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Project "E-Defence" Technical Development of Mechanical Components

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ABSTRACT: To realize "E-Defence (3-D Full-Scale Earthquake Testing Facility)", we were faced to some technical developments of the hardware, such as the hydraulic actuators, the three- dimension link and so on.

Since the required specifications of the hydraulic actuators were the rated power of 450ton, the maximum speed of 2m/sec. and the stroke of +/-1m, the physical scale became very large. Therefore, the hydraulic actuators could not be designed by the traditional ways, because of the bending effect of the piston rod due to its own weight and the lateral load and the large required bearing capacity due to the large dynamic lateral load. In addition, to minimize the frictions between the piston rod and the bearings became significant. To solve these problems, a new bearing system and sealing system were developed.

And, the new bearing system of the three-dimension link was also developed to realize the wide rotation and the large capacity.

The eight prototype actuators and three-dimension links were manufactured, assembled and installed in the test facility to verify the newly designed systems. The verification tests were started in 1995 and successfully completed at the end of 1998.

Now, these prototype actuators and three-dimension links are placing in position at Project "E-Defence", which is completed at January 2005.

1 INTRODUCTION

Earthquake testing facilities are experimental equipment that simulate the earthquake motions of a testing objects, and have been utilized for structure analysis and engineering since they give the valuable experimental data of the structure behaviours caused by the earthquakes. However, conventional earthquake testing facilities have been difficult to use in experiments studying the collapse processes of full-scale testing objects caused by the test wave of strong earthquakes because of limitation on their sizes, loading weights, exciting forces, and exciting directions.

National Research Institute for Earth Science and Disaster Prevention (NIED) was planed to construct a three-dimension full-scale earthquake testing facility (E-Defence) to solve the questions how structures collapse base on the experiment of damage caused by a huge earthquake attacked Hanshin-Awaji district on January 17, 1995. In order to satisfy the specifications for E-Defence, the new technology and design were applied for the hydraulic actuators and the three-dimension links. And the prototypes of them were manufactured, assembled and installed in the test facility to verify the manufacturing processes and the newly designed systems.

Figure 1 shows the outline of the shaking system of E-Defence. It is consisted of five sets of hydraulic actuators for horizontal X and Y directions each and fourteen sets for vertical Z direction, those are connected the three-dimension links each to translate the three-dimensional earthquake motions, which are actuated at the hydraulic actuators to the shaking table (20 m by 15 m), on which a testing object up to 1,200 ton can be loaded.

Figure 2 shows the photograph of the test facility that is consisted of two full-size prototype hydraulic actuators for horizontal X and Y directions each, four for vertical Z direction, eight full-scale three-dimension links and a shaking table (6m by 6m), on which a testing object up to 400 ton can be loaded. Table 1 shows the comparisons of the specifications for the shaking system of E-Defence and the test facility.

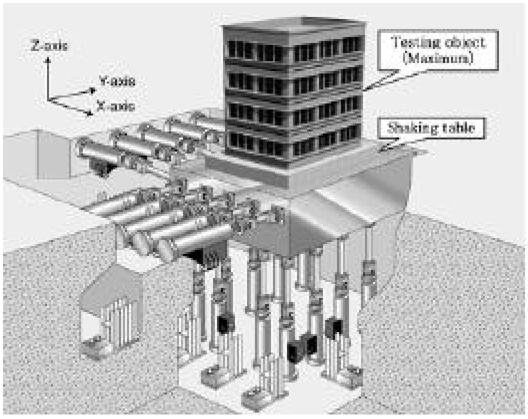

Figure 1. Outline of the Shaking system for E-Defence


Figure 2. Photograph of the test facility

Table 1. Comparison of specification

			E-Defece	Verification facility
Max. loading Capacity (ton)			1,200	400
Shaking Table size (m)			20 by 15	6 by 6
Actuators	X-axis	Accelaration (G)	0.9	0.4
		Number (unit)	5	2
	Y-axis	Accelaration (G)	0.9	0.4
		Number (unit)	5	2
	Z-axis	Accelaration (G)	1.5	0.4
		Number (unit)	14	4
Max. Speed (m/s)			2	2
Stroke (m)			+/- 1	+/- 1

2 NEWLY DEVELOPED COMPONENTS FOR HYDRAULIC ACTUATOR

There were four important design points of the hydraulic actuator for E-Defence. The First was to prevent the seizure caused by the bending effect due to its own weight and the large lateral load to the piston ring. The seizure results from the uneven contact and metal contact, which are caused by the inclination of the deformation of piston rod and from the lack of the lubrication by the high-speed reciprocating of piston rod under the high Hertz stress due to the large lateral load. The second was to satisfy the required capacities of the bearing system. The third was to prevent the seizure at the sealing system between the piston rod and the cylinder. The last one is to minimize the friction load occurred between a piston rod and the bearing system, and seals for the reappearance of earthquake wave.

And, to confirm the allowable errors when it was machined, manufactured and assembled is the another important point. Figure 3 shows the newly developed components for the hydraulic actuator.

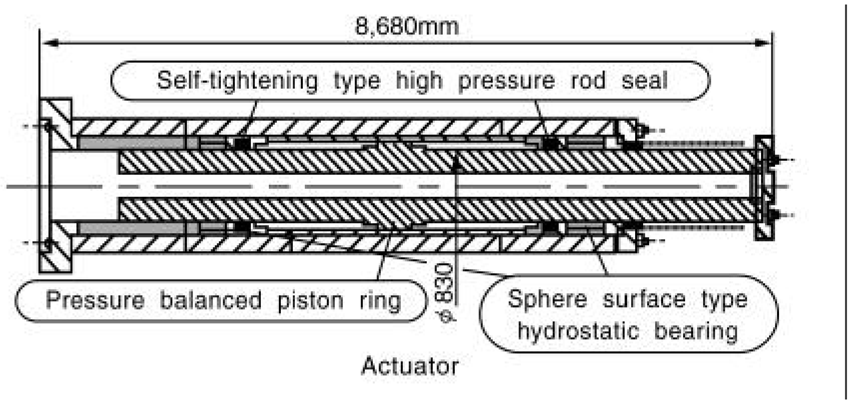

Figure 3. Newly developed components for the hydraulic actuator

2.1 **Sphere surface type hydrostatic bearing.**

Spherical surface type hydrostatic bearing shown at Figure 4 was developed with two special features. The one is having a sphere surface to allow the inclination of the piston rod. The other one is having the hydrostatic pressure pockets on the surface of bearing to supply high-pressure oil to satisfy the required capacity and to prevent the seizure. These features also have the purpose to minimize the friction.

The sphere surface type bearing has been applied for supporting the axis of the rotating crankshaft of an engine generally. Therefore, the design of the main dimensions was followed by it linearly without the manufacturing errors. As the result, the inclination of the piston rod of $1 \times 10^{-3} rad.$ due to its own weight and the lateral load was able to be satisfied. The manufacturing errors were required to maintain the clearance of 0.3~0.5mm between the outer race and inner race of bearing and 0.6~0.8mm between the inner race and the piston rod when the hydrostatic method was applied. That is, in case of the piston rod, the manufacturing errors were to be 0.2mm against the diameter of 830mm. Therefore, the manufacturing process of the full-size bearing was confirmed before the start of manufacturing the prototype hydraulic actuators.

The hydrostatic method was applied to satisfy the required capacity of 2.8MN for the bearing system. Because it was impossible to design the bearing system base on the traditional method. According to the traditional method, the capacity of the bearing system is determined by the PV value, which was depended on the material characteristics of the bearing under a few micron oil films for lubrication. In case of the bearing system of the hydraulic actuators for E-Defence, P, that is Hertz-Stress due to the lateral load of 2.8MN, is very high, and V, that is sliding speed of 2m/sec. is also very high compared with them of the conventional hydraulic actuators.

As shown in Figure 4, the hydrostatic bearing system has some pockets to feed the high pressure of 18 MPa. The capacity of the hydrostatic bearing system is described by the following formula.

$$W = A_e (p_o - p_a) \tag{1}$$

where W = the capacity; A_e = the effective area of the bearing; $p_o - p_a$ = the pressure difference between the pressure at pockets and the pressure at clearance of the bearing system.

And the supply quantity of oil is described the following formula.

$$Q = \frac{K_B h^3 (p_o - p_a)}{h} \tag{2}$$

where Q = the supply quantity of the oil; K_B = the coefficient of the flow; h = the clearance of the bearing system; h = the coefficient of the oil viscosity.

Based on the above formulas, to satisfy the design capacity of 3MN, which was exceeded the required capacity, the number, the size and positions of the pockets were designed. Figure 5, the result of the investigation test using the full-sized prototype model bearings, shows that the capacity was followed with the predicted value based on the above equations. In addition, the piston rod that was floating in the oil film generated by the high-pressure oil was able to reciprocate with few frictions.

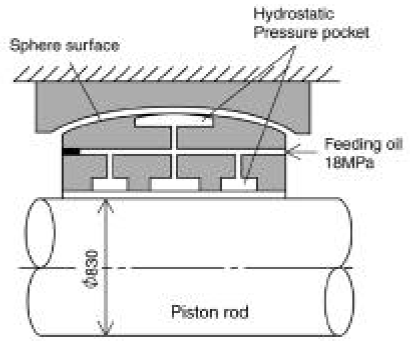

Figure 4. Sphere surface type hydrostatic bearing

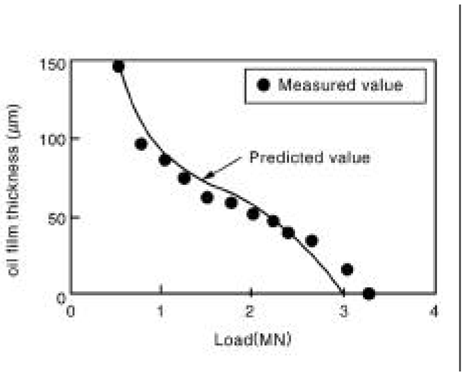

Figure 5. Result of unit investigation test

2.2 **Hydraulic pressure-balanced type piston ring**

A piston ring has a purpose to tight between two cabins for the reciprocating motion of a hydraulic actuator, which is obtained by the hydraulic pressure change in both cabins alternately. Generally a conventional type piston ring, which had a simple and uniform shape or labyrinth shape, was applied. The former one prevents the leakage from a cabin by pressing the outer face of the ring to the inner surface of the cylinder. The latter one is the non-contact type, allows the small leakage and seals through the pressure losses caused by the pressure difference between two cabins. The latter one is applied for preventing the seizure and minimizing the friction losses. However, in the case of the hydraulic actuators for E-Defence, the both conventional type piston rings could not be applied, because of the following problems.

The former one has the problem of a seizure and/or an increasing the frictions by the strong contact when the piston rod reciprocates with high speed of 2m/sec. The latter one has the problem of a big leakage, because the clearance between the outside diameter of a piston ring and the inside diameter of a cylinder becomes large due to the inclination of the piston rod and the accumulations of the machining errors of a cylinder inside.

The hydraulic pressure-balanced type piston ring was developed to solve the above problems. It has the steps at the sliding surface and the piston end surface of the piston ring to reduce the working force. To determine the most suitable dimensions, 6 models of 1/8 scale, which were analyzed about the deformation, the strength, the working force and the estimated leakage quantity by FEM beforehand, were manufactured and examined. Figure 6 shows the installations of the piston rings and the comparisons of working forces on the piston ring between the conventional piston ring and the developed one. And Figure 7 shows the leakage characteristics of the developed piston ring. Here the reason of the less leakage value, which measured at the full-scale prototype hydraulic actuator, compared with the predicted value is that the predicted value is calculated under the condition of the maximum accumulations of machining errors. And the conventional sealing method, which is shown by the broken line, means the labyrinth shape piston ring.

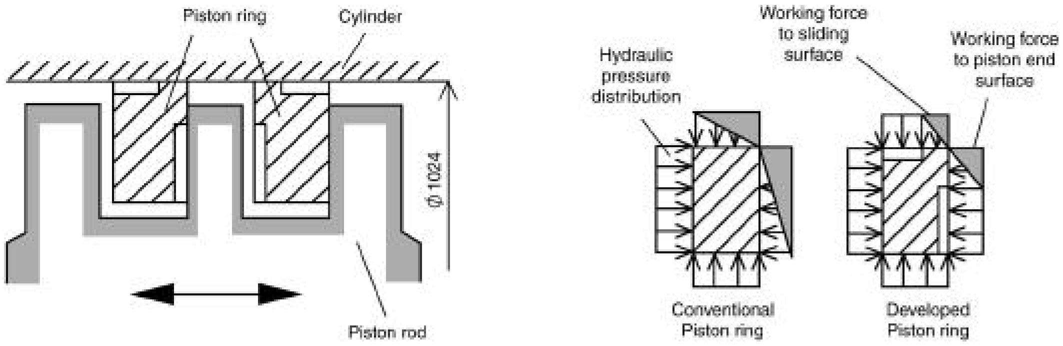

Figure 6. Pressure-balanced piston ring

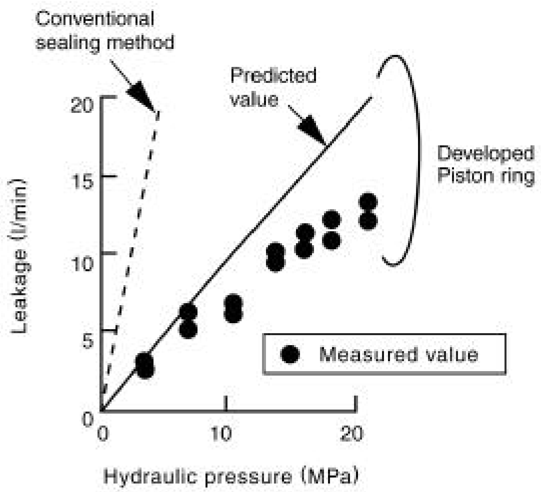

Figure 7. Leakage characteristics

2.3 Self-tightening type high-pressure rod seal

In order to prevent the leakage from the cabins of the cylinder to outside, the rod seals are installed at the both ends of the reciprocating range. The elastic and contact type seals, O-ring and V-ring are generally used for the rod seals. However, those type seals are not suitable for a hydraulic actuator working under high-speed condition, because they have the problems of the large frictions and the wear in short time. Therefore, the floating type metallic seal ring, which is made of the copper or brass, is applied instead of an elastic type seal. The conventional floating type metallic seal ring minimizes the leakage by the resistance when the oil passes through the minute clearance between the inner face of seal and the outer face of the piston rod. Therefore, it is very important to be clearance under the any conditions; otherwise the seizure occurs between the seal and the piston rod. In case of a floating seals for a small size actuator, since the shrinkage of the seal ring caused by the oil pressure difference between the outer face and inner face of ring is negligible small, it does not affect the clearance.

However, it became clear not to secure the clearance at the hydraulic pressure of 14Mpa, as the result of the FEM analysis when it was designed according to the design process of the conventional floating metallic seal, because of the physical size effect of the seal.

As shown at Figure 8, the new floating type metallic seal was designed to secure the clearance by the asymmetrical deformation, which was occurred by the existence of the steps at the inner surface and the side surface. The shape and the dimensions of the seal and steps were designed to keep the clearance of 50.m based on the results of the FEM analysis of the various cases. Figure 9 shows the comparison of the clearance at the transition of the hydraulic pressure between the conventional designed seal and the new type seal. And, Figure 10 shows the leakage characteristics of the new type floating metallic seal.

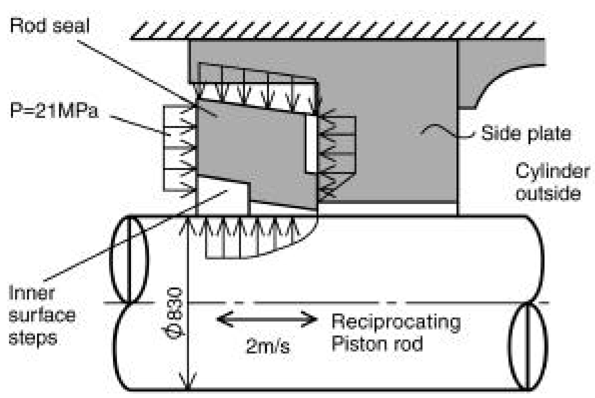

Figure 8. Cross section of the new floating type metallic seal

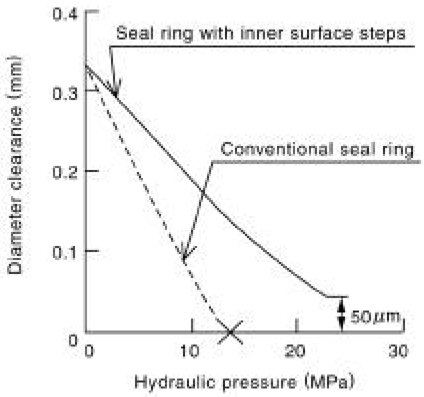

Figure 9. Comparison between
the hydraulic pressure and the clearance

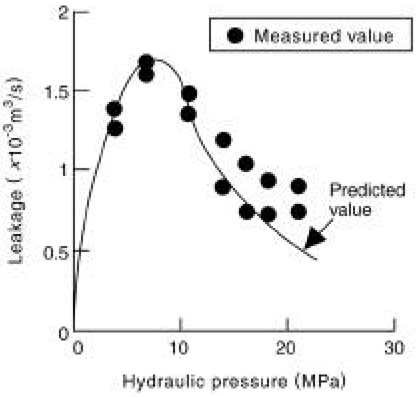

Figure 10. Leakage characteristics
of the new floating metallic type seal

3 THREE-DIMENSION LINK

The three-dimension link was newly developed and designed for E-Defence. It has the 570mm diameter spherical inner rings at both sides, which can freely rotate within ±12 degrees and the clearance adjustment function between the outer ring and inner ring of the bearings by the taper ring. And to satisfy the required design capacity of 3.5MN, the hydrostatic bearing method was applied. Figure 11 shows the outline of the newly developed three-dimension link. Figure 12 shows the detail cross section drawing of the sphere surface hydrostatic bearing with clearance-adjusting function.

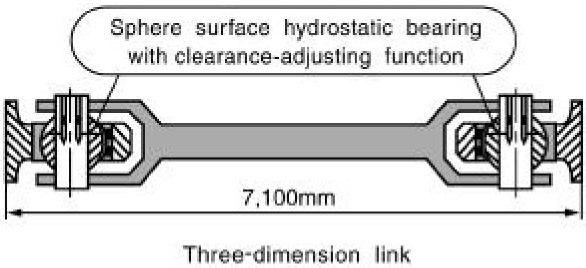

Figure 11. Outline of three-dimension link

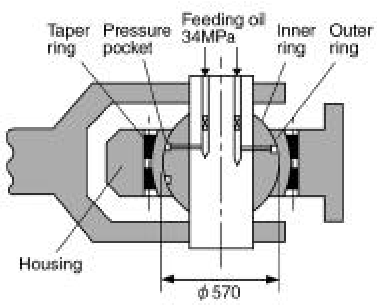

Figure 12. Detail cross section
of the bearing

The spherical inner ring of the bearing has the hydrostatic pressure pockets. The capacity of the bearing is determined by the hydraulic oil pressure, which is fed to the hydrostatic pockets. As the result of the basic studying, the oil pressure of 34Mpa has to be fed to satisfy the required design capacity of 3.5MN. Since the fed pressure is very high, the numbers, the locations and the dimensions of the pockets have to be considered about the uneven contact which is caused by the deformations of the bearing housing under the high pressure condition. Therefore, those specifications of the pockets were determined based on the deformation analysis by FEM, which was performed based on the following formulas.

$$d = \sum_{1}^{n} \left(\frac{P_n}{34} \right) d_n(q) \quad (3)$$

where d = the deformation value of the housing at the location of the pocket; P_n = the hydrostatic pressure of the pocket; $d_n(q)$ = the basic deformation value, which is analyzed under the condition of the individual hydrostatic pressure of one pocket; q = the angle at the location of the pocket.

The one of the important purpose of the three-dimension link is to transmit the displacement to the shaking table linearly besides the transmission of the load from the hydraulic actuator. The non-linear transmission, which results from the unsuitable clearance between the inner ring and the outer ring, obstructs the reappearance of the earthquake wave. Therefore, the clearance-adjustment function, which consists of the two taper rings between the housing and the outer ring at both sides, was applied. The clearance can be adjusted by tightening or loosening the taper rings to the most suitable condition of the earthquake wave reappearance.

As a result of the combination of the above-mentioned technologies, the loading capacity of 3.5MN that was confirmed by the full-scale unit test of the bearings could be achieved at the both compression and tension directions as shown in Figure 13.

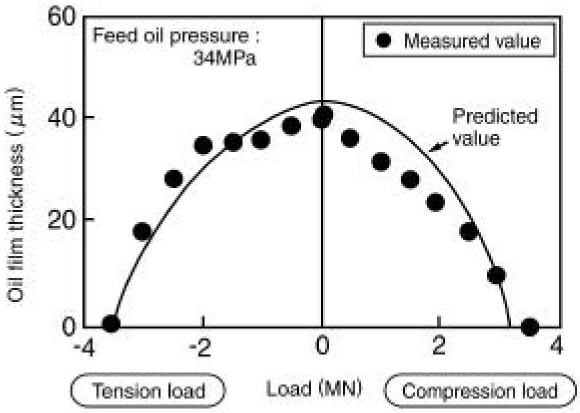

Figure 13. Loading capacity of the bearings

4 CONCLUSIONS

The important points at the designing and the manufacturing of the hydraulic actuator, three-dimension link and so on for E-Defence were that the specifications of the maximum speed and the stroke for the hydraulic actuator and the capacity for the three-dimension link, and the physical size due to their specifications could not be extrapolated base on the experiences of the designing and the manufacturing of them. Therefore, the verification of the manufacturing, the assembling, the installing processes and the mechanical performances under the exciting condition of their full-sizes were necessary in advance the practical use, to say nothing of the approach by the theoretical method and/or the computer-simulation.

The eight prototype actuators and three-dimension links, into which the newly developed components were integrated were manufactured, assembled and installed as the test facility to verify the performance, namely the maximum speed, maximum displacement and so on. The verification tests were started in 1995 and successfully completed at the end of 1998.

Figure 14 shows the result of maximum speed test. Here the reason why the wave-shape is not orderly sinusoidal wave is due to the capacity of the hydraulic equipment of the test facility.

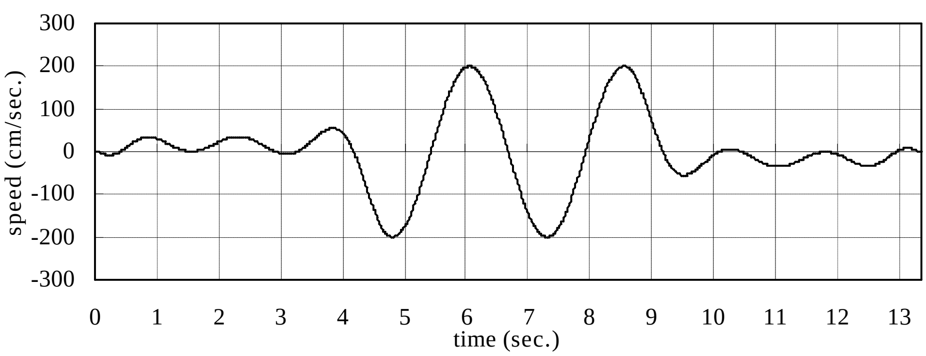

Figure 14. Test result of the maximum speed

Figure 15 shows the result of maximum displacement test.

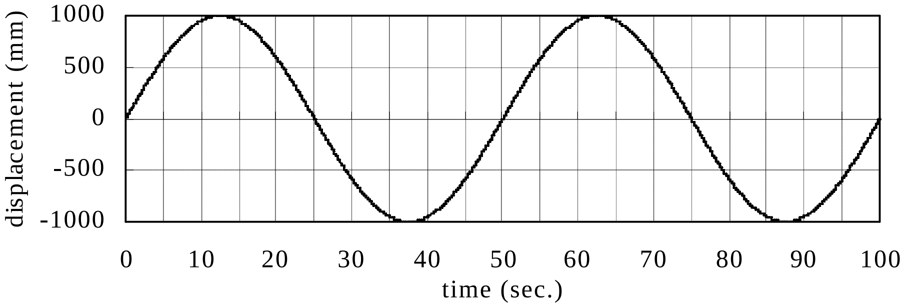

Figure 15. Test result of the maximum displacement

After completion of the all tests, all parts were disassembled to investigate the durability, the wear in the sliding parts, the effects due to the manufacturing and the machining errors and so on. Those were satisfied the mechanical requirements absolutely.

The hydraulic actuators have been transported at the appearance of the parts to the site of E-Defence, because the assembling weight of the horizontal hydraulic actuator was 116ton per each and the vertical one was 97ton per each, and re-assembled at site. Now they are being installing, and the final combination trial run with the control systems will start from April, 2004. E-Defence will be completed at January, 2005 of the 10th anniversary of Hanshin-Awaji earthquake.

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