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Experimental Study on Coned Disk Springs for Vertical Seismic Isolation System

Seiji Kitamura[1)], Tetsundo Nakatogawa[2)], Akinori Miyamoto[2)], Takahiro Somaki[2)]
1) Japan Nuclear Cycle Development Institute, Ibaraki Prefecture, Japan
2) Obayashi Corporation, Tokyo, Japan

ABSTRACT

We have developed the large sized coned disk springs for the vertical seismic isolation system with the common deck supporting the important main equipment in FBR plants, assuming that the horizontal base isolation system for the entire building would be provided. The outer diameter of disk spring in actual size is 1000mm. We have established the fabricability of such a large-sized coned disk spring, and have grasped the vertical / horizontal load-deflection relationship and the design constant such as the coefficient of friction due to experimental tests by the actual size. So the applicability of the large coned disk springs for the vertical isolation system and the design method were confirmed.

KEY WORDS: vertical isolation system for important main equipment in FBR plants, coned disk spring, fabricability of actual size, experimental tests by actual size, load-deflection relationship, hysteresis loop, friction coefficient, applicability of large sized coned disk springs for vertical isolation system and design method.

INTRODUCTION

Specifications of vertical isolation system by the common deck supporting the important main equipment are the followings.[1)]

1) Vertical isolation period equals to be one second.
2) Design stroke for S2 earthquake is ±100mm, and the maximum stroke is ±150mm.

At first, the size was decided to be 1000mm in outer diameter with considering the limit size of fabricability and the locationability of installing devices in the containment vessel. With condition of the above specifications, the combination of coned disk springs for the vertical isolation device is designed to be 5 in parallel and 14 in series, then one unit consists of 70 disk springs in total. The supporting load (design service load) per unit is 2.7MN. It is necessary to confirm the fabricability, since these coned disk springs are very huge and thick.

The experimental tests in actual size were carried out, as it is important to quantitatively evaluate the hysteresis behaviors of the coned disk. In the case of combined disk springs, the hysteresis breaks out in the load-deflection relationship due to the friction between disk springs and one between the disk spring and the washer. In this design, it is considered to be advisable to make choice of the way to effectively use the friction, since the friction is inevitable as long as the disk springs are stacked in parallel. In this connection, the effect of the friction rises up in the range of one third to a half of the required energy dissipation, according to the evaluation based on the past study[2)]. The friction coefficient should be quantitatively evaluated.

FABRICABILITY OF ACTUAL SIZED CONED DISK SPRING

1) DIMENSIONS OF SPECIMEN AND MATERIAL

As shown in Fig.1, the dimensions of coned disk springs designed are 1000mm in outer diameter, 500mm in inner diameter, 27mm in thickness and 59mm in overall height. Though the free stroke (h) of a spring is 33mm, the effective stroke is to be 24.75mm based on the limit of 0.75h. The total stroke of this device, which is calculated by multiplying that stroke of 24.75mm by 14 times (14 in series), covers the maximum stroke of 300mm (±150mm).

In this study, we conducted the trial fabrication of 2 coned disk springs with the actual size as specimens (see photograph 1).

The material of SUP10 is used for spring steels in Japan (JIS G 4801), being similar to SAE 6150 in USA or DIN 50CrV4 in Germany (see Table 1).

2) MANUFACTURING METHOD

The plates of 100mm in thickness by forging the ingot of 400mm in height were fabricated by the primary machining to be coned disk springs with 35mm in thickness, considering the heat strain at the heat treatment. This thickness is greater than 27mm, which is said to be the limit of the hardenability for SUP10, so it was needed to certify by the test piece with the same thickness, whether the quenching thermal condition would be proper, before the heat treatment of specimens' main body.

At first the Rockwell hardness tests in the thickness direction were measured after the heat treatment, and tensile tests for the inspection of mechanical property and the microstructure examinations were even done thoroughly. The hardness values measured in every 1mm pitch at 4 sections were satisfied, which were HRC 43 to 48 by Rockwell hardness. The yielding strength of 6 test pieces was over 1,200 N/mm^2 of the design strength, and it was recognized not to be abnormal at all in the microstructure.

After the heat treatment of main body under the same thermal condition as the test piece, the coned disk springs were finished by means of final machining to 27mm in thickness, presetting, shot peening and coating (Molybdenum Disulfide). The overall height reduced from 59mm to 58mm after the presetting. In this study, the test piece inspection was carried out to make sure also in the case of the heat treatment for main body. Table 2 shows the mechanical property after heat treatment obtained from the results of tensile test.

Herein, in the case of mass production of large-sized coned disk springs for the actual plant, disk plate from the rolled plate of 35mm in thickness will be cut off by plasma, and will be hot or warm press-formed to coned disk. After that, the product line might be the same way as the above-mentioned.

TESTS FOR INVESTIGATING LOAD-DEFLECTION RELATIONSHIP OF CONED DISK SPRINGS

Using these 2 coned disk springs (specimens), the experimental static tests would be carried out for investigating the load-deflection relationship, the friction coefficient between disk spring and the washer, and one between disk springs in parallel.

Photograph 2 shows the loading apparatus, and Table 3 shows its specification.

Fig. 2 and Fig. 3 show the vertical loading test cases and the loading pattern, respectively. The deflection of +/-100mm is corresponding to the design response deflection during the S2 earthquake, and one of +/-150mm is doing to 1.5 times margin as large as the design deflection. As for the test procedure, the loading satisfying the target deflection were forced to disk springs, where the loading frequency was 0.005Hz/cycle. Herein, neither the inner washer nor the middle one exist actually.

Fig. 4 shows the location of 2 way gauges for measuring the radial and the circumferential strains. As shown in Photograph 3, the load is measured by the total of 8 load cells on the upper loading plate, and the deflection is measured by the average of 4 transducers located diagonally. As for the measurement frequency, 400 steps per cycle were recorded.

After the vertical static tests, the horizontal static tests would be carried out. Fig. 5 and Fig. 6 show the horizontal loading test case and the loading pattern, respectively. As for the loading procedure, under the vertical loading of 556kN corresponding to the service loading of 2.7MN, the loading satisfying the horizontal displacement of +/-6mm was forced to disk spring by the horizontal actuator. The loading frequency was 0.01Hz/cycle, and the loading was repeatedly continued until the load-displacement relationships were stable. The load and the horizontal displacement were measured through the load cell and the transducer in the actuator, respectively. The measurement frequency was the same as the vertical tests.

TEST RESULTS

Fig. 7 shows the relationship curves of load and deflection in the vertical direction. By comparison between cases V1 and V2, the both load-deflection relationships are almost the same, so the variation of those characteristics is negligible. And by comparison between cases V3 and V3', it is recognized that the middle washer has some influence on the load-deflection relationship. Comparing among these relationships, the case of V4 has the greatest energy dissipation, so it is considered that the influence of parallel stacking is great.

Fig. 8 shows the comparison by normalized relationships. In the case of V4 the loading force data were divided by the number of parallel stacking, and in the case of V3 the deflection data were done by the number of series stacking. Comparing among normalized relationships, the energy dissipation for V1 is greater than one for V3, but is less than one for V4. Then it is recognized that the friction between disk springs and the number of contacting with washer and spring have influence on the energy dissipation.

The damage by interface friction between disk springs after cyclic vertical loading tests is shown in Photograph 4. The scratch was recognized, but the coating did not peel off at all.

Fig. 9 shows the relationship of the horizontal friction coefficient and the horizontal displacement. The horizontal friction coefficient between the washer and the dish spring was estimated with the horizontal load normalized by the vertical service loading of 556kN. The friction coefficient at the 1^{st} cycle is about 0.10. Though the friction coefficient tends to increase as the cycle number becomes greater, it is almost constant to be about 0.15 after the 5^{th} cycle.

QUANTATIVELY EVALUATION OF LOAD-DEFLECTION RELATIONSHIP

The applicability of design equations was studied by substituting the constant based on the test results in the proposal design equations. The basic load-deflection relationship and the stresses for a single coned disk springs are evaluated using the proposal equations by Curti-Orlando[3). The effect of combination stacking or friction both at disks' interface and at washer is evaluated by the Niepage's equation[4). Herein, the Young Modulus E was based on he tensile test results by test pieces (see Table 2), and the Poisson ratio was assumed to be 0.3.

At first, the friction coefficient of μR between the washer and disk spring was estimated to be about 0.1 from the test results of cases with a disk in parallel-V1, V2, V3 and V3'. And with the evaluated μR, the interface friction coefficient of μM between disk springs was estimated to be about 0.1 by counting backward to fit the load-deflection relationship of the case V4. It is recognized that these friction coefficients agree with the horizontal friction one at the 1^{st} cycle, as shown in Fig. 9.

Fig. 10 shows the comparison of load-deflection relationship between the test results and the design equations (the broken line). Herein, the reduction of the moment arm by the ground edge is considered. The design equation (design method) could approximately simulate the test results. Fig. 11 shows the comparison of circumferential /radius strains between test results and the design. The strains by the design equation can simulate the test results as well. However the stresses are not directly compared, it is considered that the design equation would be also applicable to the stress evaluation as long as judging from the agreement of strains.

Accordingly, it is certified that these design equations would be sufficiently applicable to the actual plant.

However, as the loading for the 5 disks in parallel to be a minimum unit in an actual device could be much greater, it is desirable to confirm by tests under such a condition.

NOTICE IN DESIGN FOR ACTUAL PLANT

Some information obtained through the tests should be taken notice in the design for the actual plants, as follows.

1) The height of coned disk springs became lower from 33mm to 32mm by presetting at fabrication. This means the stroke loss of the vertical isolation device. Beyond this, the stroke loss by creep during the service is considered. These stroke losses should be considered in the actual design, and the creep is necessary to be evaluated quantitatively.
2) In this study, the Young Modulus (193GPa) was not agreed with the design value (206GPa). It was also identified that it has great influence on the actual load-deflection relationship. In the case that the Young Modulus would not be satisfied with the design value, the design might be obliged to change. So it should be checked before using in the actual plant.

CONCLUSION

We fabricated the 2 large coned disk springs in the actual size, of which the outer diameter and thickness are respectively 1000mm and 27mm, and carried out the experimental tests

The vertical load-deflection relationships of the coned disk springs were very stable even if the cyclic number increased. The friction coefficients obtained quantitatively as the design constant are 0.1 for μR between disk and washer and 0.1 for μM between disks in the vertical direction.

Considering that the heat treatment and the microstructure have much influence on the Young Modulus, it should be checked before using in the actual plant, because it has much influence on the vertical load-deflection relationship.

As mentioned above, we confirmed the fabricability, the applicability of the coned disk springs for the vertical isolation system and the design method. Furthermore we are planning to carry out the experimental tests with 5 disk stacks in parallel and 2 in series for the design of actual plant.

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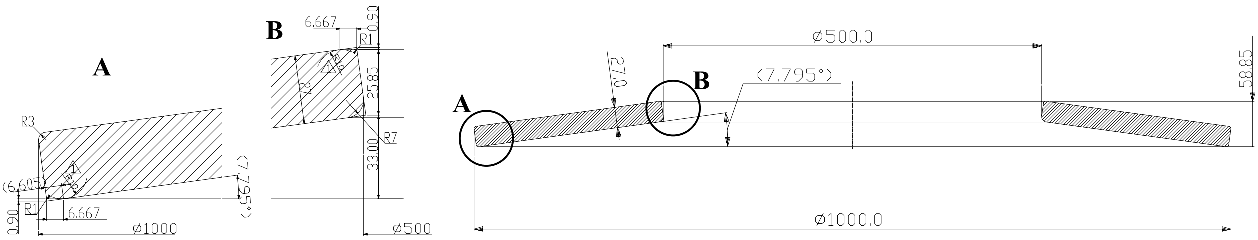


Figure 1. Dimensions of coned disk spring designed.

Photograph 1 Actual-Sized Coned Disk Springs (1000ϕ) before Presetting Process.

Table 1 Chemical Component for SUP 10

Component	C	Si	Mn	P	S	Cr	V
JIS G4801	0.47/0.55	0.15/0.35	0.65/0.95	≤0.035	≤0.035	0.80/1.10	0.15/0.25
Inspection	0.49	0.21	0.75	0.009	0.001	0.92	0.17

Table 2 Mechanical Property after Heat Treatment.

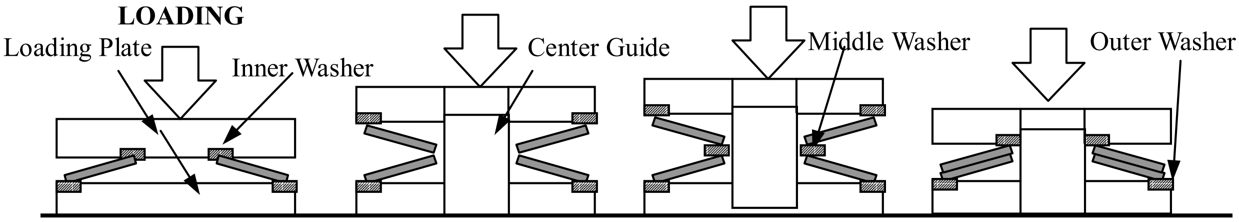
Fiber Direction	Number	Young Modulus E •$\times 10^5$ N/mm^2•	Yielding Strength* •y •N/mm^2•	Tensile Strength •u •N/mm^2•	Strain at Rupture •u •%•	Reduction of Area •%•
Transverse	1	1.933	1496	1687	7	29
	2	1.896	1483	1677	7	18
	3	1.909	1474	1665	7	24
	Average	1.913	1484	1676	7	23
Longitude •Reference•	1	1.931	1527	1710	6	21
	2	1.919	1504	1695	8	30
	3	1.896	1513	1706	8	30
	Average	1.915	1515	1704	7	27

•Note•*: Yielding strength is the strength at strain of 0.2% off-set.

Photograph 2　Bi-Axial Testing Machine

Table 3　Specification of Testing Machine

Item	Performance
Vertical Loading Capacity	Compression : 24MN (2400 tonf) Tension : 2.4MN (240 tonf) Stroke : 600mm
Horizontal Loading Capacity	Push: 13MN (1300 tonf) Pull: 10MN (1000 tonf) Stroke : ±650mm
Test Yard	Plane: 2000mm × 2200mm Height: 200 ～ 500mm



(a) Case V1,V2　(b) Case V3　(c) Case V3'　(d) Case 4V

Figure 2.　Test Cases for Vertical Loadings.

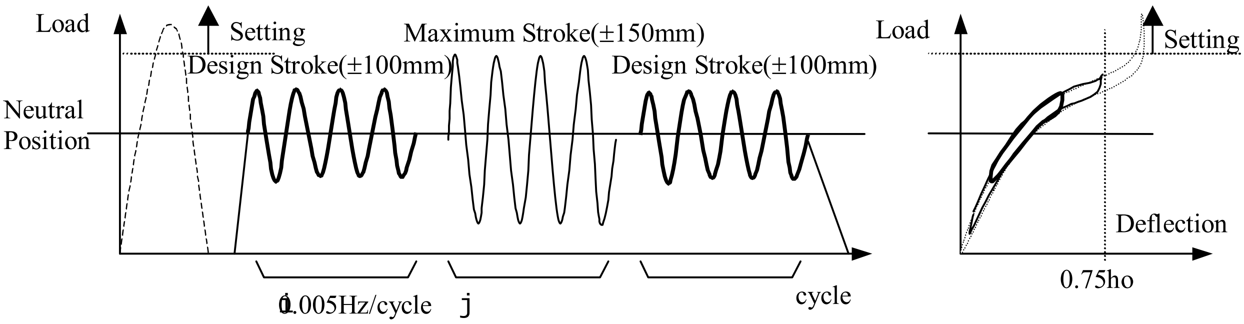


Figure 3.　Loading Pattern for Vertical Tests.

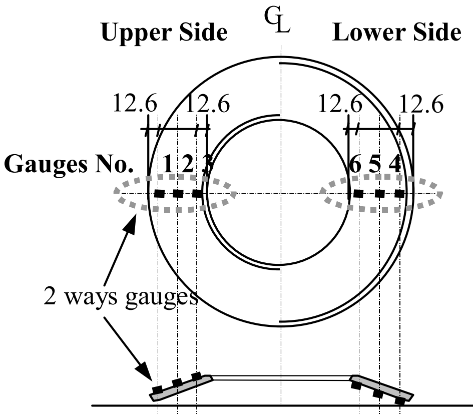
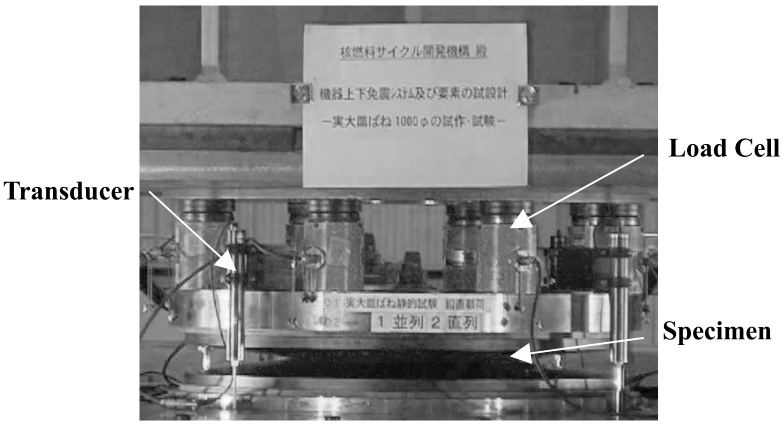


Figure 4.　Location of Strain Gauges.



Photograph 3.　Measurement (Case V3)

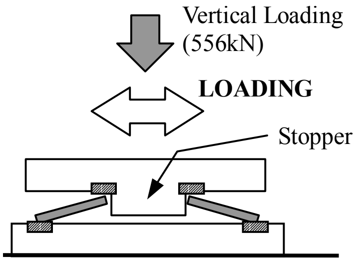


Figure 5. Test Case for Horizontal Loading.

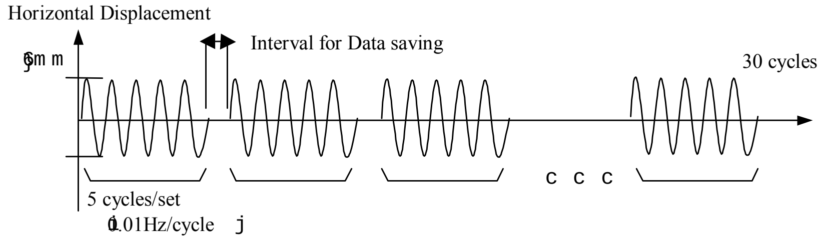


Figure 6. Loading Pattern for Horizontal Tests.

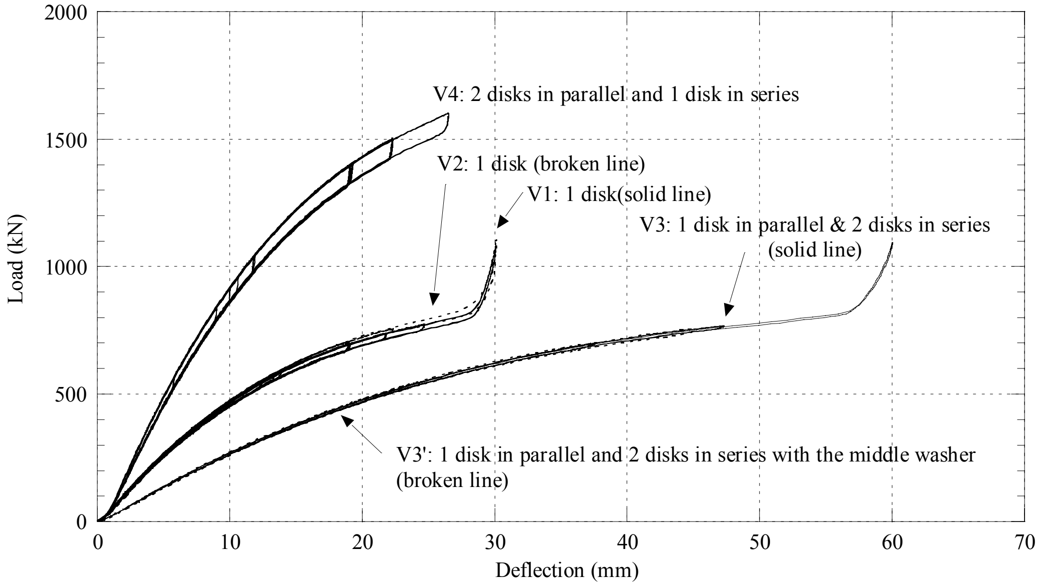


Figure 7. Relationship curves of Load and Deflection in Vertical Direction.

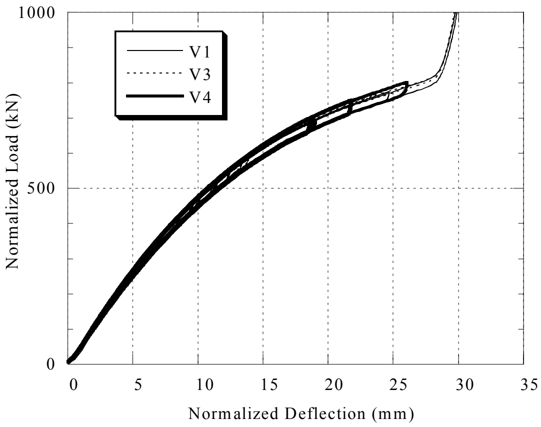
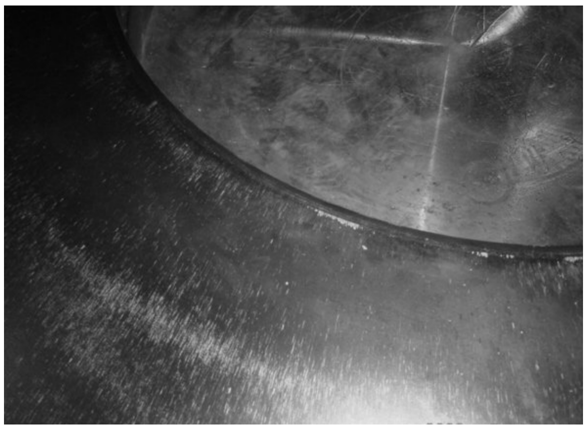


Figure 8. Comparison by Normalized Hysteresis.



Photograph 4 Scratch at Interface between Disks

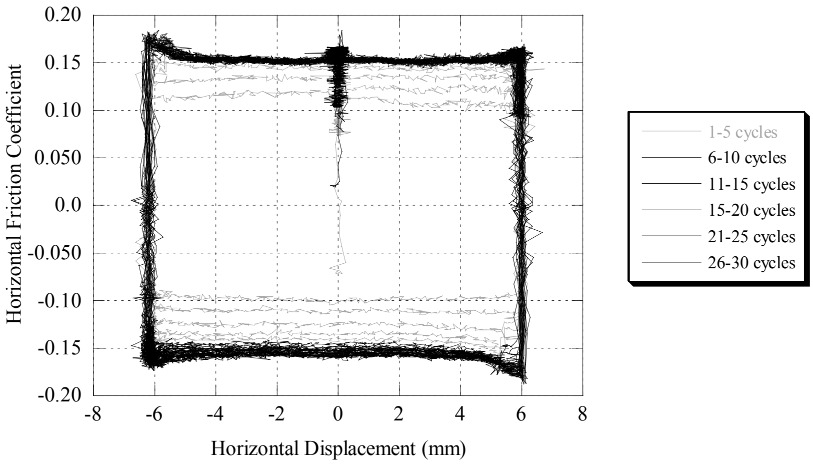


Figure 9. Relationship of Horizontal Friction Coefficient and Displacement.

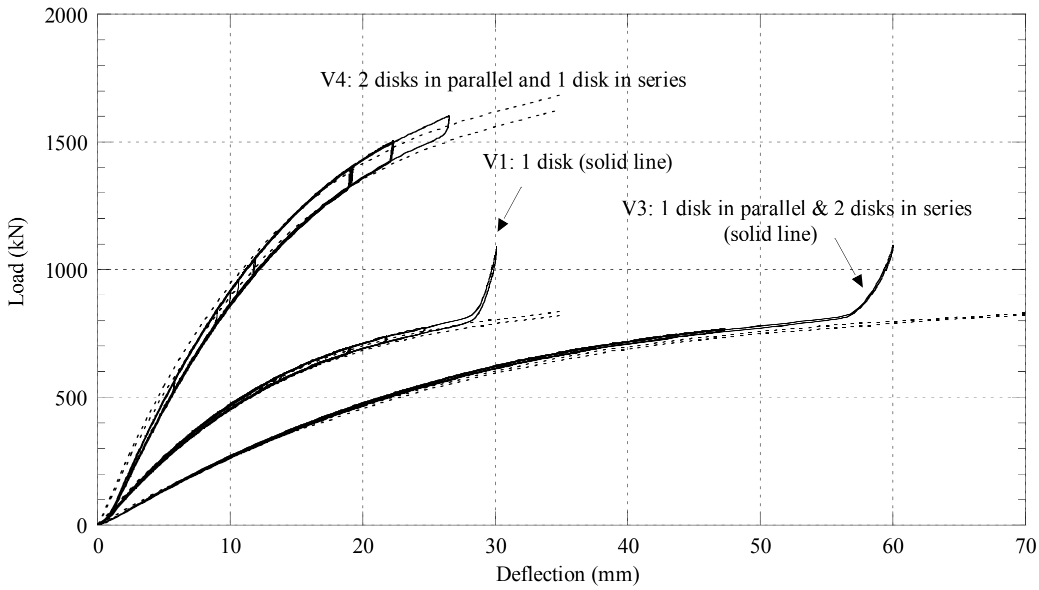


Figure 10. Comparison of Load-Deflection Relationship between Test Results and Design Equation.

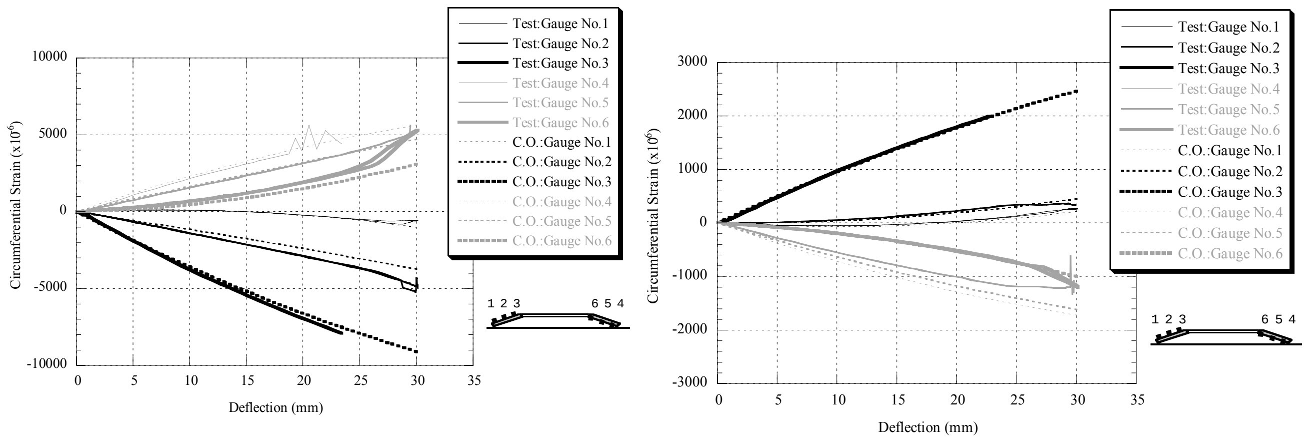


Figure 11. Comparison of Strains between Test Results and Design Equation.