ANALYSIS OF DAMAGE OF STEEL REINFORCED CONCRETE BUILDING FRAMES BY 1995 HYOGOKEN-NANBU EARTHQUAKE

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SUMMARY

Composite encased-steel and concrete structures have been called “Steel Reinforced Concrete (SRC)” structures, and popular in the building construction in Japan. This structural system originally came into Japan from the West in 1910’s, and it has been applied to high-rise buildings taller than 6-stories, being recognized as an earthquake-resistant and fireproof system after the Great Kanto Earthquake in 1923. It is also suitable for the recent construction of the high-rise and long-span urban buildings.

A large number of Steel Reinforced Concrete 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-two SRC buildings collapsed by the story failure. All of them were constructed before 1972 and open web type steels were used in SRC members. The distinctive feature of damage SRC buildings was the story failure at an upper floor level, and 27 buildings collapsed in this failure type. Buildings with this type 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 (a new seismic code has been introduced) sustained severe damage. No building with full web type SRC collapsed. But some buildings with full web SRC sustained severe damage. The feature of the damage was as follows; crushing of concrete at the column base and / or fracturing of anchor bolts, fracturing of steel flange plates, fracturing of splice plates at the joints, shear crack of concrete at the beam-column connections, and shear failure of RC structural walls surrounding the SRC frames.

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].

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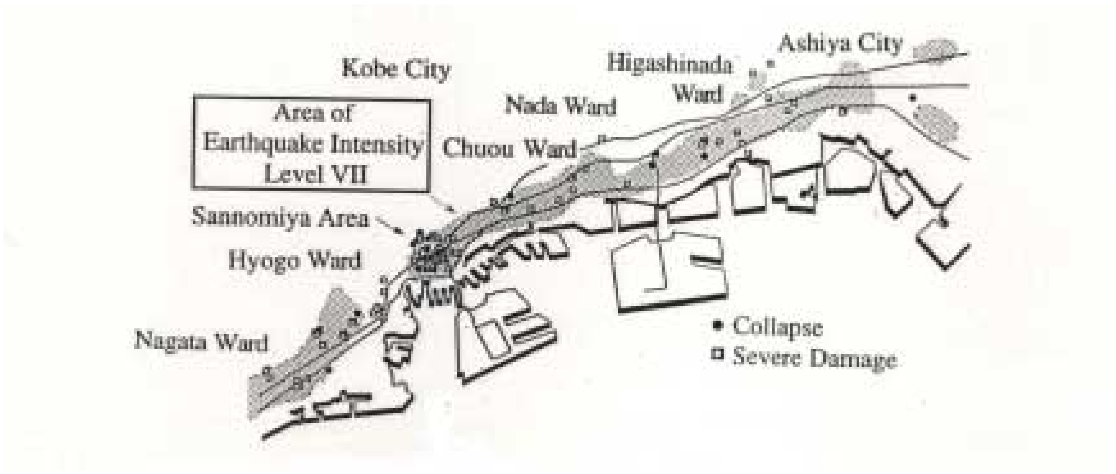


Fig. 1 Distribution of SRC buildings subjected collapse or severe damage in and around Kobe city

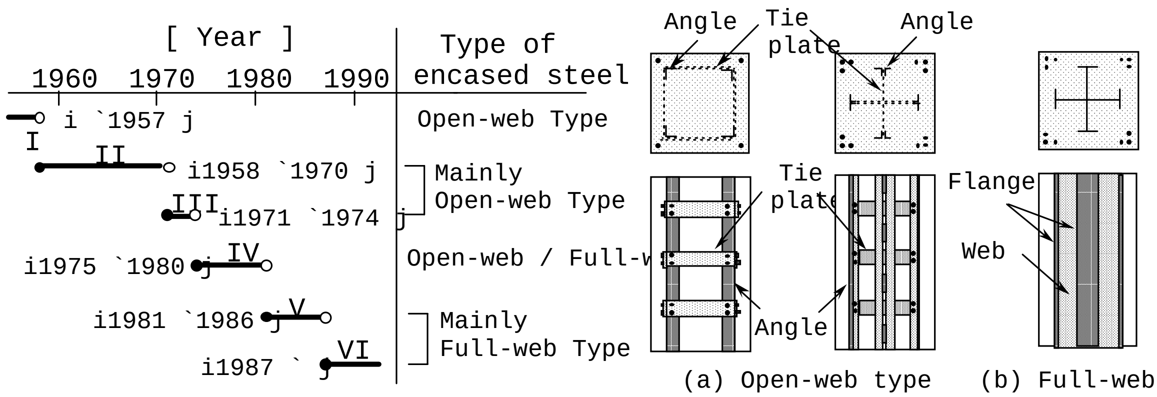


Fig. 2 Decision of Classification of Years of Completion of Buildings

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. DEVELOPMENT OF STRUCTURAL DESIGN REQUIREMENTS

The structural design of the SRC structures initiated at the end of 1910's, but there was no structural standards available at the time, and the design was done according to the philosophy of individual structural engineer. After the world War II, it became necessary to prepare the structural design standards to the SRC structures, which started to be constructed for the post war rehabilitation. In 1951, a subcommittee for the SRC structures was formed in Architectural Institute of Japan (AIJ) to write the structural design standards for the SRC structures. The first edition of the standards for structural calculation of Steel Reinforced Concrete Structures

(SRC standards) was published by AIJ in 1958, based on the systematic research investigation conducted during 10 years from 1950 under the supervision of SRC subcommittee of AIJ to store the back data for the design formulas. The method of superposed strength was employed in the standards to the design of flexural members, and members subjected to flexure and compression, although the RC method remained. It was revised in 1963, and the formulas for the shear design were shown. Tokachi-oki earthquake in 1968 caused severe damages on the RC short columns, and since then a large number of the researches on the shear failure of the RC short columns were conducted. The ductility characteristics of SRC columns under repeated loading were also investigated. The SRC subcommittee of AIJ supervised the research to establish the design formulas for the shear failure of the SRC columns. The results of these researches lead to the 2nd revision of the SRC standards in 1975, which widely revised the shear design method by introducing the formulas based on the concept that the flexural failure should precede the shear failure in a member. A new order for the seismic design of building structures was enforced in 1981, and the 3rd revised edition (present edition) of the SRC standards was published in 1987, which shows the method of the calculation of the lateral load resisting capacity required by the order. The method of the superposed strength is employed for calculating the allowable and ultimate strength of connections, structural walls and other components in addition to primary members. As to composite steel tube and concrete structures, the structural standards similar to the SRC standards were published independently, but they were absorbed to the present edition of the SRC standards.

3. 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.

3.1 Collapsed Buildings with Open Web Type SRC:

Thirty-two of SRC uildings 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 five 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.

3.2 Damage of Buildings with Full Web Type SRC:

(a) Photo 1 Collapse Buildings with Story Failure at an Upper Floor Level b)

Photo 2 Collapsed Column in Shear

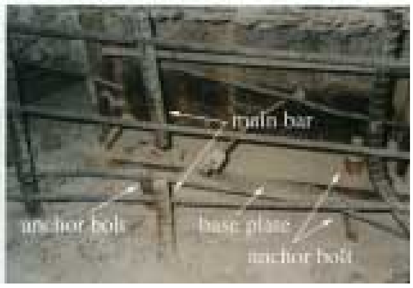


Photo 3 Fracturing of Anchor Bolt at Column Base (after chipping concrete)

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

Photo 5 Damage of Beam-to-Column Connection

Photo 6 Damage of RC Shear Wall

Photo 7 Fracturing of Splice Plate at Column Joint (after chipping concrete

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 te 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. Concree 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.

4. 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.

4.1 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.

4.2 Distribution of Building Damage Classified by Regional Group:

4.2.1 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.

4.2.2 Distribution of Building Damage Classified by Area of Earthquake Intensity Scale :

Sannomiya was one of the area where large number of buildings sustained severe damage. The distribution of damage of SRC buildings in and around Sannomiya is shown in Fig.7. Over half of the buildings constructed before 1974 collapsed or sustained severe damage (38 / 70). Ten percent of SRC buildings constructed after 1981 sustained severe damage (6 / 62).

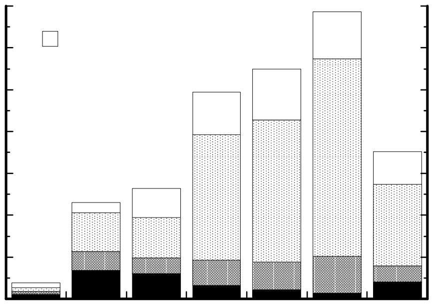


Fig. 3 Damage Classified by Construction Years

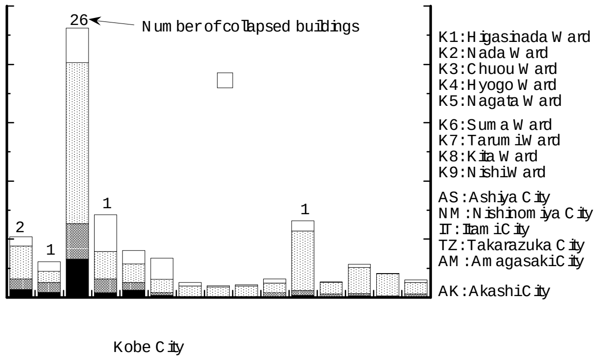
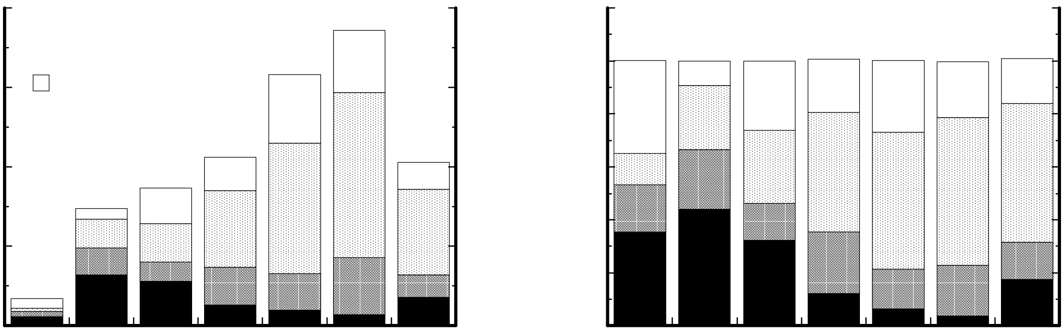
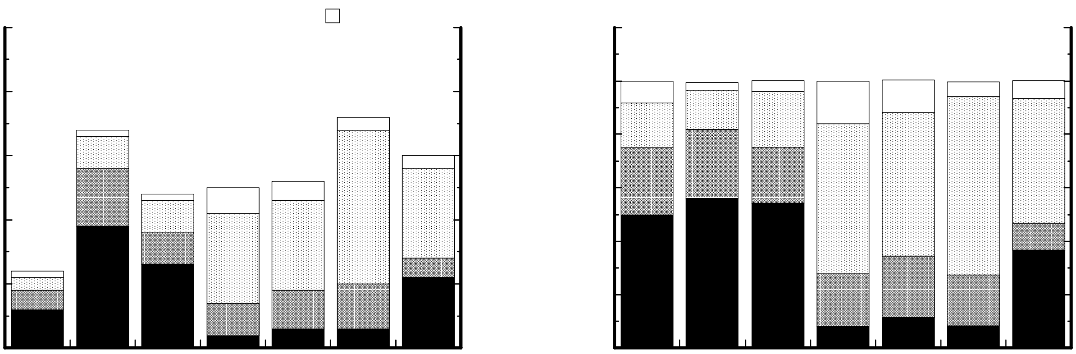


Fig. 4 Damage Classified by Locations



(a) Number of buidings (b) Percentage

Fig. 5 Damage in Area of Earthquake Intensity Level VII



(a) Number of buildings (b) percentage

Fig. 6 Damage in and around Sannomiya

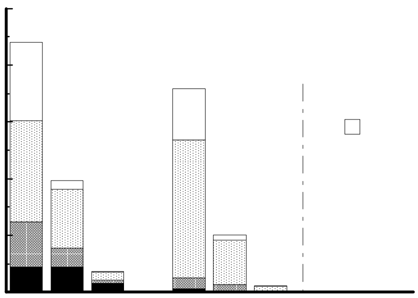
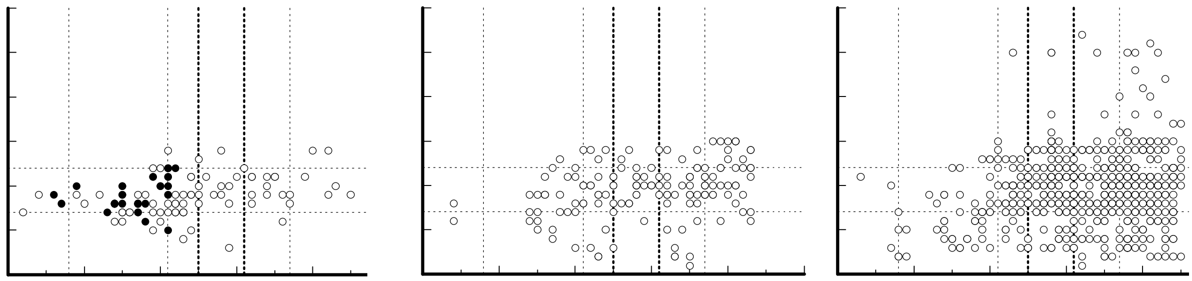


Fig.7 Damage Classified by Building Use

Sannomiya was one of the area where large number of buildings sustained severe damage. The distribution of damage of SRC buildings in and around Sannomiya is shown in Fig.7. Over half of the buildings constructed before 1974 collapsed or sustained severe damage (38 / 70). Ten percent of SRC buildings constructed after 1981 sustained severe damage (6 / 62).



(a) Collapse or Severe Damage (b) Intermediate Damage (c) under Minor Damage

Fig. 8 Damage Classified by Story and Construction Year

4.3 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. 7). 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.

4.4 Distribution of Building Damage Classified by Building Story:

Figure 8 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. Figure 9 shows the building story and construction years of collapsed buildings.

5. CONCLUSIONS

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

1) Thirty two 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.

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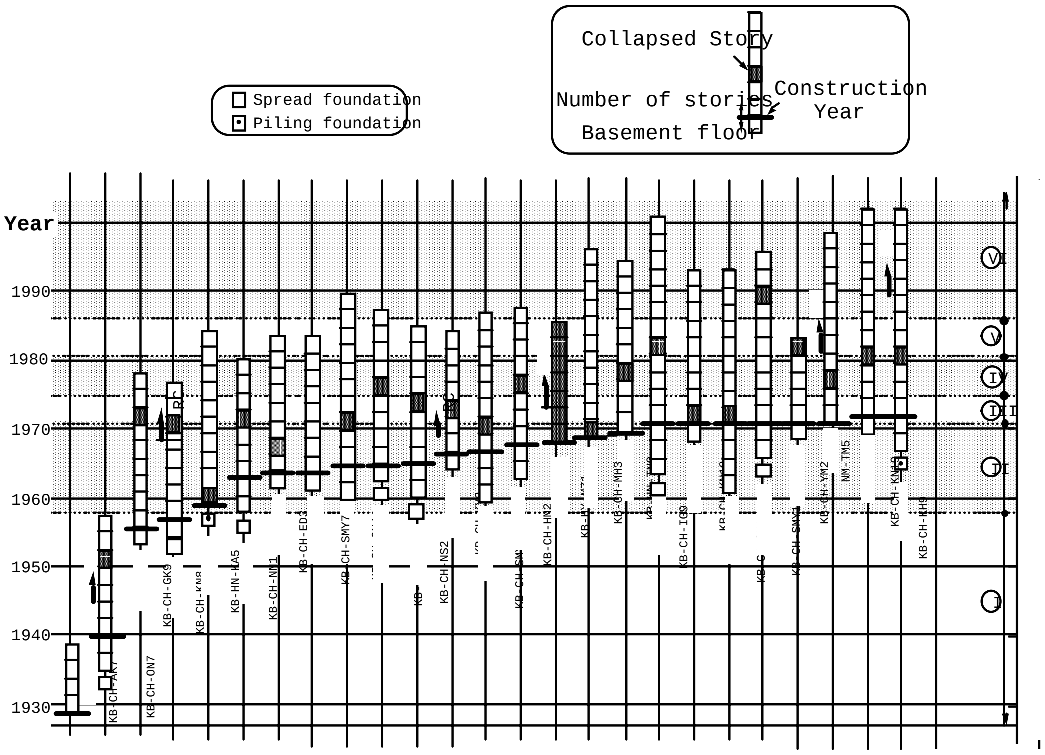

Fig. 9 Building Story and Construction Years of Collapsed Buildings