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PROVING TESTS OF ENERGY ABSORBING SEISMIC TIES FOR ASEISMIC DESIGN OF BOILER PLANT STRUCTURES

K AIDA[1], K KAWAMURA[2], N MARUYAMA[3], K SUZUKI[4], S FUJITA[5] And T CHIBA[6]

SUMMARY

The Great Kobe Earthquake struck in early morning of January 17th 1995 gave unpredictable damages to Boiler structures in thermal power plant. This paper deals with seismic proving tests of the boiler structures. After investigation of the damage on these structures by the Great Kobe Earthquake, the tests were conducted on the behavior of “Seismic Ties”. They are connecting devices installed between the boiler and the supporting structure. The tests were carried out by using scaled model of boiler structure on a large shaking table.

The seismic ties are made of steel and allowed to be used in the elasto-plastic deformation region. The seismic response can be reduced by the energy dissipation of the hysteretic deformation of the ties. Two types of seismic ties, set in a scale model of the boiler and its supporting structure, are tested. One is a link type, the other is inserted type. The stiffness of ties are also alternated to observe the effect of behavior to seismic response.

Firstly, element tests are conducted to confirm the characteristics and ability for seismic energy absorption of the ties.
It is confirmed that the link type and inserted type seismic ties possess almost same dynamic characteristics, sufficient deformation capability and enough durability against severe earthquake.

The tests have been planned and are being pursued, under the committee of a project titled Seismic Proving Test of Equipment and Structures in Thermal Conventional Power Plants (SPT). Committee on SPT (Chaired by H. Shibata) is operated by Japan Power Engineering and Inspection Corporation (JAPEIC), with a commission from Ministry of International Trade and Industry (MITI) of Japan.

INTRODUCTION

The Great Kobe Earthquake gave damages to electric power supplies as well as civil and architectural structures. From the experience of this disaster, it is desired to ascertain the structural reliability of thermal power plants against severe earthquake. In this context, a series of proving test s have been planned and performed as a national research project. This paper is concerned with the particular tests on the boiler structures.

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[1] *Kure Research Laboratory/Structural Design Dept. Babcock Hitachi K.K, Japan. E-mail: aida-k@krl.bhk.co.jp*
[2] *Kure Research Laboratory/Structural Design Dept. Babcock Hitachi K.K, Japan. E-mail: kawamura@kure.bhk.co.jp*
[3] *Mechanical Engineering Research Laboratory, Hitachi Ltd., Tsuchiura, Ibaragi, Japan*
[4] *Professor, Tokyo Metropolitan University, Tokyo, Japan*
[5] *Professor, Tokyo Denki University, Tokyo, Japanx*
[6] *Japan Power Engineering and Inspection Corporation, Tokyo, Japan*

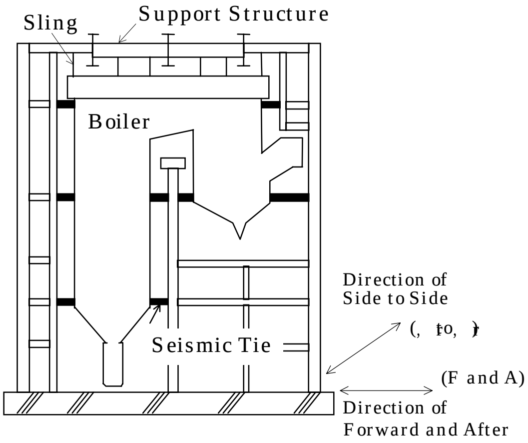


Fig 1: View of Boiler Plant

As shown in Fig. 1, the boiler is suspended from the top of the support structure for unrestrained thermal expansion during operation. In order to restrain horizontal movement during earthquake, they are connected at certain points by the seismic ties. Seismic ties are important devices for the aseismic design of a boiler structure, functioning to protect the boiler from damaging pressure parts by energy dissipation due to inelastic deformations of the tie. Furthermore, the characteristics of ties and their arrangement give great influence to seismic response on the overall structure. Given this, we have proposed optimum design methods for the connecting elements to minimize seismic response of boiler structures 1) 2) . We have also proposed high energy absorption seismic ties3).

It is noted that recent large scale boilers have been designed based on dynamic response analysis considering the interaction of the boiler and the support structure and the effect of energy dissipation of seismic ties.

In view of these facts, the proving tests are carried out by use of scaled structural model of the boiler-structure, particularly, focused on the seismic ties in a coupled model using large scaled shaking table (Table Size: 15m x 14.5m, Max. Loading Capacity: 500ton) at the National Research Institute for Earth Science and Disaster Prevention (NIED), Tsukuba, Japan.

The main purposes of the proving tests are;

1) Verification of the functional preservation of the seismic ties to examine the energy absorption during earthquake.

2) Seismic proving test of the large scale boiler structures, which were designed, based on the present design criteria.

OBJECTIVE PLANT

Model Plant

Investigative work was performed to select one model plant among numerous power stations in Japan. A power station existing in the Chubu region of Japan was most suitable as a typical model plant for the proving tests for the following reasons;

1) Designed using present design criteria based on the dynamic analysis.

2) Certified by the technical appraisal as high story building in the Building Center of Japan (BCJ).

A summary of the model plant is shown in Table.1.

Table 1 Summary of Model Plant

Boiler	700MW Coal Combustion
Natural Frequency	F & A ··············· 1.480s (0.676Hz) S to S ··············· 1.319s (0.758Hz)
Dimension	Height ·································· 74.5 m F & A ·································· 86.4 m S to S ·································· 60.0 m
Weight	Supporting Structure 41846 t Boiler 12410 t Total 54256 t
Seismic Ties	Total Yield Load Σ Py=3900 t

Input Earthquake Wave

Selection of input earthquake wave used in the proving test is one of the most important factor with its magnitude of the wave. The followings are considered for selective processing;

1) The Most critical input wave in the spectrum or dynamic response analysis among the design earthquake waves.

2) Two input levels corresponding to the design criteria have to be considered, i.e. Level 1; an earthquake level which could possibly occur once or more during the life time of the structure and Level 2; An earthquake level which could be considered as the most severe as of yet. 4),5)

As a result, Taft EW(1952) is selected for the primary input wave among the natural earthquake utilized in actual design waves shown in Table 2.

Table 2 Earthquake Waves

Input Wave	Maximum Acceleration (gal)	
	Level 1 (25kine)	Level 2 (50kine)
Taft EW	249	497
El Centro NS	256	511
Hachinohe NS	167	333

Seismic Ties

Four kinds of seismic ties shown in Fig.2 through Fig.5 are chosen from the investigation mentioned above. There are two main groups, i.e. link type, Fig.2 and Fig.3 and the inserted type, Fig.4 and Fig.5. Each one is further divided into either, elasto-plastic designed or elastic designed types.

In the link type ties, a bending of the vertical bars, called “PIN” in Fig.2, are generated when they are subject to horizontal force. The middle portion of the pin has a larger diameter than both ends and the shape of the pin is designed to acquire homogeneous stress distribution along the axis. This type is classified as elasto-plastic designed seismic tie since large plastic deformation can be obtained by reducing yield forces. While the shape of the pin in Fig.3 is straight, stress is concentrated in the middle of the pin. Therefore large deformation can not be expected. We call this type the elastic designed ties.

With the inserted type of ties, plate elements in Fig.4 have lozenge opening. The shape is determined to create homogeneous stress when the plate deformed in shear-like, out-of-plane. And therefore this is also classified as elasto-plastic designed Ties.

Finally, another inserted type is shown in Fig.5, which is commonly used as a stopper-type seismic tie. This is obviously classified as elastic designed tie since stress will be concentrated at the base due to the cantilever type deformation.

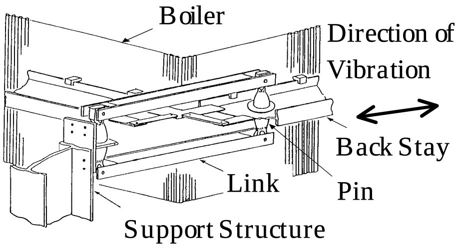


Fig.2 Link Type (A1) Elasto-Plastic Designed

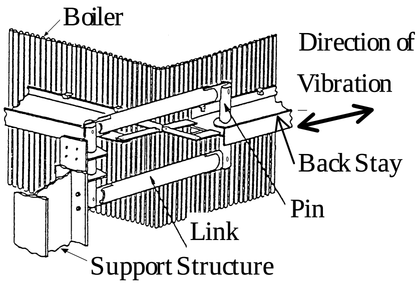


Fig.3 Link Type (A2) Elastic Designed

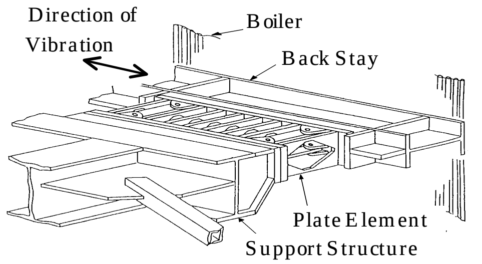


Fig.4 Inserted Type (B1) Elasto-Plastic Designed

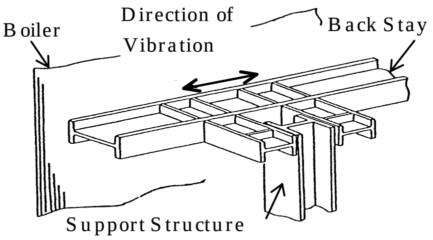


Fig.5 Inserted Type (B2) Elastic Designed

DESIGN OF THE TEST MODEL

For the purpose of the proving tests mentioned above, it is required that the test model has to represent a coupling behavior between the boiler and its support structure and to realize the seismic ties with a scale as large as possible. Hence the scale ratio of the ties should be more than one third and possibly a limit for the proving tests to observe inelastic behavior of the ties. Hereafter a procedure to allow this scale ratio for the huge coupled structures is mentioned.

Firstly, a dual mass system that can express the large complicated actual plants as a representative particle of the support structure and also a particle of the boiler is implemented. They are connected by the seismic tie.

To achieve this, we introduce a dual mass approximation method. An outline is denoted in Sec. 3.1 and the design flow based on the approximation method is described in sec.3.2.

Dual Mass Approximation

A numerical model of the boiler structural system for an aseismic design is shown in Fig.6 which consists of a multi-mass of the boiler, its support structures and also seismic ties. The dual mass approximation method transfers the multi-mass model into a dual mass of which seismic response is equivalent by using the idea of sub-structure synthesis method.

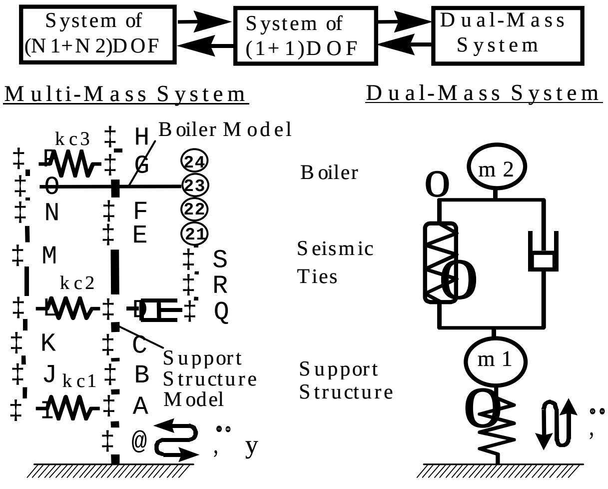
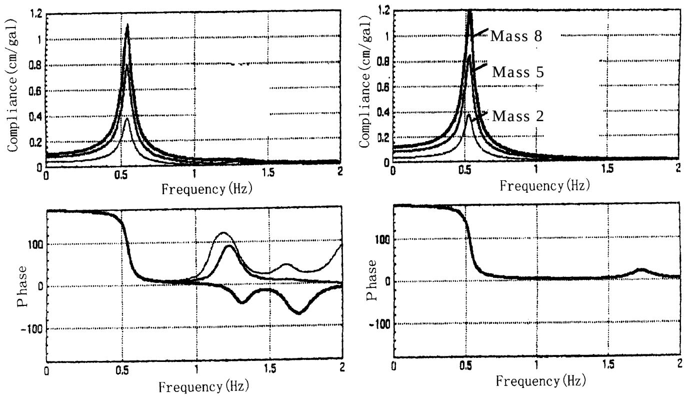


Fig.6 Method of Dual-Mass Approximation

Assuming the degree of freedom (DOF) of the support structure to be N1 and the boiler N2, would be the combined overall structure of the system (N1+N2)DOF. Under these conditions, we consider the first mode of each sub-structure in a modal expansion. The mode shape for the support structure is cantilevered and that for the boiler is almost rigid body mode. In the case of the boiler structure, as an effective mass for the first mode generally exceeds 70 %, higher modes can be neglected as the results, the system of (N1+N2) DOF can be reduced to (1+1)DOF.

Secondly, by comparing the factors of acceleration, velocity and displacement in the equation of motion for the (1+1)DOF and those in the dual mass system, the relation of characteristic parameters, spring constant and damping factors of the seismic ties can be derived.

As a relationship for the spring constant, the following equation can be established between vector X_k whose element is spring constant k_{ci} of i^{th} seismic tie in multi-mass model, and the spring constant of K_c in dual mass model.



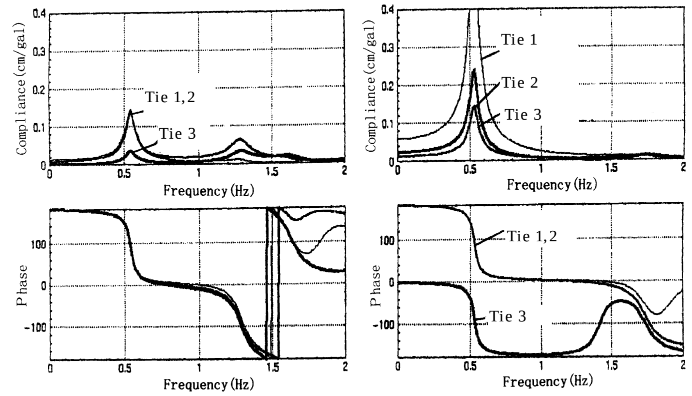
(a)Multi-Mass Numerical Model (b)Dual-Mass Numerical Model

Fig.7 Frequency Response Function of Support Structure Displacement

$$AX_k = B$$

$$A = \begin{bmatrix} m_1 \cdot \beta_2 / \beta_1 \cdot A_1^t \cdot A_2^t \\ m_1 \cdot A_1^t \cdot A_1^t \\ m_2 \cdot A_2^t \cdot A_2^t \end{bmatrix}$$

$$A_1 = T_1 \cdot \phi_1$$
$$A_2 = T_2 \cdot \phi_2$$
$$X_k = [k_{c1}, k_{c2}, \cdots, k_{cN}]$$
$$B = k_c[1,1,1]^t$$



(a)Multi-Mass Numerical Model (b)Dual-Mass Numerical Model

Fig. 8 Frequency Response Function of Relative Displacement

Where

ϕ_1 : 1st mode of support sub-structure

ϕ_2 : 1st mode of boiler sub-structure

T_1: Positioning Matrix for seismic tie of support sub-structure

T_2 : Positioning Matrix for seismic tie of boiler sub-structure

m_1: Mass of support structure in dual mass model

m_2: Mass of support structure in dual mass model

N : number of seismic tie in multi mass model

It is noted that the mass of each sub-structure is equal to square of the participation factor β_1 ;

$$m_1 = \beta_1^2$$

$$m_2 = \beta_2^2$$

Same relationship for the damping factors can be also established.

To demonstrate the validity of this method, results of numerical examples for the frequency-response curve are shown in Fig.7 and Fig.8. Fig.7 shows the displacement of support structure at nodes 8, 5 and 2, at the top, middle and bottom respectively.

Fig. 8 denotes relative displacements between the boiler and the support structure corresponds to all three points. The results of the support structure for both models coincide at all three points while relative displacements, at mid point near the center of gravity of overall structure, results are satisfactory. This means that the equivalent dual mass model is able to express response for the actual multi-mass model around the gravitational center.

Design Flow of Test Model

A conceptual flow on the design of the test model is shown in Fig.9. The first stage is the transference from actual to a dual mass model by applying the above approximation method. The second step is the preparation of a sliced model in which both the mass and stiffness are divided for equivalent dynamic characteristics. The final stage is to apply a scaling rule to the sliced model and then to design the actual test model.

A SCHEME OF TESTS ON A LARGE SHAKING TABLE.

Test Model and Method of shaking

The test model is shown in Fig. 10 with its specifications. The Seismic tie is installed on the second floor, near the center of gravity of the model. Four kinds of ties described in Fig.2 through 5 are tested in turn. Characteristics of the ties are shown bellow.

The method of shaking is as followings;

(1)Sweep test within elastic response to identify the dynamic characteristics of the test model.

(2)Earthquake wave input, Taft EW, within elastic and elasto-plastic response to evaluate dynamic response of the test model.

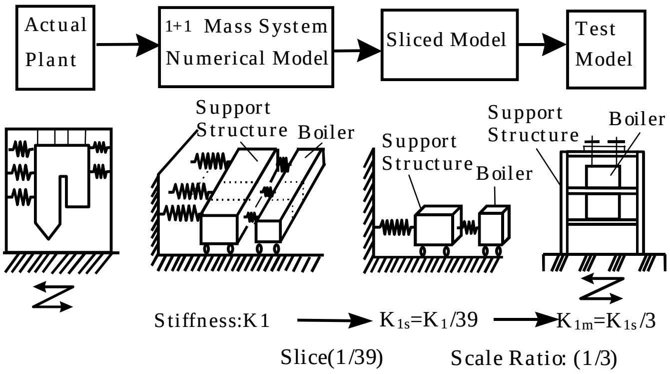
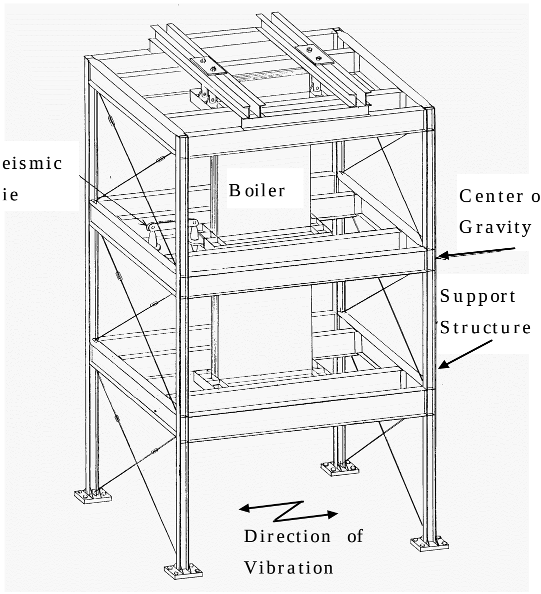


Fig.9 Design Flow of Test Model



Item	Dimension (m)	Weight (Tons)
Support Structure	Height * Width * Depth 8.3 * 4.0 * 4.0	32.4
Boiler	Height * Width * Depth 5.75 * 1.5 * 0.3	11.8

Fig. 10 Over View and Specification of Test Model

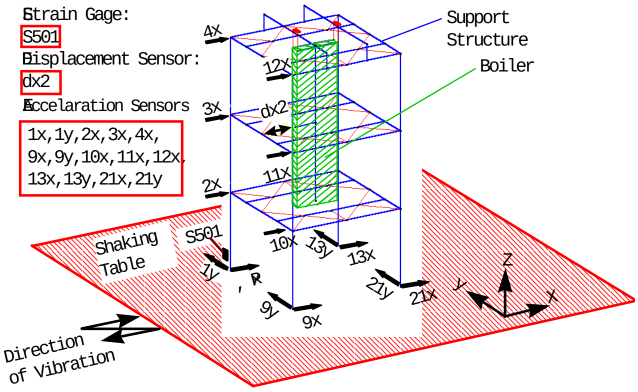


Fig.11 Sensors for Dynamic Test

Fig.12 together with the results obtained by the element test.

In the element test, displacement gradually increased to the ductility factor of μof 20 and this repeated until failure. μis the ratio of maximum displacement divided by initial yield displacement. From this figure, it is found that the Yield force, displacement, elastic rigidity and plastic rigidity, which are the primary design parameters for seismic ties, are relatively compatible.

Durability of the Seismic Tie

To evaluate the durability of the ties, accumulated plastic displacement are introduced. The concept of this method is shown in Fig. 13. Plastic displacements arise in both plus and minus directions are accumulated in the plus side only until the tie failed. The maximum accumulated displacements of each type of tie are evaluated in the element test and then they are compared with those obtained by the dynamic test. Results for A1 are shown in Fig.13(a) and Fig.13(b). As the Figure shows, accumulated displacements consumed by Level 2 of Taft EW are much smaller compared to those until failure and therefore the tie has sufficient durability.

COMPARISON BETWEEN LINK TYPE AND INSERED TYPE TIES

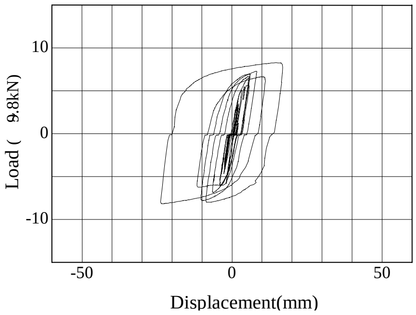
Force-Displacement relation and durability at ties

Fig. 14 shows that Load-Displacement carves of link type A1 and inserted type B1 subject to Level 2 seismic wave of Taft EW. It is found that the primary design parameters for seismic ties, which are the yield force and displacement, elastic rigidity and plastic rigidity, are almost compatible between the link type A1 and inserted type B1.

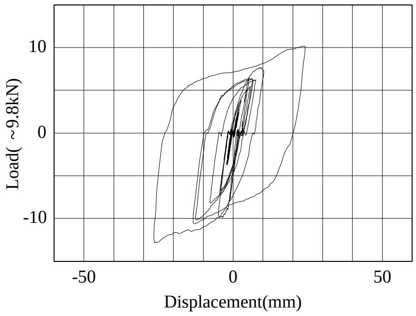
Fig. 15 displays that accumulated ductility factors of link type A1 and inserted type B1 subject to Level 2 seismic wave of Taft EW.

It is recognized that maximum accumulated ductility factors are almost same between link type A1 and inserted type B1.

It is confirmed that the type of seismic tie does not affect the dynamic characteristics of ties.

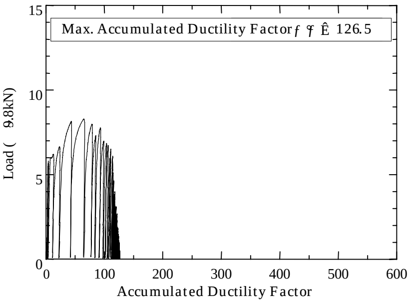


(a) Link type A1

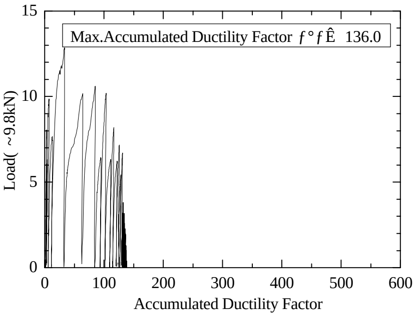


(b) Inserted type B1(2pieces)

Fig.14 Comparison of Load-Displacement curves between Link type A1 and Inserted type B1 by dynamic test



(a) Link type A1



(b) Inserted type B1 (2 pieces)

Fig.15 Comparison of accumulated ductility factor between link type A1 and Inserted type B1 by dynamic test

6.2 Seismic behavior on support structure

Fig. 16 (a)(b) shows the relation between input Level of shaking table and maximum strain at the column base. Since the test model is designed as a shear structure, the magnitude of the strain is directly related to the base shear of the support structure. The solid line denotes a linear relation, i.e. all members in the test model including ties are assumed within the elastic response and the dashed lines are actual response obtained by the test at each input level. It is confirmed that structural members are within the elastic response from the strain gauges. The difference between the solid and the dashed lines denotes the effect of reduction by the energy dissipation of the seismic ties.

CONCLUSIONS

In view of the above discussions, it can be concluded as follows;

(1) By introducing a dual mass approximation method for the large complicated boiler plants, the test model