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Study on failure mode of seismic isolated reactor building

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ABSTRACT: Stringent earthquake-resistant design requirements are imposed on nuclear facilities in Japan, one of the high seismicity countries in the world. The adoption of seismic isolation system would serve to reduce not only the design seismic load, but also construction costs. To develop a demonstration FBR, which harmonizes with high-temperature structural design, but is comparable to LWRs in terms of construction costs, reducing the design seismic load is one of the most important items. In developing seismic isolation system that can be applied to the reactor buildings where a high reliable level of safety is required, this study was focused on feasibility of a large supporting device securing endurance for large relative displacement due to earthquakes. To verify that the seismic isolated facilities have aseismic safety equal to or higher than LWRs, vibration tests were conducted to understand dynamic failure mode and to reflect it in designing practical seismic isolated facilities and assessing their safety against the earthquakes.

1 CONCEPT OF SEISMIC ISOLATED FBR PLANT

The concept of seismic isolated reactor buildings located in high seismicity areas in Japan was investigated as follows.

At first, the design basis earthquake(S_2 level : herinafter, DBE) was assumed as the largest motion that may occur. DBE includes long-period components which greatly influence the seismic isolated structure. To assure, secondary, an aseismic safety margin equivalent to reactor buildings constructed in accordance with conventional earthquake-resistant design requirements, a seismic isolated building was designed conceptually with a low center of gravity and seismic safety factor 2 against DBE.

As an isolator, the laminated rubber bearing rated at a load of 500 tons was designed and given displaceability of 100 cm. Figs. 1 and 2 show the concept of the seismic isolated building and DBE respectively. (Kato, 1991)

2 TEST OUTLINE

Groups of isolators, arranged as many as possible(hereinafter called the seismic isolated layer, or SIL) were schemed so as to be dynamically fractured by using a shaking table. The purpose of this test is to confirm the failure characteristics of the SIL during an eathquake.

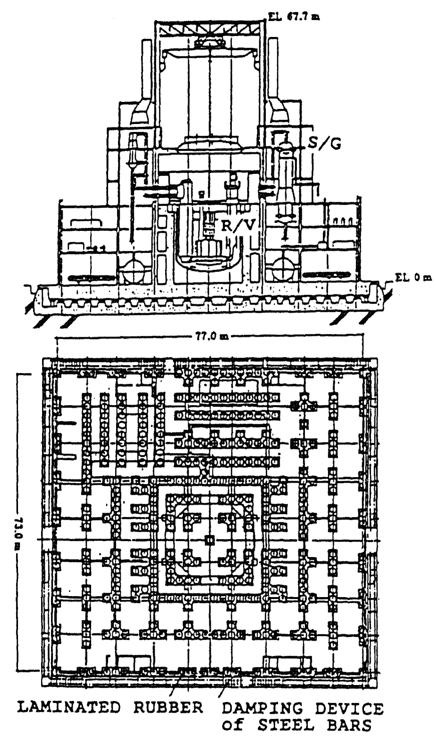

Fig.1 Seismic Base Isolated Reactor Biulding for FBR Plant

2.1 Test model

The test model consists of a rigid upper-structure, isolators, load cells, and leveling devices, as shown in Fig. 3. Fig. 4 shows the isolator used in the test which is scaled down to about 1/27 the size of an actual rubber bearing (outside diameter : 1600 mm, thickness of rubber: 9.0mm x 25, bearing stress: 27 kg/cm²). A 5 mm thick insert plate was placed in the center to take measurements. Prior testing had confirmed that this thick insert plate does not affect the mechanical properties.

2.2 Input waves

Simulated seismic waves including periods of one to five seconds, which are efficient for the period of SIL, are inputed to the model after eliminating short-period components from the DBE, and also inputed resonance sinusoidal waves. Fig. 2 shows the seismic wave patterns.

2.3 Measurement method

The shearing and axial forces of each isolator are measured by using a load cell (stress detector). Horizontal and vertical relative displacement and absolute acceleration of both the shaking table and the upper struture are measured respectively with a displacement detector and an accelerometer. (See Fig. 3)

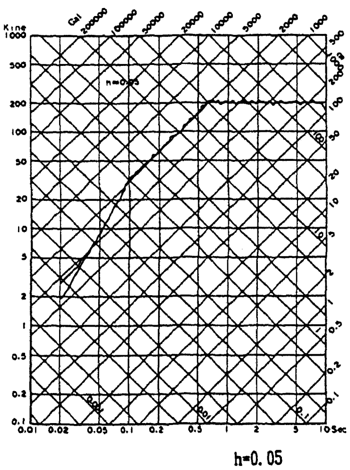

Fig.2a Response Spectrum of Design Basis Earthquake

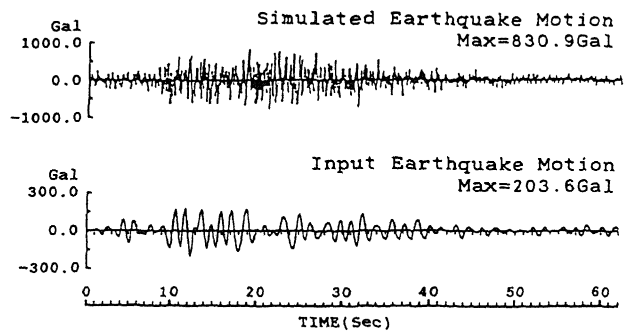

Fig.2b Time History of Earthquake Motion

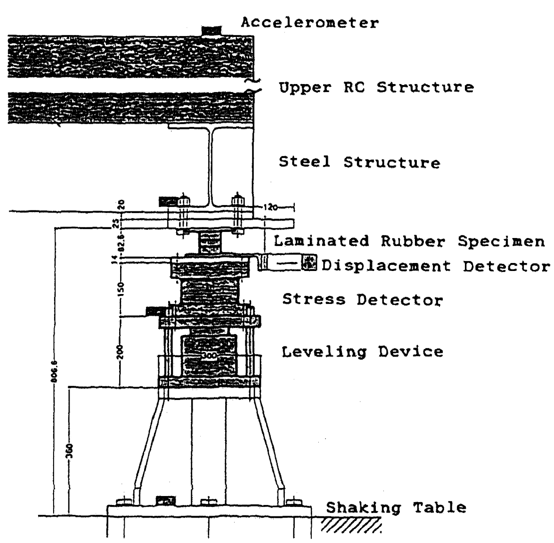

Fig.3 Test Model and Instrumentation

Design Bearing Load (t)	0.7
Scale	1/27
Outer Diameter (cm)	6.0
Total Depth of Rubber Layers (cm)	0.1×8
Total Depth of Insert Plate (cm)	0.06×6+0.5×1
Bearing Stress (kg/cm²)	24.8
Primaly Shape Factor	15.0
Secondary Shape Factor	7.5
Horizontal Natural Frequency (Hz)	2.72
Vertical Natural Frequency (Hz)	78.2

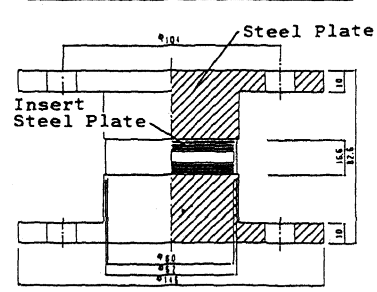

Fig.4 Laminated Rubber Specimen (Natural Rubber)

2.4 Excitation method

The test model is excited with the seismic waves to the design level (equivalent to a 150% shearing strain and about 2/3 of the hardening point), strain hardening level(equivalent to a 500% shearing strain), and breaking level (equivalent to more than a 650% shearing strain). Sweep excitation is applied to the resonance sinusoidal waves.

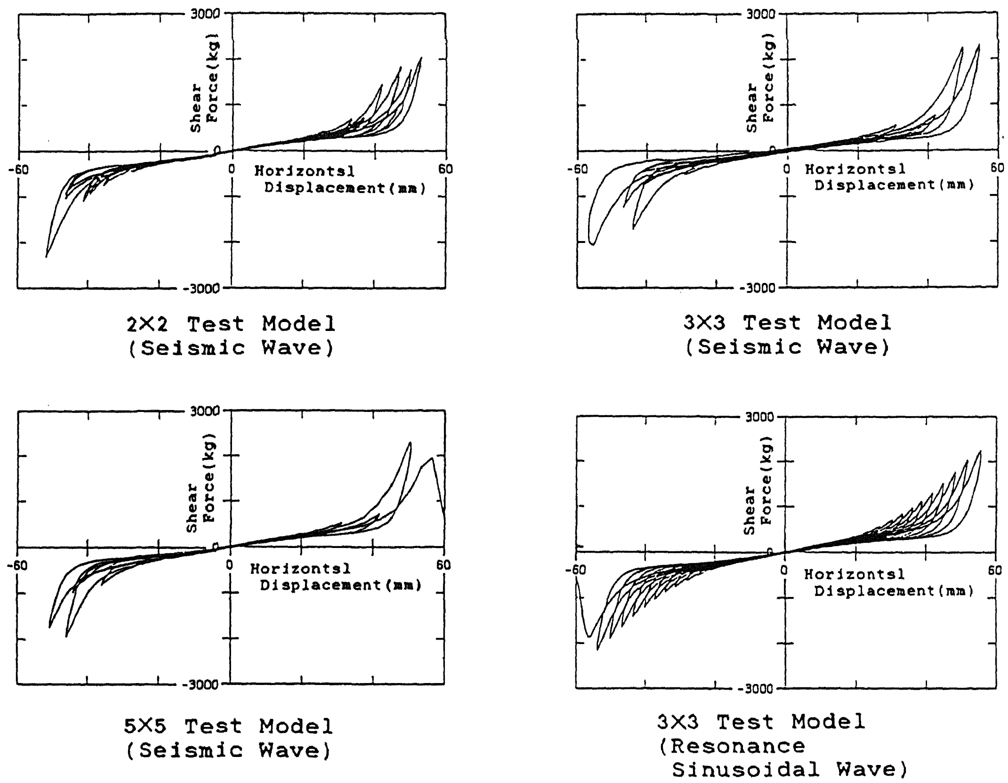

Fig.5a Shear Force-Horizontal Displacement of SIL

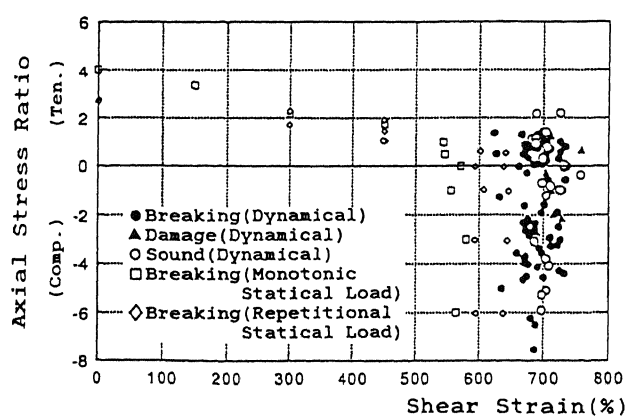

Fig.5b Maximun Stress-Strain Relation of Laminated Rubber Specimen

3 TEST RESULTS

3.1 Dynamic failure characteristics and restoring force of isolators

The hysteresis curve of shear force and horizontal displacement of the isolator before it breaks is almost the same in each test. (See Fig. 5a)

The preliminary static tests of isolator itself show the corresponding results with those of the dynamic tests. From Fig. 5b, which shows the maximum axial force and horizontal displacement of the isolators for both the dynamic and the static tests, it is clear that the dynamic breaking strain is slightly greater than the static breaking strain. Moreover, breaking is governed by the shearing strain capacity.

3.2 Failure mode of seismic isolation layer

When the test models [2 x 2], [3 x 3] and [5 x 5] were excited to the breaking level, the rate of breakage and damage to the total number decreases by 3/4, 5/9 and 4/25, respectively. This shows the effectiveness of the multi-arrangement of the isolaters. It is also found that the damage concentrates at the periphery isolators. (See Fig. 6)

The difference between the two input levels, one when partial failure is caused and the other when all isolators are broken simultaneously, was about 20%, the latter level being larger than the former in spite that the test model had a low center of gravity in order to reduce the effect of seismic overturning moment.

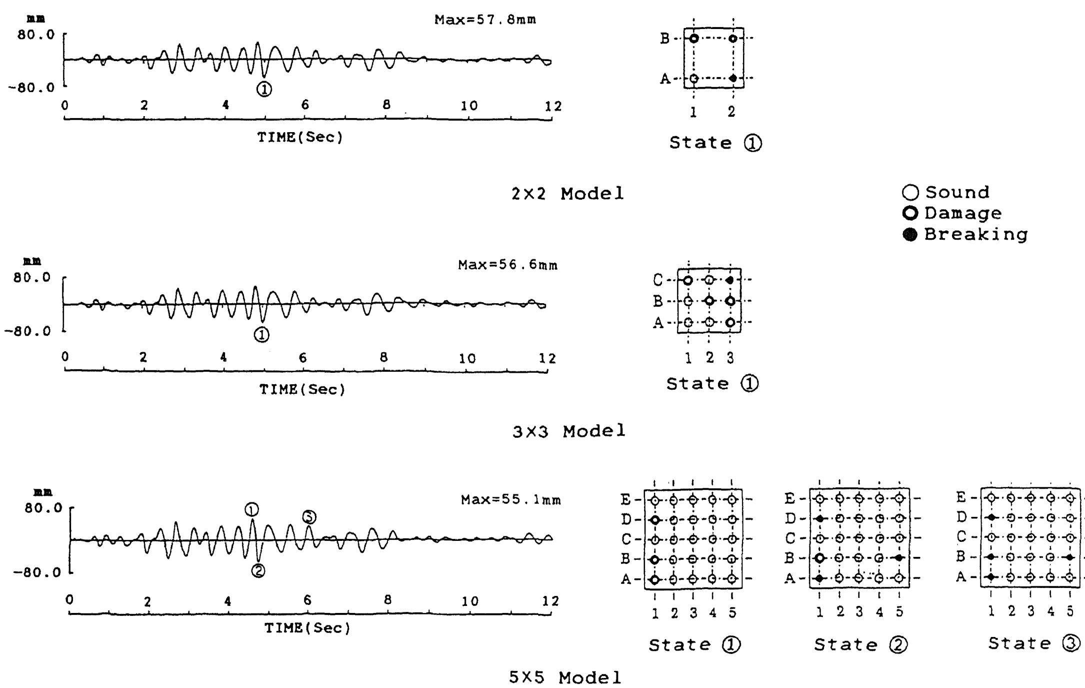

Fig.6 Breaking Mode of Laminated Rubber Specimen -Response of Horizontal Displacement-

3.3 Changes in dynamic response following the progress of breakage

Using a special failure detector, the progress of breakage of the isolators and their responses were examined by forcibly stopping the excitation of the shaking table when breakage occurrs.

Fig. 7 shows the breaking ratio and the response values. The figure indicates a correlation between the development of breakage or damage and the residual strength capacity of the SIL. Even if 30% of the SIL is fractured, no drastic change occurs in the dynamic response, which means that the SIL will continue to retain a sufficient supporting function in case of the DBE level, because that DBE design condition of the SIL has been set at 2/3 of the hardnenig point of the SIL.

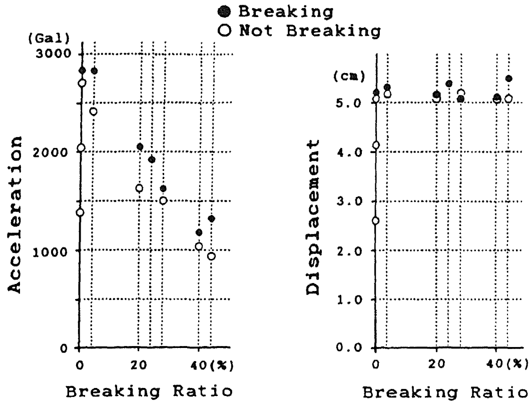

Fig.7 Breaking Ratio-
Response of SIL

4 ANALYTICAL STUDY

A simulation analysis until failure occurs was conducted, taking into account the test results.

4.1 Analytical model

The analytical model is shown in Fig. 8. That is to estimate the test results of the SIL until it failures. The results of the static monotoneous loading tests conducted on the isolators indicates that the skeleton curve is approximated by three polygonal lines. This model takes into account the effects of cyclic excitation.

The first corner point on the skeleton curve corresponds to the starting point of the strain hardening, and the second corner point is set so that it realizes the test results with the shearing strain of 400%.

Restoring force characterictics were assumed taken into consideration of relationship between the maximum displacement and slippage concerned as shown in the test results (Fig. 9). The return path of the restoring force loop was assumed to take towards the first corner point.

4.2 Simulation analysis results

Fig. 9 shows the simulation analysis results of the [3 x 3] test model used seismic waves. The curves illustrate the response acceleration and displacement hystories and shearing force-strain relationship of the SIL.

The analysis results correspond with the dynamic test results well through the strain hardening level to the breaking level. The maximum horizontal displacement and time when breakage occurrs are almost same for the simulation and the dynamic tests.

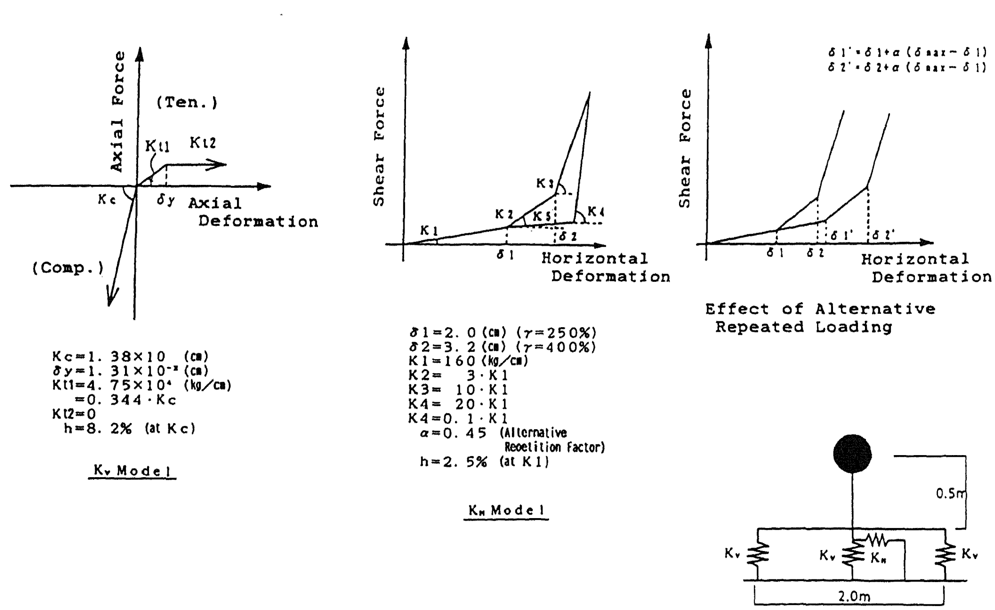

Fig.8 Simulation Analysis Model

3×3 Model

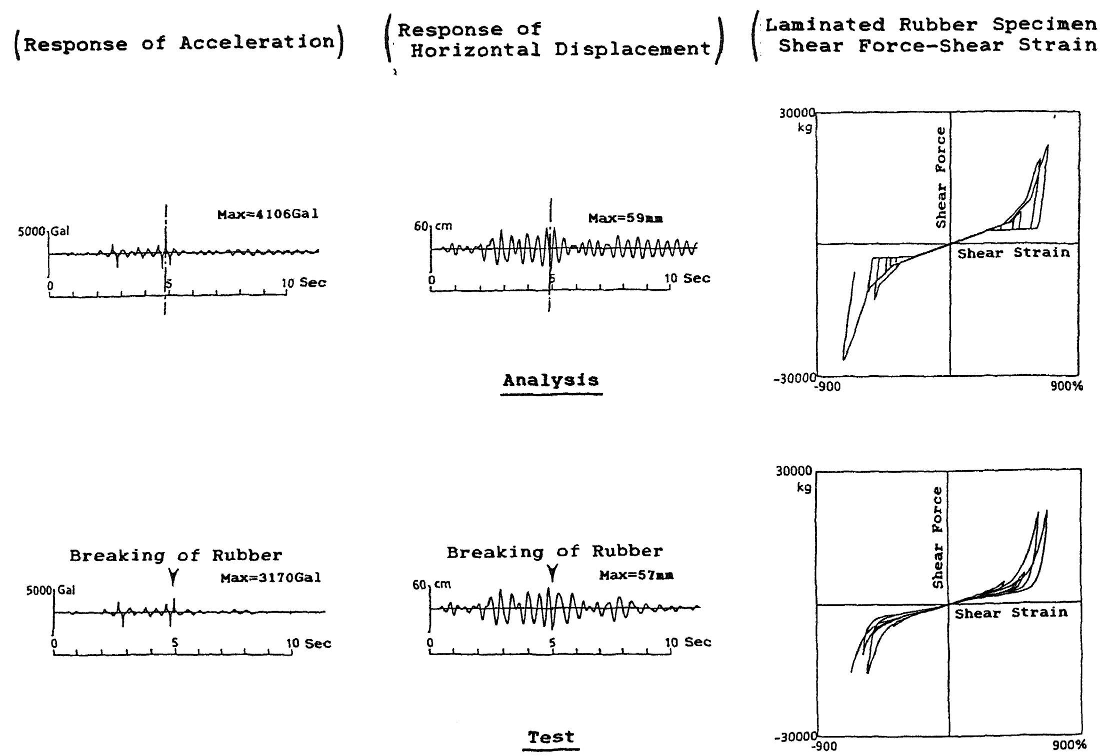

Fig.9 Simulation Analysis Result

5 CONCLUSIONS

The isolators used in the test were small and their shearing strain capacity was comparatively larger than that of the real one.

Neverthless, fruitful results are obtained on the failure mode and aseismic safty margin of the SIL. Failure of the SIL at a plant with a low center of gravity was obserbed to be caused by the shearing strain capacity. This has given a basis for assessing the safety of actual seismic isolated plant. This study has also shown that seismic isolated plant is able to be designed with a safety equivalent to the safety at those plants that comply with conventional earthquake-resistant design requirements.

Farthermore, future work has been scheduled to expand the analytical model so that it can evaluate the properties of the SIL after failure.

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REFERENCE

1. M. Kato et al., "Study on the Seismic Base-Isolated Reactor Building for Demonstration FBR Plant in Japan", K21/5, Proceeding of 11th SMiRT,(August 1991).