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SUBSTRUCTURING ON-LINE TST ON INDUSTRIAL BUILDINGS

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ABSTRACT

Structural response tests are necessitated to confirm adequateness of seismic design ways. The shaking table test is suitable for verifying overall response behavior of structures, while the on-line response test is utilized for large scaled structural model tests. The on-line test is much more facilitated by combining the substructuring method in the numerical analysis. The substructuring on-line test technique has high potential particularly to obtain earthquake response of structurally complex buildings such as industrial buildings. This paper firstly emphasizes usefulness of the substructuring on-line test and then describes a response simulation of an industrial building as an example.

KEYWORDS

Substructuring on-line test; earthquake responses; industrial buildings; steel frames; braces; braced bents; floor systems

INTRODUCTION

Most of industrial buildings have configurations of frames different from ordinary office buildings. Roofs cover wide space and sometimes their frameworks have irregular shapes due to arrangement of manufacturing line. Moreover, floors are also irregular shaped, strength and stiffness of which vary in wide range, since installed equipments and machines necessitate ample height through wide openning in the floors. These features are directly reflected on difficulties in seismic design. There exist irregular shaped frameworks. Some of them are moment resistant and others are braced by various kinds of braced systems. Connections in the frames are also quite different in strength and stiffness. Braced systems, and semi-rigid and shear connections, often used in industrial buildings, show rather complicated restoring force characteristics during earthquake response vibration. And such various types of frames scatter in a large industrial building. Accordingly, structural designers need precise structural analysis and then want to verify adequateness of analytical models, which are used in the analysis, by dynamic tests such as the shaking table tests. In most cases, however, it is impossible to test the whole structures.

As a substitute, the substructuring on-line test can be utilized. This test technique dose not necessarily use a test structure model of the whole buildings, whilė the required test structures are confined to some parts of the structures which restoring characteristics are hardly expressed as simple analytical models(Zavala et al, 1995; Dermizakis et al, 1985). As some parts of the industrial buildings which require the test, we can take the braced frames, the semi-rigid connections and the floors. This paper describes the earthquake response of industrial buildings obtained by this test technique. The industrial buildings analyzed comprise of some moment resistant bents and braced bents which are connected by rigid and/or flexible floors. The substructuring on-line test on the frame with the semi-rigid connection is already reported elsewhere (Ohi et al, 1996).

Electric power plants are such cases as mentioned above. Designers are much concerned with the behavior of planar bents during response vibration. They wonder whether each bent should be designed as an independent frame or it should be desigened considering that it is a part of the whole structural behavior. Probably, the behavior may vary according to the combination of stiffness of bents and floors. The strength must be taken into consideration beyond the elastic limit. This paper aims at an useful design guide for their inquiries.

BRIEF DESCRIPTION OF ANALYSIS

Structural Model

The model for analysis is shown in Fig.1(a), 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-typed braces, respectively. Three types of models are considered with different eccentricity due to brace arrangement. The first one is a model with large eccentricity by placing X-typed braces in the first and the second bents, the next is a small eccentricity model with X-typed braces in the first and the third bents, and the last is a symmetric model with X-typed braces at two ends of the floor. Two kinds of floors are considered; a rigid and a flexible shear floor, where the stiffness of the flexible shear floor is set equal to the initial horizontal elastic stiffness of a X-typed brace. The rigid floor is considered only in the unsymmetrical model.

There are 5 cases of the tests. As shown in Fig.1(b), a model is decomposed into 4 planar bents and 3 floors as the substructures, and then a braced planar bent is further decomposed into 2 braces and a bent as in Fig1(c). Assuming hysteresis characteristics, the decomposed parts are simulated in computer as fictitious structures except that the braces are extracted for load tests in parallel with analysis. Actually, 4 brace members are loaded simultaneously. The hysteresis characteristics measured from the test is fed back to earthquake response analysis of the whole system to simulate earthquake response. The system layout of the test is shown in Fig.2. As the loading apparatus, the actuators are controlled by the computer through the interface boards (A/D board and D/A board). The displacement meters are attached to the specimens to measure the axial displacements 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 the load cells attached to the end of the actuators.

Two kinds of brace specimens(a length is 1320 mm and the other 660 mm) are made of the steel in grade SS400, and the brace section shape is H-45 $\times$ 35 $\times$ 3 $\times$ 3 and pin-supported. Although the actual lengths of the specimen are assumed to be different, the dimensions of fictitious bents are taken as the same. Therefore, the boundary condition of both ends of the brace is considered to be different. That is, both ends of the brace of 1320 mm in length are supposed as ideally pin-supported, while the brace of 660 mm in length represents the behavior of rigidly supported brace of 1320 mm.

Equation of Motion

Only translational displacements in direction of earthquake input are considered here. The relative displacements between adjacent bents are caused by shear deformation and rotation of floors for flexible floors, while rigid rotation of the floor which can not generate shear deformation. Variables are designated as follows; $x_1 \sim x_4$ represent the vibration displacements, θ is the angle of the floor rotation, $P_1 \sim P_4$ and M are external forces and moment, $\Delta_1 \sim \Delta_4$ are the displacement of the planar bent, $F_1 \sim F_4$ are the restoring force of the planar bents. δ_A (between bent 1 and 2), δ_B (between bent 2 and 3), δ_C (between bent 3 and 4) are the relative displacements between adjacent planar bents. q_A, q_B, q_C are the shear forces associated with $\delta_A, \delta_B, \delta_C$. In the case of the flexible floor, the equation of compatibility and the equibrium equation can be written as

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

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

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

According to the d'Alembert's principle shown in Eq.(3), we can obtain the equation of motion in Eq.(4) with 5 degrees-of-freedom. For rigid floors, only 2 degrees-of-freedom are left.

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

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

where

$$[K_{\theta x}] = [k_A S_A, \quad k_B S_B - k_A S_A, \quad k_C S_C - k_B S_B, \quad -k_C S_C], \qquad K_{\theta\theta} = k_A \cdot S_A^2 + k_B \cdot S_B^2 + k_C \cdot S_C^2$$

$$I_m = m_1(S_A + S_B/2)^2 + (m_2 + m_3)S_B^2/4 + m_4(S_C + S_B/2)^2, \qquad [K_{x\theta}] = [K_{\theta x}]^T$$

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

in which $\{F_r\}$ is the restoring force vector of an assumed frame, $\{F_b\}$ is the horizontal restoring force vector obtained from the brace test, $\{F_{xp\Delta}\}$ is the force vector caused by the $P-\Delta$ effect.

PROCEDURE OF SIMULATION

Numerical Integration

The Central Difference Method is utilized for numerical integration of the response analysis. The procedure of earthquake response simulation is as follows; at the step i, the axial displacement of each brace is calculated from the displacement $\{x\}^i$, as the numerical result of Eq.(4), then this value is sent to the controllers of the actuators as the target displacement to control. After controlling is completed, the loads are read from the load cells of the actuators and is transformed into the restoring force of the braced bents. This calculation for the central difference method at the step i gives $\{x\}^{i+1}$ at the step i+1.

Restoring Forces

The analytical model of the restoring force characteristic prepared for the moment resistant bents follows the model proposed elsewhere(Takanashi et al.1992). The curve expressing the restoring force consists of two part; a trilinear skeleton curve and a hysteresis curve expressed by the Ramberg-Osgood function from the unloading point to the target point on the skeleton curve. The restoring forces of the brace members are obtained by the push-pull test and is directed to the numerical analysis. The test and the numerical analysis are conducted simultaneously.

Structural Models for Analysis

Structural models to be analyzed are identified by the code below.

B□□ − λ_c □ □ □

Earthquake waveform
H : Hachinohe 200cm/sec^2
E : El Centro 500cm/sec^2

Type of floor
F : Flexible floor
R : Rigid floor

Generalized slenderness(0.5,1.0,1.5,2.0)

Bent position for braced bents
1 to 4 from the left in Fig.1

The slenderness of the braces is expressed as the generalized slenderness λ_c. Namely,

$$\lambda_c = \sqrt{N_y / N_e} \tag{5}$$

where N_y = squash load
N_e = Euler buckling load

PARAMETERS OF STRUCTURAL MODEL

Strength and Stiffness

The sum of the yield strength of a moment resistant bent, $\sum F_F$, against a horizontal external load is set to be equal to the sum of the yield strength provided by a pair of brace members (mainly by a tension brace), $\sum F_{BT}$. There are two braced bents and two unbraced bents(Fig. 1). As the yield strength of a braced bent is already assumed the sum of F_F and F_{BT}, then $F_F = 0.5 F_{BT}$ where F_{BT} is found at the push-pull test on brace members. The horizontal stiffness of a moment resistant bent, K_I, is calculated as

$$K_I = 0.5 F_{BT} / H R_y \tag{6}$$

if the yield story drift angle R_y is set to 1/150 *a priori*, where H is the story height. The stiffness of a pair of brace members against a horizontal load is defined as

$$K_B = 2EA \sin\theta \cos^2\theta / H \tag{7}$$

where A: The section area of a brace
θ: The angle of a brace against the ground floor
E: The Young's modulus

The stiffness of the floor against the shear force acting in the floor is always assumed to be equal to K_B in Eq.(7).

Period and Mass

In the simulation, a reduced scale structural model was assumed. The length of the model is presumed to be 1/4 of the prototype. Then, the time is also scaled down to 1/2. The duration of the earthquake waveform was condensed to a half. Moreover, the $P-\Delta$ effect acting on the prototype must be preserved, satisfying the following equation.

$$\frac{K_{P\Delta}}{K} = \frac{T^2 g}{H} = const. \tag{8}$$

where $K_{P\Delta}$ = the stiffness of negative slope due to $P-\Delta$ effect
K = the initial stiffness
T = the fundamental period
g = the gravity acceleration

Thus, the period of the model must be a half of the prototype. To set 0.5 sec. for the prototype, the period of the model is 0.25 sec. The mass of the model is automatically determined with the values of the stiffness already assigned and the fundamental period. The 1/6 of the total mass is allotted to each outer bent, while the 1/3 of the mass to each inner bent. The basic parameters are summarized in Table 1.

Earthquake Wave Forms

Two recorded earthquake waveforms were used in the simulation. One is the EW component of waveform recorded at Hachinohe in 1968, and the other is the NS component of waveform recorded at El Centro in 1940. The peak accelerations were adjusted to 200 cm/sec^2 and 500 cm/sec^2, respectively.

RESULTS

Some typical results obtained from the simulations are shown here. As an example, the results of the simulation coded as B13-λ_c2.0FH are illustrated in Fig.3. In this simulation the braces are framed into Bent 1 and 3, and the slenderness of the braces λ_c is 2.0. The floor is flexible and its stiffness is assumed the same as the stiffness defined as Eq.(7). Among the hysteresis loops shown in Fig.3, only the hysteresis denoted as BRACE is the result of the push-pull test. The hysteresis loops denoted as MRB followed the assumed analytical model, and the loops denoted as BRACED BENT is the sum of the brace's and MRB's. It is shown that the test results are satisfactorily taken into the simulation and combined with the analytical model. The twisting of the floor is the most interesting item in the simulation. Fig.4 shows the response displacements of the bents at the instant when the displacement of Bent 4 took the maximum. The solid circles, squares and triangles in the figures show the braced bents. It clearly indicates that the rigid floor makes large twisting if the bents with higher strength were allocated asymmetrically in the plan.

Participation of bents in resistance against earthquake motion is an another interesting item, particularly for designers. Fig.5 shows the maximum restoring forces recorded during the simulations. It is well understood that the symmetrical allocation of the braced bents induce relatively uniform inertial forces, while asymmetrical allocation of the braced bents makes irregular participation, particularly in the rigid floor.

CONCLUSION

The following conclusions are drawn from the simulations.

1. It was verified that the substructuring on-line test technique can be utilized for the earthquake response simulation. Structural tests can be confined to some particular tests on specific structural models which show too complex force-deformation relationship to be expressed in analytical models.
2. Allocation of seismic bents, the braced bents for example, which can mainly resist against earthquake load should be a basic item for seismic design. Unbalanced allocation sometimes induces large twisting vibration of the structure.
3. It is concluded that the rigid floor sometimes makes a large twisting vibration beyond the tolerable response behavior, while insufficient stiffness of the floor cannot restrain the irregular displacements of the bents in case of their unbalanced allocation.

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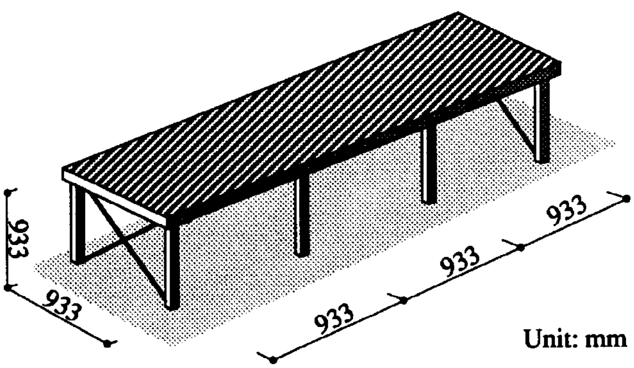
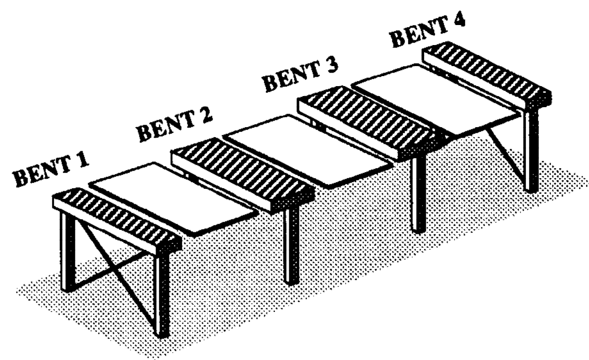
Table 1. Parameters used in the simulation

β	Fy (ton)	K_1 (ton/cm)	K_2 (ton/cm)	K_3 (ton/cm)	Fu (ton)	W (ton)	T (sec)
0.5	4.04	6.50	$0.03K_1$	0	$1.3Fy$	219	0.25

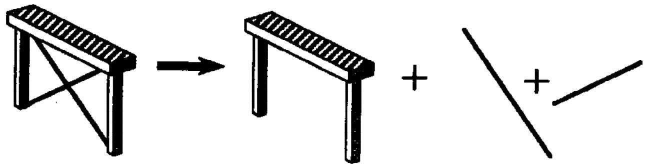
Notes
β : the participation ratio of a moment resistant bent(MRB) in the horizontal strength of a braced bent
Fy : the yield strength of a MRB
K_1 : the initial stiffness of a MRB
Fu : the ultimate strength of a MRB
W: the total weight of the floor
T : the fundamental period



(a) Structural model



(b) Bents and flexible floors



(c) Decomposition of a braced bent

Fig.1 Structural model of a power plant building

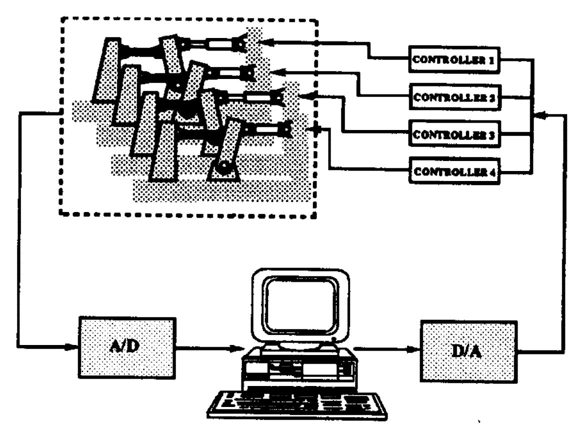


Fig.2 Hybrid earthquake response test system

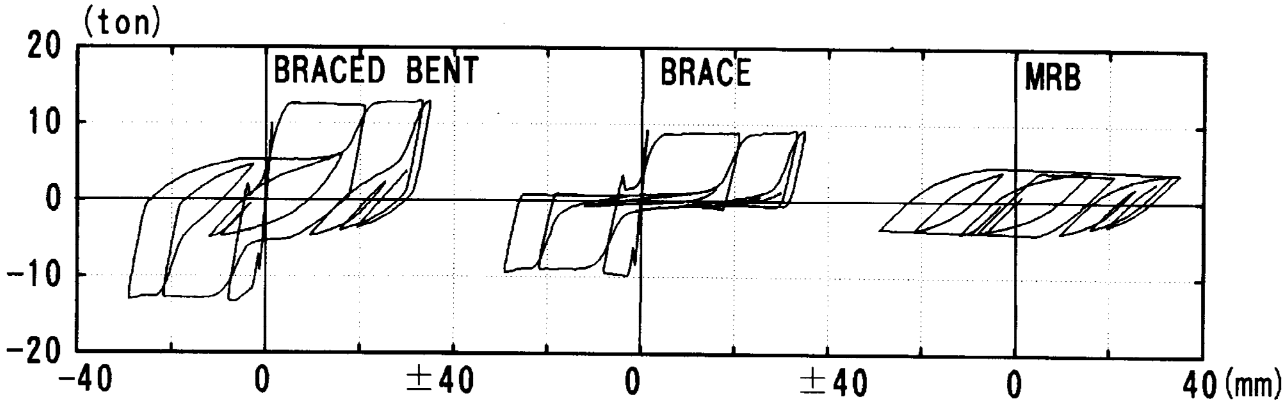


Fig.3 Response of B13-λ_c2.0FH

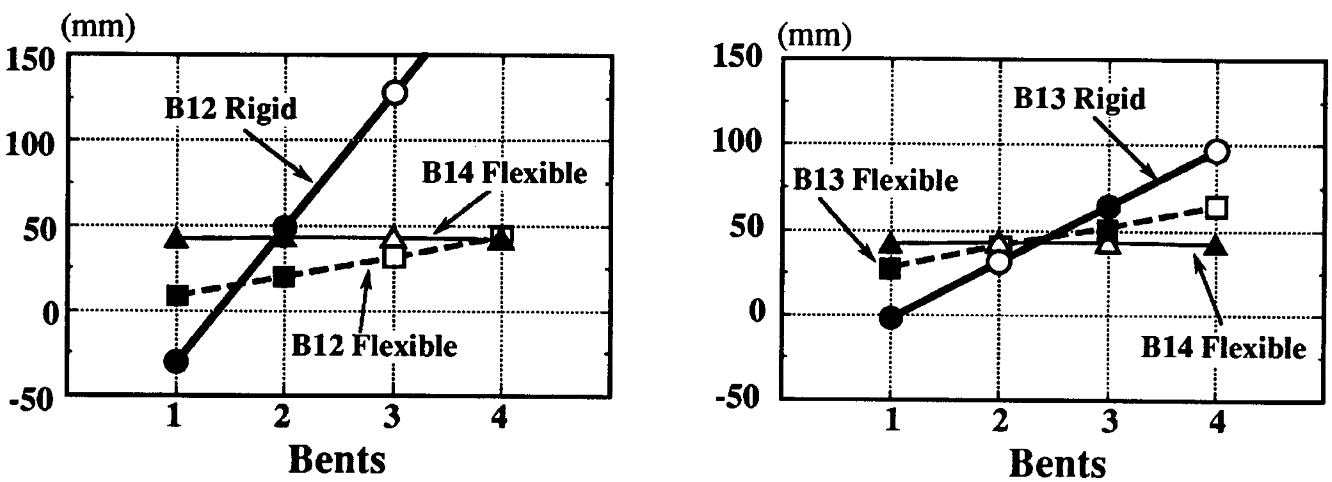


Fig.4 Displacements of bents

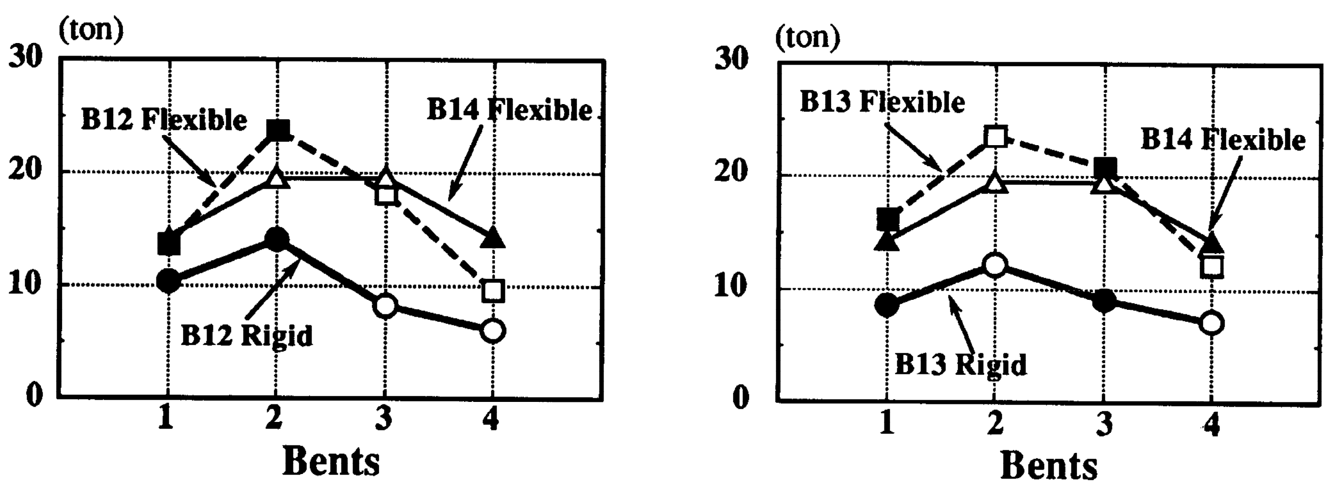


Fig.5 Restoring forces of bents