Observations on the Performance of Structures in the Kobe Earthquake of January 17, 1995

S. K. Ghosh, Ph.D.
Director
Engineering Services, Codes and Standards
Portland Cement Association
Skokie, Illinois

From February 14 to 20, Dr. S. K. Ghosh, along with a select group of investigators, inspected the site of the Kobe earthquake in Japan. This article presents an overview of the author's assessment of the damage to various types of structures caused by the earthquake. Although there was a relatively small number of precast, prestressed concrete buildings in the Kobe area, the structures withstood the earthquake remarkably well.

At the break of dawn on January 17, 1995, a devastating earthquake hit the Japanese port of Kobe, wreaking havoc along a narrow corridor extending as far east as the city of Osaka. The initial shock wave had a duration of 20 seconds and registered a 7.2 JMA (Japan Meteorological Agency) magnitude (a moment magnitude of 6.9). The earthquake, called the Hanshin-Awaji earthquake and the Hyogo-Ken Nanbu earthquake, will be referred to as the Kobe earthquake in this article for brevity.

With a population of $1^1/_2$ million, Kobe is Japan's second largest port. As of February 15, an estimated 5373 people had died, 34,568 had suffered serious injuries, and 320,298 were left homeless as a result of the earthquake. To aggravate matters, leaking gas and broken powerlines caused hundreds of fires, thus adding more devastation and casualties to an already tragic scene.

Property damage has been estimated at over $100 billion. To put this figure in perspective, the January 17, 1994, Northridge earthquake in California is estimated to have caused $20 billion in damage. Therefore, in economic terms, the Kobe earthquake caused about five times as much damage as the Northridge earthquake.

This article is a sequel to the brief, but excellent report on the Kobe earthquake that appeared in the January-February 1995 PCI JOURNAL.[1] It presents an overview of the geotechnical aspects of the location, Japanese building code issues, soil characteristics, and the performance of structures during the earthquake. In particular, the behavior of precast, prestressed concrete structures is reported.

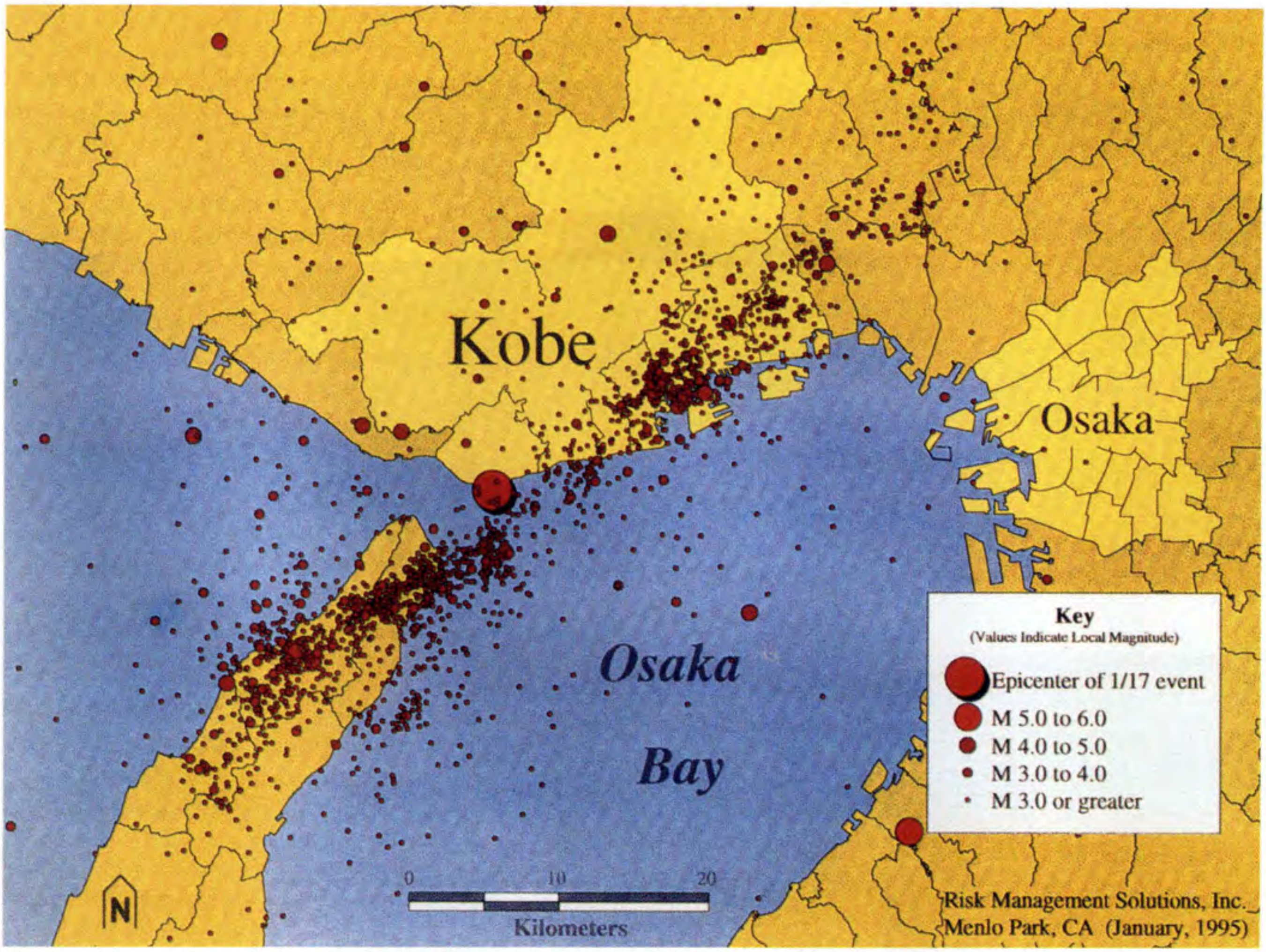

Fig. 1. Epicenter of foreshocks and aftershocks of the Great Hanshin (Kobe) Earthquake, January 16-23, 1995 (Ref. 3).

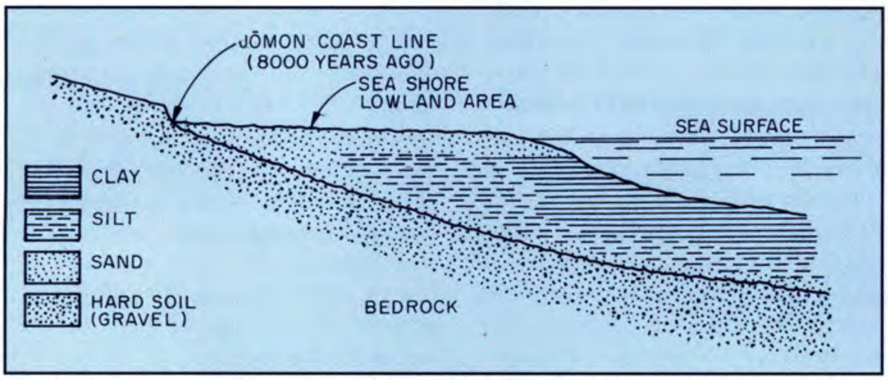

Fig. 2. Soil profile from the mountains north of Kobe to Osaka Bay on the south.

Near-Fault Effects

The epicenter of the earthquake was located at a depth of 6 miles (10 km) and at a distance of about 12 miles (20 km) southwest of downtown Kobe between the northeast tip of Awaji Island and the main island of Honshu.[2] Fig. 1 from Ref. 3 is a plot of epicenters of foreshocks and aftershocks recorded before and after the January 17 quake. This plot also represents an approximate trace of fault rupture in the January 17 event.

Significantly, a vast majority of the damage was concentrated within a relatively narrow band centered on the trace of fault rupture, indicating that the so-called near-fault effects were extremely important. Damage orthogonal to the fault rupture (buildings failing approximately in the north-south direction) predominated.

Japanese Code

The document loosely referred to as the Japanese Code is the Building Standard Law, including the Enforcement Order of the Building Standard Law. The Enforcement Order contains requirements enabling implementation of the Building Standard Law, which is brief and contains very few details.

While the Building Standard Law (including its Enforcement Order) specifies only loads and allowable stresses, and certain minimal requirements for detailing of members, details of structural design (such as methods of structural analysis and the proportioning of members) are specified in the Structural Standards issued by the Architectural Institute of Japan

Fig. 3. Collapse of timber houses with heavy roofs and inadequate walls.

Fig. 4. Failure of a nonductile concrete column.

(AIJ). These Standards, prepared separately for each structural material, serve as supplements to the Law. The AIJ Standard for reinforced concrete bears roughly the same relationship to the Building Standard Law as the ACI 318 Building Code Requirements for Reinforced Concrete does to the Uniform Building Code requirements and the other two U.S. model codes.

The 1968 Tokachi-oki earthquake caused significant damage to modern buildings designed in accordance with building regulations then in force and had a profound impact on seismic design practice in Japan. The Building Standard Law underwent a partial revision. More importantly, a large-scale revision of AIJ Standards ensued, incorporating ultimate shear strength design of reinforced concrete beams and columns, including much more stringent shear reinforcement requirements. These changes were comparable in many ways to important changes made to the Uniform Building Code in 1973, following the San Fernando earthquake of 1971. Post-1971 concrete structures performed significantly better in the Kobe earthquake than their pre-1971 counterparts, primarily because of the improved shear design of columns.

The Miyagiken-oki earthquake of 1978 was another milestone in the evolution of Japanese seismic codes. Damage was as severe as in the 1968 Tokachi-oki earthquake, largely centered in the city of Sendai. The earthquake led directly to a revision of the Enforcement Order of the Building Standard Law that began to be enforced, together with supplementary documents, from June 1981. The revision introduced a requirement of two-phase design for most buildings.[4]

The purpose of the first phase design, which is essentially the same as seismic design prescribed by the previous Building Standard Law, is to protect buildings against loss of function in earthquakes that can occur several times during the life of a building. Such earthquake motions may be considered as having an intensity of 5 or 6 on the Modified Mercalli Intensity (MMI) scale, with expected peak ground accelerations of $0.08g$ to $0.10g$. This design objective is assumed to be achieved by adoption of the traditional level of seismic force and the traditional method of allowable stress design.

The newly added second phase design is intended to ensure safety against an earthquake that could occur once in the lifetime of a building. Such an earthquake motion may be as strong as the 1923 Kanto earthquake was in Tokyo, with an MM intensity of 7 to 10, and peak ground accelerations of $0.3g$ to $0.4g$. Traditional seismic design assumed that buildings would survive severe earthquakes as a result of built-in overstrength and ductility. Whether the structure possessed adequate levels of overstrength and sufficient ductility did not expressly require confirmation.

Post-1981 structures designed by the two-phase procedure described above performed much better in the Kobe earthquake than pre-1981 structures. Severe damage in such modern structures was relatively rare.

Soil Characteristics

Fig. 2 shows a soil profile of the quake-affected area from the mountains to the north to the sea on the south. Higher ground accelerations were generally recorded on softer soils. However, as far as structural damage was concerned, near-fault effects appear to have been more important than soil characteristics. Also important were the age of the structure and its foundation type.

Newer structures supported by deep foundations performed quite well, even when soil conditions were very poor. The man-made Port Island just off Kobe, which is entirely made of fill, has a large number of modern multistory residential, commercial and other buildings, mostly built of reinforced concrete and predominantly supported by deep pile foundations. All these structures performed satisfactorily in spite of ground displacements of several feet in some places.

Fig. 5. Failure of a segment of the elevated Hanshin Expressway system.

Damage to Dwellings

Most deaths and injuries occurred in one- or two-story houses accommodating one or a small number of families. Such houses in Japan are almost invariably built of timber post-and-beam construction (see Fig. 3). The roofing consists of ceramic tiles that, in older houses, are set in an insulating layer of clay or mud. Walls between the posts consist of either bamboo thatch (traditional Shinkabe construction) or a lattice-work of thin wood strips (more modern Okabe construction), with a thin layer of plaster on the outside. These types of walls obviously have a very poor resistance to lateral loads. The weight of the clay and ceramic tiles on the roof, combined with the inadequate walls, contributed to the total or partial collapse of many of these houses.

Also contributing significantly to such failures was the traditional Japanese practice of constructing wooden houses using interlocking parts of wood, without the use of nails or other positive (non-wood) connectors. "Thus, during severe shaking, beams frequently pulled out of their socketed supports in columns or other beams, leading to the immediate caving-in of the supported story."[5] Traditional houses built in recent years have had to comply with specifications requiring extensive nailing, the use of steel connectors, and provision of walls as a percentage of the total floor area. These and other newer houses, some of "2 by 4" or stud wall construction (imported from the United States) performed well.

Nonductile Columns and Transportation Structures

After residential construction, nonductile concrete columns were the second biggest factor in Kobe's devastation. Concrete columns built before 1971, when Japan changed its seismic design codes, were nonductile, i.e., deficient in transverse reinforcement that provides shear strength and confines the concrete in compression. Failures of these columns (see Fig. 4) were responsible for the total or partial collapse of buildings (discussed in the next section) and railway and highway bridges.

The Hanshin expressway system consists of elevated roadways, supported mostly on single column bents, that convey traffic above surface streets throughout the Osaka-Kobe area. "The superstructure constantly changes from simple span steel stringers to continuous steel box girders to concrete T-girders with drop-in sections. The columns also varied from concrete or steel circular sections to concrete or steel rectangular sections of varying heights and widths."[2]

A stretch of the Hanshin Expressway approximately 2000 ft (600 m) long in Nishinomiya, east of Kobe, suffered what is probably the most spectacular failure caused by the earthquake (see Fig. 5). The superstructure had changed from steel to

Fig. 6. Failure of "gas-pressure welded" splices in a bridge pier.

Fig. 7. Loss of the first story of a nonductile concrete frame school building.

Fig. 8. Failure of nonductile corner column of building depicted in Fig. 7.

concrete in this stretch, thus increasing the mass considerably. The lower ends of the single column supports failed and allowed rotation of the deck until the edge was resting on the roadway below. The columns failed in shear at a location where flexural hinging had apparently occurred because of premature discontinuation of a significant portion of the longitudinal steel at a particular section.

Throughout the remainder of the expressway system, a large number of columns suffered significant damage. Damage in concrete columns appeared to be caused by a combination of shear and flexure. Damage, however, was not limited to concrete columns. Local buckling of steel columns was common; complete failure due to member buckling also occurred in a number of cases.

Several elevated portions of the Hankyu railway line, which links Osaka with Kobe and runs through Kobe, collapsed because of nonductile concrete column failure. In downtown Kobe, the brittle fracture of steel columns in a bent supporting the same line was observed.

Portions of the Shinkansen (bullet train) line linking Tokyo with the Osaka-Kobe area suffered significant damage because of joint failure and/or shear failure in the upper or lower columns of one-bay, two-story bents that support the railway, except at river crossings where single column bents are used. The single columns also suffered flexure-shear damage.

A fairly common feature of bridge column failure was the popping of "gas pressure welded" splices, which represent fairly common Japanese practice (see Fig. 6). These splices failed frequently in older bridges, less frequently in older buildings, and occasionally in new construction.

Structural Irregularity

An inordinate number of low- to mid-rise (2- to 15-story height range) reinforced concrete and steel reinforced concrete (SRC) frame buildings, without significant shear walls that continued down to the foundation level, lost one or more stories. This type of "pancaking" or soft-story failure occurs due to a concentration of inelastic deformations in a particular story or stories. Such excessive deformations, coupled with non-ductile detailing of columns and joints that rendered them deficient in shear strength, caused column failures.

Steel reinforced concrete, or SRC, is a type of composite construction that uses structural steel frames encased in concrete.[4] This composite construction has a long history in Japan, probably dating back to the 1920s, when buildings were constructed with exterior steel frames encased in brick masonry and interior steel frames encased in concrete. SRC is generally believed to be more ductile and, hence, more earthquake resistant than ordinary reinforced concrete. For buildings beyond seven stories and up to about 20 stories, or even higher in some cases, SRC is the most common type of construction in Japan. For economy in older SRC buildings, the steel frame was used only over the lower stories.

Many of the story failures occurred in the first story above ground. This is

Fig. 9. Leaning wood-frame building with soft first story.

Fig. 10. Pancaking of floor in Kobe City Hall building.

Fig. 11. One of many collapsed steel buildings in Ashiya.

quite often a soft story because it is usually taller than the other stories and also because shear walls are quite often discontinued below this level to have open space for stores or ballrooms or other column free spaces. Sometimes, the building leaned without collapsing. Other times it collapsed (see Fig. 7).

The nonductile columns not only lacked transverse reinforcement, but quite often contained smooth, rather than deformed, longitudinal bars (see Fig. 8), which apparently continued to be used in Japan after their use was discontinued in the United States. Also, soft-story failures were not limited to concrete buildings. Fig. 9 shows a wooden building that is leaning because of soft-story failure.

Soft-story failures also occurred at various locations along the heights of multistory buildings. Almost invariably, there was a stiffness discontinuity at the level that failed. The reasons could be discontinuation of shear walls, column section changes that used to be frequent in older designs, geometric offsets (setbacks) and other factors. Fig. 10 shows the Kobe City Hall, which pancaked in the first level above the location where SRC columns ended and RC columns began. Across a corner from the City Hall was a building that pancaked at an upper level, which contained meeting rooms requiring long column-free spans.

Importantly, to the best of the author's knowledge as of this writing, all story collapses have been observed in older buildings designed before the 1971 code change introduced what can be considered ductility details for reinforced concrete beams and columns. Although newer RC and SRC buildings suffered structural damage in some instances, they did not totally or partially collapse.

While the above discussion focused primarily on vertical irregularity, plan irregularities also caused damage, as expected. For instance, corner buildings with shear walls on the back and side face, and with more open framing on the front and the other side face, performed quite poorly.

No building relying on reinforced concrete shear walls for lateral load resistance collapsed. This was true even though many ductile and nominally ductile shear walls suffered a considerable amount of damage, which was often quite extensive in older buildings.

Fig. 12. Severely damaged steel braced frame building in Sannomiya district of Kobe.

Fig. 13. Satisfactorily performing low-rise precast, prestressed apartment building in the Kobe area.

Steel Buildings

Many older steel buildings dating back to the early 1960s, which were designed and constructed without much regard for seismic considerations, suffered a considerable amount of damage. "The potential ductility of these buildings is severely limited as the cold-formed steel sections used for columns will typically develop local buckling prior to attainment of their plastic moment capacity."[5] Many such buildings collapsed in Ashiya (east of Kobe) and other places (see Fig. 11). Others that survived often shed their cladding.

A large number of braced frame buildings suffered damage, sometimes to the point of being rendered useless (see Fig. 12). Generally, frames with slender braces had the braces rupture in tension or buckle in compression; these braced steel frames performed quite poorly. Frames with more substantial braces also experienced brace buckling, gusset buckling and fractures.

In moment frame construction, it appeared common practice to shop-weld beam studs to columns prior to erection and to bolt beams to beam studs during erection. A few moment frames suffered damage in their beam-to-column connections; such damage could possibly be attributed to failure of the welds.

At the time of this writing, some new steel buildings were known to have suffered significant damage. "While most of the damage observed in these new steel buildings has been ductile deformation, expected as per the design philosophy, some brittle failures of steel sections and welds have been observed."[5]

A major residential complex at Ashiyahama (Ashiya Beach) used steel "superframes" consisting of large built-up columns and horizontal trusses to support precast concrete dwelling units. Many of the columns suffered brittle fractures not only at the location of the welds, but also along their height. "While speculations abound as to the cause of these failures, more elaborate studies are underway to provide definitive answers on these matters."[5] Some of the truss members in the Ashiyahama complex also buckled in compression.

Precast, Prestressed Concrete Structures

One bright spot amidst all the devastation in Kobe was the performance of precast, prestressed concrete structures. Apartment buildings in Japan in the two- to five-story height range are usually of reinforced concrete bearing wall construction. Some of these buildings utilize precast concrete wall or panel units. Donald R. Logan of Stresscon Corporation, who along with Mark Kluver of the Portland Cement Association (PCA) accompanied the author on his visit to Kobe, supplied the following observations concerning these buildings:

"The typical construction consisted of generally stiff, mid-rise shear wall structures utilizing NMB Splice Sleeve connections to tie the shear walls to the foundation system, and to connect the stacked shear walls to each other. This system permits ductility to occur, if required, in the grouted reinforcing bars encased by the NMB Splice Sleeve. The group inspected three of these structures (see Figs. 13 to 15) and found no damage in the precast concrete structures themselves, and only minor spalling or cracking in the cast-in-place concrete at the location of the splice to the foundation, in a few areas. These structures did not suffer any functional damage and were ready for continued occupancy immediately after the earthquake, except in certain cases where soil subsidence adjacent to the structure may have cut off some of the utility services connected to the building."

Taller precast concrete structures are increasingly being built in Japan. These are likely to use frames, rather than bearing walls, at least in one direction. To the best of the author's knowledge, the area that bore the major impact of the earthquake did not contain any of these buildings.

Fire Damage

According to a report just issued by the Earthquake Engineering Research Institute (EERI),[2] approximately 100 fires broke out within minutes of the earthquake. These fires occurred primarily in densely built-up, low-rise areas of the central city which house mixed residential-commercial occupancies, predominantly of wood construction. The total number of fires that occurred on January 17 was 142. The fire spread by radiant heat and flame impingement, building to building in the densely built-up areas. Fortunately, the wind was calm so the fire advanced relatively slowly. Final burnt areas in Kobe are estimated to be 10 million sq ft (1 million m^2), with 50 percent of this area in Nagata-ku.

One impressive performance by a structure was the survival of the Takahashi Hospital in Nagata-ku (see Fig. 16). This five-story concrete shear wall structure not only survived the strong earthquake with no apparent damage, but also survived the intense fire that engulfed virtually everything around it. The hospital reportedly continued with normal operations immediately following the earthquake.

Fig. 14. A second undamaged low-rise precast, prestressed apartment building in the Kobe area.

Fig. 15. A third low-rise precast, prestressed apartment building exhibiting good performance in the Kobe earthquake.

Statistical Data

The Disaster Prevention Research Institute of Kyoto University has issued some revealing statistics, which are presented in Table 1.[5] While the total population of engineered concrete buildings and that of engineered steel buildings in Chuo-ku are not known, the total number of concrete buildings is undoubtedly much larger than that of steel buildings. The figures in Table 1 indicate that the percentage of collapsed or severely damaged buildings in the concrete category is lower than that in the steel category.

Fig. 17, also adapted from Ref. 5, clearly shows that the strongest correlation of damage was with the age of the structure. Significant changes in the Japanese Building Code in 1971 and 1981 are major factors in this correlation.

Conclusions

Based on the author's on-site observations of earthquake damaged structures, the following conclusions can be made:

1. The major reason for the large number of casualties and heavy damage to structures is the fact that a very severe earthquake occurred almost directly below a highly populated area. The epicenter was located at a depth of only 6 miles (10 km) below the island of Awaji.

2. Older buildings and dwellings, especially those built prior to the adoption of the 1971 and 1981 Japanese Building Code changes, suffered the heaviest damage.

3. Most of the casualties and collapses occurred in the old timber dwellings that were poorly constructed.

4. Damage to reinforced concrete

Fig. 16. Undamaged reinforced concrete shear wall hospital building amidst widespread fire damage at Nagata-ku.

Table 1. Statistics on damaged concrete and steel buildings in downtown Kobe.*

Number of damaged buildings in Chuo-ku (downtown) area of Kobe City	Concrete buildings	Steel buildings
Total	1638	1032
Percent experiencing collapse	4.89	5.33
Percent experiencing severe damage	7.69	9.01
Percent experiencing moderate damage	10.56	17.15
Percent experiencing minor damage	20.57	28.59
Percent experiencing slight damage	56.29	39.92

*Data extracted from Ref. 5.

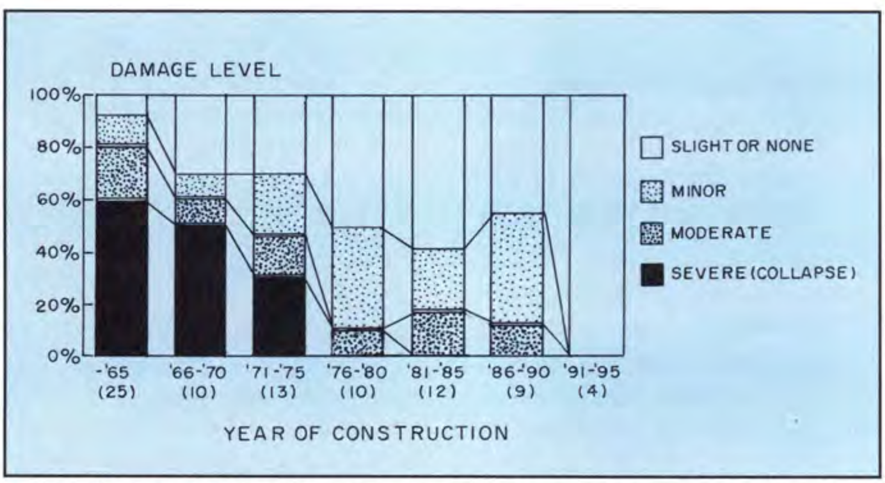

Fig. 17. Correlation between degree of building damage and year of construction (Ref. 5).

and steel reinforced concrete structures was understandable and predictable. Structural irregularities, combined with nonductile detailing of columns and beam-to-column joints, accounted for the vast majority of the cases of serious damage or collapse.

5. While the damage to older steel buildings was also understandable and predictable, significant damage in a number of new steel buildings is more troublesome. Causes of such damage are at this point unclear.

6. Statistical data from Kyoto University show that the percentage of collapsed or damaged concrete buildings is lower than that of steel buildings.

7. Low-rise apartment buildings of precast, prestressed concrete, designed and built emulating monolithic construction, performed remarkably well.

8. It is believed that the soil conditions underlying the earthquake area did not play a decisive role in the damage to structures. Predictably, dwellings and buildings on soft soils suffered severe damage. On the other hand, structures with pile foundations going down to bed-rock performed well.

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