SUBSTRUCTURING HYBRID TESTS ON MULTI-BAY SPACE FRAMES WITH ROTATION AND SHEAR DEFORMATION OF FLOOR

by

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1. INTRODUCTION

Brace is widely used in structures such as thermal power stations being seismic element, and the assumption of rigid floor is usually not applicable when considering the effect of transmission of inertial forces by floor with voids, and then the analysis is becomes complicated. As for the steel brace, its hysteresis behavior greatly differs from that of moment frames. This is because of the buckling, degradation of strength and stiffness after post-buckling, and relaxation.

In order to study seismic behaviors of such kind of framed structure, numerical analysis by computers is generally used. If non-linear hysteresis model over inelastic region is given, response of frame can be calculated. However, the reliability of results from numerical analysis mainly depends on the validity of the model, it is necessary to conduct to check the validity of the model with experiments.

Besides the shaking table test, an on-line earthquake response test can also be conducted by using computers and loading apparatus. For quite large buildings like thermal power stations, it is almost impossible to carry out a full-scale test. Accordingly, substructuring technique is necessary to be employed. In this study, multi-bay space frame model has been proposed by taking into account factors such as arrangement of brace, eccentricity from the arrangement, non-rigid floor, and so on. Then, inelastic earthquake response simulation has been performed by use of substructuring hybrid earthquake response test, incorporating the substructuring method into a on-line earthquake response test. Reports on hybrid earthquake response test system and experiment of the multi-bay braced space frame are presented in this paper.

2. BRIEF DESCRIPTION OF EXPERIMENT

The model for testing is shown in Fig.1, which is a multi-bay space frame composed of four planar bents and three shear floors. As for the planar bents, two of them are reinforced by X-type braces, respectively. And three types of models are considered with different eccentricity due to brace arrangement, the first one is the model with large eccentricity by placing X-type braces in one side (the first and second bents), the next one is a small eccentricity model with X-type braces in every other side (the first and third bents), and the

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last one is a symmetric model with X-type braces at two ends (the first and fourth bents) and without eccentricity. Two kinds of floors are considered with rigid and flexible shear floor respectively. Stiffness of flexible shear floor is set equal to initial horizontal elastic stiffness of one X-type brace. Only the unsymmetrical model is used in the test for rigid floor. There are 5 cases of the tests for each kind of braces.

As shown in Fig.2, the test model is decomposed into 4 planar bents and 3 floors as substructures, and then the braced planar bent is further decomposed into 2 braces and 1 bent. With hysteresis characteristics assumed, the decomposed parts are simulated in computer as fictitious structures. Only the braces are extracted for loading in parallel with analysis. In case of unsymmetrical arrangement, 4 braces are loaded simultaneously. And 2 braces are for symmetric model. The hysteresis characteristics measured from the test feedbacks to earthquake response analysis of the whole system to simulate the earthquake response.

The system layout of the test (in case of unsymmetrical model) is shown in Fig.3. Being as loading apparatus and controllers, actuators are connected to the computer through interface boards (A/D board and D/A board). In measurement, axial displacement of brace could not be exactly evaluated from the actuator displacement due to the limit of clearance in the junction, the displacement meters are attached to the specimen to measure the displacement of the brace directly, and the test is controlled to make this displacement reach to the aimed value. The value of load can be read from load cell attached to the end of actuator.

Two kinds of test specimen of braces (one's length is 132 cm and the other's 66 cm) are made of steel in grade SS400, and the brace is H-45 $\times$ 35 $\times$ 3 $\times$ 3 with pinned ends. Although the actual lengths of the specimen are different, the dimensions of fictitious bents in test are taken as the same, and the boundary condition of both ends of the brace are assumed different. That is, both ends of brace 132cm in length are supposed as ideal pin joints, while the brace 66cm in length represents the behavior of rigidly supported brace 132cm in length. Test code is defined by length of brace, the arrangement of brace and stiffness of floor as shown in Fig.4, and 10 cases in total were simulated.

Table 1 gives parameters of specimen and assumed frame models. The yield point of brace was measured in material test. The contribution of bents in strength is taken as 0.5, which is the ratio of ultimate strength of bent to that of the whole system, where only the tension braces are taken into account. In the actual behavior, the compression brace will contribute to the system a little, and then the real contribution of bents is a little smaller than 0.5. Elastic natural period is set to be 0.25 sec in case of translation motion, and then the total inertia mass of each case can be determined in common. (As the time axis of the earthquake wave has been compressed, the used model is equal to the system of 0.5 sec). Taking into account the floor area covered by each planar bent, the mass of the side bent is set to 1/6 of total, while that of the others is 1/3 of total.

As shown in Fig.5, only translational displacement in direction of earthquake input is considered here. The relative displacement of adjacent bents are caused by shear deformation and rotation of floors for flexible floors, rigid rotation which could not generate shear force is indicated in Fig.6. Here assumptions are made as follows: $x_1 \sim x_4$ represent for the vibration displacements, θ is angle of the floor rotation, $P_1 \sim P_4$ and M are external forces and moment, $\Delta_1 \sim \Delta_4$ are displacement of the planar bent, $F_1 \sim F_4$ are restoring force of the planar bent. δ_A (between bent 1 and 2), δ_B (between bent 2 and 3), δ_C (between bent 3 and 4) is each part of the relative displacement of adjacent planar bents. They are called shear displacement of the floor. q_A, q_B, q_C are shear forces in accordance with $\delta_A, \delta_B, \delta_C$. In the case of flexible floor, the equation of compatibility can be formed as

$$\begin{Bmatrix} \Delta_1 \\ \Delta_2 \\ \Delta_3 \\ \Delta_4 \\ \delta_A \\ \delta_B \\ \delta_C \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ -1 & 1 & 0 & 0 & -S_A \\ 0 & -1 & 1 & 0 & -S_B \\ 0 & 0 & -1 & 1 & -S_C \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ \theta \end{Bmatrix} \tag{1}$$

Therefore, equilibrium equation can be written as

$$\begin{Bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \\ M \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & -S_A & -S_B & -S_C \end{bmatrix} \begin{Bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ q_A \\ q_B \\ q_C \end{Bmatrix} \tag{2}$$

in which k_A, k_B, k_C=spring coefficients of floors between planar bent 1 and 2, 2 and 3, 3 and 4 respectively, S_A, S_B, S_C=spans of them, h_1, h_2, h_3, h_4=the heights of planar bents, respectively.

According to the d'Alembert's principle shown in equation (3), we can obtain the equation of motion for a pseudo-space model with 5 degrees-of-freedom shown in equation (4). On the other hand, for rigid floors, only 2 degrees-of-freedom are left in horizontal and floor rotation.

$$\left.\begin{aligned} P_i &= -m_i(\ddot{x}_i + \ddot{y}), \quad i = 1, \cdots, 4 \\ M &= -I_m \ddot{\theta} \end{aligned}\right\} \tag{3}$$

$$\left.\begin{aligned} &[M]\{\ddot{x}\} + [K_{xx}]\{x\} + [K_{x\theta}]\theta + \{F_r\} + \\ &\qquad + \{F_b\} + \{F_{xp\Delta}\} = -[M]\{\ddot{y}\} \\ &I_m\ddot{\theta} + [K_{\theta x}]\{x\} + K_{\theta\theta}\theta = 0 \end{aligned}\right\} \tag{4}$$

stiffness matrix:

$$[K_{\theta x}] = [k_A S_A, \quad k_B S_B - k_A S_A, \quad k_C S_C - k_B S_B, \quad -k_C S_C], \qquad [K_{x\theta}] = [K_{\theta x}]^T$$

$$[K_{xx}] = \begin{bmatrix} k_A & -k_A & 0 & 0 \\ -k_A & k_A + k_B & -k_B & 0 \\ 0 & -k_B & k_B + k_C & -k_C \\ 0 & 0 & -k_C & k_C \end{bmatrix}, \quad K_{\theta\theta} = k_A \cdot S_A^2 + k_B \cdot S_B^2 + k_C \cdot S_C^2$$

mass matrix and load vector:

$$[M] = \begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & m_3 & 0 \\ 0 & 0 & 0 & m_4 \end{bmatrix}, \qquad \{F_{xp\delta}\} = \begin{bmatrix} -m_1 g x_1 / h_1 \\ -m_2 g x_2 / h_2 \\ -m_3 g x_3 / h_3 \\ -m_4 g x_4 / h_4 \end{bmatrix}$$

$$I_m = m_1(S_A + S_B/2)^2 + (m_2 + m_3)S_B^2/4 + m_4(S_C + S_B/2)^2$$

in which $\{F_r\}$=restoring force vector of assumed frame, $\{F_b\}$=horizontal restoring force vector obtained from reaction of braces, $\{F_{xp\delta}\}$=force vector caused by $P-\Delta$ effect.

Based on the equations mentioned above, the restoring force of the brace can be measured by loading test, and that of fictitious bents are assumed by using the skeleton shift model[1], which describes the moving skeleton as tri-linear with hysteresis based on Ramberg-Osgood curve. And shear floor is supposed to be elastic element.

An original 10 sec of EW component recorded at HACHINOHE Harbor in 1968 is used as input earthquake wave, which are compressed in time to the half of original duration, that is from original 10 sec into 5 sec. What is under consideration here is that the height of story assumed in the model is about 1/4 of real size in dimension. The response spectrum of earthquake input is shown in Fig.7.

The Central Difference Method is utilized for numerical integration of the response analysis. The procedure of earthquake response simulation is as follows: in step i, displacement of each brace is calculated from the displacement $\{x\}^i$ of this step, then this value is sent from computer to controllers as the target displacement to control the actuators. After controlling is completed, load is read from load cell of actuator and is transformed into brace restoring force of step i. This calculation for central difference method are completed in step i, and then $\{x\}^{i+1}$ can be calculated and we can proceed to the next step. If the procedure mentioned above is carried out repeatedly, the hybrid earthquake response test of the multi-bay space frame model will be accomplished.

3. RESULTS

The results of complete numerical analysis are shown in Fig.9 in dotted line. In the analysis, a non-linear hysteresis model proposed by Wakabayashi is modified slightly by adding initial buckling load for purpose of simulating the hysteresis behavior of brace. The others are the same as those in a hybrid earthquake response test. And the level of input earthquake wave for both of test and analysis are set to 200 gal.

The hysteresis behavior of brace measured by loading test is shown in Fig.8. Differences of initial buckling loads of braces are found out, and the unevenness is quit large. The case which initial buckling load is 2 times greater than predicted value also appeared. The strain hardening effect, beginning after reached to 10 times of yield strain, agreed with the results of material test on brace.

Fig.9 shows time histories of displacements of planar bents, and the shapes of response wave both of analysis and test are found similar. For series of 132cm brace, even if the restoring force of brace measured in test increases after yielding because of strain hardening, the response of test becomes larger than that of analysis to some extent. This may be resulted from the unappropriate estimation of strength after buckling of brace. After buckling, deterioration of restoring force is remarkable in the test and the axial force measured increases in a quite low rate in the stage from post-buckling to tension. For this reason, it seems overestimated in complete numerical analysis. In the test of series of 66cm brace, there are a lot of cases which show that the responses in the analysis are greater than those in the test. Fig.9 also gives the response of rigid floor model (B12-R132) with the largest eccentricity until its collapse. As shown in Fig.8, the collapse begins with the bent, and the resistance of the bent is getting lost just before the displacement is reached about 7cm, then by shear floor the load is translated to adjacent braced bent. However, the collapse does not occur in complete numerical analysis, it is obvious that there is a difference between the test and analysis.

Fig.10 shows the response displacements of bents while that of bent 4 was taking maximum. Other two cases of collapse (B12-R##) are not indicated here. For cases of rigid floor frame, the response of displacement is dominated by rotation of the floor.

Fig.11 gives the relationship between inelastic response and elastic one. The vertical axis represents for ratio of yield shear force to peak response shear of elastic system, and the horizontal axis represents the peak drift angle of inelastic response. The dotted line is based on the property of energy conservation after Newmark, and the solid line shows that of displacement conservation. The mark is also plotted in the figure to indicate the peak response displacements for 4 planar bents, and it is found that except the cases of collapse, the others are located between the two lines in series of 132cm brace. Especially, case B12-F132 and B14-F132 are agree well with the displacement conversation while the series of 66cm brace are also close to.

4. CONCLUSION

The hybrid simulation system of earthquake response on multi-bay braced space frame has been developed with taking into account of the omnipresence of braces, eccentricity and non-rigid floor. The non-linear effect caused by buckling, yield and relaxation of brace are also considered by loading test. Earthquake response simulation of space frame model with 4 planar bent was carried out.

For this earthquake response experiment where interaction of multi-planar is considered, it is difficult to test a full-size model but easy to do a substructuring hybrid test as demonstrated here.

For earthquake response of multi-bay frame like this, it is found that the participation of the displacement caused by rotation of floor is quite large. Therefore, it seems necessary to treat the multi-bay frame of this kind as the space model when a test or numerical analysis is carried on for design purpose.

REFERENCE

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Table 1. Parameters used in the simulation

L (cm)	A (cm^2)	σ_y (ton/cm^2)	I (cm^4)	λ_c	P_{vc} (ton)
66.0	3.7	3.1	2.3	1.0	7.1
132.0				2.0	2.3

β	F_y (ton)	K_1, K_2, K_3 (ton/cm)	F_u (ton)	W (ton)	T (sec)
0.5	4.04	6.5, $0.03K_1$, 0.0	1.3 F_y	218.8	0.25

Notes

L: length of a brace

A: sectional area of a brace

σ_y: yield stress of a brace

λ_c: slenderness ratio of a brace

I: geometrical moment of inertia of a brace

P_{vc}: initial buckling load of a brace

β: participation ratio of moment bents in the horizontal strength of whole model

F_y: yield strength of a bent

K_1: initial stiffness of a bent

T: elastic natural period

F_u: ultimate strength of a bent

W: total mass of the floor

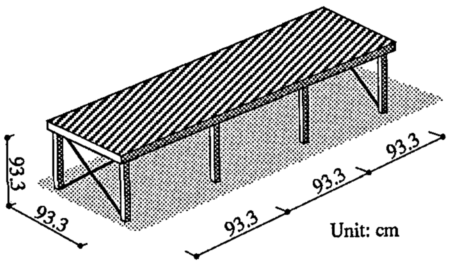

Fig.1 Structural model

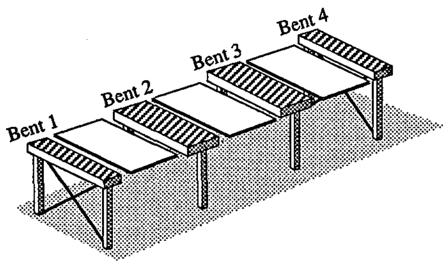

Fig.2 Decomposition of structure

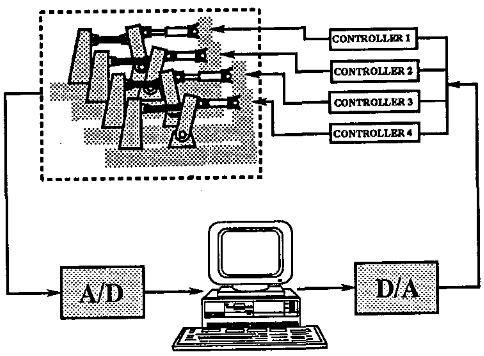

Fig.3 Hybrid earthquake response test system

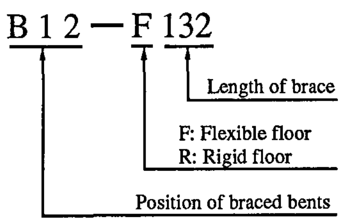

Fig.4 Test code

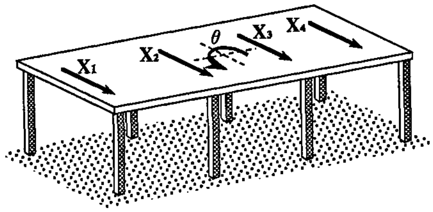

Fig.5 Space frame model of 5 degree-of-freedom

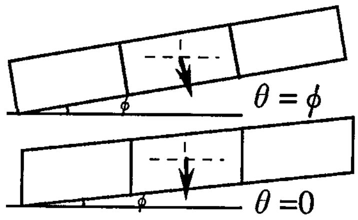

Fig.6 Image of floor rotation

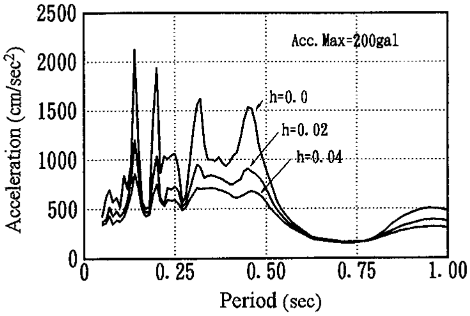

Fig.7 Spectra of HACHINOHE earthquake wave (EW)

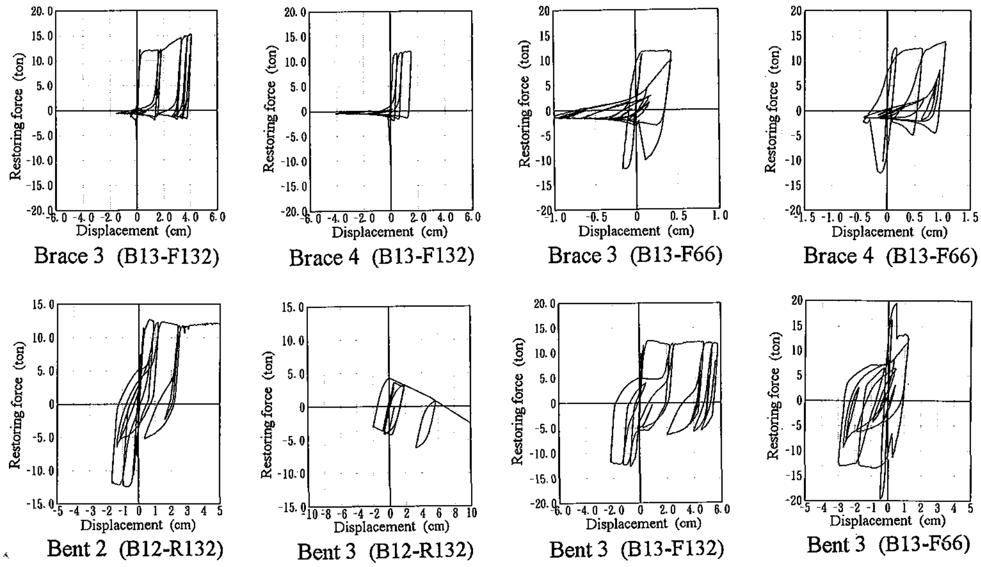

Fig.8 Measured restoring forces

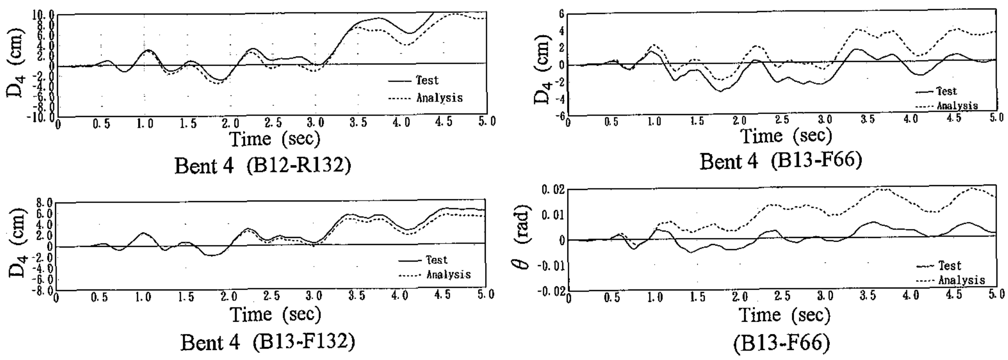

Fig.9 Time histories of displacements

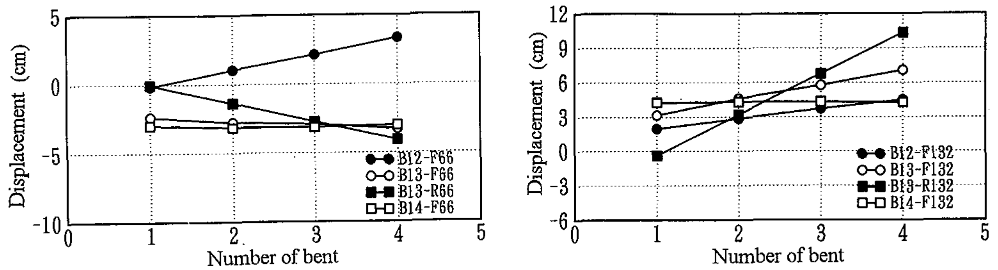

Fig.10 Deformation mode at time of maximum response

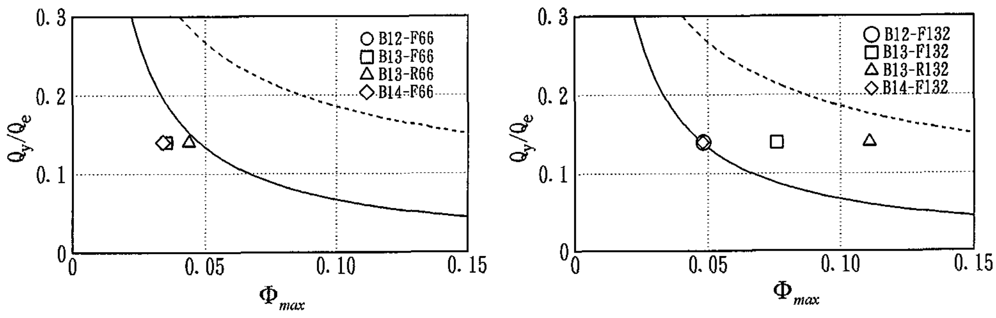

Fig.11 Relationship between inelastic response and elastic response