

STUDY ON 3-DIMENSIONAL SEISMIC ISOLATION SYSTEM FOR NEXT GENERATION NUCLEAR POWER PLANT - VERTICAL COMPONENT ISOLATION SYSTEM WITH CONED DISK SPRING

Masaki MORISHITA¹, Seiji KITAMURA², Satoshi MORO³, Yoshio KAMISHIMA⁴ and Takahiro SOMAKI⁵

SUMMARY

A structural concept of a vertical component seismic isolation system for fast reactors, assuming a building adopting a horizontal base isolation system, has been studied. In this concept, a reactor vessel and major primary components are suspended from a large common deck supported by isolation devices consisting of large coned disk springs. The outline of the vertical component seismic isolation system and a series of model tests with full scale coned disk spring and damper are shown in this paper.

INTRODUCTION

Although the horizontal force of an earthquake ground motion is sufficiently reduced by a base isolation system with laminated rubber bearings, the vertical force is transmitted directly. If a three-dimensional isolation were achieved by adding a vertical isolation system, it would substantially enhance plant economy and safety. In order to realize a three-dimensional isolation system, two types of systems can be considered. One is a three-dimensional base isolation. In FBR plants, structural problems in which the consideration for vertical motion is required are uplift of fuel assemblies, reactivity change and buckling of reactor vessel. Since vertical isolation coverage can be limited to the area in which a reactor vessel and primary coolant system are installed, we have constructed a structural concept of vertical component isolation system" [1].

When the vertical isolation system is adopted in individual component separately, the relative displacement will be dynamically taken in the primary coolant system piping, because each response is different. In order to avoid this problem, a reactor vessel and major primary components are suspended from a large slab structure called "common deck", and vertical isolation devices are installed between the deck and the substructure. From next two features of this system, it seems to be advantageous from the

¹ Japan Nuclear Cycle Development Institute, Ibaraki, Japan. Email: morisita@oec.jnc.go.jp

² Japan Nuclear Cycle Development Institute, Ibaraki, Japan. Email: kita@oec.jnc.go.jp

³ The Japan Atomic Power Company, Tokyo, Japan. Email: moro.satoshi@oec.jnc.jp

⁴ Advanced Reactor Technology Co. Ltd, Tokyo, Japan. Email: kamishima@artech.co.jp

⁵ Obayashi Corporation, Tokyo, Japan. Email: t-somaki@o-net.obayashi.co.jp

three-dimensional base isolation system. Excessive rocking responses do not take place in native, because the offset between the center of gravity and the isolation support position of the support structure can be made small. Each isolation system becomes simple by separating the isolation direction. On the other hand, the component layout has to be changed a little with the common deck installation.

The outline of the vertical seismic isolation system for component and a series of model tests with actual size coned disk spring and damper are shown in this paper.

SYSTEM OUTLINE

Coned disk spring

It is necessary to select spring element for the vertical seismic isolation device considering installing near the primary cooling system. The followings are considered as functional requirements for the device.

1) The heavy weight of the installation structure should be supported, and simultaneously, a longer period in vertical direction should be attained.

2) It has high rigidity for degrees of freedom except for vertical direction.

3) Throughout the plant life, the function should be maintained.

4) And, assumed failure modes are not catastrophic.

A coned disk spring with metallic material was chosen as vertical isolation device, because it satisfies these requirements. The disk spring can be stacked in various configurations. By stacking the coned disk spring of the same shape in parallel, it is possible to increase support load per one element. By stacking this set more and more in several series, large stroke can be achieved. The structure of the isolation system is composed of some isolation devices under the common deck, while the allocation of rigidity and weight is considered. The coned disk spring for seismic isolator has following features.

1) The restoring force characteristics of the coned disk spring show nonlinearity.

2) The effect of the ground end cannot be disregarded.

3) The effect of the friction becomes remarkable, because large number of coned disk springs is stacked.

Considering above features, a single coned disk is designed using the equation by Curti-Orland [2]. And, the equation of Niepage [3] which can appropriately consider the effect of the friction is also used in the design of the isolation device.

"The three-dimensional isolation development project" set the maximum input earthquake motion, named "Case Study S2 wave", for the isolation device development, and evaluated the required performance for the isolation device which could be applied to the FBR plant [4]. In this examination, the required performance has been evaluated from the viewpoint of prevention of uplift of fuel assembly, prevention of reactivity change, prevention of the buckling of reactor vessel, and control of relative displacement. As a result of the examination, the development target of the vertical isolation frequency is around 1.0Hz, and damping ratio shall have 20 to 40%.

In order to examine applicability of the vertical isolation element with the target characteristics to a fast reactor plant, a design of the isolation element was attempted under following conditions: isolation frequency of 1.0Hz, design stroke of ± 100 mm (both sides effective stroke becomes 300mm including margin), supported structure weight of 2.7MN.

As material of the coned disk, ordinary high tensile spring steels, Japanese Industrial Standard (JIS) SUP10, which is almost the same as SAE 6150 in USA, can be used. This material is generally used as spring material and is easy to be obtained. As shown in Fig.1, outside diameter of the coned disk was set to be 1m and thickness was set to be 27mm, considering current productivity from the viewpoint of machining and heat treatment.



Fig.1 Coned disk spring



Fig.2 Isolation device

A design example of the structure of the isolation device is shown in Fig.2. By stacking 5 disks in parallel and 14 sets in series, the isolation device is made up 70 disks in total. The loaded height of a stack becomes about 2.5m.

The middle washers are inserted between coned disk springs of the series stack to transmit the vertical force. The center guide is installed in the stack in order to prevent excessive side slip. The restoring force characteristics of the device are shown in Fig.3.



Fig.3 Force-displacement relation of isolation device

Design example of damper

It is necessary to install the damper used by combining with the coned disk spring, because sufficient damping force is not obtained only in the frictional force. The requirements of the damper suitable for the vertical component isolation system are that it is small and simple, while the stability is good. A steel beam damper with the hysteretic behavior has satisfied these requirements. In order to increase the low cycle fatigue strength, a tapering beam damper (Fig.4) was designed. The force-displacement relation of the damper is shown in Fig.5, which was evaluated by inelastic analysis. It is possible to produce the necessary damping force, when the device was combined with 3 dampers per one unit.



Fig.4 Damper



Fig.5 Force-displacement relation of damper

Response analysis

In order to confirm the effect of the isolation device with dampers, the seismic response analysis was carried out. At first, the response analysis for the FBR building (Fig.6) was carried out and response acceleration at the isolation device installation level was obtained. Next, the seismic response of the common deck was calculated by using a single-degree-of-freedom model, considering the nonlinear force-displacement relation of the coned disk spring and the damper. Fig.7 shows results of the analysis. Since it together satisfies 100mm tolerance of the response displacement and 1G tolerance around 10Hz in the floor response spectrum, it can be judged that this system has the appropriate isolation effect.



Fig.6 Analysis model



Fig.7 Results of response analysis

Plant layout

The applicability of the common deck isolation system to a 750MWe sodium cooled loop type FBR plant [5] was examined. In this plant, the common deck supports reactor vessel and two integrated components which combined the intermediate heat exchanger with the pump. The common deck becomes a rectangle of 32m×12m size. The thickness of the deck is made to be about 2m in order to ensure the necessary rigidity. Total installation weight is about 57MN, and it is supported by 20 isolation devices. Considering weight distribution and rigidity allocation, the isolation device was mainly placed at circumference of reactor vessel and peripheral part of the deck (Fig.8). The layout planning example is shown in Fig.9. For the common deck, it is necessary to establish support structure such as cantilever column and key for the horizontal seismic load and thermal expansion load.



Fig.8 Plant layout - plan



Fig.9 Plant layout – elevation

In case of this layout planning, it is necessary to reinforce ceiling slabs of a reactor vessel upper room, because vertical walls on the common deck is not installed. From the viewpoint of the protection of radiation, additional shields are installed in the circumference of primary piping and equipments on the common deck. By controlling the relative displacement at 100mm or less, the secondary system piping can be designed as well as the non-isolation plant. From them, the common deck system judges that it can be applied to the FBR plant.

TEST

Static test of coned disk spring

The static test was carried out in order to confirm the applicability of design equation, while the productivity of coned disk spring of the full scale size is confirmed.

Specimen

Ten coned disk springs were produced as test specimen. As shown in Fig.1, the dimensions of the specimen are 1,000mm in outside diameter, 500mm in inside diameter, 27mm in thickness and 59mm in overall height. Though the free stroke (ho) of a spring is 34mm, the effective stroke is to be 25.5mm based on the limit of 0.75ho [5].

When full scale coned disk spring is mass-produced, 35mm roll material is cut by plasma, and it is processed by the hot forming in the shape of coned disk spring. After the heat treatment, the coned disk springs were finished by means of final machining to 27mm in thickness, presetting, shot peening and coating. As number of the test specimen produced in this study was only 10, the forming as a coned disk spring of the 35mm thickness was processed by the machine cutting, after 400mm material was forged into 100mm plate. The hardness values of the specimen were HRC 43 to 52 by Rockwell hardness. The yielding strength was over 1,200 N/mm2 of the design strength. The overall height reduced from 59mm to 58mm after the presetting.

Static tests

A series of test for investigating restoring force characteristics and friction coefficient of the coned disk spring was carried out. The combination of 10 sheets of test specimen, namely parallel stack and serial stack number of sheet, was made to be a test parameter. Photo.1 shows the specimen. The cyclic loading tests with a parameter of the deflection amplitudes were carried out, which were the design stroke of ± 14.3 mm for the S2 earthquake and 1.5 times of the design amplitude. Photo.2 shows the typical test and measurement. The vertical load was detected by the sum total of 8 load cells on the top of the specimens, and the deflection was made to be a mean value of 4 transducers.



Photo 1 Test specimen

Photo 2 Typical test and measurement

Test results

By the static test of full scale coned disk spring, a following knowledge was obtained. The restoring force characteristics of coned disk spring shows the softening property. At either load, stabilized loop was

described. The characteristic curve of each test specimen was almost same. In case of the parallel pile, the hysteretic loop became remarkable. Fig.10 shows the restoring force characteristics of the stack of 5 in parallel and 2disks in series. The hysteretic loop gradually swelled, as number of cycles of the load increased. After 33 cyclic loadings of the design stroke, the loop was stable.



Fig.10 Restoring force characteristics of isolation device Stack of 5 in parallel * 2 in series

Use limit of the coned disk spring is 0.75ho. In case of this test, when the deflection exceeded 0.8ho, hardening of the characteristic curve began. The characteristic curve of test specimen which experienced hardening had been stabilized, and it was almost equal to the characteristic curve before hardening (Fig.11).



Fig.11 Effect of hardening

Applicability of design equation

The friction coefficient between coned disk spring and washer was estimated to be about 0.1 from the test result of single disk spring. Next, the friction coefficient between coned disk springs was estimated to be about 0.1 from the test result of the stack of 5 disk springs in parallel.

Using this friction coefficient, the applicability of design equation was examined. Fig.12 compares the load-deflection relationship between test results and the design. Applicability of the design equation for large coned disk spring and validity of the friction coefficient for design equation can be confirmed, because the design equation simulates test result approximately. The comparison of the strain between test results and the design is shown in Fig.13. Stress calculation formula can be also applied to the large coned disk spring.



Fig.12 Comparison of force-displacement relation between test and design Stack of 5 in parallel * 2 in series



Fig.13 Comparison of strain between test and design Stack of 5 in parallel * 2 in series

Test of damper

The test was carried out in order to grasp characteristics and performance of the damper of the full scale size (Fig.3)._The test specimen was manufactured using the rolled steel material for general steel structure in full scale. This damper was designed in order to obtain 150kN damping force.

In order to investigate the stability of dynamic characteristics and fatigue strength of the damper, the cyclic loading tests by constant displacement of the design stroke and the seismic tests by the estimated response wave were carried out. Furthermore, for investigating the deformability of the damper system including the spherical bearings, the cyclic loading tests by 1.5 times displacement of the design stroke were carried out using 2 specimens (Photo 3).



Photo 3 Damper test

Test results

The restoring force characteristics of the damper is shown in Fig.14 It was confirmed that the damping force of the damper was about 150kN of designed value. The damping force gradually decreased as the cyclic load number increased, but the characteristic curve has been stabilized. This damper was ruptured by the fatigue at 33 cycles for the cyclic loading of the design stroke and at 7th dynamic input for the S2 earthquake. For the cyclic loading of 1.5 times the amplitude of the design displacement, the stable damping performance and deformability of the damper system were confirmed.



Fig.14 Force-displacement relation of single damper

CONCLUSION

The structural concept of vertical component seismic isolation system applied to the FBR plant was constructed. Full scale coned disk spring and damper performance test were carried out, and the validity of the design technique was confirmed. As the result, the prospect that the common deck vertical isolation system could technically realize was obtained. In the near future, a series of verification tests with the corned disk springs, the damper and the horizontal load support system would be carried out to establish this technology.

ACKNOWLEDGMENTS

This study was made as a part of the Ministry of Economy, Trade and Industry of the Japanese sponsored R&D project on three-dimensional seismic isolation.

REFERENCES

- 1. Kitamura S. and Morishita M., "Design method of vertical component isolation system", PVP-Vol. 445-2, pp.55-60, 2002
- Curti G. and Orland M., "Ein neues Berechnungsverfahren fur Tellerfedern", DRAHT 30-1, pp.17-22, 1979
- 3. Niepage P., "Uber den Einfluß der Reidung und kreiskegelformiger Last einleitungselement auf die Kennlinie von Einzeltellerfedrn und Tellerfederpaketen", Konstruktion, pp.379-384, 1984
- 4. Kato A. et al, "A large scale ongoing R&D project on three-dimensional seismic isolation for FBR in Japan", PVP-Vol. 445-2, pp.1-10, 2002
- 5. SAE HS 1582, "Manual on design and manufacture of coned disk springs (belleville springs) and spring washers", 1988