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Autor: Sakai, Junichi / Minami, Koichi / Matsui, Chiaki
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Damage of SRC Building Structures by 1995 Hyogo Earthquake

Junichi SAKAI
Research Assistant
Kyushu University
Fukuoka, Japan

Junichi Saka, born 1962, received master degree of Eng. from Kyushu Univ. in 1989. His research interests are analyses of beam-columns, joints, and frames in steel and composite structures.



Koichi MINAMI
Professor
Fukuyama University
Fukuyama, Japan

Koichi Minami, born 1939, received Dr. of Eng. from Kyoto Univ. in 1985. His research interests are analysis of beam-columns, joints, and frames in RC and composite structures.



Chiaki MATSUI
Professor
Kyushu University
Fukuoka, Japan

Chiaki Matsui, born 1937, received Dr. of Eng. from Kyoto Univ. in 1971. His research interests are analyses of beam-columns, joints, and frames in steel and composite structures.



Summary

A large number of Steel Reinforced Concrete (SRC) building structures were damaged seriously owing to 1995 Hyogoken-Nanbu Earthquake in Japan. The authors have investigated the damage of buildings and collected the data of 1,307 SRC buildings in and around Kobe city. Thirty-one SRC buildings collapsed by the story failure. All of them were constructed before 1972 and open-web type steels were used in SRC members. In this paper examples of damage of SRC buildings and members, and statistical analysis of damage are described.

1. Introduction

Steel Reinforced Concrete (SRC) building structure did not sustain severe structural damage owing to Kanto earthquake (1923) and has been developed as reliable earthquake resistant structure in Japan. Miyagiken-Oki Earthquake (1978) was the first strong earthquake that modern SRC structures had experienced. About three hundred high-rise buildings were shaken in Sendai city. Then cracks were observed in many nonstructural reinforced concrete exterior walls of high-rise apartment houses, however structural skeletons such as beams and columns were not damaged even though accelerations of 100 percent of gravity acceleration g were recorded in the upper stories [1].

Hyogoken-Nanbu Earthquake occurred on January 17, 1995 with a magnitude 7.2 on the Richter scale by Japan Meteorological Agency. Its epicenter was located close to a densely populated area. The earthquake caused severe damage to building structures and over 5,500 people were killed due to fire and collapsed buildings resulting from the severe shaking.

Hyogoken-Nanbu Earthquake was the first time that a large number of SRC buildings were subjected to severe structural damage. The distinctive feature of collapsed buildings was the story failure at an upper floor level, and most part of the collapsed buildings with mid-height

failure were constructed of SRC structures or mixed structures with SRC members in lower stories and reinforced concrete members in upper stories, in Sannomiya area, the downtown of Kobe city, where many office buildings and commercial buildings stand.

2. Damage of SRC Buildings

SRC members can be divided into two types. One of them is called open web type SRC, that was composed of angle steel as principal steel components and steel sections were fabricated with angles arranged to form lattices or ladders by rivet or bolt (see Fig. 2). This type of SRC had been used for most of SRC buildings constructed before 1975. The other is called full web type SRC, that is composed of H shaped steel as principal steel components (see Fig. 2). After 1968, it had made clear by some tests that earthquake resistant performance of SRC members using open web type steel was worse than one using full web type steel from the view point of shear behavior [2].

A new seismic code has been introduced in 1981, the ultimate strength of the structure and member ductilities under lateral load are considered, and the required lateral strength is given as a function of the deformation capacity assigned to various building types and members. With revising the code, the full web type SRC has been used for most of the SRC buildings constructed since then.

Figure 2 shows the relation of SRC type and construction year of buildings, and the construction years are divided into six periods according to the revising of the standards for structural calculation of SRC structures published by Architectural Institute of Japan [3] (AIJ standard). The term IV (1975-1980) show the period that buildings were constructed with either open web type or full web type.

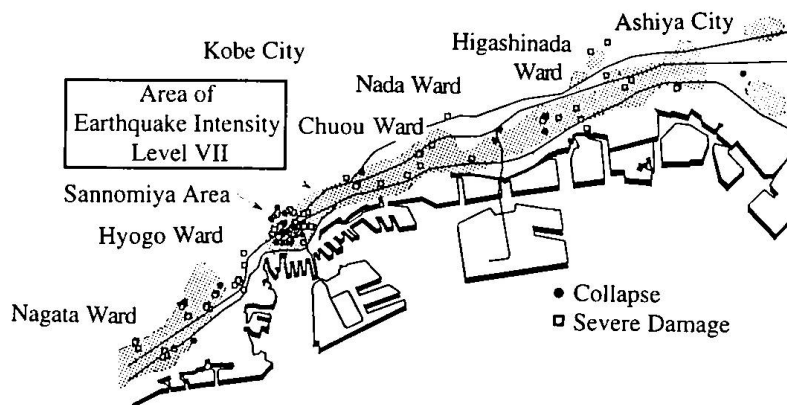


Fig. 1 Distribution of SRC buildings subjected collapse or severe damage.

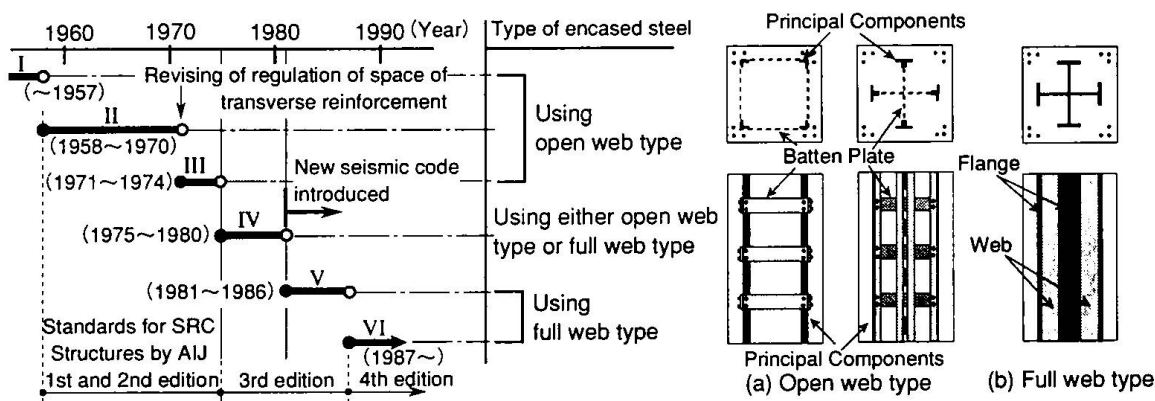


Fig. 2 Decision of Classification of Years of Completion of Buildings



(a)



(b)



(c)

Photo. 1 Collapsed Building with Story Failure at an Upper Floor Level



Photo. 2 Collapsed Column in Shear

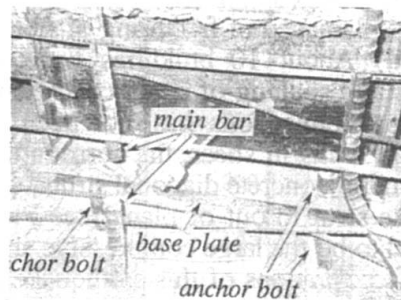


Photo. 3 Fracturing of Anchor Bolt at Column Base (after chipping concrete)

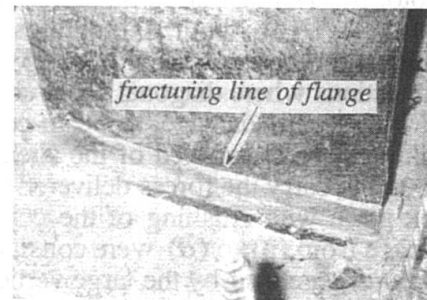


Photo. 4 Fracturing of Column Steel Flange Plate (after chipping concrete)

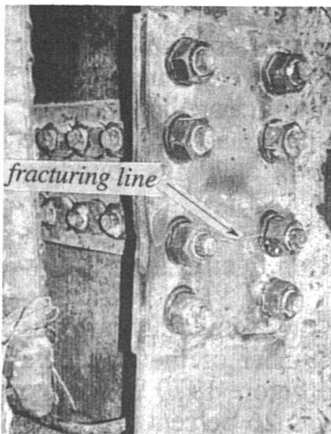


Photo. 5 Fracturing of Splice Plate at Column Joint (after chipping concrete)

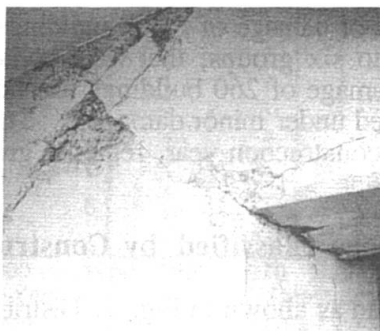


Photo. 6 Damage of Beam-Column Connection

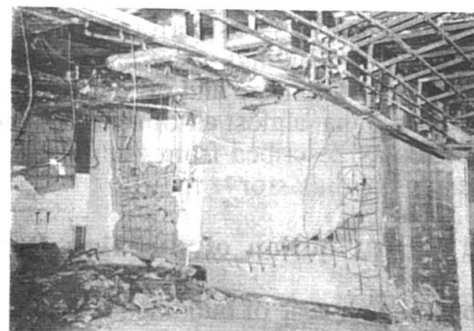


Photo. 7 Damage of RC Shear Wall

2.1 Collapsed Buildings with Open Web Type SRC

Thirty-one of SRC buildings collapsed by the story failure. All of them were constructed before 1972 and composed of the open web type SRC. Twenty-seven buildings collapsed by the story failure at an upper floor level (see Photo. 1) and four buildings collapsed at the first story. At the failure story, SRC columns collapsed brittly in shear (see Photo. 2) and concrete in RC shear walls crushed to out of plane. Collapse by the story failure at an upper floor level was characterized of the damage caused by this earthquake. Several factors potentially responsible for these failures can be considered as follows: (a) The design earthquake force distribution over the height used in the old design codes is different from the one used now, and the proportion of design story shear force is smaller at the mid-stories in the old codes. Then the ultimate strength of

the collapsed story was insufficient to sustain the lateral load induced by the earthquake. And also the ductility of the columns and the shear walls was insufficient. (b) Damage concentrated at the collapsed story where the lateral strength and/or stiffness changes abruptly between adjacent stories. And eccentricities of stiffness and mass caused torsional failure. (c) Large vertical accelerations generated large compressive and tensile axial forces in the columns, causing reductions in ductility and shear strength, respectively. (d) Joint of encased steel was located in the collapsed stories and the columns collapsed brittly in shear at this story.

2.2 Damage of Buildings with Full Web Type SRC

Buildings with full web type SRC did not collapse at all. However the following damages were observed in these buildings: (a) About 40 buildings were damaged at the column base. There were many buildings in which the steel base plate was anchored at the ground floor level using a detail known as "non-embedment type steel base". Severe damage was observed in buildings that used this base plate detail. Concrete crushed at the column base and anchor bolts were pulled out (see Photo. 3). (b) About 10 buildings were damaged of fracturing of encased steel flange plate (see Photo. 4). (c) About 10 buildings were damaged of fracturing of steel splice plate at the joints of columns or beams (see Photo. 5). (d) About 10 buildings were damaged at beam-column connections where diagonal shear cracks and spalling of cover concrete were observed (see Photo. 6), but severe damage at beam-column connections has not been reported. (e) About 40 buildings were damaged of the shear RC walls in shear; the surrounding SRC frame was strong enough to carry the forces delivered from the concrete diagonal struts, so sliding failure of the wall took place with crushing of the concrete strut to out of plane (see Photo. 7). Reasons for the damage from (a) to (d) were considered to be the large compressive and tensile axial forces in the columns generated by the large vertical accelerations of this earthquake and the existence of multi-story shear walls. A large number of columns or beams with flexural cracks, shear cracks, and shear bond cracks were observed, but severe damage has not been reported.

3 Statistical Analysis of Damage of SRC Buildings

Statistical analysis was performed by data of damage of 1,307 buildings in and around Kobe city. Damages of buildings were classified into six groups, that were collapse, severe, intermediate, minor, slight damage and no damage. Damage of 260 buildings has not been clear, but it can be considered that almost all of them sustained under minor damages. Statistical analysis of damage degree was described from the point of construction year, regional group of buildings, building use and building story.

3.1 Distribution of Building Damage Classified by Construction Year

Construction year of buildings was divided as shown in Fig. 2. Distribution of building damages classified by construction years is shown in Fig. 3. The ratio of the number of the buildings collapsed or sustained severe damage to the total of buildings constructed before 1970 was up to 30 percent (40/134), and the ratio of buildings constructed before 1974 was 26 percent (70/266). Almost all of them were composed of open web type SRC. On the other hand, with full web type SRC constructed after 1981, only 3 percent of buildings sustained severe damage (18/618), and no such a building collapsed.

3.2 Distribution of Building Damage Classified by Regional Group

3.2.1 Distribution of Building Damage Classified by Location

Distribution of building damage classified by locations is shown in Fig. 4. Locations are nine ward of Kobe city, Ashiya city, Nishinomiya city, Itami city, Takarazuka city, Amagasaki city and Akashi city. The number of SRC buildings constructed in chuou ward of Kobe city was 462, and the ratio of this number to all buildings was 35 percent. In this ward, 26 buildings collapsed, 40 buildings were subjected to severe damage, and the ratio of the number of buildings sustained those damage to total buildings was 15 percent.

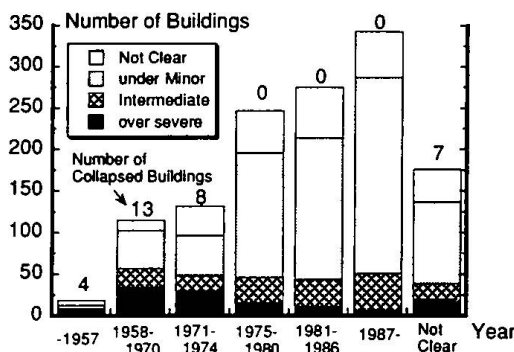


Fig. 3 Damage Classified by Construction Years

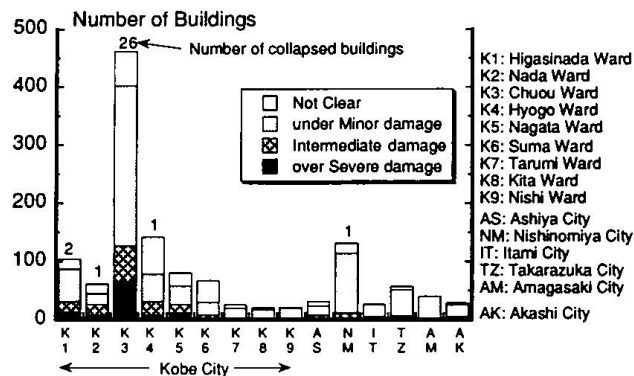


Fig. 4 Damage Classified by Locations

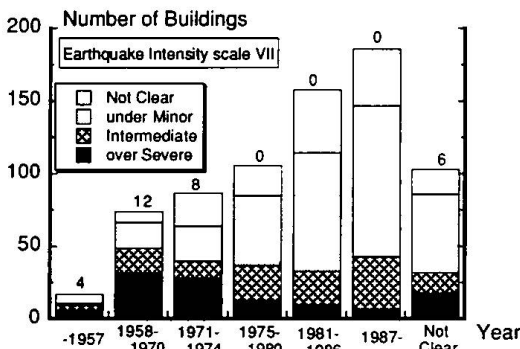


Fig. 5 Damage in Area of Earthquake Intensity Level VII

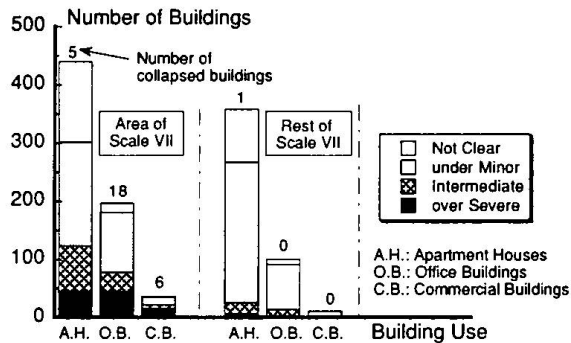


Fig. 6 Damage Classified by Building Use

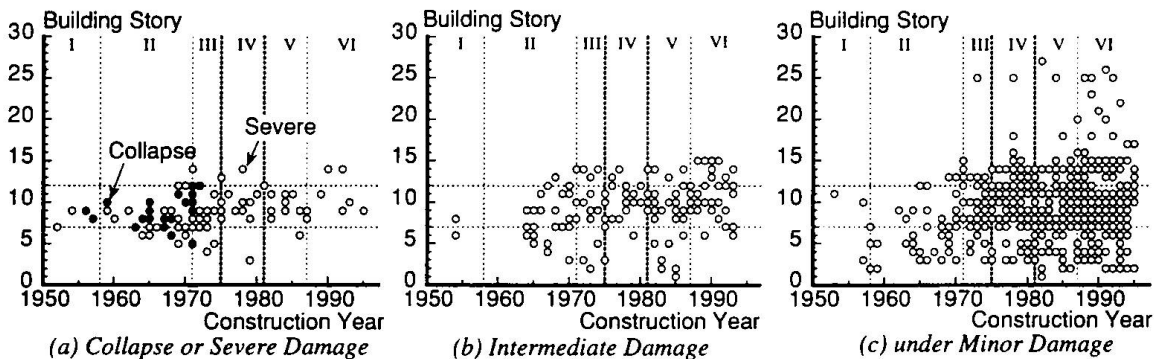


Fig. 7 Damage Classified by Story and Construction Year

3.2.2 Distribution of Building Damage Classified by Area of Earthquake Intensity Scale

An earthquake intensity scale is defined eight grade scales by Japanese Meteorological Agency. The intensity scale VII is the most intense grade, where the maximum acceleration of ground motion is over 400 gal. The area of earthquake intensity scale VII (area VII) spread widely in and around Kobe city. The area VII was defined on the map by Geographical Survey Institute of Japan, and M. Murakami presumed the address of the area from this map [4]. The ratio of the number of buildings constructed in the area VII to the total of buildings was 56 percent (731 buildings). Figure 5 shows the distribution of the building damage classified by construction years in the area VII. The buildings constructed before 1974 in the area VII tended to be subjected severer damage, and about half of the buildings constructed from 1958 to 1970 collapsed or sustained severe damage (32/74). On the other hand, only 5 percent of buildings constructed after 1981 sustained severe damage (17/344).

3.3 Distribution of Building Damage Classified by Building Use

Buildings were divided by building use as apartment houses, office buildings, commercial buildings and the others (see Fig. 6). The ratio of the number of apartment houses, office buildings and commercial buildings to the total of buildings were 61 percent (802 buildings), 23 percent (298) and 4 percent (49), respectively. The number of collapsed buildings were 5, 19 and 7 for apartment houses, office buildings and commercial buildings, respectively. The ratio of the number of commercial buildings collapsed or sustained severe damage to the total of buildings constructed in the area VII was up to 43 percent (16/37). The ratio for office buildings and for apartment houses was 23 percent (45/197) and 16 percent (45/441), respectively.

3.4 Distribution of Building Damage Classified by Building Story

Figure 7 shows the distribution of damage classified by building story and construction years. From these figures, it was clear that almost all of the buildings collapsed or sustained severe damage had over seven to twelve stories, and the buildings under six stories tended to be able to avoid severe damage, regardless of construction years of buildings. The buildings over fifteen stories did not sustain severer damage.

4 Conclusions

It has been made clear from performing analysis of damage of SRC buildings that;

- 1) Thirty one SRC building structures were collapsed with the story failure. All of them were constructed before 1972 and composed of open web type SRC. The distinctive feature of damage of SRC buildings was the story failure at an upper floor level, and 27 buildings collapsed in this type. No building structure with full web type SRC collapsed at all.
- 2) Some buildings with the full web type SRC sustained severe damage. The feature of the damage was as follows; crushing of concrete at the column base and/or pulling out of anchor bolts, fracturing of steel flange plates, fracturing of steel splice plates at the joints, crack of concrete at the beam-column connections, and shear failure of RC walls surrounding the SRC frames.
- 3) Buildings using the open web type SRC constructed before 1974 tended to sustain to severer damage. In the earthquake intensity scale VII, half of the buildings constructed from 1958 to 1970 collapsed or sustained severe damage. On the other hand only 5 percent of buildings constructed after 1981 sustained severe damage in this area. The ratio of the number of commercial buildings collapsed or sustained severe damage to the total of buildings constructed in this area was up to 43 percent. Almost all of the buildings collapsed or sustained severe damage had over seven to twelve stories, and the buildings under six stories tended to be able to avoid severe damage. The buildings over fifteen stories did not sustain severer damage.

Acknowledgment

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