This paper was presented at JSPS Seminar on Engineering in Japan at the Royal Society, London, on September 27, 1999. The seminar was organized by the Japan Society for the Promotion of Science.

Disaster Mitigation Engineering
- The Kobe Earthquake Disaster -

SHUNSUKE OTANI,
Professor, Department of Architecture, University of Tokyo

INTRODUCTION

The concept of plate tectonics is generally accepted in earth science and seismology. The surface of the earth is divided into rigid tectonic plates that move on the earth surface at extremely slow speed. The islands of Japan sit on the North American and Eurasian plates. The Pacific plate moves westward and the Philippines plate moves to northwest direction; both plates sink under the islands of Japan forming troughs along the boundaries. The strain energy is accumulated gradually by relative movement of adjacent tectonic plates and is suddenly released at the plate boundary in a form of an earthquake. Most of large magnitude earthquakes in Japan have taken place along the plate boundaries (plate boundary earthquakes). If we take one region along a boundary, an earthquake occurs once every one to two hundred years. This is almost a deterministic event for a human society, but the epicenter is normally further away from large cities.

By contrast, an inland earthquake, such as the 1995 Kobe earthquake, is caused by the fracture of active fault(s) due to constant compression stresses developed by the relative movement of tectonic plates. There are many active faults reported throughout the country; some traces of fault movement appear on ground surface, and some do not. There may be many unrevealed faults, especially under alluvial plains where modern cities have been developed. An active fault is known to break once in one to three thousand years. This makes it more difficult to predict the location and timing of an inland earthquake. The magnitude of inland earthquakes is generally smaller than that of major plate boundary earthquakes; the epicenter depth is shallow and approximately 15 km or less; the duration of strong motion is short and ten to fifteen seconds long. The inland earthquake may occur immediately under a large city such as Kobe.

From 1950 to the 1995 Hyogo-ken Nanbu earthquake (official name of the earthquake that caused the Kobe earthquake disaster), there were many earthquakes in and around the Japanese islands. Fortunately, none caused casualties larger than 100.

KOBE EARTHQUAKE DISASTER

The Hyogo-ken Nanbu earthquake occurred at 5:46 am on January 17, 1995. Table 1 shows the loss from the Kobe earthquake disaster. This earthquake caused an overall damage of approximately 10 trillion Yen, or fifty billion pounds in the UK. The loss reached to almost 20% of annual budget of the Japanese Government. The disaster gave significant impact to the national economy and society.

Table 1: Property Losses from Kobe Earthquake Disaster (Billion Yen)

Properties	Losses
Buildings	5,800
Railroads	344
Highways	550
Public Civil Engineering Facilities	283

Harbors, Filled Lands	1,000
Educational Facilities	335
Agriculture, Forestry, Fishery	118
Health, Medical, Welfare	173
Water, Gas, Electricity	474
Communication, Broadcasting	120
Commercial	630
Other Public Facilities	80
Total	9,914

Property loss of buildings is almost 60 percent of the total loss. The lifelines and infrastructures were significantly damaged, causing difficulty in civil life for a couple of months after the earthquake.

Typical examples are the collapse of highways (Fig. 1) or the collapse of Shinkansen line (Fig. 2). The city of Kobe was developed in the east-west direction along the seashore with steep hills behind. Therefore, all major traffic networks like highways and railways run in the east-west direction. Once the networks were cut by major damages at a few limited points, the entire system stopped functioning. Without highways and railways, the transportation of relief goods was delayed by traffic jams on major ground routes despite the efforts to control traffic by police and local government.

Fig. 1: Collapse of highway overpass

Fig. 2: Collapse of the Shinkansen overpass

Fires occurred in many places after the earthquake. The fire retardant materials such as mortar cover on timber houses fell down due to the earthquake shaking and fires spread in densely populated areas of old timber construction. The number of fire engines was not sufficient to deal with many simultaneous fires because the allocation of fire engines was planned for normal fire occurrence. Furthermore, water for fire fighting was not available due to the fracture of main city water lines at various locations. Fortunately the wind was not so strong. The spread of fire was stopped by the trees in parks. The effective planning of parks was recognized to be important not only for daily life but also for prevention of fire spreading.

CAUSES OF DEATH

Approximately 5,500 people were killed immediately after the earthquake. If we include those who died of indirect causes, then more than 6,000 people were killed as a result of this earthquake. The causes of death were studied from medical reports and classified as shown in Table 2. Approximately 90% of the dead people were killed by the collapse of buildings. In this respect, structural engineers should hold the responsibility. Approximately 1.2% of the total were killed by overturned furniture; in Japanese apartments or houses space is limited and sometimes people have to put heavy household objects such as TV sets in high places that could potentially drop and injure or sometimes even kill people. Of those 5,500 people we observed, more people in the older age groups, from sixty years of age upwards, were killed than those in the younger age band.

Table 2: Causes of Death by the 1995 Kobe Earthquake

Cause	Number	%
Collapse of Buildings	4,816	87.9
Fire	570	10.4
Highways	17	0.3
Land Slides	11	0.2
Overturned Furniture	65	1.2
Total	5,479	100.0

Medical inspectors studied 3,651 death cases out of 3,875 direct earthquake caused death cases in Kobe city. They reported that 3,540 (97 %) out of 3,6551 were killed on the same day of the earthquake. Furthermore, 2,940 deaths (80.5%) were judged to have taken place in 15 minutes from the earthquake occurrence. This statistic indicates the importance of safe building construction before strong earthquakes rather than the emergency rescue operation after an event.

Major death occurred under the collapse of traditional timber houses. This is related to their construction; i.e., heavy mud and tiles are used in the roof in these timber houses (Fig. 3). The heavy roof attracted large inertia forces during earthquake shaking and caused the collapse. We need to study this point further. The weather in Japan is quite warm and humid in summer. In order to insulate heat we have to use heavy materials in the roof; this is necessary to gain comfort during the summertime. At the same time, in every autumn, we have one or two typhoons. In order to protect roof against blow-up, we have to make roofs heavier. By these reasons of the amenity in daily life and safety against annual events, we made roofs very heavy in old traditional timber houses. However, the heavy roofs caused ill effects on earthquake resistance. Note that the last earthquake that hit in this area was in the 1590's, more than four hundred years ago.

Fig. 3: Collapse of old timber house with heavy roof

Which one do “you” choose; safety from an earthquake of once in a few hundred years or daily comfort during summertime and safety from annual typhoon attacks? As the last earthquake occurred four hundred years ago, people paid more attention to daily comfort and annual safety from typhoons. I believe that it was this way of thinking that unfortunately led to this disaster.

At the same time the collapsed houses were generally very old. Structure decayed with age, and sometimes the column was even eaten up by termites. The structure did not give us redundant strength to resist an earthquake motion.

Why did the people leave these conditions in their houses? Elderly people, after retirement, lived in these old houses. Without any additional income they could not afford to retrofit these houses. Or even if they had the income their priority was not to spend it on strengthening their property.

If we look at new timber construction, roofs are very light but well insulated and also tightly fixed to the structure. Therefore, there would be no problem from heat or from typhoons, and from earthquakes.

Figure 4 shows damage statistics of timber houses at different construction ages (Ref. 1). The data were reported for houses in Awaji Island near the epicenter. The construction age may be classified as new if constructed within 5 years, normal within 5 to 20 years, old within 20 to 50 years, and very old more than 50 years. Note that heavy damage increases with old construction age. More than half of those constructed within 5 years suffered no damage while most of those constructed more than fifty years ago suffered damage ranging from collapse to minor damage. The figure indicates a significant improvement in technology for earthquake resistant construction of timber houses in recent years, and also implies the importance of maintenance work on houses.

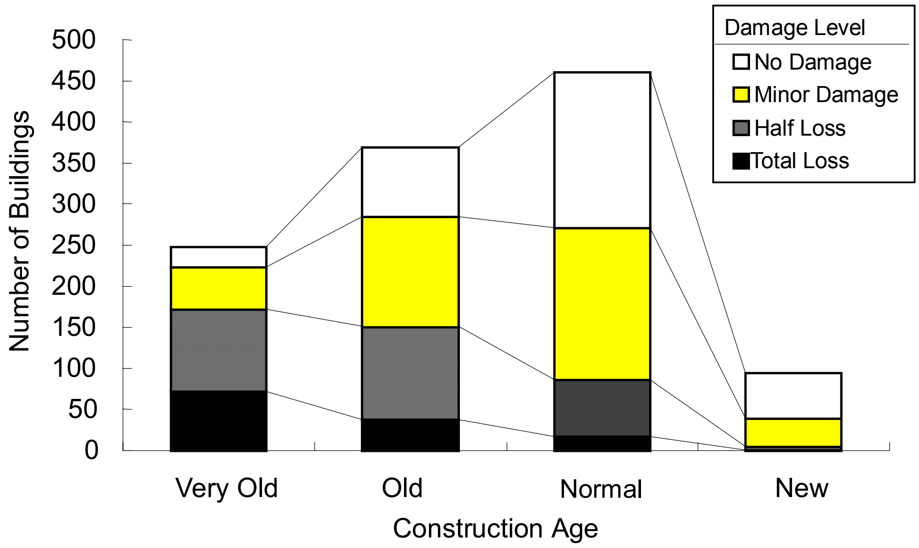

Fig. 4: Damage statistics of timber houses

If people could spend more money to improve the structures of their houses partially by maintenance work on decayed materials and partially by strengthening old construction, the damage and accompanying casualties could have been reduced. The improvement in engineering is not meaningful unless the new technology is adopted in real construction by citizens.

NEW PROBLEMS IN STEEL CONSTRCUTION

Steel materials were made available for construction use since the mass production methods were invented in the late 19th century. The steel is strong in tension and ductile after reaching its yield stress. The material can dissipate large hysteretic energy under cyclic loading. Therefore, the steel has been believed to be ideal for earthquake resistant construction. Indeed, there were many steel buildings that did not collapse even after experiencing large horizontal deformation. However, when ductile steel elements are connected by some methods, for example by welding, the connection may not be as ductile as the steel. The failure at the connection was observed in Kobe as shown in Fig. 5. This particular failure was caused by poor design practice. It is so easy for a structural engineer to specify welding to connect two steel elements.

Fig. 5: Failure of steel structure at welding connection

Even in the welding connection using the state of practice, the failure was observed in the steel element after developing yielding near the welding. Similar failure was observed in steel construction in California after the 1994 Northridge earthquake. Researchers of steel structures are extensively studying this problem in U.S. and Japan.

We found another major problem in steel construction; brittle fracture of large size steel members as shown in Fig. 6. Crack width is almost 15 mm. This damage was observed in some high-rise apartment buildings in a large residential development. Steel plates of approximately 50 mm thick were welded to form large square column section. Before the construction, steel members were tested in the laboratory under simulated earthquake loading to confirm the safety, but using “small scale” specimens. It appears that the behavior of thick steel members is significantly affected by their size. Although I doubt the capability of carrying out full-scale testing of the column in the laboratory, we should be careful when we develop new technology.

Fig. 6: Brittle fracture of large-size steel members

Figure 7 shows the damage statistics of steel buildings with respect to construction age. The Building Standard Law was significantly revised in 1981 to require the examination of horizontal load resisting capacity at the formation of the yielding mechanism under lateral forces. The minimum lateral load resistance was specified in accordance with the deformation capacity of members forming yield hinges. It should be noted that the rate of severe damage decreased appreciably for those constructed after the 1981 revision of the law. We believe that the current state of the art is sufficient for the earthquake resistant building construction. However, some of those buildings constructed before the revision of the law should be examined as to the earthquake safety and must be strengthened if significant deficiency is found.

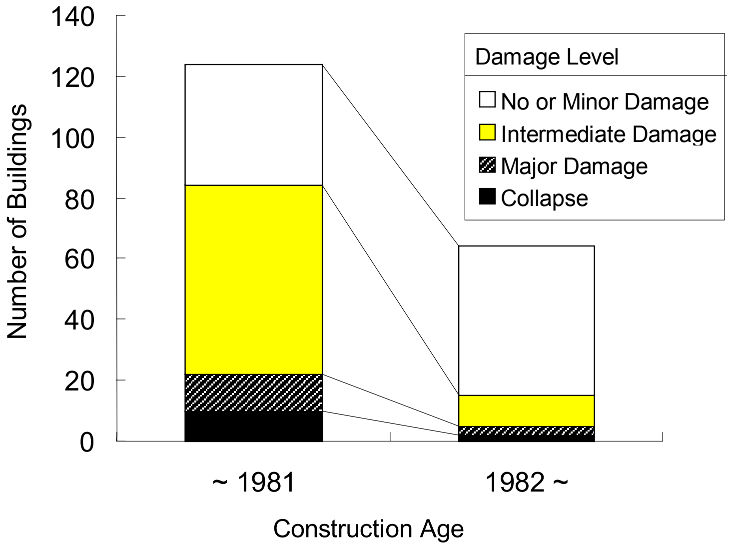

Fig. 7: Damage statistics for steel buildings with construction age

DAMAGE OF REINFORCED CONCRETE BUILDINGS

Many reinforced concrete buildings collapsed by the earthquake. The column supporting the weight of the structure above failed in a brittle manner, the failure mode of which is commonly known as “shear failure.” The same failure mode was observed in the 1968 Tokachi-oki earthquake in school buildings. The characteristic of this failure mode is that the width of the column becomes much larger after failure than the original width as shown in Fig. 8. Therefore, the failure can be prevented by reinforcing the column laterally.

The Building Standard Law was revised in 1971 to require close spacing of lateral reinforcement in columns. The performance of reinforced concrete building constructed after the 1971 revision of the law was generally improved. The Building Standard Law was further revised in 1981 to require higher lateral resistance from a building irregular in the distribution of stiffness in plan or along height in addition to the examination of lateral load resistance at the formation of the yielding mechanism under earthquake loading.

Fig. 8: Shear failure of reinforced concrete column

The Architectural Institute of Japan investigated the damage level of all buildings in Nada and Higashi-Nada districts in Kobe where the seismic intensity was highest; 3,911 buildings in total were investigated (Ref. 2). Seventy-five percent were residential buildings (including those used partially for office or shop). Forty-eight percent were built in conformance with the current Building Standard Law (revised in 1981). The damage level was classified as operational damage (no damage, light damage and minor damage), heavy damage (intermediate damage and major damage), and collapse (including those already removed at the time of investigation). Buildings with operational damage could be occupied immediately after the earthquake. Buildings with heavy damage needed some or major repair work for the occupancy.

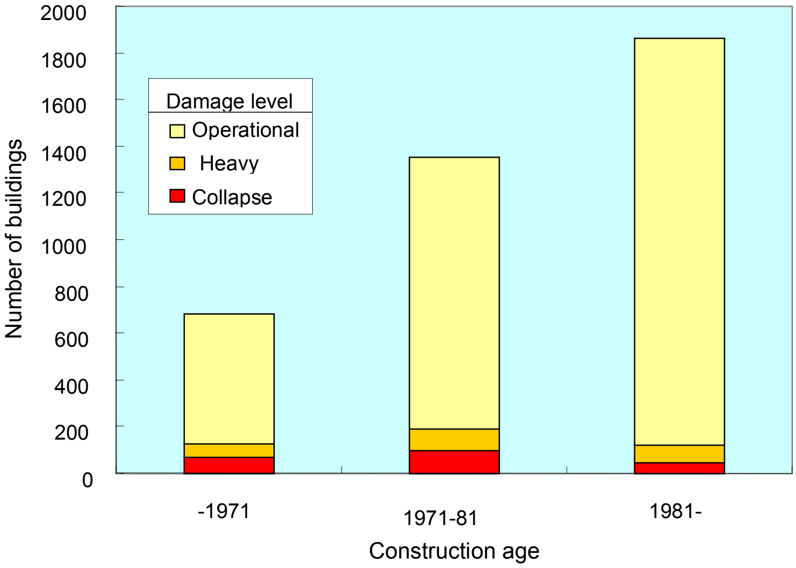

Fig. 9: Damage of reinforced concrete buildings with construction age

Eighty-nine percent suffered operational damage, 5.9 percent suffered heavy damage and 5.7 percent collapsed. Among those 2,035 buildings constructed before the current Building Standard Law (1981), 7.4 percent suffered heavy damage and 8.3 percent collapsed. Among those 1,859 buildings constructed using the current Building Standard Law, 3.9 percent suffered heavy damage and 2.6 percent collapsed. The 1981 revision of the Building Standard Law enhanced significantly the performance of reinforced concrete buildings against earthquake attack.

We may say that the reinforced concrete building designed using the state of the art and practice is reasonably safe against earthquakes. Approximately 15 percent, or possibly 20 percent, of those buildings constructed before the current Building Standard Law (revised in 1981) need strengthening in Japan for the preparation against future earthquake events.

Figure 10 compares the damage of those buildings constructed before the 1971 revision of the Building Standard Law with respect to the height (number of stories). The damage levels are operational damage, heavy damage and collapse. You can observe that the ratio of buildings suffering operational damage is much larger for low-rise buildings. The ratio of buildings suffering heavy damage and collapse increases in medium-rise buildings (say, taller than five-stories). A structural designer should pay more attention to earthquake resistant design when he/she designs taller buildings.

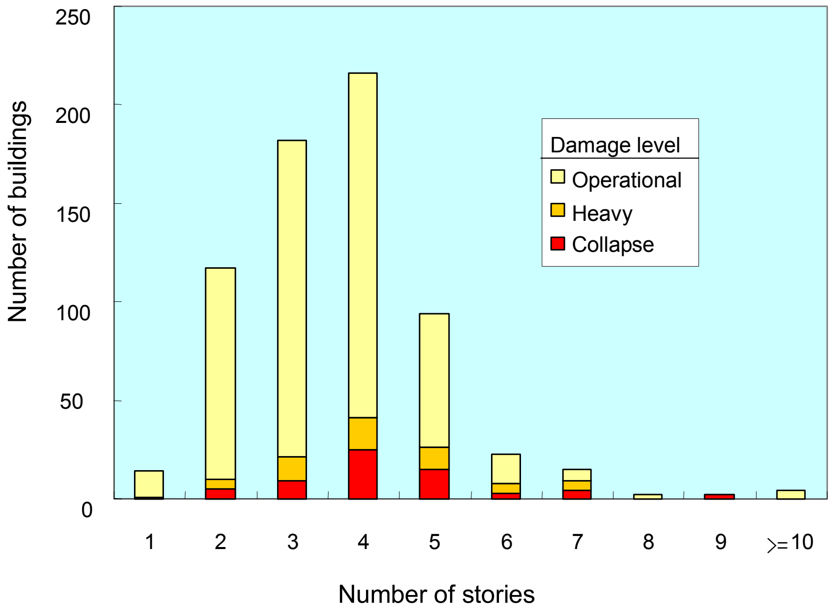

Fig. 10: Damage of pre-1971 reinforced concrete buildings with story height

Figure 11 shows a similar diagram for those constructed after the 1981 revision of the Building Standard Law. A significant improvement may be observed in the protection of buildings using current Building Standard Law. However, the ratio of severe damage is higher in taller buildings.

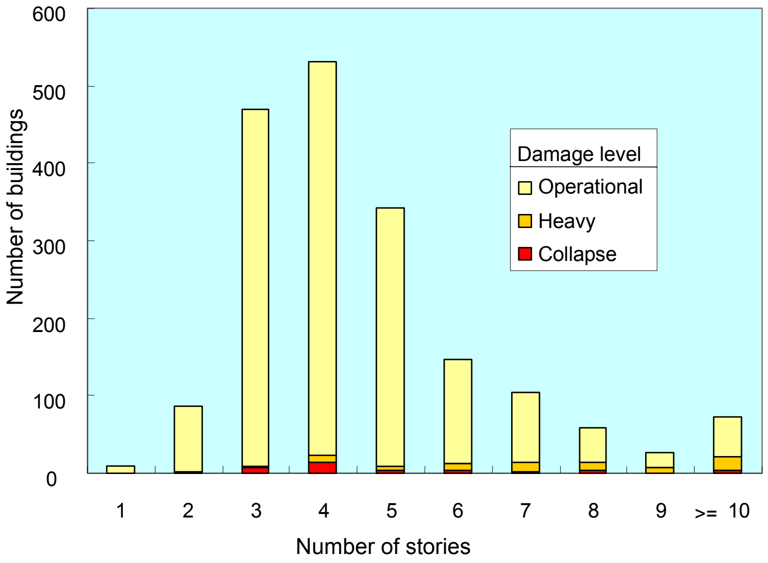

Fig. 11: Damage of post-1981 reinforced concrete buildings with story height

One characteristic failure of reinforced concrete buildings in Kobe was the collapse in the first story as shown in Fig. 12. This type of failure was observed in many apartment and condominium buildings. Residential units are separated by partition walls, normally by reinforced concrete structural walls, which effectively resist earthquake forces without much deformation. The ground floor is normally used for garage or stores in Japanese residential buildings due to the limitation in area. Therefore, no partition walls were placed in the ground floor. In other words, the upper stories are generally strong with ample structural walls whereas the ground floor is bare against earthquake attack. This type of the structure is called “soft first-story buildings.” By this reason, the collapse took place in the ground floor in the form of shear failure of columns.

Fig. 12: Collapse of reinforced concrete buildings in first story

Figure 13 compares the damage of soft first-story buildings with construction age; i.e., before the 1971 revision of Building Standard Law, between 1971 and 1981, and after the 1981 revision of the law. You can note a significant improvement in the safety of the soft first-story buildings with the revisions of the Building Standard Law. Almost one half of those soft first-story buildings constructed before the 1971 revision suffered severe damage or collapse. We are not satisfied with the performance of soft first-story buildings constructed in accordance with the current Building Standard Law. We need the improvement in design of these buildings.

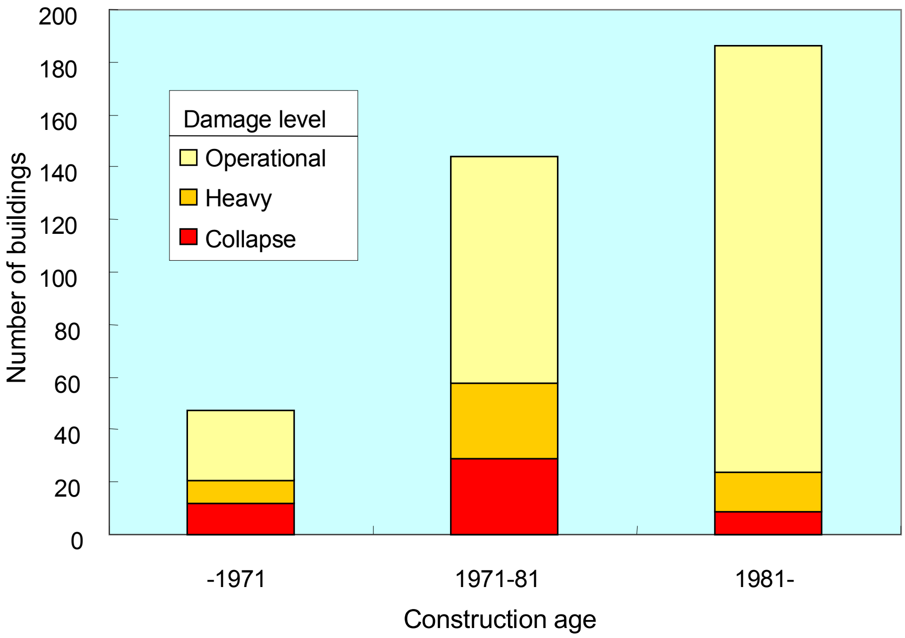

Fig. 13: Damage of soft first-story buildings with construction age

IS SAFETY AGAINST EARTHQUAKE ENOUGH?

Since the 1923 Kanto (Tokyo) earthquake, we studied hard to develop methodology for design and construction of earthquake resistant structures in Japan. The major purpose was to protect human life from unexpected earthquake occurrence. From the inventory damage survey of reinforced concrete buildings in Nada and Higashi-Nada districts in Kobe, 93.5 percent of buildings constructed in conformance with the current Building Standard Law suffered operational damage, 3.9 percent suffered heavy damage and 2.6 percent collapsed. From this statistics, we may say that the current state of the art achieved the goal although we need further improvement in design of soft first-story buildings.

Let us look at the damage of an apartment building in Fig. 14. You can observe extensive damage in reinforced concrete partitions and windows. No one would want to live in the unit after seeing such damage. However, if we examine the damage carefully, there is almost no damage in structural elements such as columns and girders. I looked at this building as a structural engineer, and concluded the structural damage was minor. Damage was observed only in non-structural elements such as partitions, doors and windows. These non-structural elements were not intended to support the weight of the building, but are necessary for the use of the building as residential units.

We structural engineers paid too much attention to structural safety. Even though a structure survives an earthquake with minor damage, if the building loses its function, the design may not be judged to be successful.

The structure of a building should accommodate building functions, not to just support structure itself. The structure should provide the space for the usage of the building. Unfortunately structural engineers are only concerned about their own profession; i.e., the design of a structure itself rather than the design of a structure for building purpose. We tended to forget the original purpose of a structure.

For example, the breakage of non-structural partitions in Fig. 14 will not allow people to live in the residential unit. The partition is not a structural element, but the partition was broken, people cannot use the unit at all. In the past, structural engineering placed too much emphasis on the safety of people, but now I think it becomes more important to protect functions of a building.

Fig. 14: Damage of non-structural elements

If the owner of a building is informed of a possible consequence about the function of his building after an earthquake, he might be willing to pay additional expenses for higher performance. There should have been closer communication between the owner and engineers for the protection of properties in addition to the protection of human life.

CONCLUDING REMARKS

The state of the art and practice in earthquake resistant building design and construction allows us to construct safe buildings against earthquakes. Such technology is meaningful only when it is utilized in real construction by the choice of people. The utilization of such technology is often hindered by the desire of people to solve immediate necessity in daily life. Close communication between the owner and structural engineers is necessary to achieve desired performance of a building.

References

1. Timber Construction Committee: Damage of Timber Construction, the 1995 Hyogo-ken Nanbu Earthquake (in Japanese), Kinki Branch, Architectural Institute of Japan, September 1995, 193 pp.

2. Reinforced Concrete Construction Committee: Damage Investigation Report on Concrete Buildings, the 1995 Hyogo-ken Nanbu Earthquake (in Japanese), Kinki Branch, Architectural Institute of Japan, July 1996.