HYBRID EARTHQUAKE LOADING TEST (PSEUDO-DYNAMIC TEST) OF BI-DIRECTIONAL BASE ISOLATION BEARING FOR A LARGE PEDESTRIAN BRIDGE

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SUMMARY

We adopted the high-damping rubber bearing (HDR) in the process of the construction of a large scale pedestrian bridge. This system serves for making the structure itself more flexible, greatly reducing the power of earthquakes, and consequently enhancing resistance against the shock. We conducted both the analysis and the test by the bi-directional loading and clarified the difference of the results from those of one-directional loading. We confirmed the safety of the bridge structure through the non-linear dynamic analysis, as well as the hybrid earthquake loading test (pseudo-dynamic test). The application of the seismic isolation bearing to a bridge which has such a full structure on it is first of kind in the world.

INTRODUCTION

Hyogo-ken Nanbu earthquake attacked Kobe city, Japan on January 17, 1995. Since then, the standard of the seismic design has changed greatly. To secure high resistance of structures to earthquakes, the deformation performance of structures corresponding to behavious of earthquakes has been improved. Among the revised standards of seismic design in Japan, this seismic isolation design system is attracting attention as the most effective method and has been adopted for many structures. Under this system, earthquake strength can be reduced and better seismic effects can also be obtained, because the cycle of vibration becomes longer and damping effects are also caused by bearings.

This time, in constructing a large-scale pedestrian bridge (Higashi-Shizuoka pedestrian bridge) spanning above the railway lines in the east part of the Shizuoka City, we adopted this seismic isolation design. In this case, the isolation design which can cope with earthquakes from all directions has been adopted, because it is difficult to exactly forecast from what direction an earthquake will come. In order to grasp the behaviors of base isolation bearing at earthquakes and restoration characteristics of the bearings, hybrid earthquake loading tests were conducted by loading from two different horizontal directions. Furthermore, non-linear dynamic analysis was also carried out assuming the bridge as a solid frame model.

This paper describes the results of the hybrid test concerning the dynamic complex behaviors of structures in the large deformation area at earthquakes. The emphasis of the description is placed on the results of the test of two types (one by loading from one direction, and the other by loading from two directions), as well as the analysis and comparison of the test. In this connection, the above-mentioned bridge with a roof over its entire section is an unprecedented case of this kind in the world to which the seismic isolation system has been applied.

Large-scale pedestrian bridge (Higashi-Shizuoka pedestrian bridge)

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In the eastern district of Shizuoka City, a development project for new city-function creation is in progress in the areas of 87ha including the former site of a freight railway yard and its surrounding zones. The Higashi-Shizuoka pedestrian bridge was established as the joint program the JR Higashi-Shizuoka station. They were opened on October 30, 1998 as the front entrance of the district. This bridge spans over Tokaido Shinkansen and JR conventional lines, has a length of 141.5m in extension, and plays the role to promoting flow of persons in the southern and the northern part of the city demarcated by the railway. Therefore, a roof has been installed on the bridge for ensuring pleasant space, and a universal design has been applied to the bridge to from a scenic view suitable for the landmark of a new city **(Photo.1)**. Furthermore, since this bridge is an important structure and is located Tokai-earthquake watching area, it has high performance of disaster prevention, such as the seismic function.

Photo.1 Higashi-Shizuoka pedestrian Bridge

Basic structure

To surely prevent the bridge from falling at the earthquake, a 4-span continuous steel box girder is used for this bridge (span: 35.5m+60.0m+16.0m+30.0m). Moreover, the both ends of the bridge girder have been widened in consideration of the stay of users. Base isolation bearing system (HDR: high-damping-rubber bearing) has been adopted, and the proper cycle of the total structural system has been made twice or more larger for seismic isolation. As the base isolation bearings, φ700mm (for piers P3□A1□A2) and φ830mm (for piers P1□P2) have been adopted, according to the difference of the reaction of the bridge girder **(Fig.1)**.

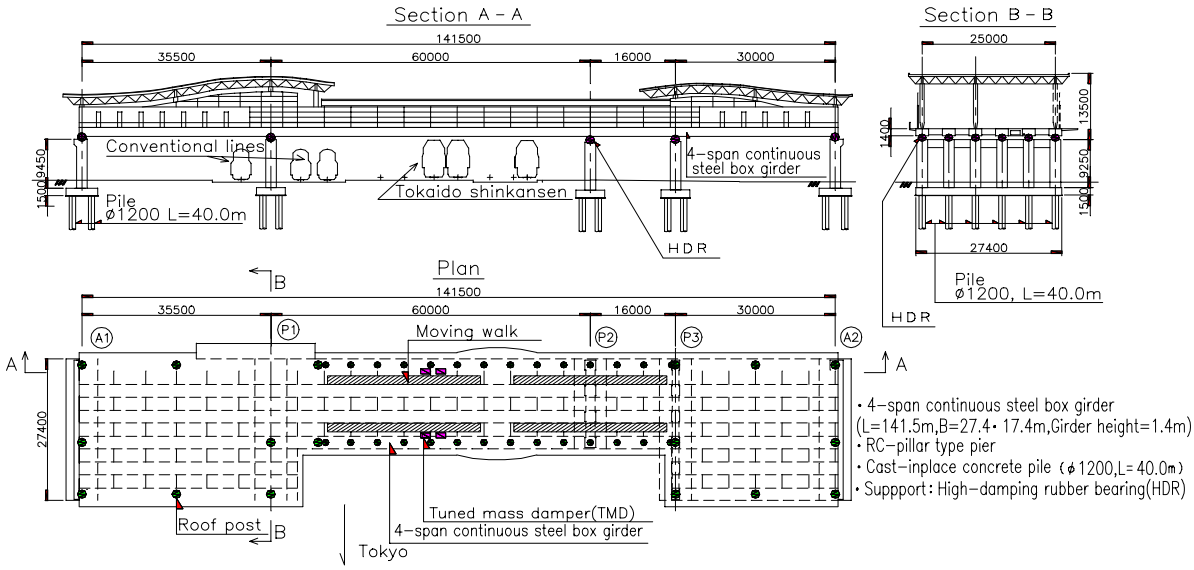

Fig.1 Higashi-Shizuoka pedestrian bridge design

Isolation system design

This bridge is an unprecedented case in the world in which seismic isolation design has been applied to a bridge with a roof covering its entire sections. Furthermore, the seismic isolation design which can cope with earthquakes from all directions has been applied **(Fig.2)**. At an earthquake, the isolation system design is effective to the dispersion of structural horizontal forces of the bridge girder and also lengthening the vibration

cycle. The seismic performance of the bridge against level 2 earthquake motions (very big earthquake) has been sufficiently ensured, and the reduction of sections of piers and roof pillars have also been realized.

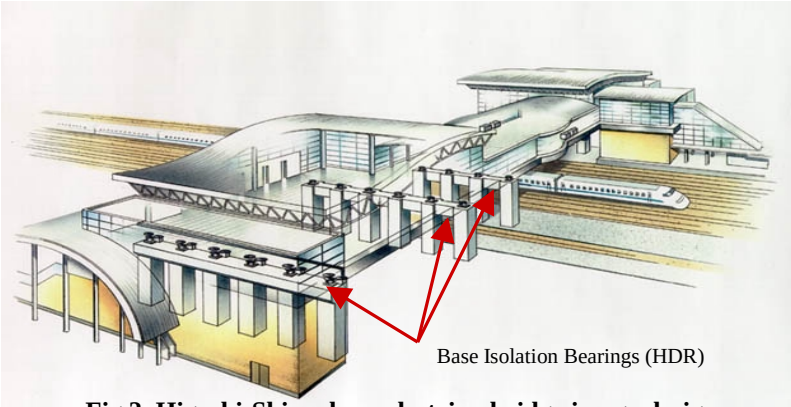

Fig.2 Higashi-Shizuoka pedestrian bridge image design

Moreover, the stability of the base peripheral ground at an earthquake has great influence on the isolation system. Although the ground of the bridge is relatively weak, safety is ensured. From the results of the dynamic ground analysis (effective stress analysis), it was confirmed that the bridge would not enter the state of resonance as a dynamic interaction of the ground even if the ground is liquidized a little. Thus it was confirmed that the isolation performance of the bridge would not be hampered by influence of the ground.

Development of base isolation bearing which improves performance in limit

To deal with displacement in all directions, the introduction of circular bearing for base isolation was aimed at. For this purpose, we developed a base isolation bearing which would not easily break. A main cause of bearing breakage at large deformation is the concentration of the stress in the bearing. Therefore, the thickness of the top and bottom layers of laminated rubber for base isolation bearing was made thinner than that of the center parts. On the other hand, the thickness of a steel board inside the top and bottom layers was made larger than that of the center parts. This enables uniform transmission of stress. Many base isolation bearings were fabricated for a test with various combinations of rubber materials, rubber, and steel board thickness and so forth, and conducted many examinations. Based on the study results, the best performed one was adopted **(Fig.3, Photo.2)**.

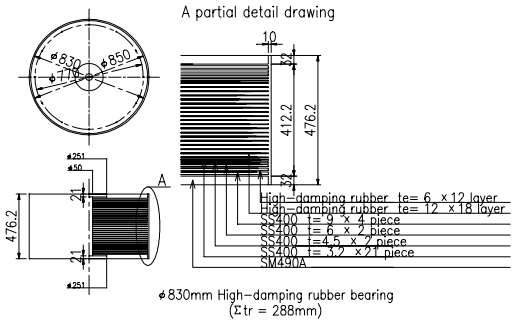

Fig.3 Base isolation bearing(HDR)

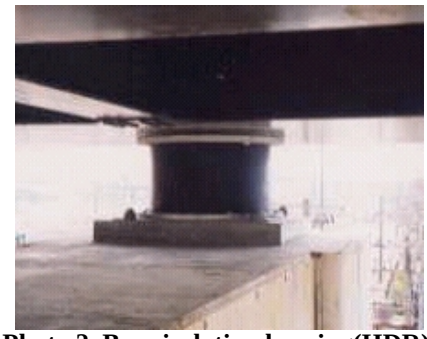

Photo.2 Base isolation bearing(HDR)

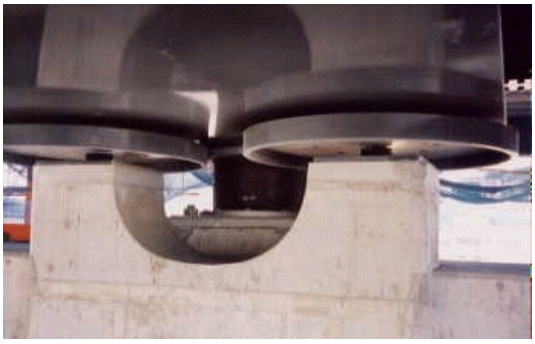

Photo.3 Movement limitation device

Moreover, a steel disk-type device to limit movement has been developed. The designed maximum length of movement is 500mm **(Photo.3)**.

Grasp of complex movement in area of large transformation at earthquake

The plane shape of this bridge is special, because the bridge is an earthquake insulation structure with a roof over it. Therefore, it is estimated that the bridge would make fairly complicated dynamic movement at the earthquake. Since such movements cannot be accurately verified by a simple method, two highly-developed technological methods have been applied this time for the verification. One is the non-linear dynamic analysis using a solid model. The other is the bi-directional hybrid earthquake loading test (pseudo-dynamic test).

Bi-directional hybrid earthquake loading test of base isolation bearing

As shown in **Fig.4**, the concept of the hybrid earthquake loading test (pseudo-dynamic test) is that "concerning the materials with characteristics which are difficult to treat by model calculations, such characteristics are detected by executing the added force test, and seismic response analysis is made by sending through on-line the necessary date to the computer one by one. "

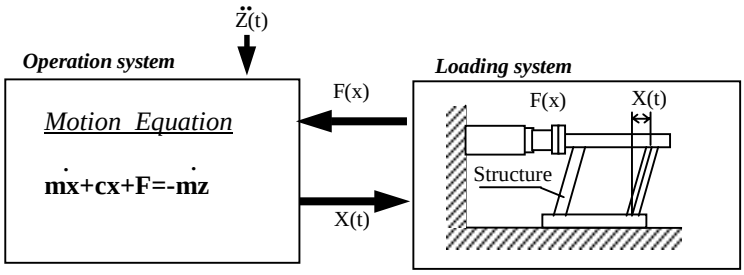

Fig.4 Concept of the hybrid earthquake loading test

The base isolation bearing with the highest ratio of energy was taken up in the bi-directional hybrid earthquake loading test in which a load is imposed from two different horizontal directions at the same time. In this case, a full-size model and 1/2-size model of bearings were used. It is most desirable if the loading test can be conducted under the same conditions as in an actual earthquake. However, due to the restriction of examination devices, high-speed loading at a speed of 1/5 that in an actual earthquake was carried out this time. A multi-mass vibration model (sway- rocking model of 3 layers) was used for the computer analysis **(Fig.5)**.

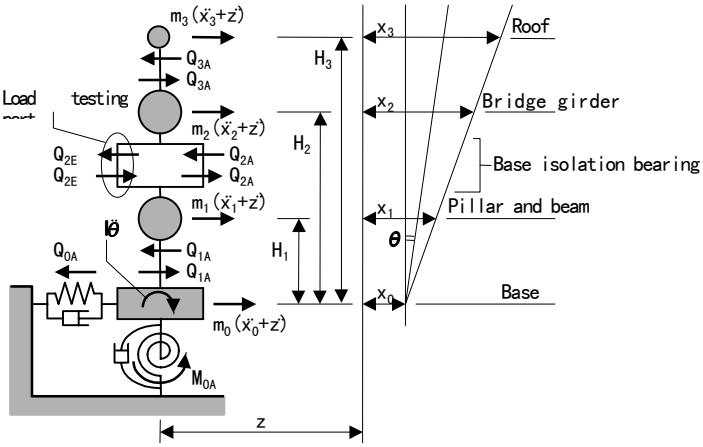

Fig.5 Vibration model of hybrid test

The result of this examination have confirmed that even the earthquake motions of level 2 would not cause any damage on the structure system. Moreover, we obtained many new technological findings, including the complicated restoration characteristics of insulation bearing, peculiarities of the bi-directional loading, influence of the size of the test piece, and dependency on speed. The hybrid test which uses the one of multi-mass system like this time by the vibration model is a little **(Fig.6, Photo.4)**.

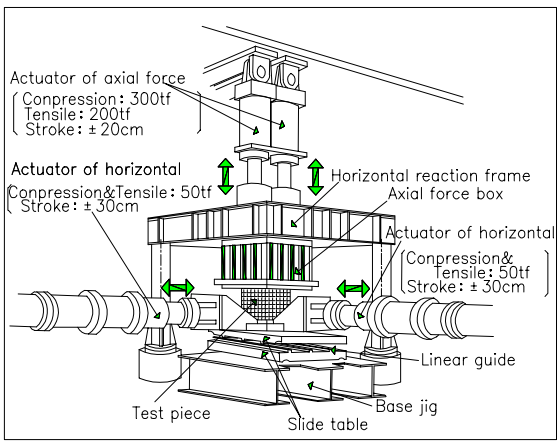

Fig.6 Bi-directional loading apparatus

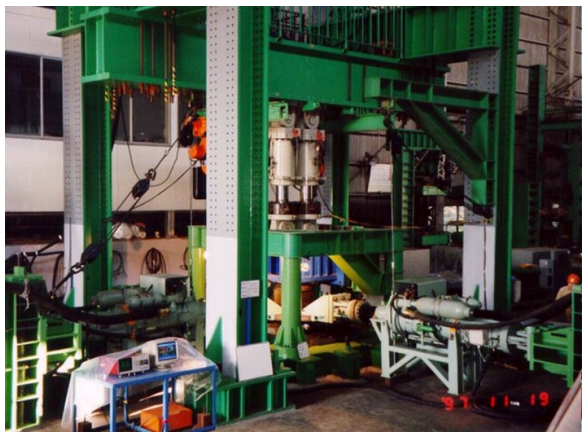

Photo.4 Bi-directional loading apparatus

The seismic waves used to test contain the one of Hyogo-ken Nanbu earthquake. They are seismic waves of the seismic wave (G-wave) used to design the railway structure and Specifications for Highway Bridge□Part □ Seismic Design (Japan Road Association). The phase difference of the seismic wave is considered for two directions loading.

About equation of motion and the numerical analysis method, in the hybrid test at this time, the equation of motion of five degree of freedom is independently set up respectively in a bridge axial direction and a right-angled direction of bridge axis. The numerical analysis has gone by the centered difference method. Moreover,

the effect of two directional loading is included in the load data fed back to the computer as for the numerical analysis.

The greatest result of the examination is the career characteristic of the bi-directional loading. The rigidity of the structure increases and decreased locally, causing the structure to be of bow-shape. The structure then becomes fatter or thinner, and the peak point of the deformation becomes somewhat circular. Thus the structure shows more complex behaviors compared with those in the one-directional loading **(Photo.5)**.

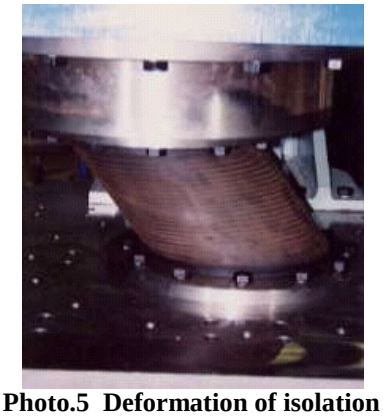

Photo.5 Deformation of isolation

However, although there are some differences between the result of the one-directional loading and those of bi-directional loading in the respective responses according to the lapse of time, such differences are not large enough to have great influence on the maximum displacement which is important in design. That is to say, it has been confirmed that the influence of the twist not considered in the one-directional loading and influence of other such factors including the amplification would be small, if the situation is within the permissible range for the design, that is, within the stable range before hardening **(Fig.7, 8, 9, 10)**.

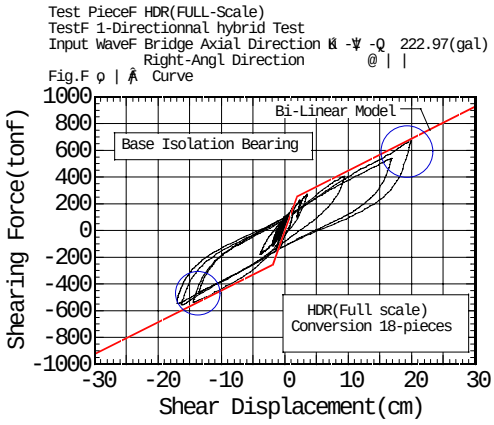

Fig.7 One-directional loading test results

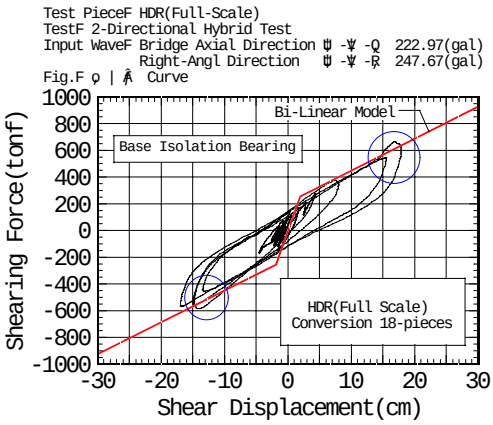

Fig.8 Bi-directional loading test results

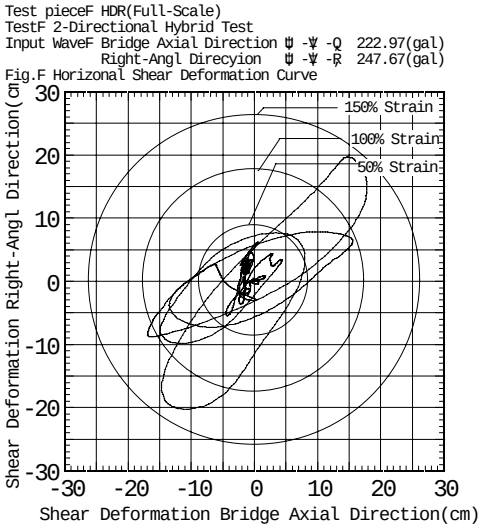

Fig.9 Horizontal shear deformation

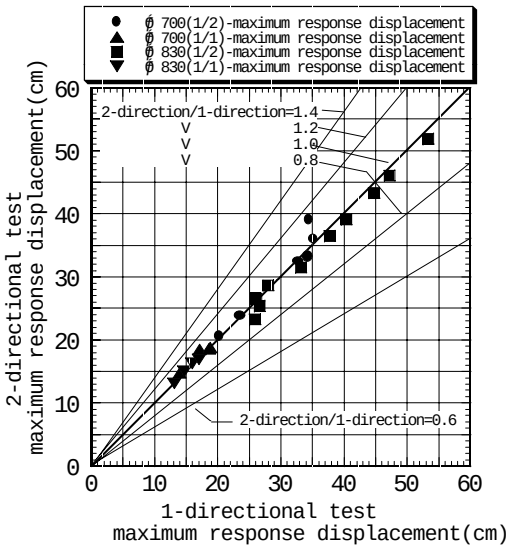

Fig.10 1-directional vs. 2- directional test results

In the relation of the comparison of the sizes of the test piece (full-size model and 1/2-size model), to assume a hybrid test to be a response at the actual earthquake, the test piece uses two kinds from the limitation of the

stroke of the actuator of the lateral loading of the hybrid test device according to the size of the response displacement. Then, the hybrid test is corrected by the difference of the test piece. The amount of the transformation compels the real response displacement in case of the full-size model. The half of the size of the response displacement is compelled for 1/2-size model. The size of the load made the value by which the number of bearings was multiplied responded to the load response of the actuator in case of the full-size model. Four load responses of the actuator are multiplied for 1/2-size model. This is converted into the full-size model corresponding. And, the test multiplies the number of bearings by the response and responds. The hybrid test results is shown in **Fig.11,12**.

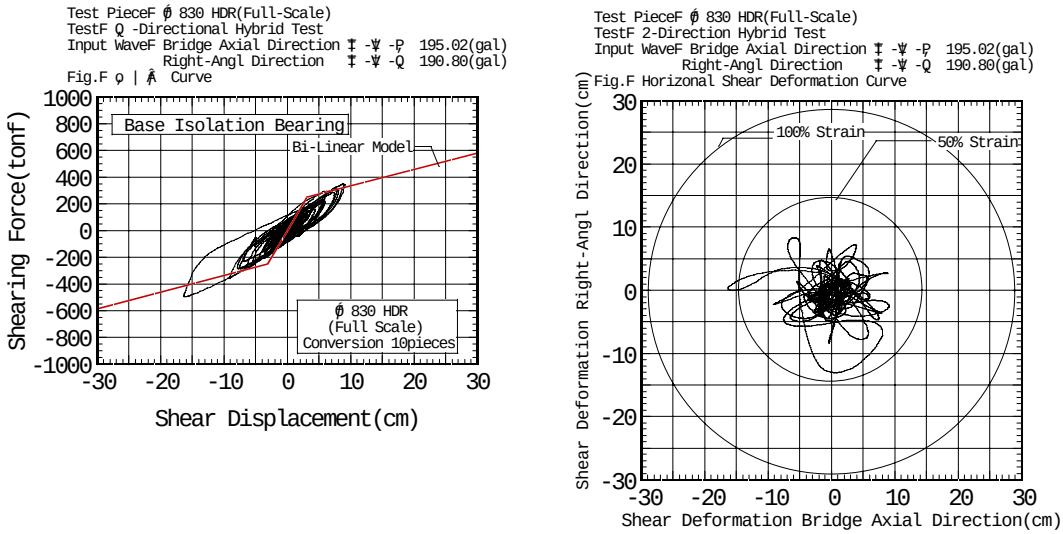

Fig.11 Test results of different sizes (full-scale*)*

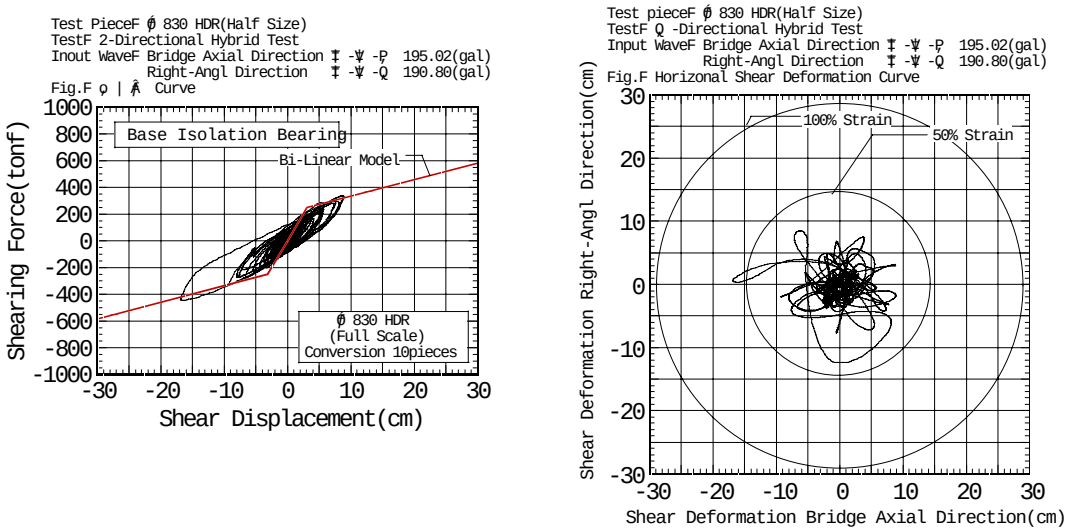

Fig.12 Test results of different sizes (half size*)*

Both of the test results correspond. The difference of the maximum response is very few. The influence of the size of the test piece hardly appears. That is, the test with a small test piece is easier than the test of the full-size model. Then, if the model ratio is appropriately corrected even when a small model is used, the test by the full-size model and the results of the same are achieved.

Non-linear dynamic analysis of solid model

Non-linear dynamic analysis was conducted by using a full model of the solid including the bridge and the roof. Just like the hybrid test, the analysis was made by loading from two directions. This time, we have grasped the situation of deformation and influence of the twist which cannot be elucidated by the hybrid test **(Fig.13)**.

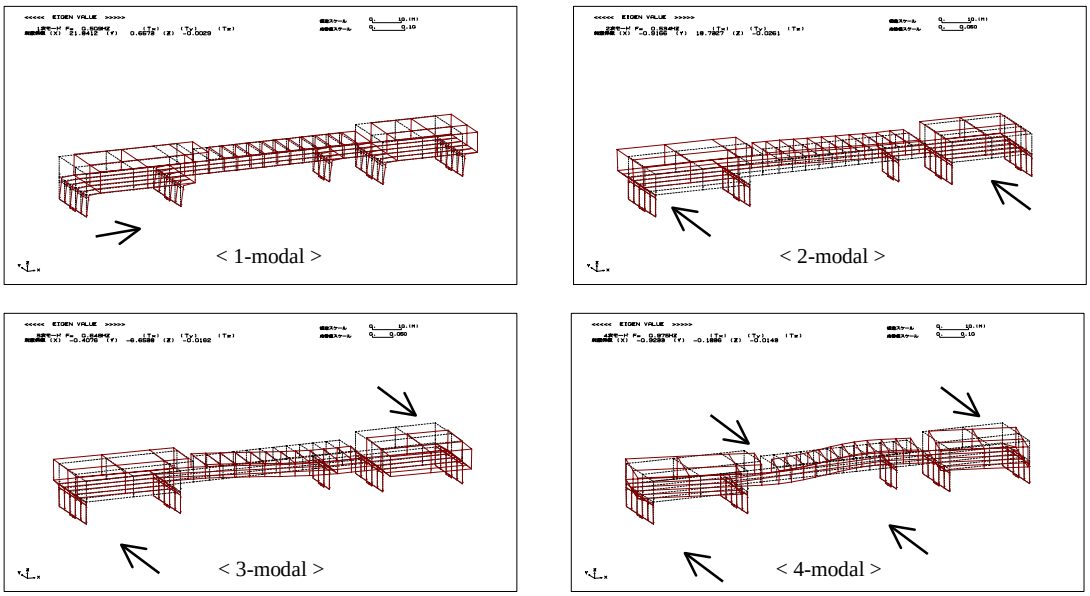

Fig.13 Non-linear dynamic analysis model and eigen modal

According to the analysis, although a part of reinforced concrete under the pillars and the piers yields, the situation does not go into the stage of destruction (final stage).

The results of the hybrid test and those of the analysis generally correspond to each other concerning the loading in the bridge axial direction (difference of 1-22% of the response displacement). However, they greatly differ concerning the loading in the direction at right angles to the bridge axis according to the difference of the vibration model. Especially, the difference of the response displacement at bridge edges is conspicuous. Therefore, the development of a simple vibration model which can consider such factors as the influence of the twist will be a task for us in the future **(Fig.14, 15)**.

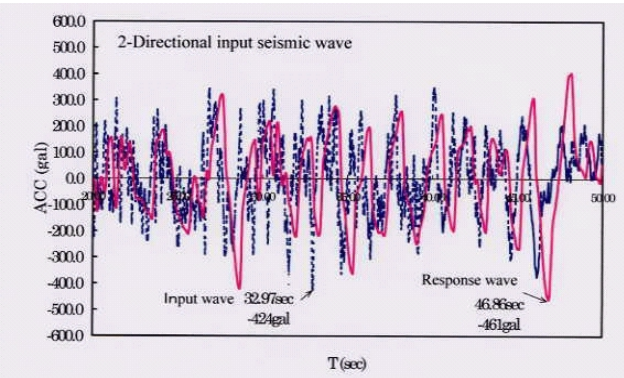

Fig.14 Acceleration of dynamic analysis

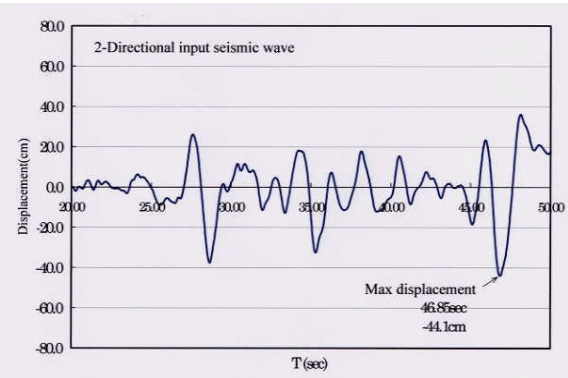

Fig.15 Displacement of dynamic analysis

Postscript

The seismic isolation bridge structure with a roof realized in this pedestrian bridge is a case where enhancement of performance has been enabled corresponding to diversification of the structure. It is considered that the technology which has elucidated complicated behaviors of large deformation at an earthquake will greatly contribute to the upgrading of analytical technology and also to the planning and designing of bridges. Therefore, we would like to further promote studies and development concerning the seismic isolation which will become all the more important in the future.

Lastly, we would like to express our sincere gratitude to many persons who have provided us with various useful guidance and kind assistance in the planning, designing and construction of the pedestrian bridge.

Photo.6 Surrounding of Higashi-Shizuoka pedestrian bridge

REFERENCE DOCUMENTS

1) Shuji IWATA, Hirokazu IEMURA, Toshiaki AOKI, Kouichi SUGIYAMA, and Yoshifumi UNO: Hybrid earthquake loading test (pseudo-dynamic test) of bi-directional base isolation bearing for a large pedestrian bridge, The 10th Japan Earthquake Engineering symposium, Special theme session 5-2, pp.207-212, 1998.11

Shuji IWATA and Hirokazu IEMURA: Seismic isolation and control structure of the Higashi-Shizuoka pedestrian bridge, Japan Society of Civil Engineer Earthquake Engineering committee Seismic Response Control Sub Committee "Seismic isolation and control of bridge and underground structure" Course association pp.159-162, 1999.5