there were two steel buildings, one 14-story (MRF) department store and one 45-story (MRF/EBF dual system) office/hotel tower under construction. Before the earthquake, most of the steel works in these two building have been completed and the concrete slabs were poured. However, fire proofing, window walls and partitions were not installed yet and all the steel beam-to-column joints were still visible following the earthquake. Noted that the 14-story building adopted the typical details described above and the 45-story structure employed reduced beam sections with the radius cut details. Detailed inspections conducted for these two buildings following the earthquake indicate no apparent connection damages. Except the collapse of a few old light metal structures, damage to steel buildings had not been reported at the time of this writing. However, experience in other post-earthquake investigations shows that such damage take much longer time to discover as steel members and joints are generally covered by fire proofing or architectural finishing. Further investigations are required in order to confirm the extent of the steel building damages in the severely shaken regions.

CONCLUSIONS AND RECOMMENDATIONS

Findings from this earthquake concur with those from prior events, emphasizing the need for stringent enforcement of implementation of ductile detailing requirements. All failure modes observed are well known and have been extensively described in the past. In

many instances, the contribution of non-structural partitions to seismic response had apparently a positive impact. Although generally neglected by the designer while considering lateral-load resistance, the use of reinforced concrete as in-fills transformed the structural system from moment frames to shear walls. Preliminary results of some case studies indicate that the greatly enhanced supplied strength have more than overcome the increased demand resulting from the lower structural fundamental period of vibration. This could explain why so many buildings survived where strong shaking peak ground acceleration exceeded 0.3g. Unfortunately, in many cases, only a few such walls or partitions existed at the ground level, which proved fatal when ductile reinforcing details were not implemented. In the perspective of the damage reported above, the following recommendations are made for consideration during the initial recovery period:

1. Given the extensive damage suffered by reinforced concrete building clearly exhibit lack of ductile detailing, it is essential that steps be taken to ensure that only ductile details be used in all new constructions and in the repair of damaged structures. Furthermore, until further research findings become available, buildings having "soft-story" characteristics should not be allowed in new constructions. In light of the fact that some of this knowledge is currently present in the enacted codes, it seems that efforts must be directed, through education, professional development, and legislation as appropriate, to ensure a better understanding and enforcement of capacity design principles and full implementation of ductile detailing.
2. Seismic zonation maps has been

critically reviewed to re-assess the national seismic risk and desired earthquake protection levels. This simultaneously entails a critical reassessment of the design-spectra in light of the new data.

3. The extensive vulnerability of the existing building inventory, as revealed by this earthquake, must be addressed before other equally destructive earthquakes strike again in the country. A particular attention should be paid to buildings having soft stories and open front. This requires the establishment of priorities, timetable, policies and criteria for seismic retrofit. It is not fiscally possible to retrofit all structures in cities having extensive building inventories, but key post-emergency building (such as hospitals and other critical facilities) require special measures to ensure that they will be made available.
4. In light of the damages observed in the school buildings, it is recommended that the lateral force resisting system in the direction parallel to the exterior corridor for new school buildings be carefully configured in order to avoid the occurrence of "short column" brittle failure mode. The observed damages also suggest the urgent need of retrofitting the existing vulnerable school buildings.

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