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Development of 3D Seismic Isolator using Metallic Bellows

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ABSTRACT

3D seismic isolation system is effective to mitigate both horizontal and vertical earthquake loads. As for realization of economical Fast Breeder Reactor (FBR), it seems to be indispensable to adopt the 3D isolation system because of severe seismic load conditions in Japan.

The authors had been previously investigated a 3D isolation system with the combination of metallic bellows as vertical isolation spring and the commercialized lead rubber bearing (LRB) as horizontal, for International Thermonuclear Experimental Reactor (ITER) building[1].

The vertical device was modified and developed to satisfy the FBR seismic requirements in this study. Bellows is generally known as the flexible pipe joint and has been got enough experience for the fabrication and design know-how. It is effective to absorb large displacement and also works as air spring by filling up with gas.

This paper describes about design concept of the bellows to meet the FBR seismic isolation requirements and the feasibility test results.

In the feasibility tests, 1/5 scale model of the isolation device was used to measure basic characteristics and behaviors and the static and fatigue strength, reliability and stability of the proposed isolator are evaluated from the experimental results. Simplified formula for the vertical spring rate, applicability of FEM simulation analysis and future optimizations are also discussed.

The study was made as a part of the Development Program of Three-Dimensional (3D) Seismic Isolation for Advanced Reactor Systems in Japan

KEY WORDS: 3D seismic isolator, Bellows, Lead Rubber Bearing, FBR, Scale model test, Contact Analysis

REQUIREMENTS FOR THE ISOLATOR

Specific requirements for 3D isolator development had been given from the project Case Study S2 Wave (CSS2) [2], whose vertical response spectra with various damping are shown in Fig.-1 and the present FBR building structure, as shown in Fig.-2.

Specifications are as follows.

- Total weight capacity : $1.7\text{x}10^6$ kN
- Vertical isolated frequency fv : less than 1Hz
- Vertical damping Hv : 20-40%
- Horizontal isolated frequency fh: 0.5Hz
- Vertical damping Hh : 20%

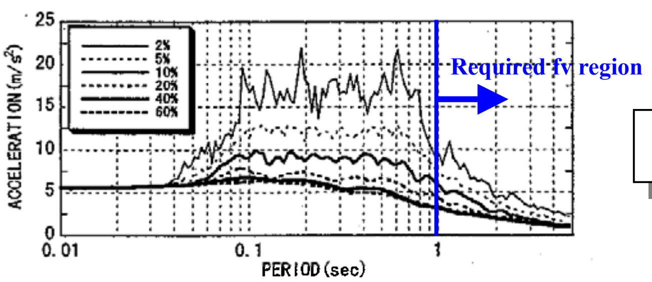


Fig.-1 Vertical response spectra of CSS2

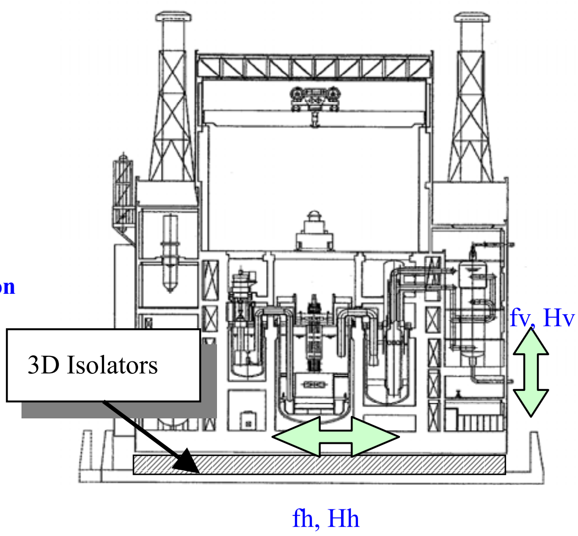


Fig.-2 FBR building schematic with3D isolator

OUTLINE OF THE SEISMIC ISOLATOR USING THE METALLIC BELLOWS

(1) Concept of the seismic isolator module

Figure-3 shows the proposed 3D seismic isolation module. It consists of a LRB in the upper part, and a couple of concentric bellows in the lower. The LRB is well known as a horizontal isolation one and has already been practiced in many actual plants.

The metallic bellows, which is well known as piping expansion joint and has many fabrication practices, are used for a vertical isolation device because it can work as a low frequency air spring. Additionally, bellows has own damping function because it works with the material plastic region.

Double bellows system by main and auxiliary is used considering a fail-safe concept against either damage. Reinforcement rings are wrapped on each convolution of both bellows to resist high internal pressure and buckling failure.

Outside the bellows, inner/outer casings with metallic slide bearing are arranged to transmit shear force between LRB and base flange. For optional function, thick rubber ring at the bottom of the outer casing against excessive vertical sinkage and additional vertical damper in the bellows can be compactly arranged.

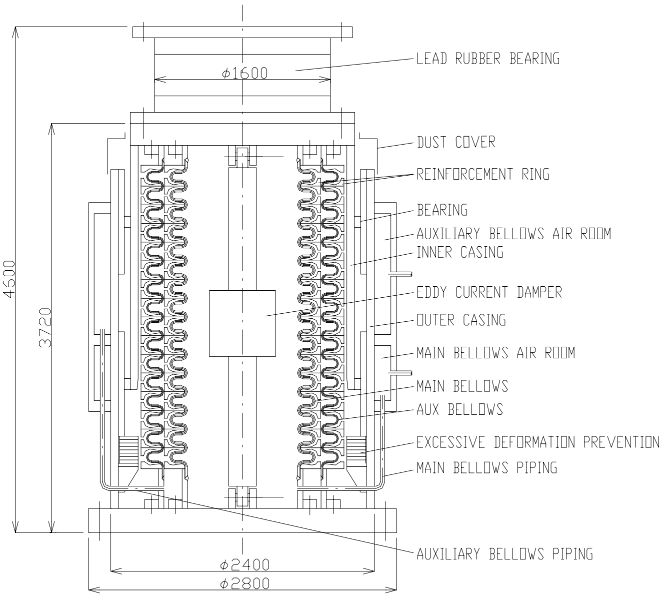


Fig.-3 Schematic of the proposed 3D isolator

(2) Designed specification for the FBR building

Functional specification of the present module is shown in Table-1. Pressure conditions of the both bellows are summarized in Table-3.

For horizontal spring rate Kh concerning with the required isolated frequency fh, it is easy to decide commercial LRB specification because it had been already established how to design. Horizontal damping 20% can easily be included in the lead.

As for the vertical spring Kv, the two kinds of spring rates should be considered each.

Kv = Ka + Kb

Ka: spring rate of air

Kb: spring rate of metallic bellows

Here, Ka is expressed by the eq.-(1), assuming adiabatic compression theory.

$$Ka_i = A_i \frac{\gamma \cdot P_{i0} \cdot (x_0 + L)^{\gamma}}{(x + L)^{\gamma+1}}, i = 1, 2 \quad (1)$$

suffix i: •=1;Main, =2;Auxliary

A_i: Section area of equivalent cylinder

P_{i0}:Internal pressure

x_0:Initial length of bellows

x : Axial displacement of bellows

L: Dummy length (Total-x_0)

•:Gas constant (=1.4 ,air)

Table-1 Functional specifications of the module

Vertical support load capacity	9807 kN
Vertical isolation frequency fv	0.56 Hz / 9807 kN
Vertical damping Hv	20 %
Vertical max. displacement	±0.4 m
Horizontal isolation frequency fh	0.5 Hz / 9807 kN
Horizontal maximum load	5884 kN
Horizontal damping Hh	20 % (Included in lead)
Horizontal max. displacement	±0.3 m

Table-2 Details of the main and auxiliary bellows

	Main	Auxiliary
Type	U type with reinforcement ring	U type with reinforcement ring
Material	SUS316	SUS316
Diameter (mm)	•1000	•1430
Convolution height (mm)	141	146
Pitch (mm)	170	170
Thickness (mm)	2.5	2.5
Num. of layers (-)	9	6
Num. of convolutions (-)	16	16

Kb is defined with the consideration of plastic deformation of bellows structure. Even though EJMA[3] gives the spring rate formula by elastic theory, the actual spring rate is less than the theoretical one.

The resultant isolated frequency fv in Table-1 depending on the actual Kv is determined by the scale model test. Kb is discussed again in the later discussion of this paper.

Required maximum displacements were defined by seismic response analyses with various sets of spring rates and damping. As for the vertical, it was severely defined as 0.4m considering maximum translation and rocking effect. Generally lager required displacement needs more convolutions of bellows.

The multiple thin-layered bellows are adopted because this concept has benefits on reducing each stress caused by axial deformation and carrying together stresses by high pressure. Design details according to the above concept are shown in Table-2. Internal pressure conditions of both bellows are summarized in Table-3.

Table-3 Pressure and support load condition of each operation mode

Mode	Item	Main bellows	Auxiliary bellows	Sum total
Normal	Pressure	5.9MPa	4.1MPa	-
	Load	5982kN	3825kN	9807kN
Leakage Condition of Main bellows	Pressure	-	5.0MPa	-
	Load	-	9807kN	9807kN
Leakage Condition of Auxiliary bellows	Pressure	9.6MPa	-	-
	Load	9807kN	-	9807kN
Maximum pressure		11.8MPa	6.4MPa	-

(2) System description

Concept of the gas supply system and the layout for applying on the FBR building are shown in Fig.-4 and Fig.-5,respectively. One buffer tank is provided for a group of several number of isolator module. One compressor is provided for a number of groups, and air is stored in the buffer tank.

At the time of bellows' damage, air is supplied from a buffer tank.

As for the maintenance, the isolators can be easily removed by loosing the bolt connections at the time of replacement.

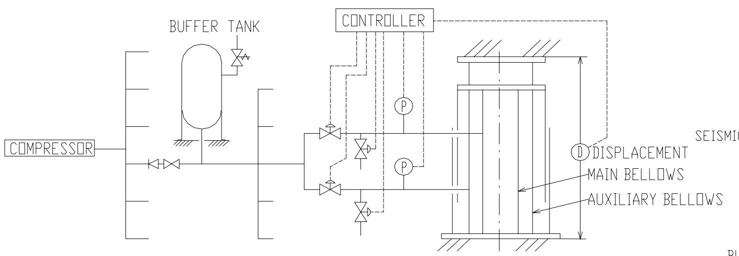


Fig-4 Concept of gas supply system

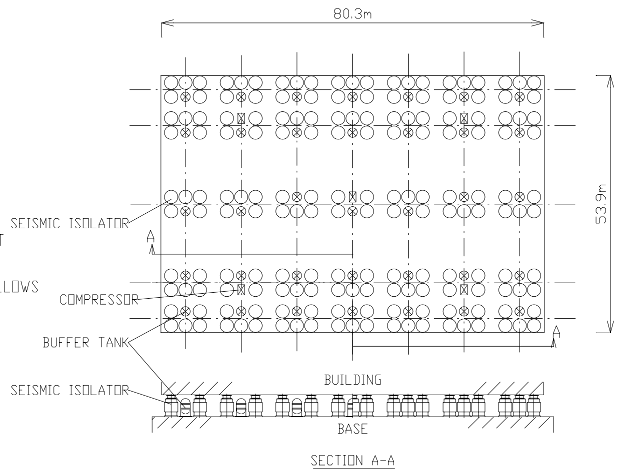


Fig.-5 Layout for the FBR building

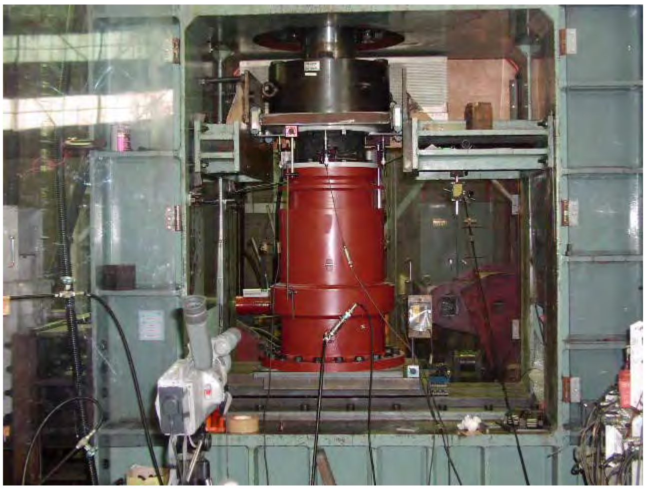
SCALE MODEL TEST

(1) General description of the tests

A scale model of the isolator was manufactured and experimented in order to obtain static and cyclic characteristic data and confirm the feasibility of the proposed 3D isolator.

Picture-1 shows the test appearance and Fig.-6 shows the loading methods. The test model was precisely fabricated into 1/5 scale model with the both of main, auxiliary bellows, cylindrical casing and metal bearing and LRB except the additional vertical damper and excessive deformation prevention rubber. An inert gas N_2 was used to pressurize the both bellows. The tests were carried out using two axes of horizontal and vertical actuators with displacement control. Horizontal and vertical displacement, pressures of the both bellows and reaction forces were measured.

Test conditions were also scaled by the similarity rule. The maximum required displacement 400mm was scaled into 1/5(80mm). Support load was scaled to 1/25(392kN). Sine wave with 0.03Hz speed was applied as input wave



Pic.-1 Testing appearance

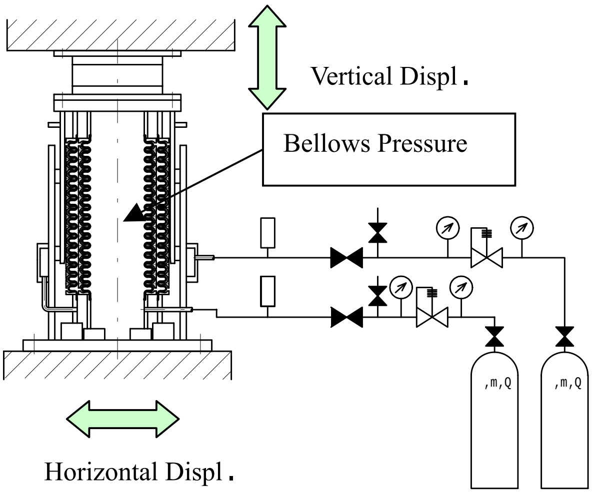


Fig.-6 Schematic of the loading in the test

Evaluation items with related loading conditions are summarized in Table-4.

As the basic characteristics of the bellows, equivalent spring rate and damping were evaluated from 4 cycle tests.

In the case of fatigue test, cyclic vertical loading was applied until the leakage occurred in the main bellows. From the fatigue test result natural reliability of the bellows structure were evaluated.

As for stabilities, simultaneously combined horizontal and vertical loading test was carried out by both of the maximum horizontal and vertical displacements. Single bellows supporting test was also performed in order to simulate the other bellows damage condition.

Main test results and evaluations are described in the followings.

Table-4 Evaluation items and loading conditions

Evaluation Items	Displacement (mm)		Bellows Pressure (MPa)	
	Horizontal	Vertical	Main	Aux.
Stiffness Damping Fatigue Life Reliability	0	•±80	5.9	4.1
Stability & Reliability	•±60	•±80	5.9	4.1
			5.0(*1)	5.0
			9.6(*2)	

Note: (*1) Main bellows damage, (*2) Auxiliary bellows damage

(2) Cyclic load-displacement relations

Load and displacement relations of combined horizontal and vertical displacement test are shown in Fig.-4 and Fig.-5. Test results are summarized below.

a. Vertical stiffness and damping

- Load and displacement relation obtained form the vertical loading test is shown in fig.-7. Dotted line shows the working spring rate Kvw of the load-displacement hysteresis. Vertical spring rate Kv is estimated from this value and it corresponds to fv=0.56 Hz in the actual size.
- Own damping calculated from the plastic loop is approximately 10%. This means only 10% additional damping device is needed in the isolator for the requirement of this study.

b. Load-displacement relation at the combined load

Load-displacement curves at the simultaneous horizontal and vertical loading are shown in Fig.-8 and Fig.-9,respectively. Both curves were same as those at the single loading, so the stability including the maximum shear force transmission was verified.

c. Support functions at the one bellows damage

Vertical support function tests at either bellows damage were simulated by means of the pressures controlling shown in Table.4. Spring rates changes corresponded to those predicted by eq.-(1) with applied pressures.

These facts represent the stability and reliability of the vertical spring by the bellows at the damaged conditions

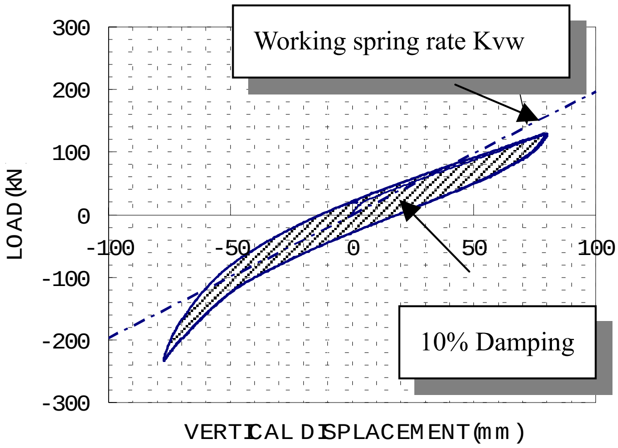


Fig.-7 Vertical load-displacement relation of the isolator at the single vertical loading with normal pressure

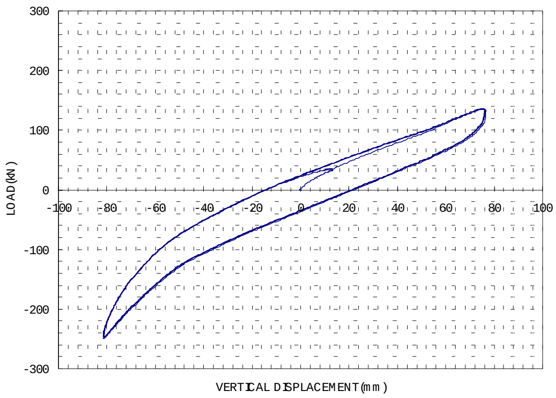


Fig.-8 Vertical load-displacement relation of the isolator at the combined horizontal and vertical displacement test with normal pressures

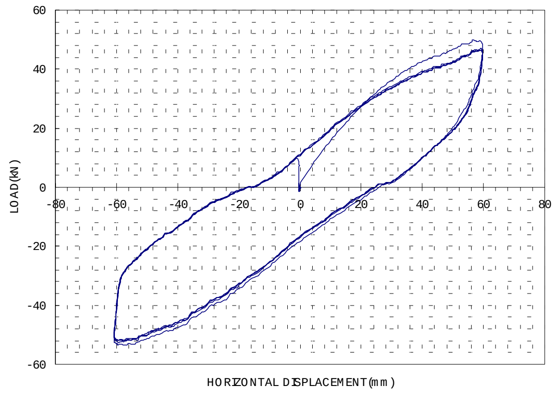


Fig.-9 Horizontal load-displacement relation of the isolator at the combined horizontal and vertical displacement test with normal pressures

(3) Fatigue Life Tests

Fatigue damage seems to be the most critical failure mode in the proposed isolator because the bellows work in the large plastic strain region. Fatigue life test was performed finally by the maximum displacement range of ±80 mm at the condition of normal pressures.

The history of the spring rate and damping of bellows in fatigue test are shown in Fig.-10. The history of internal pressure is shown in Fig.-11.

The life cycle number of the main bellows leakage was about 700. Since the predicted life cycle number of the main bellows by EJMA equation [3] was about 900, it is sufficient as a prediction equation for the fatigue life of bellows.

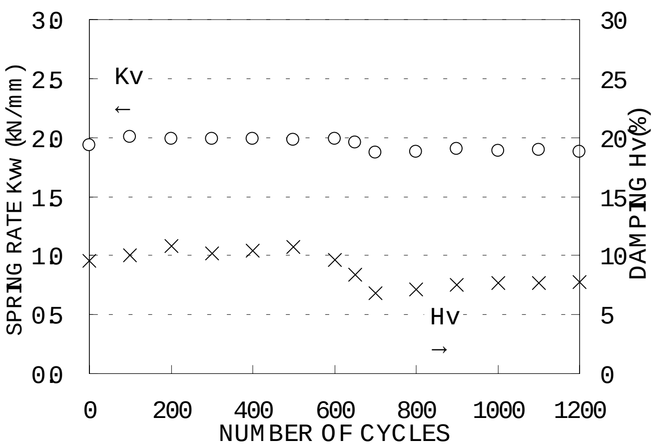


Fig.-10 Spring rate and damping ratio changes depend on load cycles during the fatigue test

Moreover, if an earthquake continues for 40 seconds by 0.5Hz in the frequency, although considering the safety factor of 20, the required life cycle number is at most 400 and the bellows has sufficient fatigue life.

Pic.-2 shows the sectional cut of the main bellows after the fatigue damage. From the picture it is said that the root region must have been damaged from the outer layer, whereas the crown region from the inner layer.

Slow leakage shown in Fig.-11 can be explained by the above fact and this means the vertical spring of the isolator has the natural redundancy.

In fact, the bellows fatigue damage never affect catastrophic stiffness lost as shown in Fig.-10. It can be said that this isolator has essential reliability for supporting function.

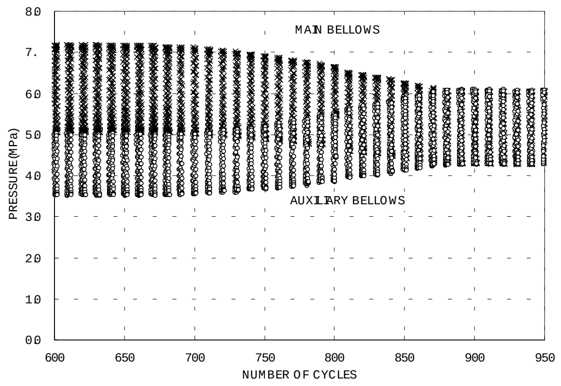
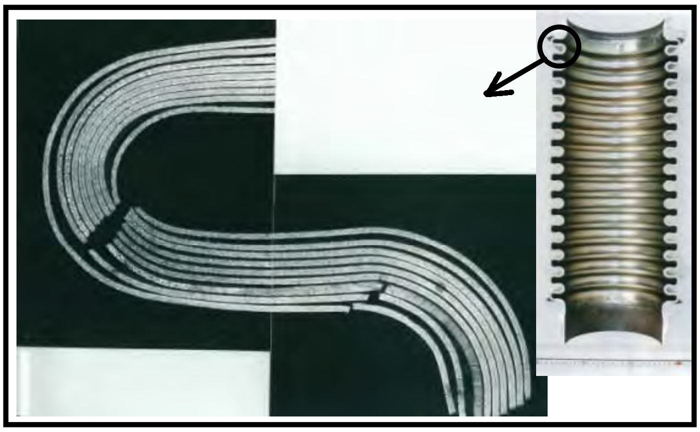


Fig.-11 History of internal pressures in main and auxiliary bellows during the fatigue test



Pic.-2 Section Cut of the main bellows after the fatigue test

DISCUSSIONS

(1) The simplified formula for the vertical spring rate

Simplified formula on the actual vertical spring rate is discussed in the following.

Even though gas spring rate given in eq.-(1) is actually not constant about axial displacement x, a mean value can be obtained for x=0 in eq.-(1), which is applicable to design value as eq.-(2). Here, suffix • denotes main and auxiliary bellows' cylinder, respectively.

$$Ka_i(design) = A_i \frac{\gamma \cdot P_{i0} \cdot (x_0 + L)^{\gamma}}{L^{\gamma+1}}, i = 1, 2 \tag{2}$$

Summed Ka $(= Ka_1 + Ka_2)$ for design is compared with the pressure load hysteresis in fig.-12. It shows sufficiently good applicability.

As for the metallic bellows, a theoretical formula for one convolution is given in EJMA[3] as eq.-(3) using parameters of the bellows. See ref[3] for the definitions of these parameters.

$$Kb_i(theory) = 1.7 \frac{Dm_i \cdot Eb_i \cdot tp_i^3 \cdot n_i}{(W - Cr_i \cdot q_i)^3 \cdot Cf}, i = 1, 2 \tag{3}$$

Then Kv(theory) by eq.-(3) is expressed as eq.-(4).

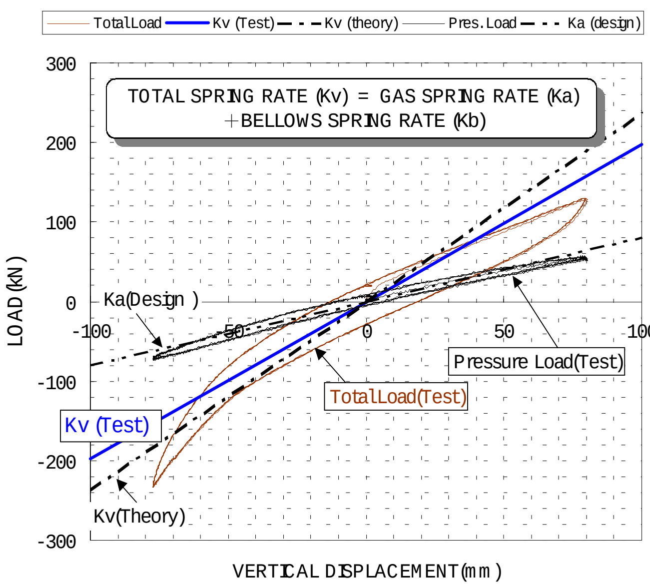


Fig.-12 Spring rate comparison of the bellows

$$Kv(theory)= Ka_1 + Ka_2 + Kb_1/Nc + Kb_2/Nc \quad (4)$$

Here, Nc denotes number of convolutions.

When the simple formula for the Kv(design) is assumed as eq.-(5), modification factor to the effective spring rate •can be decided to approximately 0.71 from the agreement with the experimental work spring rate.

$$Kv(design)=Ka_1 + Ka_2 + \bullet Kb_1/Nc + \bullet Kb_2/Nc \quad (5)$$

Here, $\bullet$=0.71 (empirical value)

(2) Nonlinear contact analysis

In order to examine the bellows axial deformation and strain concentration, nonlinear contact analysis was carried out using explicit FEM code “RADIOSS”. Deformed strain contours of the auxiliary bellows’ half convolution model at the maximum tension and compression are shown in Fig.-13 and Fig.-14, respectively.

From the results, the load hardening at the compression region is affected by contact between bellows and reinforcement ring. Strain concentration locations of the bellows correspond to damage location in the fatigue test. It is also suggested that more exact load and displacement relation by the simulation analysis could be obtained if the material cyclic hardening condition would be applied properly.

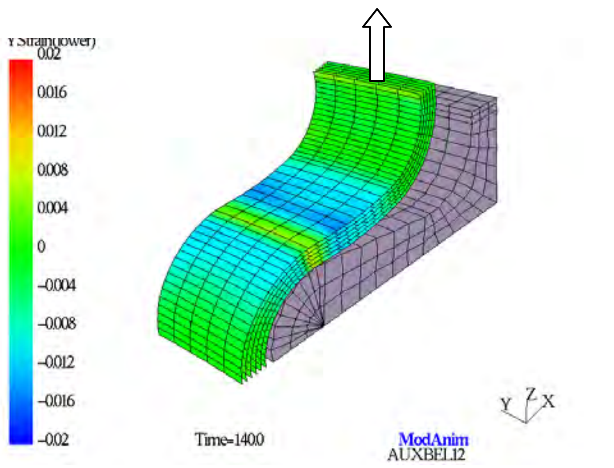


Fig.-13 Deformation and strain contour at the maximum tension of the auxiliary bellows by analysis

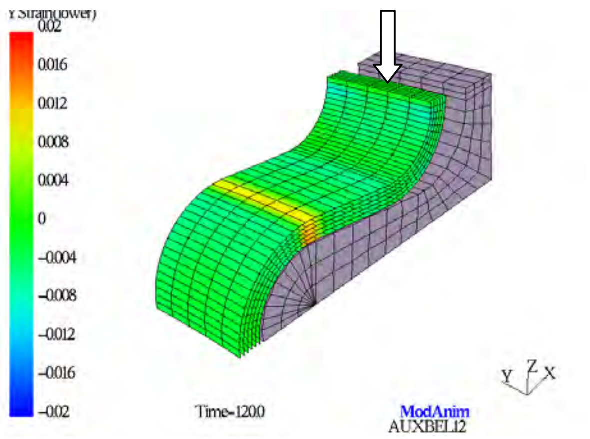


Fig.-14 Deformation and strain contour at the maximum compression of the auxiliary bellows by analysis

(3) Optimization for the future design

It should be noticed that the tuning of horizontal and vertical isolation frequency ratio and building shape are also important to mitigate the rocking movement. From this point of view, a series of response analyses with the parameters of building shapes and ratios of the horizontal/ vertical isolation periods was carried out by one mass model. The maximum displacement results, which should be absorbed in the vertical isolation device, are compared in Fig.-15 and the case of a square building, 3 seconds for horizontal period and 1.5 for vertical shows less rocking in these cases.

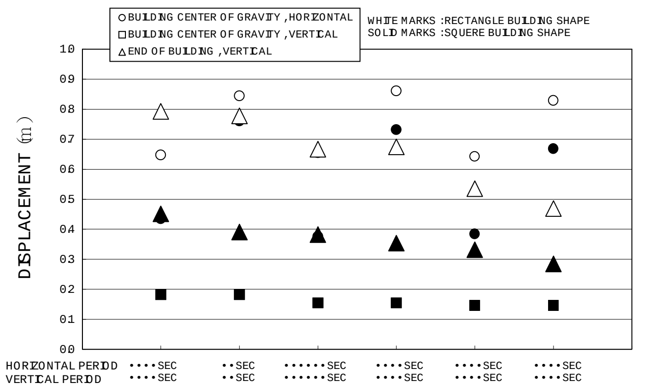


Fig.-15 Building response analysis result by various seismic isolator specifications and building shape

Moreover, the past study [4] indicates the inclined installation of the isolators, as shown in

Fig.-16 conceptually, is effective to mitigate rocking when horizontal / vertical frequencies can be adequately isolated.

This consideration seems to be needed in order to optimize the 3D isolation system for economical FBR plant design in the future.

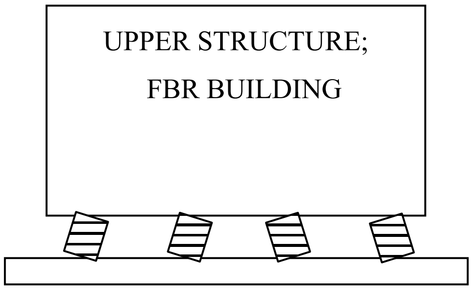


Fig.-16 Concept of the inclined installation to reduce rocking movement

CONCLUSIONS

Even though the basic idea of the 3D isolation is simple, the realization of the isolation system is complicated because various design factors such as isolation frequency, damping, resultant large displacement including rocking effect, cost, manufacturability, maintenance, reliability or aging effect and etc. should be considered in the better balance.

Authors have developed and designed a 3D isolation system based on the combination of the experienced components of bellows and LRB to meet the first screening requirements of the present Development Program of 3D Seismic Isolation. The study shows the proposed isolation module has essential stability and reliability based on natural equalization even at the damage and it is sufficiently feasible for commercial FBR building isolation.

Further study for the overall cost performance including the upper structure design is needed for the optimization of 3D isolation system to FBR actual plant. Authors can finally emphasize that the proposed 3D isolator has flexible design window to the better tuning in the future.

ACKNOWLEDGEMENTS

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