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DAMAGE OF R/C RESIDENTIAL BUILDINGS IN THE 1995 HYOGOKEN-NANBU EARTHQUAKE

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ABSTRACT

Damage and reinforcement details of 76 heavily damaged or collapsed reinforced concrete residential buildings, located in Nada Ward and Higashi-Nada Ward, Kobe City, were surveyed extensively to study the cause of the damage. Ninety percent of the buildings suffered damage in the first story, where the use was dominantly shops, offices, storage rooms or parking garage with little structural walls. The failure was caused by shear failure of columns, where the ends of lateral reinforcement were bent only 90 degrees and did not develop tension yielding.

KEYWORDS

1995 Hyogoken-Nanbu Earthquake; reinforced concrete residential building; damage survey; column shear failure; lateral reinforcement detailing.

INTRODUCTION

The 1995 Hyogoken-Nanbu Earthquake, JMA Magnitude 7.2 with an epicenter located about 20 km to the southwest of City of Kobe, caused significant damage to modern reinforced concrete (R/C) residential buildings. Immediately after the earthquake, a preliminary reconnaissance was carried out by teams from the Architectural Institute of Japan (AIJ). Two heavily damaged wards in Kobe were selected: Nada Ward and Higashi-Nada Ward, which are located at the eastern part of the city (Fig. 1). The survey covered all the heavily damaged or collapsed R/C residential buildings in the two wards, and damage state of the buildings and structural characteristics of damaged members were carefully recorded. Buildings of heavy damage were defined when spalling of concrete, exposure of reinforcement, buckling of longitudinal reinforcement, and rupture or opening of lateral reinforcement were found in more than one-third of the total number of columns of the most heavily damaged story, and when lateral resistance was apparently reduced. Buildings of collapse were defined when the floor sank more than 30 cm. The statistics of the damaged buildings were established as to (a) number of stories, (b) location of heavy damage in each building, (c) use of heavily damaged floors, (d) materials used as reinforcement, and (e) lateral reinforcement in columns.

DAMAGE STATISTICS

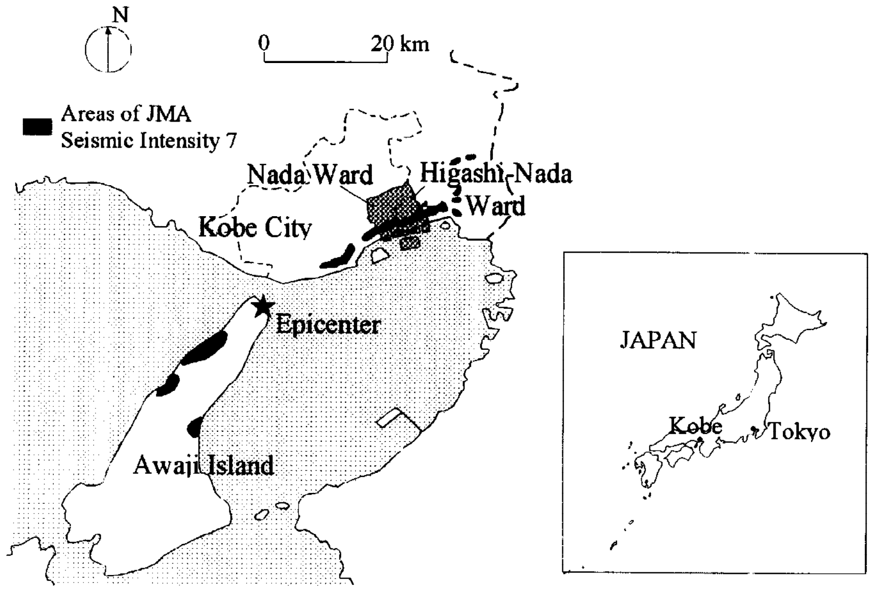

Fig. 1. Location of Nada Ward and Higashi-Nada Ward

A total of 76 R/C residential buildings were judged to have collapsed or heavily damaged in both Nada and Higashi-Nada Wards, excluding already demolished or unapproachable buildings; 24 buildings were heavily damaged; 52 buildings collapsed. Results of the survey are described below in detail.

Number of Stories

The number of stories of the heavily damaged buildings is important for future design. For example, statistics which show that the damage ratio in low-rise buildings (short natural periods) was higher than that of high-rise buildings (long natural periods) can be materials for earthquake resistant design. Unfortunately, the number of all existing R/C buildings in the area could not be obtained through the survey. The number of heavily damaged or collapsed buildings with different number of stories is shown in Table 1.

Table 1. Number of heavily damaged or collapsed buildings with different number of stories

number of stories	1	2	3	4	5	6	7	8	9	10	11	12	total
heavy damage	0	0	4	10	3	1	3	1	0	0	1	1	24
collapse	0	0	7	18	12	2	11	1	0	1	0	0	52
total	0	0	11	28	15	3	14	2	0	1	1	1	76

71 buildings (93 % of the 76 investigated buildings) were low-rise buildings of three to seven stories. No heavily damaged one- or two-story buildings were found in the survey. 5 buildings (7 %) were more than eight stories high. Local government requires that the construction of R/C buildings taller than 20 meter should be provided with special reinforcement detailing for ductility and should be of regular structural configuration. Therefore, these high-rise buildings might have been more earthquake resistant.

Locations of Heavy Damage

The locations of the heavy damage in each building was classified as (1) damage of foundation leading to tilting of the building, (2) collapse or heavy damage of the first story (Fig. 2), (3) collapse of an intermediate story, or (4) distributed damage, as shown in Fig. 3.

(a) 4-story building (b) 5-story building

Fig. 2. Collapse of the first story

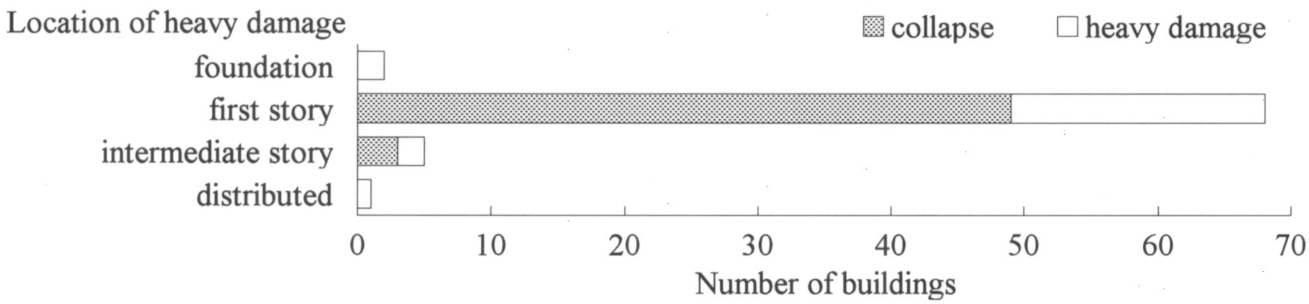

Fig. 3. Locations of heavy damage in the collapsed or heavily damaged buildings

In 68 buildings (89 % of the 76 investigated buildings), heavy damage and collapse were observed in the first story. Relatively few buildings exhibited a mid-height failure. The use of heavily damaged first story was studied for the 68 buildings (Fig. 3); in 63 buildings (93 % of the 68 buildings), the first story was used not for residence, but for parking of automobiles, shops, offices, or warehouses. In residential stories, residential units were separated by structural walls. However, the structural walls were removed in the first story for use for shop, garage or storage. Therefore, structural walls can be considered to be less in the first story than in the upper residential stories. In some collapsed buildings, structural walls were provided only in one of the principal direction, and the collapse occurred in the other direction.

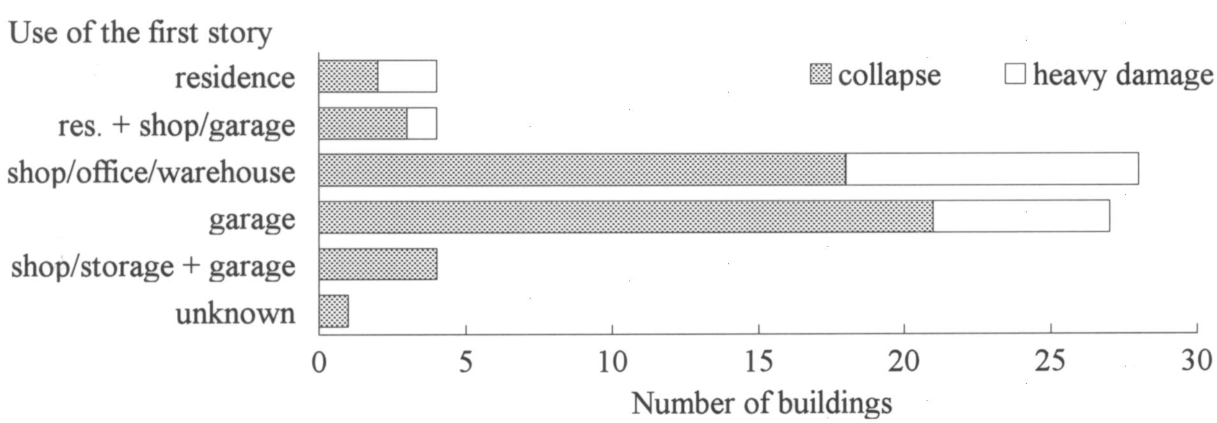

Fig. 4. Use or occupancy of the heavily damaged first-story

Materials Used as Reinforcement and Construction Period

Although definite information on the construction year of each building could not be obtained through the survey, the construction period was judged from the materials used as reinforcement. In Japan, deformed bars were standardized by Japanese Industrial Standard (JIS) in 1964, and then Kozai-Club published *Design Guideline for Reinforced Concrete Using Deformed Bar* in 1971. Deformed bars may have been used for longitudinal reinforcement since around 1971 and have been used for lateral reinforcement since around 1975. The materials used as reinforcement in columns are shown in Table 2.

Table 2. Materials used as reinforcement

longitudinal reinforcement	lateral reinforcement	heavy damage	collapse	total
plain round bar	plain round bar	4	13	17
deformed bar	plain round bar	10	28	38
deformed bar	deformed bar	6	8	14
unknown		4	3	7
total		24	52	76

Of the 69 heavily damaged or collapsed buildings in which identification of type of reinforcement in columns was possible, plain round bars were used for longitudinal and/or lateral reinforcement in 55 buildings (80 %); deformed bars were used for lateral reinforcement in 14 buildings (20 %). Probably, the heavy damage was observed in relatively old buildings constructed before 1970 or 1975. However, without statistics of all existing buildings in the area, it can not be said that the damage ratio of old buildings is large.

SHEAR FAILURE OF COLUMNS

Most of the heavy damage and collapse were caused by shear failure of the first-story columns (Fig. 5). Therefore, the amount and arrangement of lateral reinforcement were studied. Generally, closely spaced lateral reinforcement is expected to restrain shear cracks from opening and confine the concrete if the lateral reinforcement is well anchored at both ends. The survey revealed that the bend at the ends of the lateral reinforcement opened after the spalling of cover concrete, and that the columns failed in shear without yielding of the lateral reinforcement.

(a) shear failure of the first-story columns (b) 90-degree and 135-degree hooks at the two ends

Fig. 5. Shear failure of columns

Spacing of Lateral Reinforcement

All buildings in Japan must satisfy the requirements of the Building Standard Law. The methods of construction and structural calculation are specified in the Building Standard Law Enforcement Order (Cabinet Order). The Cabinet Order, proclaimed in 1950, required that a column should be reinforced by at least four longitudinal bars which were firmly fastened by tie reinforcement at a vertical spacing not exceeding 300 mm and 15 times the smallest diameter of longitudinal reinforcement. In the 1968 Tokachi-oki Earthquake (M 7.9), many R/C buildings collapsed due to shear failure of short columns. Such damage raised some doubt about the earthquake resistance of R/C construction. Researchers examined the cause of the damage and recommended that amount of shear reinforcement should be increased and placed effectively. The Cabinet Order was revised in 1971 to prevent shear failure of columns; the vertical spacing of lateral reinforcement should be 100 mm or less within a range twice the smallest dimension of column section above and below the face of horizontal members. The vertical spacing of lateral reinforcement in columns are shown in Fig. 6.

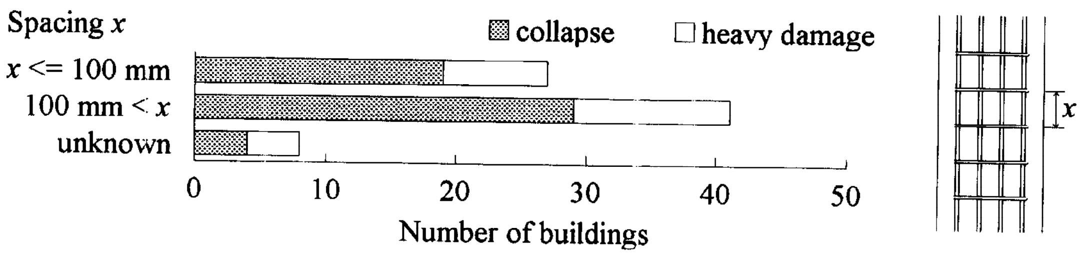

Fig. 6. Vertical spacing of lateral reinforcement

Of the 68 heavily damaged or collapsed buildings where the spacing of lateral reinforcement could be observed, the vertical spacing of lateral reinforcement exceeded 100 mm in 41 buildings (60 %); the vertical spacing of lateral reinforcement was 100 mm or less in 27 buildings (40 %). Statistics show that the quantitative requirement of lateral reinforcement was not sufficient to avoid shear failure of columns.

Bent Angle at Ends of Lateral Reinforcement

The AIJ provides engineering procedures through *Standard for Structural Calculation of Reinforced Concrete Structure* (R/C Standard) for structural calculation and design guidelines, which are normally deemed as technical references and technical recommendations by the academia. The AIJ has recommended in R/C Standard that free end of lateral reinforcement should be bent more than 135 degrees since 1933. The bent angle at the ends of the lateral reinforcement in the columns is shown in Fig. 7.

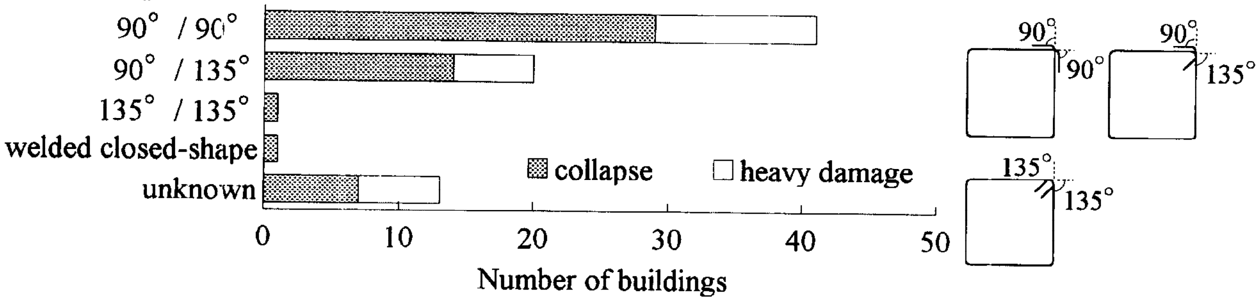

Fig. 7. Bent angle at ends of lateral reinforcement

Of the 63 heavily damaged or collapsed buildings where the ends of the lateral reinforcement in the columns could be observed, 135-degree hooks were found at both ends in one building; welded closed-shape reinforcement was used in one building; the lateral reinforcement was anchored with either both 90-degree hooks or 90-degree and 135-degree hooks at the two ends (Fig. 5(b)) in the other 61 buildings (97 %). Although R/C Standard has recommended the use of 135-degree hooks since 1933, the difficulty in construction did not permit such detailing in construction practice until special devices were developed for the 135-degree bending. The existing buildings are susceptible to the earthquake disaster due to the same inadequate lateral reinforcement workmanship. The importance of reinforcement detailing was reconfirmed.

In the building in which welded closed-shape reinforcement was used, the perimeter hoops were found not sufficient to confine the concrete after shear cracking; supplementary cross ties should be used in a region where large plastic deformation is expected. There was, however, one building in which the first-story columns failed in shear although both perimeter hoops and supplementary cross ties were used and well anchored by 135-deg hooks. Further research is needed to study the cause of the damage and to review the required story shear capacity of the soft first story.

CONCLUSIONS

A total of 76 heavily damaged or collapsed R/C residential buildings, located in Nada Ward and Higashi-Nada Ward, Kobe City, were surveyed. 52 buildings collapsed; 24 buildings were heavily damaged. 71 buildings (93 %) were low-rise buildings of three to seven stories, and the other 5 buildings (7 %) were more than eight stories high. 55 buildings (72 %) were relatively old buildings in which plain round bars were used for longitudinal and/or lateral reinforcement. 68 buildings (89 %) suffered damage in the first story, where the use was dominantly for parking of automobiles, shops, offices, or warehouses with little structural walls.

Most of the heavy damage and collapse ware caused by shear failure of the first-story columns. As a result of the 1968 Tokachi-oki Earthquake, the Building Standard Law Enforcement Order (Cabinet Order) of Japan was revised in 1971 to reduce the vertical spacing of lateral reinforcement in columns from 300 mm to 100 mm. The vertical spacing of lateral reinforcement was, however, 100 mm or less in 27 buildings (40 % of the 68 buildings in which the vertical spacing of lateral reinforcement could be observed); the quantitative requirement of lateral reinforcement was not sufficient to prevent shear failure of columns. Either both ends or one end of lateral reinforcement were bent only 90 degrees and did not develop tension yielding in 61 buildings (97 % of the 63 buildings in which the reinforcement detailing could be observed); although the Architectural Institute of Japan has recommended the use of 135-degree hooks since 1933, the recommendation was not implemented in the Cabinet Order. Perimeter hoops were found not sufficient to confine the concrete after shear cracking; supplementary cross ties should be used in a region where large plastic deformation is expected. The importance of reinforcement detailing was reconfirmed.

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REFERENCES

Architectural Institute of Japan (published in 1933, and revised in 1937, 1947, 1949, 1958, 1962, 1971, 1975, 1979, 1982, 1988, 1992), Standard for Structural Calculation of Reinforced Concrete Structures (in Japanese)