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# STRUCTURAL DESIGN OF BASE-ISOLATED HIGH-RISE BUILDINGS WITH HIGH-DAMPING LAMINATED RUBBER BEARINGS

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## ABSTRACT

A 14-story building of steel-reinforced concrete structure was designed as a base-isolated building using high-damping laminated rubber bearings. Construction of this building, which is one of Japan's high-rise base-isolated buildings, began in March 1995 and is scheduled for completion in August 1996.

## KEYWORDS

base-isolated structure, design, high-damping laminated rubber bearings, failure testing of laminated rubber bearings,reduction of seismic force, cost

## OVERVIEW OF THE BUILDING

There are three buildings on this plot of land: 14-story buildings A and B, and 8-story building C, which are designed as base-isolated buildings. Buildings A and B are the tallest base-isolated residential buildings in Japan at the time of their start of construction, and building C is of tiered shape, with 8, 7, and 6 stories. (Figures 1-5 are photos of a model of the entire construction, the floor plan of buildings A and B, a diagram of the arrangement of the laminated rubber bearings, elevations, a cross-sectional view of the base isolation layer, and views of an isolator.)

In this paper we describe the high-rise base-isolated buildings A and B. The structure is outlined as follows.

| | | |
|---|---|---|
| Name of project | : | Shiki New Town Garden Plaza |
| Location | : | city of Shiki, Saitama Prefecture |
| Purpose of use | : | community housing |
| Area of the plot of land | : | 8,845 $m^2$ |
| Total floor area | : | 20,534 $m^2$ (buildings A and B: 6,060 $m^2$ each) |
| Number of floors | : | 14 floors, no basement |
| Height of building | : | 41.03 m |
| Typical floor height | : | 2.86 m |
| Superstructure | : | steel-reinforced concrete structure with bearing walls |
| Foundation | : | steel-reinforced concrete |
| Isolator | : | high-damping laminated rubber bearing (buildings A and B: 24 each)<br>total rubber thickness = 16 cm |

Fig. 1-1. Overall view from north side
(from left, buildingsA, B, C)

Fig. 1-2. Overall view from south side
(from left, buildingsA, B, C)

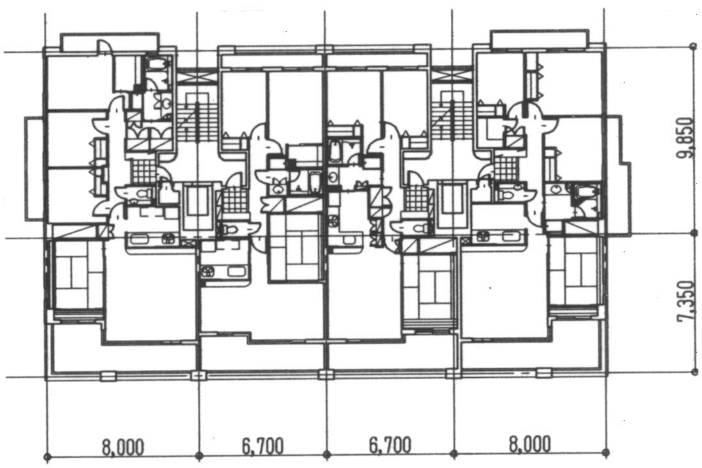



Fig. 2-1. Floor plan of buildings A and B

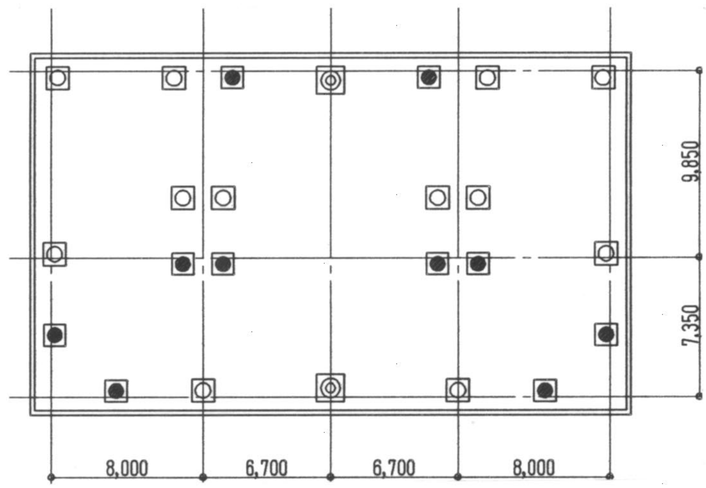



Fig. 2-2. Arrangement of the rubber bearings

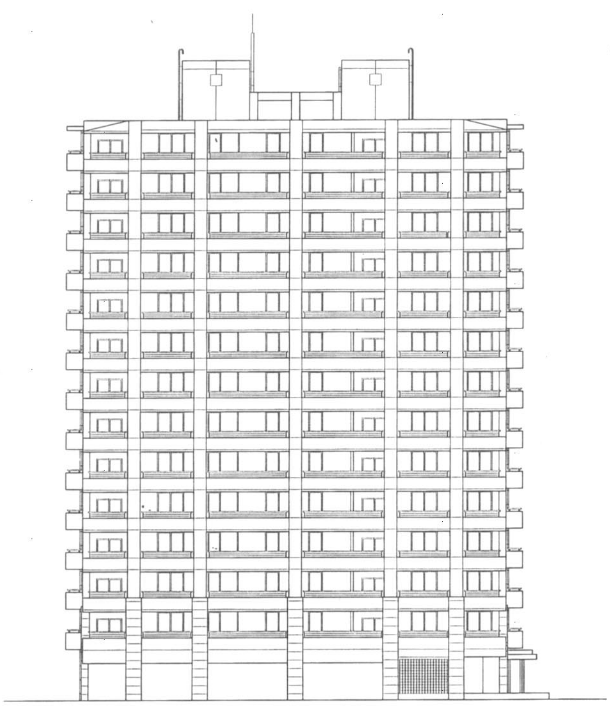


Fig. 3-1. South-side elevation

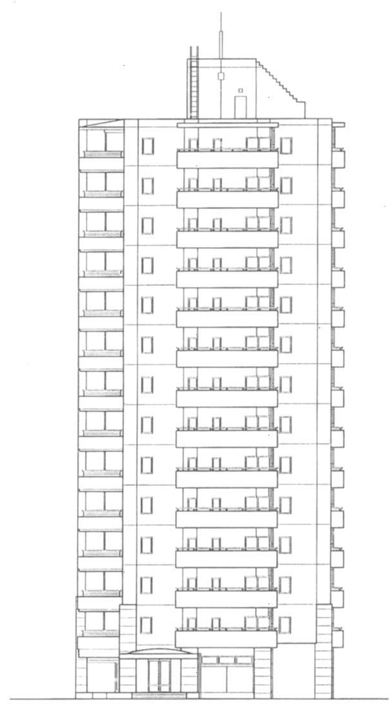


Fig. 3-2. East-side elevation

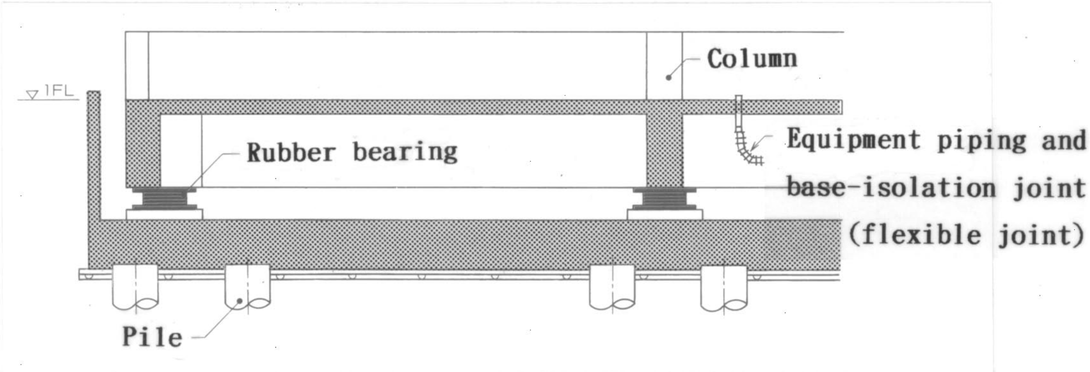



Fig. 4. Cross-sectional view of base isolation layer

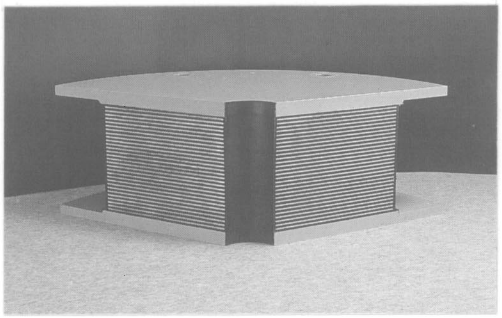


Fig. 5-1. Cross-section of high-damping laminated rubber bearing

Fig. 5-2. Installing a laminated rubber bearing

## SYNOPSIS OF THE STRUCTURAL DESIGN

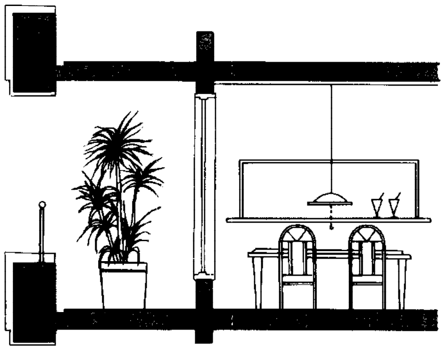
- The aspect ratio of the short span is 2.4.
- The size of a typical column is 500 mm x 800 mm, and the typical beam is 450 mm x 900 mm.
- The design seismic force of the superstructure of this building is 70% of the seismic force in a non-base-isolated structure.
- Because the laminated rubber bearing is made compact, it's average face pressure is 90 kgf/cm$^2$, and it is used at a higher face pressure than designed by the authors.
- A failure test by horizontal force was performed on the laminated rubber bearing while it was under high face pressure. Several characteristics of failure mode were studied, especially the buckling characteristics of the laminated rubber bearing in the large-deformation region. The test results were used to determine the size of and the appropriate face pressure for the laminated rubber bearings.

### High-damping laminated rubber bearing

- Thin layers of sheet steel and rubber are laminated together, supporting the building with a structure that is highly resistant to deformation.
- Rigidity and a damping mechanism are combined into a single structure to shield from seismic motion, and these units are installed under each column.

Table 1: Laminated rubber bearings of this building

| Name | Diameter (cm) Do | Rubber thickness tr (cm) × number of layers n = total thickness h (cm) | Intermediate steel plate (cm) | Secondary shape coefficient $S_2$ |
|---|---|---|---|---|
| ∅1000 | 100 | 0.75×20=15.8 | 0.31 | 6.33 |
| ∅ 800 | 80 | 0.54×30=16.2 | 0.22 | 4.94 |
| ∅ 750 | 75 | 0.54×30=16.2 | 0.22 | 4.63 |



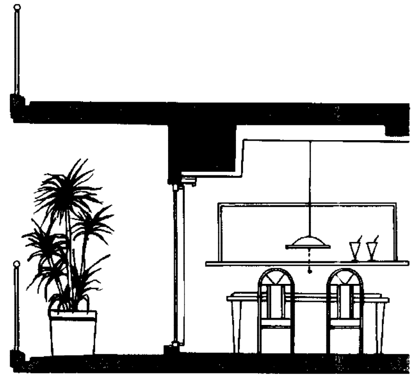


Fig. 6-1. This structure Fig. 6-2. A conventional structure
(south face cross-sectional view)

DESIGN POLICY

In order to realize the concept of this plan, "the realization of a urban environment that is kind to the old," the structural design policy was set as follows.

Safety: To reduce the shaking during an earthquake to 1/3 or less that of a conventional structure.

In a conventional structure, it is permissible for some structural members of the building to be destroyed in a major earthquake, provided the building does not collapse and no human life is lost. In a base-isolated structure, on the other hand, the earthquake input to the superstructure is greatly reduced, reducing the response acceleration of the superstructure and preventing furniture and appliances from toppling over, and because the deformation between layers of the superstructure is very small, damage to secondary structural members such as doors and sashes is prevented.

Livability: To increase the degree of freedom of design by not requiring columns and beams within occupied rooms.

The building was designed so that the short span (the north-south span) is a wall structure and no columns or beams appear within rooms. The long-span frame is made on only the south face and north face, and the beam on the south face also serves as part of the balcony-end railing.
By making the beam do double duty as part of the railing, room windows can be made nearly as high as the ceiling, brightening the interior of the rooms. And because no columns appear in occupied rooms, no space is wasted, providing freedom in the placement of furniture.
(See Fig. 6 for a comparison of this structure and a conventional structure.)

Economics: To reduce costs by reducing the cross-section of structural members of the superstructure and by reducing the size of the laminated rubber.

In earthquake-prone Japan, it is usual to make the columns and major beams of an apartment building of this size with steel-reinforced concrete, but reduction of the seismic force makes it possible to reduce the cross-section of the steel-reinforced concrete structure and to simplify the details of the various parts. Economy was pursued by verifying the properties of the laminated rubber bearing under high axial stress and by simplifying the laminated rubber bearing.
A comparison of the total life-cycle cost, including the amount of damage and loss when the building is struck by an earthquake, clearly shows that a base-isolated structure is cheaper than a conventional structure, although in initial cost it is designed to be about the same.

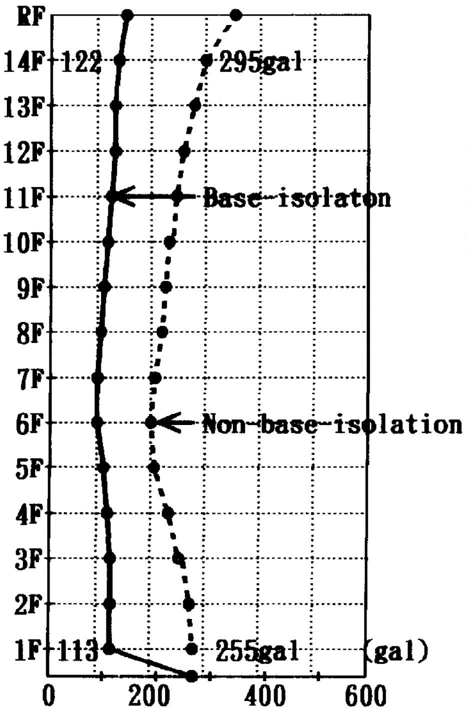



Fig. 7-1. Response maximum acc.
(long span)

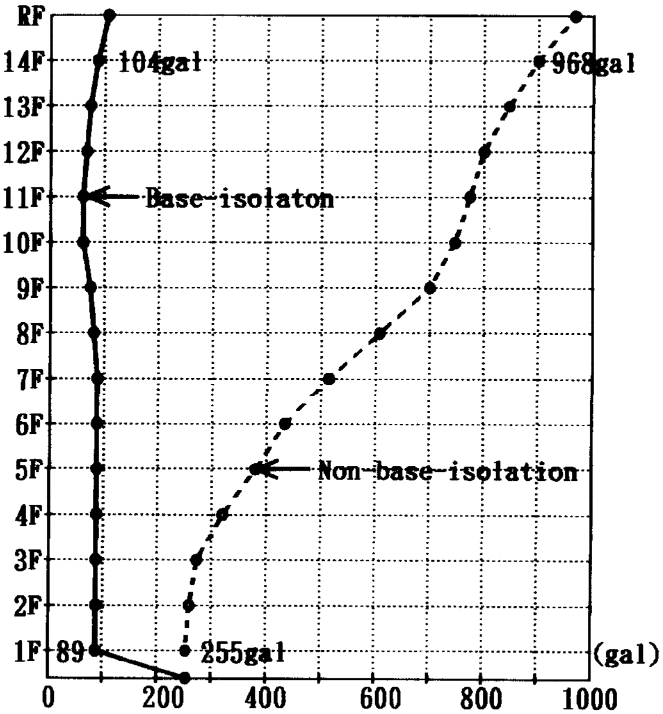



Fig. 7-2. Response maximum acceleration
(short span)

## EARTHQUAKE RESPONSE ANALYSIS

### Summary of the analysis

Earthquake response analysis by seismic motion hypothesized for the design of the building was done for the case in which laminated rubber bearings are installed and the case in which they are not (the non-base-isolated case).

For the input seismic motion, the input level is normalized to a maximum speed of 25 cm/s using the EL CENTRO wave (NS), which have different properties. Moreover, it corresponds to about 225 cm/s$^2$ at maximum acceleration.

Used for the analysis model was an equivalent shearing type multi-mass model involving 15 mass points at which the weight is concentrated at the position of each floor, and an elasto-plastic earthquake response analysis was made. The laminated rubber bearing is modeled as a nonlinear horizontal spring and a linear rotary spring. The input position of the seismic motion is taken to be the base of the laminated rubber bearing.

### Analysis results

The results of the earthquake response analysis are shown in Fig. 7. In the direction of the short span, because a bearing wall having both rigidity and bearing force is sufficient, no reduction is made in the rigidity as is done in the direction of the long span, and the shaking of the earthquake exhibits a quite large value.

This result too shows that because a base-isolated structure has a long natural period and a large damping constant, the effect of the seismic force on the building is reduced, and there is a resonance suppression effect. It was also learned that the superstructure of this base-isolated building generally remains within the elasticity range even with respect to seismic motion having a maximum speed of 50 cm/s.

DYNAMIC AND FAILURE PROPERTIES OF HIGH-DAMPING LAMINATED RUBBER BEARING UNDER HIGH AXIAL STRESS

In order to evaluate the correct face pressure level for the laminated rubber bearing, tests were carried out on the dynamic and failure properties of high-damping laminated rubber bearings under high face pressure.

Testing method for dynamic properties

Test structures A and B shown in Table. 2 are subjected to $\sigma = 65$ kgf/cm$^2$ as conventional face pressure and $\sigma = 120$ kgf/cm$^2$ as high face pressure. Next, horizontal force was dynamically applied to the laminated rubber bearing with a 0.33 Hz sine wave. The shear strain amplitude is set to six levels, namely $\gamma$ =10, 25, 50, 100, 150, and 200%.

Test results for dynamic properties

Figure 9 shows the ratio of the effective shear modulus G and the equivalent damping ratio heq at various shear strains in the case of $\sigma = 65$ kgf/cm$^2$ and in the case of $\sigma = 120$ kgf/cm$^2$. With a shear strain of 50% or less, at a high face pressure, G is reduced by 8-10% and heq is increased by 10-15%. This result indicates that the effect of the face pressure on the value of the rigidity and damping constant of the laminated rubber bearing should be taken into account. Test structure A, in which the secondary shape coefficient of the laminated rubber bearing is small, undergoes greater change than test structure B.

The secondary shape coefficient of the laminated rubber bearing is an important element when used at a high face pressure.

From the above results, a higher face pressure at an appropriate secondary shape coefficient tends to improve the dynamic properties.

Testing method for dynamic properties

A shear load was applied until failure to test structures C and D at face pressures of $\sigma = 120$, 180, 240, and 300 kgf/cm$^2$. The failure test was performed on test structure C after accelerated thermal aging equivalent to 30 years and 60 years.

Test results for dynamic properties

Figure 10 shows the load-deflection curves under various face pressures. In Fig. 10, in all cases other than the test structure used for the 240 kgf/cm$^2$ failure test, a 200% shear strain was experienced prior to the failure test. This is because the data for $\sigma = 240$ kgf/cm$^2$ yields a rather peculiar shape when compared with the others. Also, under all face pressures, buckling occurs before failure. The breaking strain was determined as the strain at which the horizontal load is zero. The results indicate that the ultimate performance of the isolator under high face pressure is determined mainly by buckling. The relationship between buckling, breaking strain, and face pressure is shown in Fig. 11.

Figure 12 shows the large-deformation properties of a laminated rubber bearing after heat aging with air equivalent to 30 years or 60 years. From the results, the laminated rubber bearing still maintains a deformation capacity of 350% or more even after heat aging with air equivalent to 60 years.

Table 2: Laminated rubber bearings of test structures

| Test structure | Diameter (cm) | Rubber thickness × number of layers = total thickness | Steel plate | Secondary shape coefficient |
|---|---|---|---|---|
| A | 20.6 | 0.17 ×27=4.59 | 0.08 | 4.5 |
| B | 20.6 | 0.17 ×23=3.91 | 0.08 | 5.2 |
| C | 16 | 0.133×27=3.59 | 0.08 | 4.5 |
| D | 16 | 0.133×24=3.19 | 0.08 | 5.0 |

$S_2$=Do/h : Secondary shape coefficient

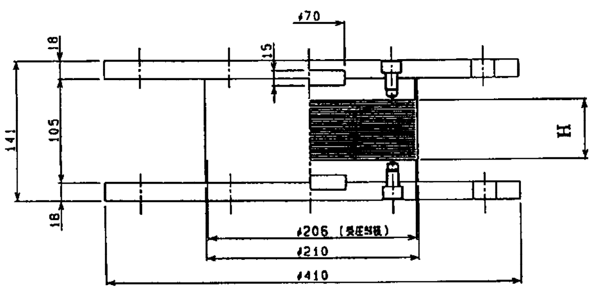



Fig. 8. Test structure C

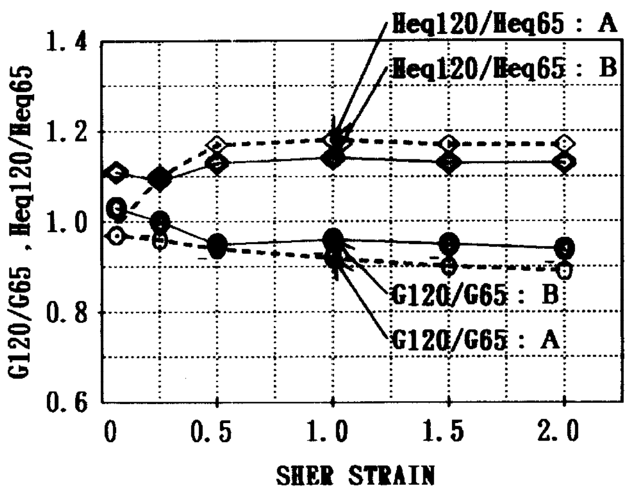



Fig. 9. Dynamic properties and face pressure

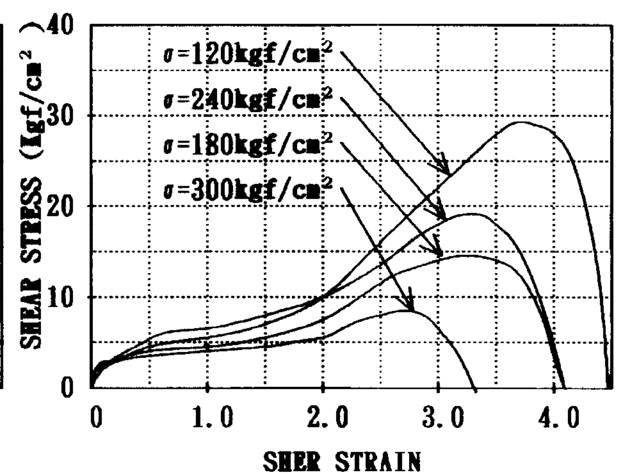



Fig. 10. Failure properties of test structure C

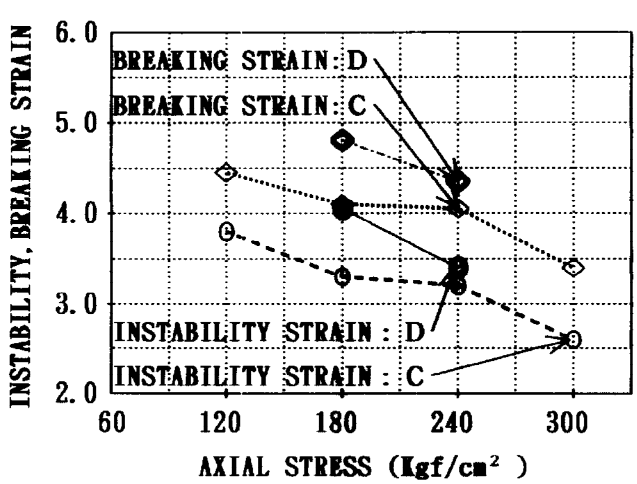



Fig. 11. Relationship between instability, breaking strain, and face pressure

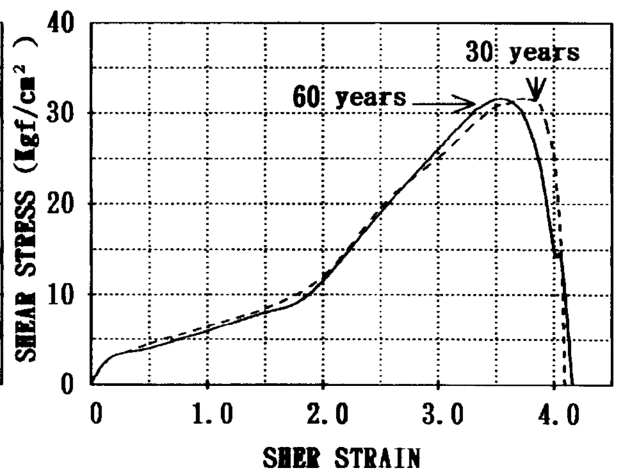



Fig. 12. Failure properties after heat aging with air

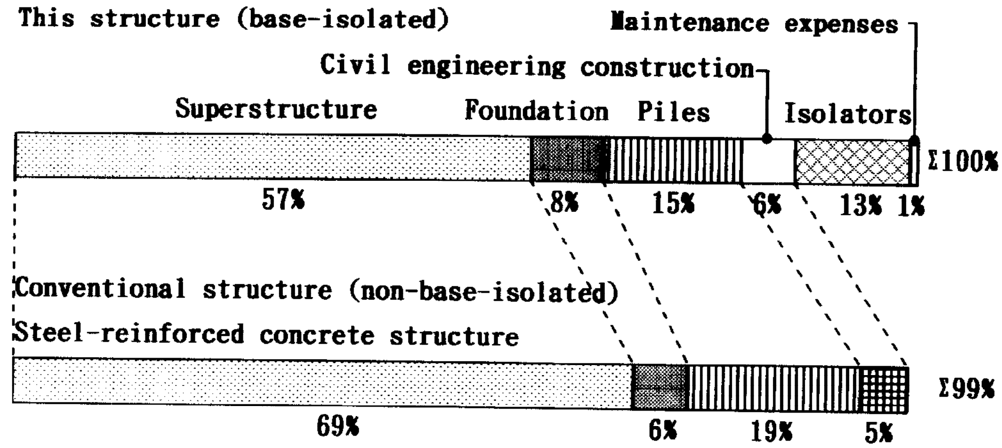



Fig. 13. Comparison of base-isolated and non-base-isolated structure costs
(Test study as of December 1994)

## ECONOMICS

Figure 13 compares the structure cost with the case in which this building is not base-isolated. As is clear from this diagram, the added expense of isolators, foundation, civil engineering construction, and maintenance management is roughly cancelled out by the decrease in the cost of the superstructure and piles. It is fortunate that with this building as a 14-story base-isolated structure, the ratio of its increase because it is tall is small.

## CONCLUSION

The Kobe earthquake of January 17, 1995, known officially in Japan as the Great Hanshin Earthquake, revealed that current earthquake-proof designs, although they ensure safety against hypothetical seismic motion, are not invulnerable to indeterminate seismic motion, and there is no guarantee that buildings will remain safe and functioning in the face of unexpectedly large seismic motion. A major feature of the base-insulated structure is that it attempts to shield the building from as much of the energy of an earthquake as possible by preventing resonance between seismic motion and the natural frequency of the building. This should have a major effect on improving safety and ensuring that the building remains functioning even in the face of seismic motion involving many indeterminate factors.

This building was designed prior to the recent Kobe earthquake, and we would like to express our respect to those who worked diligently to solve many difficult problems at a time when awareness of base-isolated structures was much different from what it is today, and to the Bridgestone company, which has done much experimentation and research in high-damping laminated rubber bearings.

## REFERENCE LITERATURE

Hidetake Ishizuka, Nobuo Murota, Takeshi Fukumori (1995). "Dynamic and Failure Properties of High Damping Rubber Bearing under High Axial Stress" PVP-Vol. 319, Seismic, Shock, and Vibration Isolation, ASME 1995