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DAMAGE TO ENGINEERED BUILDINGS FROM THE 1995 HYOGOKEN-NAMBU EARTHQUAKE

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ABSTRACT

A large number of engineered structures suffered damage due to the Hyogoken-nambu earthquake of January 17, 1995. Visual evidence of this damage to reinforced concrete and steel buildings together with preliminary descriptions of the possible reasons for this damage is given.

1. INTRODUCTION

For years in Japan, the earthquake-resistant design issues for buildings have been emphasized almost exclusively for new constructions, without much regard to the risks posed by existing buildings. On January 17, 1995, the Hyogoken-nambu earthquake brutally changed that perspective. With some noteworthy exceptions, the major lesson of the Hyogoken-nambu earthquake is that existing buildings, designed and built at a time when seismic-design requirements were still in their infancy, remain most vulnerable to earthquakes. Unless retrofitted, the level of seismic-resistance remains less than what is nowadays considered the necessary minimum, and their material detailing lacks the essential features that ensure reliable ductile behavior. Whereas newer buildings designed using the latest earthquake engineering knowledge embedded in the codes and standards also are expected to suffer damage when subjected to rare and unusually intense earthquakes, their damage, contrary to that done to older buildings, is unlikely to result in total or partial collapse, thus allowing the occupants to evacuate unharmed from these newer buildings.

This paper briefly reviews the seismic performance of engineered buildings during the Hyogoken-nambu earthquake of January 17, 1995, and emphasizes the differences in performance between older and newer buildings. Due to space constraints, the preliminary descriptions of the possible reasons for this damage are kept to a minimum.

KEY WORDS: Hyogoken-nambu earthquake, Building, Reinforced Concrete, Steel

2. REINFORCED CONCRETE BUILDINGS

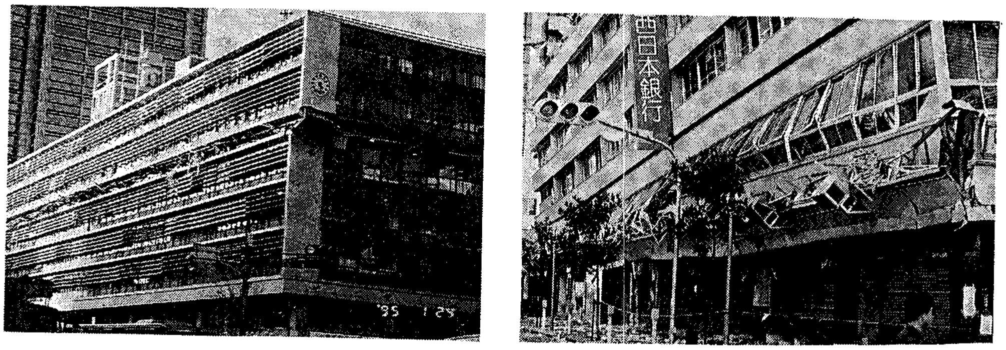
2.1 *Collapses*

Never since the 1985 Mexico earthquake have so many reinforced concrete buildings in an urban area lost one or many stories completely, or collapsed totally (Photo 1). Although some of the causes for these collapses are identical to those identified following the Mexico earthquake, a number of the contributing reasons for this fatal damage are new due to the sometimes distinct Japanese construction practices.

Loss of a story is typically the consequence of the excessive accumulation of damage in a single story, as opposed to the uniform sharing of damage and ductility through all stories which is implicit in modern building design codes. During the Hyogoken-nambu earthquake, these failures, also known as soft-story failures, frequently were found for the first story of buildings. Past experience during prior earthquakes worldwide has demonstrated that the contemporary architectural design of buildings, which emphasizes a maximum amount of clear open space at the first story, combined with the taller story height typical of these buildings, is responsible for higher flexibility and thereby the accumulation of damage in that first story.

Loss of a higher story can be attributed to a number of different causes. Frequently, setbacks and adjacent lower building-portions provide additional strength and rigidity to lower stories, and damage is concentrated in the first story above these lower stories. Another type of story loss was at the first story above a structural discontinuity, such as the end of a shear wall, a change in column cross-section, or even the transition story from a composite steel-reinforced-concrete structural system to a pure reinforced-concrete system. In the last case, it must be understood that the encasement of a steel frame in a reinforced-concrete frame has been a popular, uniquely Japanese approach to enhance the seismic resistance of buildings. Until a few decades ago, for economy the steel frame was constructed only over part of the height of building. This is the first earthquake in which story losses at the point of discontinuity of embedded steel frames have been observed.

All-story collapses occurred in older buildings designed prior to the introduction of the requirement of the use of ductile material in Japanese buildings codes. For example, a close view of typical reinforcement detailing discloses the gross inadequacy of transverse reinforcement as compared to current requirements (Photo 2). It was standard practice prior to 1971 to space transverse reinforcement at a 300 mm interval center-to-center. Code changes introduced in 1971



(a) (b)

Photo 1 Story collapse in RC buildings
[(a) 6th story collapse, (b) 2nd story collapse)]

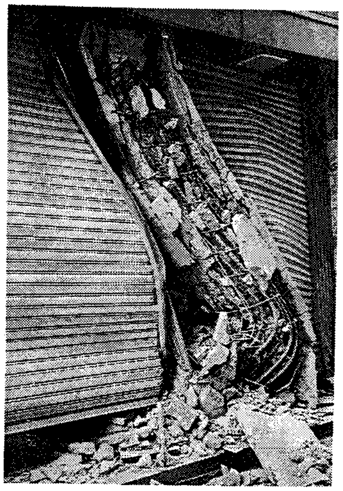
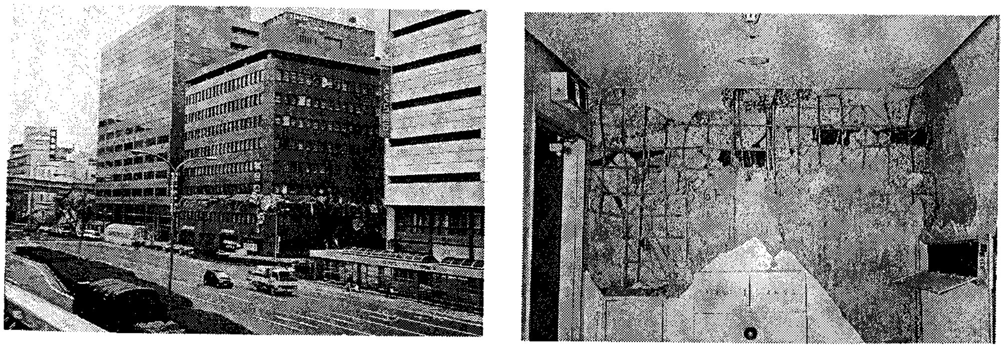


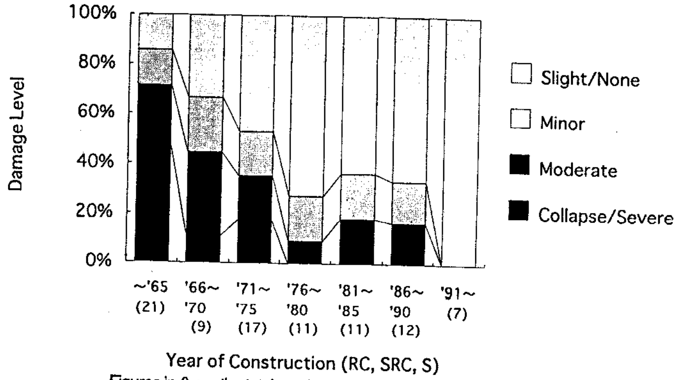
Photo 2 Failure of an RC column with insufficient transverse reinforcement



(a)

(b)

Photo 3 Difference in damage sustained by new and old RC buildings
[(a) new building (left) and old building (right), (b) damage to shearwalls in the new building]

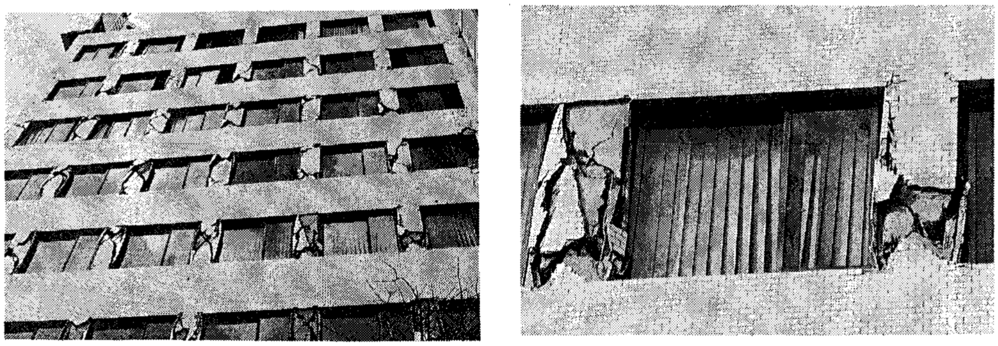


Figures in () are the total number of buildings examined.

Fig. 1 Correlation between damage level and year of construction limited the spacing to 150mm, further reducing it to 100 mm at the ends of structural members, thus providing more appropriate shear resistance and concrete confinement. Furthermore, the latest building code changes (1980) introduced other stringent ductile-design requirements as well as a two-level design procedure which effectively requires that the *ultimate* seismic-resistance of buildings be verified. As a result of this evolution of design requirements, striking contrasts in the life-safety protection afforded by adjacent buildings of different eras were readily observable following the earthquake (Photo 3). Although newer buildings sometimes suffered internal structural damage, they did not totally or partially collapse. This observation is supported quantitatively by data collected in a portion of downtown Kobe where damage was particularly severe (Fig.1).

2.2 *Non-Fatal Damage to Buildings*

Photo 4 Damage to shearwalls in an older RC building



(a)

(b)

Photo 5 Shear cracking to RC columns
[(a) overview, (b) close-up]

Very diversified types of non-fatal damage to reinforced concrete also were observed in this earthquake. For example, ductile and nominally ductile shear walls suffered considerable amounts of damage, even when properly detailed boundary elements were present. These shear walls, however, have behaved as expected as apparantly no buildings relying on shearwalls for lateral load resistance collapsed. This is true in spite of the sometimes extensive damage to the walls in older buildings. Photo 4 shows such an example, in which, despite significant damage to the shearwalls, the building itself survived with neither much damage to its beams and columns nor a large permanent lateral deformation.

Furthermore, a large number of buildings suffered severe shear cracking and other damage to their columns, beams, or joints. In all cases, the damaged elements were visibly of non-ductile detailing. When damage occurred in columns, buildings owed their survival mainly to the presence of numerous large columns and other fortuitous features that increased their redundancy (Photo 5).

3. STEEL BUILDINGS

3.1 *Older Steel Buildings*

A typically Japanese type of steel buildings construction was developed in the early 1960s in answer to steel shortages and the high cost of structural steel in Japan. Many of these buildings, designed and constructed without much regard for seismic considerations, suffered considerable damage during the Hyogoken-nambu earthquake. The potential ductility of these buildings is severely limited, because the cold-formed steel sections used for columns typically develop local buckling prior to reaching their plastic moment capacity. Ductile column-hinging therefore is not possible, and such buildings are distined to brittle failure unless some other ductile mechanism develops prior to column damage. Yet, although numerous such buildings collapsed (Photo 6), many others survived (Photo 7), but they most frequently shed their veneer finishes in the process. The surviving buildings probably owe their sometimes surprising seismic performance to a combination of semi-rigid framing action and interaction with their internal wood-frame partitions.

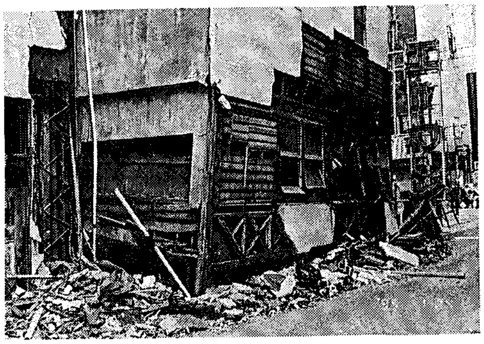


Photo 6 Collapse of a steel building

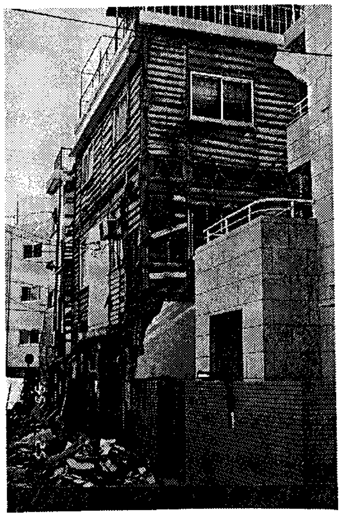


Photo 7 Loss of mortar finishes on a steel building

3.2 *Damage to Braces and Beam-to-Column Connections*

A large number of braced frame structures suffered damage, but few collapsed, even when poor workmanship was discovered. Generally, frames with extremely slender braces, such as rods or thin plates, had poor seismic performance (Photo 8), with the braces frequently rupturing in tension. Braced frames made of cold-formed sections also were encountered (Photo 9) and showed signs of local buckling.

Constructions with more substantial braces performed markedly better although brace buckles (Photo 10), and gusset buckling and fractures (Photo 11) were frequent. It is noteworthy that the survival of buildings with such significant damage may owe much to the redundancy used in Japanese steel construction. This is notable, for example, in Photo 12, where all the bays of a long parking garage can be seen to be braced.

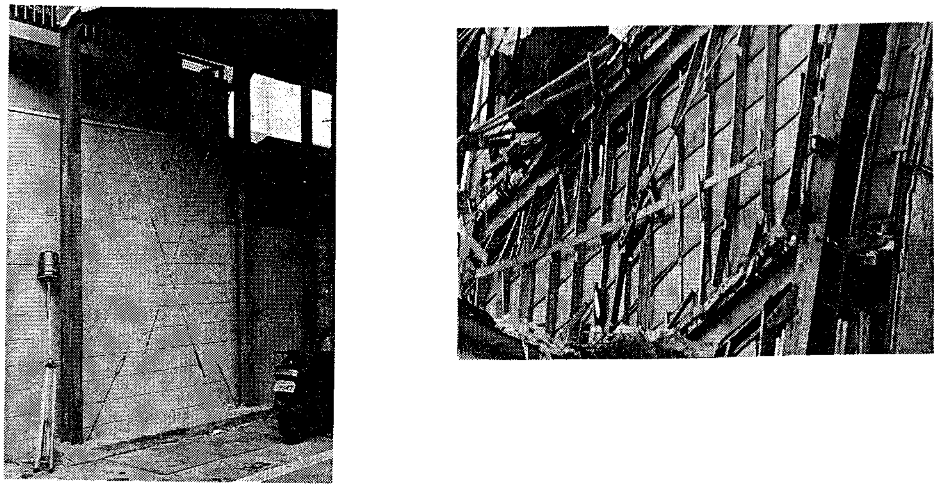

(a) (b)

Photo 8 Rupture of steel braces [(a) rod brace, (b) flat-bar brace]

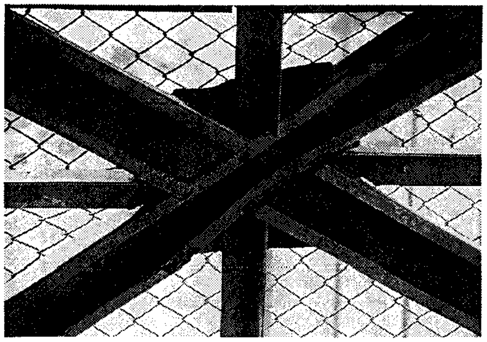


Photo 9 Local buckling of braces with a cold-formed section

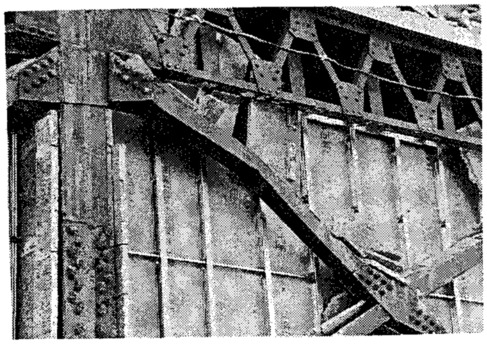


Photo 10 Bucking of a brace

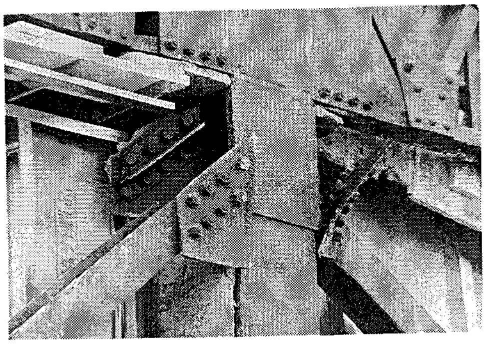


Photo 11 Gusset buckling and fracture

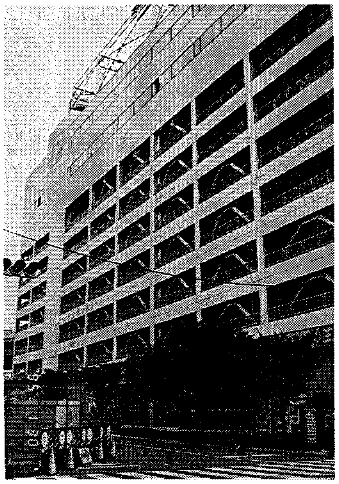


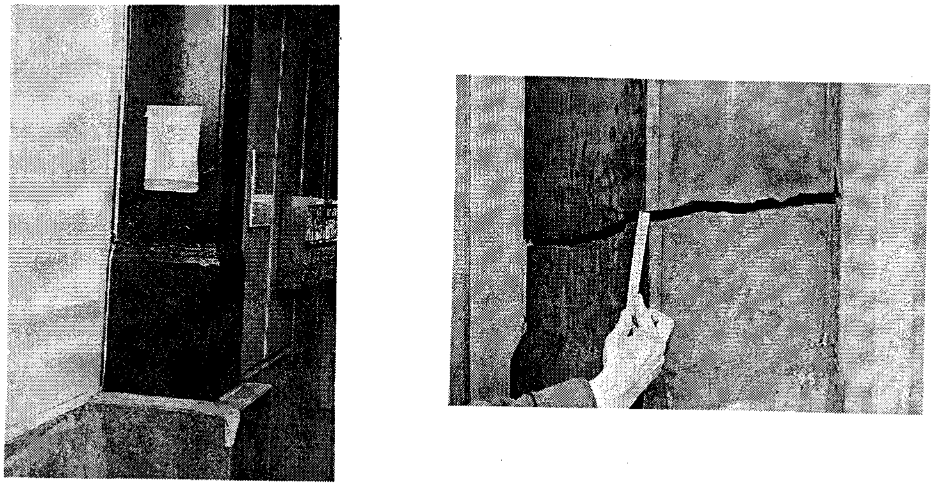
Photo 12 Arrangement of braces in a long parking structure

Photo 13 Failure of a beam-to-column connection

Few moment-frames suffered damage in their beam-to-column connections. In many cases, damage could be attributed to the failure of the welds (Photo 13). Many connections in Japan have been designed to permit shop-welding and field bolting, under the ensuring premise of a higher quality for the welds. Further study therefore is urgently needed to identify the true causes of the damage to beam-to-column connections.

3.3 *Newer Steel Buildings*

As steel structures frequently are hidden behind fireproofing coatings and architectural finishes, it will take more time before the full extent of damage to steel buildings is known. At the time of this writing, however, some new steel buildings are known to have suffered important damage. Whereas most of the damage to these new steel buildings has been ductile deformations, expected as per the design philosophy, some brittle failures of steel sections and welds also have been found (Photo 14). Speculations abound as to the cause of these failures, and more elaborate studies are underway to provide definitive answers.



(a) (b)

Photo 14 Rupture of heavy steel sections
[(a) rupture along a column-to-column connection, (b) wide opening due to fracture]

4. CONCLUSION

A large number of engineered buildings suffered damage in the Hyogoken-nambu earthquake of Magnitude of 7.2. As visible from the exterior of buildings, fatal damage appeared to be almost exclusively confined to older buildings constructed with non-ductile material detailing. This clearly emphasizes the need for the responsible Japanese agencies to immediately address the need for seismic rehabilitation to avoid similar disasters in future Japanese earthquakes. From this perspective, coordinated research activities should be funded to develop and implement efficient retrofit strategies that will efficiently remedy the deficiencies common to older Japanese buildings.

Finally, although only a few instances of significant damage to newer structures are known at the time of this writing, it must be understood that important damage to new structures frequently may be hidden by non-structural finishes and sometimes discovered only months after an earthquake, as in the 1994 Northridge experience. The reader therefore is cautioned against hastily concluding that all new construction survived unscathed by the Hyogoken-nambu earthquake. The writers believe, however, that all findings and observations reported herein will in no way be invalidated by future developments.