BUILDING DAMAGE DUE TO 2008 WENCHUAN EARTHQUAKE AND COOPERATIVE ACTIVITIES ON DAMAGE RESTORATION BY JAPANESE EXPERTS

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Abstract: A destructive earthquake occurred on May 12, 2008, and caused extensive damage to Sichuan Province in China. Immediately after the event, Japanese scientific/engineering societies that had experiences and know-how on damage restoration of structures in the past major earthquakes jointly formed a liaison council to technically support the restoration of the hardest hit areas through mutual cooperation and sharing information. Since then, the council has been actively cooperating with Chinese experts from academic and engineering fields through damage investigations and extensive discussions on technical and practical issues for damage restoration. This paper briefly overviews damage to buildings and their restoration activities made in cooperation with Southwest Jiaotong University in Chengdu city, Sichuan Province.

Keywords: Sichuan (Wenchuan) Earthquake, Damage Restoration, Technical Support Liaison Council

1. INTRODUCTION

The Wenchuan Earthquake of magnitude 7.9 (USGS) jolted major cities in Sichuan Province, Central China at 14:28 local time on May 12, 2008. The damage is widespread and devastating, and more than 80,000 including missing people are reportedly killed mainly due to building collapse.

Immediately after the event, the following eight Japanese scientific/engineering societies (initially the first five societies listed below) jointly set up the Technical Support Liaison Council for Damage Restoration after Sichuan (Wenchuan) Earthquake (Council Chair: Dr. M. Hamada, Professor of Waseda University).

* Council member societies

1. JSCE (Japan Society of Civil Engineers)
2. AIJ (Architectural Institute of Japan)
3. JGS (The Japanese Geotechnical Society)
4. JAEE (Japan Association for Earthquake Engineering)
5. SSJ (Seismological Society of Japan)
6. CPIJ (The City Planning Institute of Japan)
7. AJG (The Association of Japanese Geographers)
8. ISSS (The Institute for Social Safety Science)

The major purpose of the Council's activity is to form a technical support team in close cooperation with eight societies that are well experienced in post-earthquake activities and to help researchers, engineers, and practitioners in the affected area restore damaged structures and communities through sharing knowledge and experiences of recent damaging earthquakes such as 1995 Hyogo-Ken Nambu (Kobe), 2004 Niigata-Ken Chuetsu, and 2008 Iwate-Miyagi Nairiku earthquakes.

After the earthquake, the Council dispatched technical support teams during May 28 through June 1 and June 20 through 25, and organized a series of special lectures on engineering seismology and earthquake engineering at the Southwest Jiaotong University, Chengdu city, Sichuan Province, in September and October. In this paper, the damage observation of building structures and technical support activities for their restoration made during the second visit in June are briefly described.

2. BUILDING DAMAGE OBSERVATIONS

Damage surveys were primarily made in Dujiangyan city and Hanwang town of Mianzhu city. Figure 1 shows the surveyed areas. In especial, damage in Hanwang, where the seismic fault runs across the northern edge of the town, is extensive, and many buildings are found totally collapsed. The surveys were arranged by the Southwest Jiaotong University, which

Figure 1 Surveyed areas

Photo 1 Seriously Damaged Brick Buildings (Hanwang town of Mianzhu city)

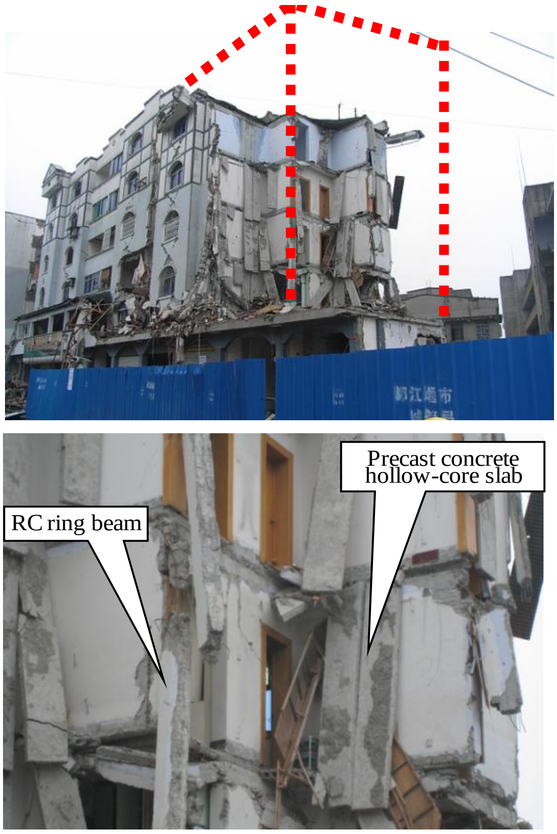


Photo 2 Partially Collapsed Brick Buildings with Precast Concrete Hollow-core Slabs (Dujiangyan City)

was the Chinese counterpart for the technical support activities. During surveys, two major structural types, brick structures and RC frames with URM (unreinforced masonry) walls, are found. In the subsequent sections, major damage patterns found during surveys are briefly described for each structural type.

2.1 Brick buildings

Brick buildings are most seriously damaged and they often sustain partial or total collapse, resulting in the primary source of human damage. They have UR brick walls having RC ring beams and precast concrete hollow-core slabs above the walls. The major cause of the fatal damage is attributed to the low resistance and brittleness of URM walls and poorly detailed joints between precast concrete members and RC beams. Photos 1 and 2 show typical damage to brick buildings.

2.2 RC buildings

In RC buildings, several damage patterns are found. They include damage to UR brick walls, shear failure in columns, flexural compression failure at column top and/or bottom, beam-column joint failure, and structural damage resulting from soil/ground failure underneath.

2.3 Damage to UR brick walls

Reinforced concrete shear walls are much less frequently provided in RC buildings than UR brick walls. Lightly reinforced small-sized columns (tie columns) are often placed later between UR brick walls so that the walls should serve as the form in casting concrete of RC tie columns. During the surveys, shear cracks and failure of brick walls are found in many buildings as shown in Photo 3. It should be noted, however, that lath-mortar finishing on the exterior surface of UR brick walls is found to help avoid their out-of-plane failure, although they are heavily cracked. Such efforts therefore should be encouraged to minimize falling hazard to residents and users during and after major earthquakes.

2.4 Shear failure in RC column

Shear failures in RC columns shortened by partial height UR brick walls are found in several buildings, as

Photo 3 Failed Brick Wall (left) and Survived Brick Wall (right)

Photo 4. Typical shear failure in RC short columns

Photo 5. Shear failure in RC column shortened by partial height brick wall

Photo 6 General view of a six story RC apartment house

have been found elsewhere in the past damaging earthquakes. Photo 4 shows a typical shear failure in the first story of a building in Dujiangyan city. Photo 5 shows another failure, where the column is shortened and failed in shear leaving vertical cracks along the interface between the column and brick wall. The damage is attributed to the presence of partial height brick walls, which are generally neglected in the structural design but significantly affect the building's behavior during strong shaking.

2.5 Flexural compression failure in RC column

Seriously damaged RC buildings often show flexural compression failure at the top and bottom of their columns. Photos 6 and 7 show the damage to columns in the first story of a six story apartment building in Dujiangyan city. Hooks of lateral reinforcement are pulled out of crushed concrete core. Main rebars buckle and fracture as shown in the photos. As will be found later in this paper, the building is employed for a sample building to investigate possible restoration schemes and to discuss their feasibility with Chinese engineers.

2.6 Damage to RC beam-column joints

Damage to beam-column joints are less frequently found than other failure patterns such as shear failure in columns, flexural compression failure in columns. Photo 8 shows the damage to beam-column joints of RC apartment buildings, which were under construction at the time of the earthquake.

2.7 Structural damage due to soil failure

Structural damage due to soil failure underneath a building resulting in the differential settlement is found in some buildings located at the foot of a mountain slope

Photo 7 Flexural Compression Failure at the top and Bottom of Columns

Photo 8 Failure in beam-column joint

Photo 9. Structural damage due to failure in retaining wall

in Dujiangyan city. Photo 9 shows damage to a retaining wall, causing soil outflow and differential settlement of superstructures.

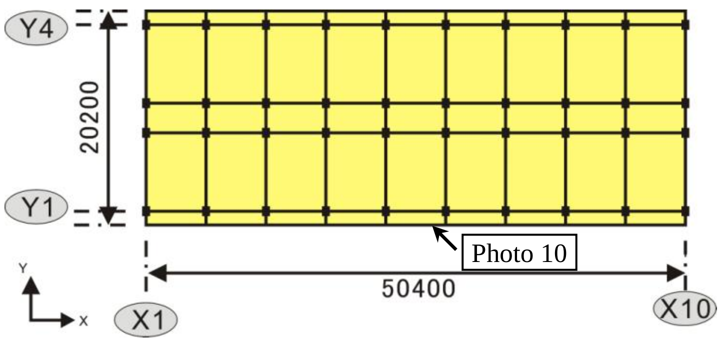
Photo 10 Example six story RC partment building (See also Photos 6 and 7)

3. SINO-JAPAN SEMINAR ON RESTORATION OF DAMAGED BUILDINGS

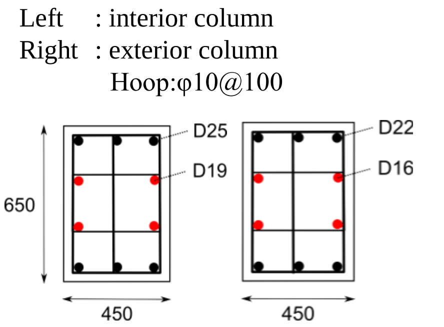
Along with the aim of the liaison activities, the Council, in corporation with Architectural Institute of Japan (AIJ), dispatched an expert team on building damage assessment and restoration led by Prof. Yosiaki Nakano during the period of June 20 through 25 following the first preliminary surveys in May. After two-day surveys of affected areas in Dujiangyan city and Hanwang town of Mianzhu city, the Sino-Japan Seminar on Techniques for Rehabilitation and Reconstruction after the Sichuan (Wenchuan) Earthquake was held on June 24 at the Southwest Jiaotong University (SJU).

3.1 Outline of the seminar

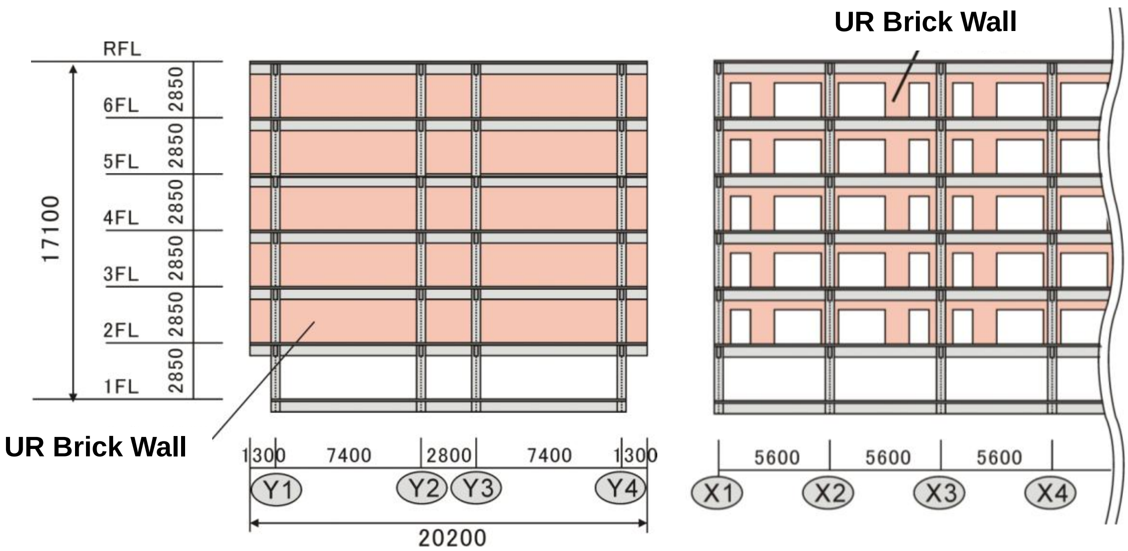
The purpose of the seminar is primarily to present concrete strategies and solutions for damage restoration and to discuss their feasibility and applicability with seminar participants in detail. To this end, an example building is selected from those inspected during the field surveys considering Chinese side requests and then



(a) Plan view



(c) Column sections



(b) Elevation view

Figure 2. Structural configuration and column size of example RC building

restoration schemes for the building are investigated and proposed by the Japanese side in the seminar.

In the seminar, summaries of damage surveys and basic ideas widely applied in Japan to restore earthquake-damaged buildings are first presented. Then restoration scheme candidates for buildings damaged by the Wenchuan Earthquake are proposed by the Japanese side and their applicability, problems to be solved from the practical design and construction point of view in China are discussed in detail.

3.2 Example building

The example building is a six story RC apartment building in Dujiangyan city, which appeared earlier in Photos 6 and 7. The building was under construction but its structural construction was already completed at the time of the earthquake. The first story designed for a parking garage has no walls, while the upper stories have dwelling units with UR brick walls as shown in Photo 10 and Figure 2.

Almost all columns in the first story form plastic hinges both at their top and bottom, causing concrete crushing and rebar buckling (Photos 6 and 7) resulting in the soft first story mechanism with a residual lateral drift of approximately 10% of the story height. No major damage is, however, found in upper stories.

The observed damage is rated [unsafe] based on the Japanese post-earthquake quick inspection manual (JBDPA1997) and [heavy damage] based on the Japanese post-earthquake damage evaluation guidelines (JBDPA 2001, Nakano et al. 2004). The building therefore is identified to be [no occupancy] and needs to be shored to avoid life-threatening risk and further damage progress due to aftershocks.

3.3 Restoration strategies

To understand the fundamental seismic performance of the building, the Japanese seismic evaluation procedure (JBDPA 2001, Nakano et al. 2004) is applied and the seismic capacity index *Is* of the first story is evaluated. The basic concept and procedure of the Japanese Standard (JBDPA 1977, 1990, 2001, 2005) can be found in Appendix of this paper.

Table 1 summarizes the result. The building is found ductile with *F* index (ductility index, see also Appendix) of 2.6, which is consistent with observed damage with a large lateral residual displacement. In the Standard, the required seismic capacity index is recommended to be equal or larger than 0.6 for standard RC buildings in Japan as is shown in the Appendix. The criteria value is determined considering results on non-linear response analyses of typical RC buildings, and studies on the relationship between observed damage to buildings and their seismic capacity indices after major earthquakes in Japan including 1968 Tokachi-Oki Earthquake, 1978 Miyagi-Ken-Oki Earthquake, 1995 Hyogo-Ken Nambu (Kobe) Earthquake, etc.

To restore the damage, the following six schemes are investigated and proposed in the seminar. Table 2 summarizes and illustrates the basic ideas of the schemes and their expected post-restoration performance, where the capacity recovering factor ψ (i.e., the reduction factor to take into account of damage prior to restoration defined in the Guidelines (JBDPA 2001) and Nakano et al. (2000)) is conservatively assumed 0.7 herein.

Scheme 1 aims primarily to repair the damaged columns after re-centering the building, replacing buckled rebars with new rebars, and re-cast concrete in the damaged region. Since the performance may not be fully recovered to the original due to extensive damage and hence the seismic capacity index *Is* after restoration (ψ=0.7 assumed) is lower than the original value of 0.67, the restored building is likely to collapse when subjected to the future shaking with intensity similar to the main event on May 12.

Scheme 2 aims to repair and upgrade flexural strength and confinement of columns by RC jacketing after re-centering the building. In Scheme 2, the flexural strength after restoration is estimated neglecting reinforcement in the original section, which is found buckled in the survey, while the whole section including repaired inner (i.e., original) section is assumed effective on the shear strength. As is found in Table 2, the expected performance may be better than the original, but both Schemes 1 and 2 need re-centering of the building, which may not be necessarily easy and requires well-experienced engineers with high-level skills.

Then Schemes 3 and 4, which do not employ re-centering of the building, are proposed to facilitate the restoration work. It should be noted, however, that the

Table 1 Seismic capacity index of example building prior to damage

Location	*C*	*F*	*Eo*	*Is*
Interior	0.14	2.60	0.67	0.67
Exterior	0.12	2.99		

Note: Is = *Eo* x S_D x *T* (See also Appendix)

Eo = (0.14 + 0.12) x 2.6 = 0.67

Eo: basic structural capacity index defined by *C* x *F*

C: strength index defined in terms of shear coefficient

F: ductility index (ranging from 1.0 to 3.2) defined mainly by shear-to-flexure strength ratio, yielding displacement, height-to-depth ratio etc.

S_D and *T*: reduction factors for *Eo* to allow for irregularity and deterioration of building (both assumed 1.0 herein)

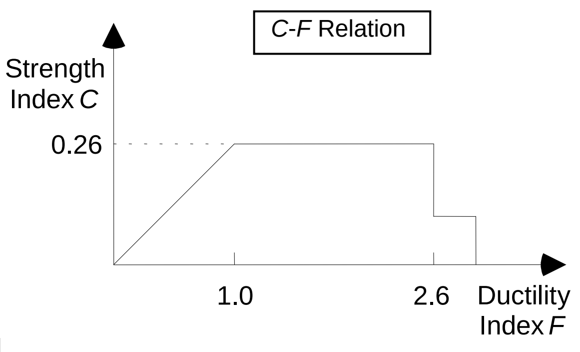
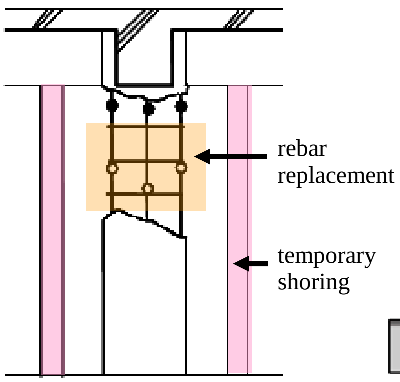


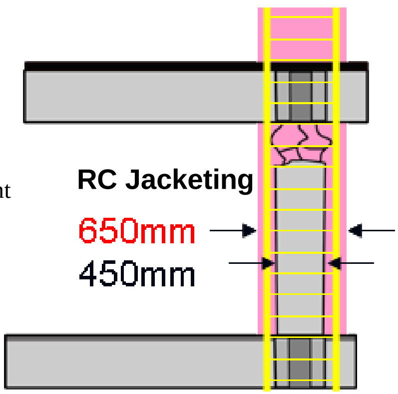
Table 2. Restoration scheme candidates

Scheme (F-: flexural / S-: shear)	General description	Expected difficulties*1	Expected performance*2	*Is* Index*3
0. Original	Prior to damage	-	-	0.67
1. Repair	Repair to initial configuration after re-centering	(1)	(a)	0.47
2. F-strengthening	RC jacketing*4 after re-centering	(1) (2)	(b)	0.71
3. F-strengthening	RC jacketing*4 without re-centering	(2)	(b)	1.04
4. F- and S-strengthening	Scheme 3 and steel jacketing	(2)	(b)	1.19
5. Repair & strengthening with new wing walls	Scheme 1 and wing walls	(1)	(b)	0.60
6. Repair & strengthening with new shear walls	Scheme 1 and shear walls	(1)	(b)	0.35

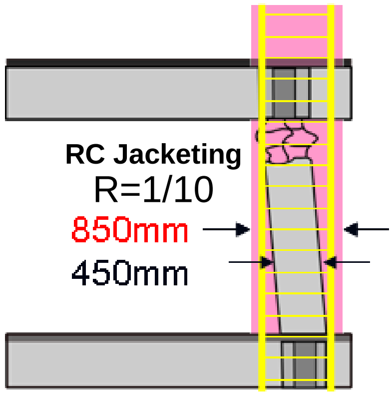
*1 Expected difficulties and necessary construction works
(1) Jack-up and re-centering of building; (2) Anchorage of longitudinal rebars for jacketing and arrangement of shear reinforcement in beam-column joints
*2 Expected post-restoration performance
(a) Damage expected under future major earthquake; (b) Higher resistance and stiffness expected but careful examination needed on their vertical distribution
*3 The strength index C is evaluated assuming the building weight per unit area is 10 kN/m^2. The capacity recovering factor ψ after restoration (i.e., reduction factor due to damage prior to restoration) employed in the Guidelines (JBDPA 2001, Nakano et al. 2000) is assumed 0.7 in this study.
*4 The amount of new reinforcement is assumed the same as the original. The column size of Schemes 1, 5, and 6: 450 x 650 mm; Scheme 2: 650 x 850 mm; Scheme 3: 850 x 850 mm; Scheme 4: > 850 x 850 mm.



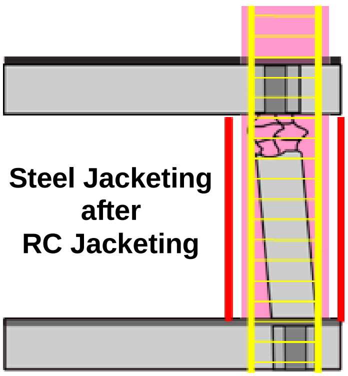
Scheme 1



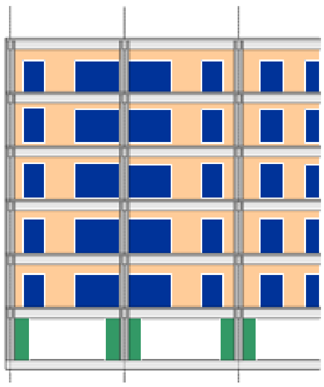
Scheme 2



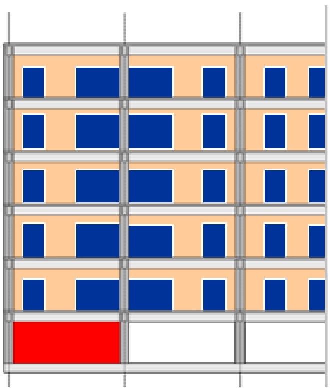
Scheme 3



Scheme 4



Scheme 5



Scheme 6

column size after Schemes 3 and 4 would be almost twice as large as the original since the new RC element around the original section needs to be large enough to jacket the tilted column and new reinforcement. In Scheme 3, as is assumed in Scheme 2 above, the flexural strength is estimated neglecting reinforcement in the original section while the whole section is assumed effective on the shear strength. It should also be noted that it is more favorable to provide crossties to confine such a large size section although difficult due to the presence of the original section. Scheme 4 therefore aims to provide flexural, shear, and confinement strength higher than those expected in the earlier Scheme 3 through employing steel jacketing after RC jacketing.

In Schemes 5 and 6, additional lateral resisting elements are provided in the first story as shown in Figure 3. Scheme 5 aims to increase in lateral resistance through providing wing walls in each column, while Scheme 6 provides six sets of RC shear walls which are expected to provide high lateral resistance. In both cases, the contribution of new sections is simply estimated by the product of the sectional area *Aw* and the ultimate shear strength τ_u of the wall, where τ_u is assumed 2 N/mm^2. Since the original structure is designed to absorb seismic energy through large plastic deformation rather than high lateral resistance, *Is* index after scheme 6 is still much lower than the original and the six sets of new shear walls may not be sufficient to fully improve the overall behavior of the structure as shown in Table 2.

3.4 Discussions in the seminar

More than ninety participants including researchers, engineers, and SJU students attended the seminar, and

After long and enthusiastic discussions, the Chinese participants concluded that Scheme 3 would be most realistic and practical if the oversized section after repair can be accepted by the residents, and that Scheme 2 may be the second best solution to restore the building if the applicability of the proposed restoration schemes are discussed as well as other general issues related to restoration techniques. Photo 11 shows snapshots from the seminar.

In the seminar, the Japanese side emphasized that the continuous distribution of strength and stiffness, smooth transfer of actions through structural members and their interface under seismic excitations, anchorage of new reinforcement into existing RC members etc. were of highest priority in re-designing the damaged buildings, although the restoration proposals were made only in the first story for simplified discussions. It was also pointed out that the buckling of column reinforcing bars associated with flexural compression failure could be observed in areas close to their interface between column ends and adjacent beams, and the confinement of beam-column joints using additional lateral reinforcement therefore is recommended to effectively eliminate further damage.

Scheme 3 is not accepted. It was also very interesting for Japanese participants to learn that Schemes 5 and 6 were much less acceptable by the Chinese participants although they might be most likely to be accepted in Japan. This is mainly because the mixture of different

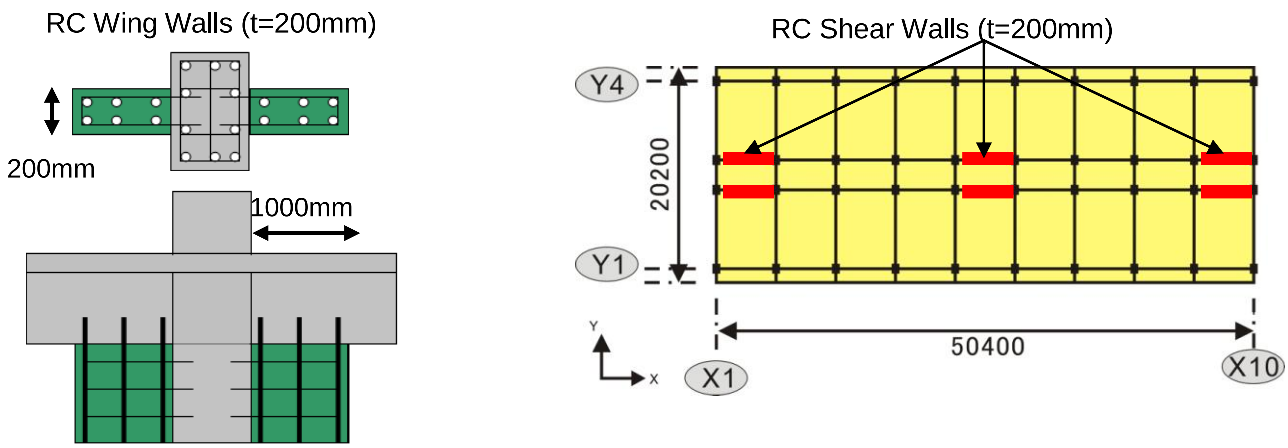


Figure 3. Location of wing walls for Scheme 5 (left) and shear walls for Scheme 6 (right)

Photo 11. Discussions in the Seminar

structural types (i.e., RC frames with shear walls in the first story and RC moment resisting frames in the upper stories) is not specified in the Chinese structural design code while it may be accepted in Japan if its effects by the change in stiffness and strength distribution along building's height on structural behavior are carefully taken into account.

4. CONCLUSIONS

Typical structural damage to URM and RC buildings due to the Wenchuan Earthquake and liaison activities for their damage restoration by the Japanese experts in close cooperation with Southwest Jiaotong University (SJU) are briefly presented. In especial, possible solutions for damage restoration of an example RC building in Dujiangyan city, which were proposed and discussed in the seminar held at SJU, are highlighted.

The central Chinese government has high-level background on seismic design and restoration techniques, but there still remain various types of difficulties even on the technical aspects as has been usually found in the earthquake aftermath elsewhere since such a devastating disaster and its aftermath are always the first experience to researchers and engineers in the most affected areas. The author therefore sincerely and deeply wishes that continued cooperative efforts, sharing information and experiences such as those having been done by the Council would effectively help restore damaged structures and communities.

ACKNOWLEDGMENT

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APPENDIX: BASIC CONCEPT OF JAPANESE STANDARD FOR SEISMIC EVALUATION OF EXISTING RC BUILDINGS

The Standard for Seismic Evaluation (JBDPA 1977, 1990, 2001), designed primarily for pre-earthquake existing RC buildings in Japan, defines the following structural seismic capacity index *Is* at each story level in each principal direction of a building.

$$Is = Eo \times S_D \times T \qquad (1)$$

where,

Eo : basic structural seismic capacity index, calculated by the product of Strength Index (*C*), Ductility Index (*F*), and Story Index (ϕ) at each story and each direction when a story or a building reaches the ultimate limit state due to lateral force ($Eo = \phi \times C \times F$)

C : index of story lateral strength expressed in terms of story shear coefficient

F : index of story ductility, calculated from the ultimate deformation capacity normalized by the story drift of 1/250 when a typical-sized column is assumed to fail in shear. *F* is dependent on the failure mode of a structural member and its sectional properties such as bar arrangement, member's geometry size etc. *F* is assumed to be in the range of 1.27 to 3.2 for ductile columns*, 1.0 for brittle columns* and 0.8 for extremely brittle short columns. (* Note: The Standard of 1990 version is applied in this study and *F* index of columns is evaluated as shown above.)

ϕ : index of story shear distribution during earthquake, estimated by the inverse of design story shear coefficient distribution normalized by the base shear coefficient. The value of $\phi = (n+1)/(n+i)$ is basically employed for the *i*-th story of an *n* story building.

S_D : reduction factor to modify *Eo* index due to stiffness discontinuity along stories, eccentric distribution of stiffness in plan, irregularity and/or complexity of structural configuration, basically ranging from 0.4 to 1.0

T : reduction factor to allow for time-dependent deterioration grade after construction, ranging from 0.5 to 1.0

A required seismic capacity index *Iso*, which is compared with *Is* to identify structural safety against an earthquake, is defined as follows.

$$Iso = Es \times Z \times G \times U \qquad (2)$$

where,

Es : basic structural seismic capacity index required for the building concerned. Considering past structural damage due to severe earthquakes in Japan, the standard value of *Es* is set 0.6 (see also Figure A1.).

Z : factor allowing for the seismicity

G : factor allowing for the soil condition

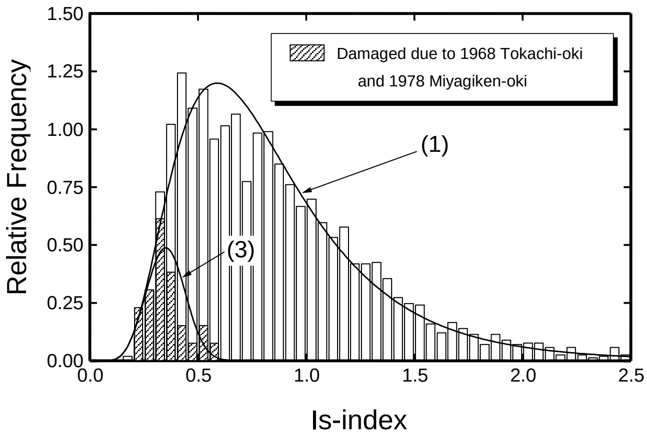
U : usage factor or importance factor of a building

Typical *Iso* index is 0.6 considering *Es* = 0.6 and other factors of 1.0. As can be found in Figure A1., buildings with *Is* larger than 0.6 successfully survived the 1968 Tokachi-Oki and 1978 Miyagi-Ken-Oki earthquakes. It should be noted that $C_T \times S_D$ defined in Equation(3) is required to equal or exceed $0.3\ Z \times G \times U$ in the Standard to avoid fatal damage and/or unfavorable residual deformation due to a large response of structures during major earthquakes.

$$C_T \times S_D = \square \times C \times S_D \qquad (3)$$

Seismic rehabilitation of existing buildings is basically carried out in the following procedure.

(1) Evaluate seismic capacity of the structure concerned (*Is* and $C_T \times S_D$)
(2) Determine required seismic capacity (*Iso*)
(3) Compare *Is* with *Iso* and $C_T \times S_D$ with $0.3\ Z \times G \times U$
* If $Is < Iso$ or $C_T \times S_D < 0.3\ Z \times G \times U$ and therefore rehabilitation is required, the following actions (4) through (6) are needed.
(4) Select rehabilitation scheme(s)
(5) Design connection details
(6) Re-evaluate the rehabilitated building to ensure the capacity of re-designed building equals or exceeds the required criteria



NOTE: *Is* indices of more than 1,600 existing RC buildings in Shizuoka prefecture, Japan, together with those of damaged buildings were evaluated and plotted in this figure. The horizontal axis [*Is*-index] indicates seismic index of structure which signifies the seismic capacity of a building calculated in accordance with the Standard. The vertical axis indicates relative frequencies of *Is* index. Bars shown in blank correspond to existing buildings in Shizuoka prefecture, which are prior to damaging earthquakes, while those in hatched correspond to buildings damaged in the past earthquakes in 1968 and 1978 in Japan. Curves in the figure were obtained from a probabilistic study.

Figure A1 *Is* index vs. observed damage in the past major earthquakes in Japan (Okada and Nakano 1988)