SUBSTRUCTURING HYBRID SIMULATION ON STEEL BRACING SYSTEM

TAKANASHI Koichi(1), OHI Kenichi(2),
YAMADA Takao(3) and OGURA Hiroyuki(4)

Abstract

Earthquake response of braced frame with X-type braces was analyzed utilizing the substructuring technique. The braced frames analyzed were substructured into brace subassemblages and moment resistant frames. A realistic analytical model was used for the moment frames, while in pseudodynamic tests of the brace subassemblages, a set of two push-pull tests on brace members was conducted using the on-line computer test control technique. The performance of the system for substructuring method was verified to be satisfactory.

1. INTRODUCTION

Advantages of substructuring method in structural tests were already discussed from the technical and economical view points [1]. There, it was emphasized that the substructuring concept was substantially necessary in the pseudodynamic test method. To overcome some problems arisen in the substructure pseudodynamic test for the multi-degree of freedom system, an algorithm has been proposed [2]. In spite of that the importance of the substructuring technique is widely known, there are only a few test results reported in the past. The authors believe that experiences in these tests must be more accumulated in order to extend its application into other experimental approach and to explore advanced techniques. In this paper a simple example recently carried out by the authors is described.

There are two objectives of this test: The first is to verify the performance of the test system using the substructuring technique in Institute of Industrial Science, UT, while the second is to examine availability of a high strength steel (tensile strength σ_u = 80kg/mm^2) with high ductility.

2. A FRAME ANALYZED AND SUBSTRUCTURED SUBASSEMBLAGES

A simple frame shown in Fig. 1 was taken for the analysis. It is composed of two planar frames; one is a braced bent with X-type braces and the other is a moment resistant bent. These planar frames are connected with a floor. The frame is decomposed into substructured assemblages as shown in Fig. 2 in the analysis. There are two possible decomposition ways. In the case that the floor has high stiffness and mass on the floor is uniformly distributed, the floor behaves as a single body. On the other hand, separating floor is preferable in case the floor stiffness is not so high. A large spanned steel structure is such a case. In this analysis, subassemblages as shown in Fig. 2 were treated, adding the separated floors to the planar frames which are connected with a shear plate. The braced frame was further decomposed into a moment resistant bent and a brace subassemblage as shown in Fig. 3. The brace members are cyclically pulled and pushed during response to earthquake motion. This behavior was realized by a set of two push-pull tests controlled by computer, where the tensile displacement applied to a tension brace member and the compressive displacement to a compression member are commanded to adjust them to the right horizontal displacement of

(1) Professor, IIS, University of Tokyo, (2) Associate Professor, ditto.,
(3) Director, NKK Corporation, (4) Graduate Student, University of Tokyo.

the above–mentioned brace subassemblage. Response behaviors of the remaining part of the subassemblages were simulated by computer analysis using predetermined analytical models. The numerical analysis and the test were conducted pseudo–dynamically, using the on-line test control technique. The horizontal displacements of the moment resistant frame and the brace subassemblage were precisely controlled in conformity with each response displacement at each time step obtained from step–wise numerical solution of the equation of motion.

3. BRACE MEMBERS

The brace members used in the test were manufactured from high strength steel plate which tensile strength is greater than 80 kg/mm^2. This steel material was newly developed for structural steel which is required to have both high strength and high ductility. To use it as a brace member is an application, since high tensile force is expected to resist horizontal forces induced by earthquake and wind pressure. The brace members are also exposed to severe cyclic loadings. To approve enough ductility it possesses, simple cyclic push–pull tests were carried out. Fig. 4 shows a brace specimen used in the cyclic tests and the pseudo–dynamic test as well. The material properties obtained by the coupon tests are summarized in Table 1. The yield strength was defined as 0.2 % offset strength in the round house type stress–strain curve. The yield ratio YR is an important parameter to represent the ductility required. Lower values in YR are preferable.

Cyclic test results are shown in Fig. 5. In the tests, a 8 cycle push–pull test was conducted at each amplitude. Large reduction in strength is observed in later cycles at an amplitude, but the steel material kept enough ductility even in the large amplitude.

4. DESCRIPTIONS OF ANALYSIS

Five types of analysis were carried out. These are denoted as CODE A to E. Yield strength of each subassemblage, designated by β_B or β_F, was arbitrarily assumed though the brace members used in the test part have the same section. Only the slenderness of the braces used in CODE E was different.

The parameters used in the analysis are summarized in Table 2, and the definitions of the parameters are illustrated in Fig. 6. In CODE A, B and E, a single planar frame was considered, while in CODE C and D a braced and an unbraced planar frame connected with a floor were analyzed. Difference in the yield strength of frames should be noted.

5. ANALYTICAL MODEL AND STRUCTURAL TEST

The equations of motion solved in the analysis are:

$$\begin{aligned} m_1\ddot{x}_1 + F_1 + K_S(x_1-x_2) &= -m_1\ddot{y} \\ m_2\ddot{x}_2 + F_2 - K_S(x_1-x_2) &= -m_2\ddot{y} \end{aligned} \qquad (1)$$

where x_1 and x_2 are response displacement of Braced Frame 1 and the Frame 2, respectively. F_1 and F_2 are the restoring force of each frame. F_1 is the sum of the restoring forces of the moment resistant bent and the brace subassemblage obtained from the test. K_S is the floor stiffness for the plane shear force. $\ddot{y}$ is the input acceleration. Here, the wave form of 1940 El Centro NS was used.

The restoring forces in the analysis part were calculated using the skeleton curve and the hysteresis rule defined in Fig. 7. This analytical model was already proposed by OHI et al.[3] and is not here explained in detail. The test part is composed of two push-pull tests illustrated in Fig. 8. Two brace members of H-shaped section were installed in the test rigs and stretched and compressed under precisely controlling according to computed deformation. In this procedure the on-line computer test control technique was fully utilized [4].

6. RESULTS

Only a part of results obtained in the analysis are shown in this paper. Fig. 9 shows hysteretic behavior of substructured assemblages in CODE B(left) and C(right). The top figures show hysteretic loops of the braced subassemblages which were obtained in the test part. The middle figures show the hysteretic behavior of a single moment resistant bent in CODE B and two moment bents in CODE C, respectively. The bottom figures show the response behavior the braced bents. The hysteretic behavior of the braced bent was made summing the values in F_B obtained in the test and F_1 obtained in the calculation at the same displacement B. In the analysis of CODE C, the braced and the unbraced have a quite different yield strength. Nevertheless, the response behaviors in both bents are almost same as shown in the right-middle figure of Fig. 9. It can be also recognized from the time history of response displacement in the third figure of Fig. 10. Preliminary study on the effect of floor stiffness on the response behavior of both bents taught us that a noticeable difference in both responses appears in case the floor stiffness becomes small. Further studies, however, are needed to reach a definite conclusion. The figures in Fig. 10 show the time history of the response displacements and the restoring forces. Smooth curves obtained show the evidence that the analysis and the test were well conducted.

7. CONCLUSIONS

(1) A new developed test system utilizing the substructuring technique was applied to an analysis of a simple frame model. Performance of the system was verified well by this analysis and expected to use for further problems.

(2) Difference in stiffness of a floor, which connects two planar frames with different behavior models, did not affect the response behavior of the frames. Further studies on this subject are still needed.

(3) A newly developed high strength steel can be used for brace members which are expected to be subject to severe cyclic loading.

REFERENCES

[1] Dermitzakis, S.N. and Mahin, S. A, "Development of Substructuring Techniques for On-line Computer Controlled Seismic Performance Testing," UCB EERC-85/04, Feb., 1985

[2] Nakashima, M., "Experiments of Hybrid Structural Testing," Report of Grant in Aid for Scientific Research No.02555127, March 1992.

[3] Ohi, K. and Takanashi, K., "Multi-Spring Joint Model for Inelastic Behavior of Steel Members with Local Buckling," Stability and Ductility of Steel Structures under Cyclic Loading., June 1992, 215-224.

[4] Takanashi, K. and Nakashima, M., "Japanese Activities on On-line Testing," J. Engrg. Mech., ASCE, 113(7), 1014-1032.

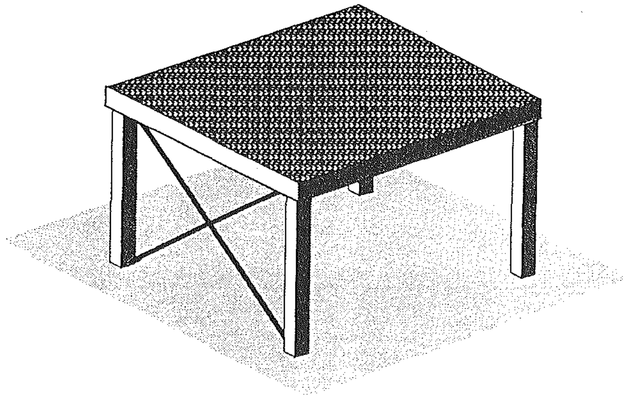


Fig. 1 A frame analyzed

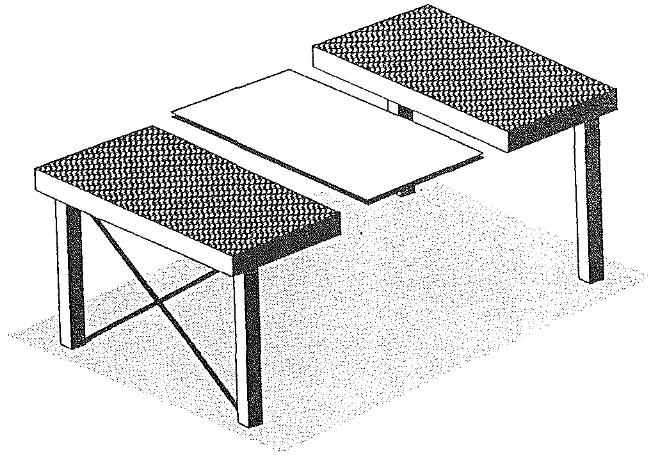


Fig. 2 Substructured subassemblages

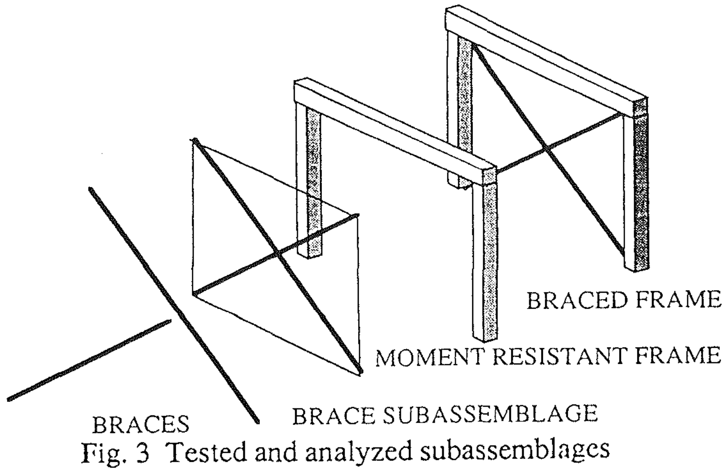


Fig. 3 Tested and analyzed subassemblages

Table 1 Material properties of steel

CODE	B (mm)	t (mm)	L (mm)	A (cm^2)	σ_y (t/cm^2)	σ_u (t/cm^2)	YR (%)	E_{st}/E	EL (%)
HT80K-1	25.00	5.05	60	1.263	6.63	8.15	81	1/27	20
HT80K-2	25.00	5.05	60	1.263	7.53	8.86	85	1/26	18
HT80K-3	25.00	5.05	60	1.263	7.20	8.63	83	1/27	18

Note B: Width
t : Thickness
L: Gauge length
A: Section area
σ_y: Yield strength = 0.2% offset strength
σ_u : Tensile strength
YR: Yield ratio = σ_y/σ_u
E: Young's modulus
E_{st}: Strain hardening modulus
EL: Elongation

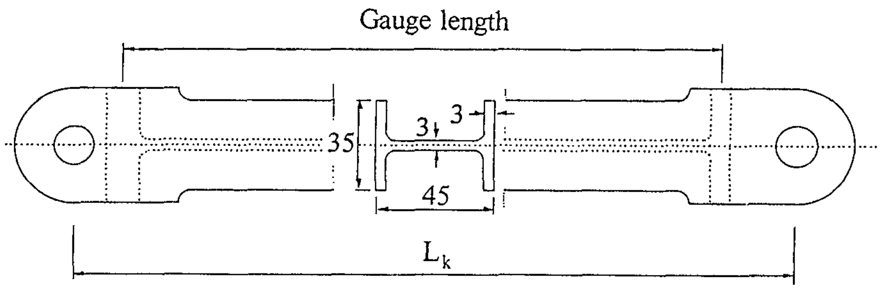
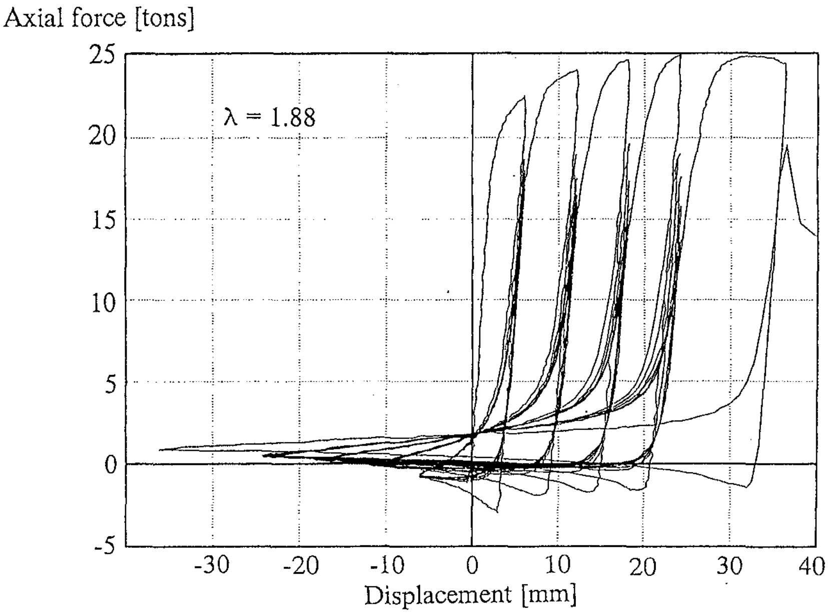


Fig. 4 Brace specimen



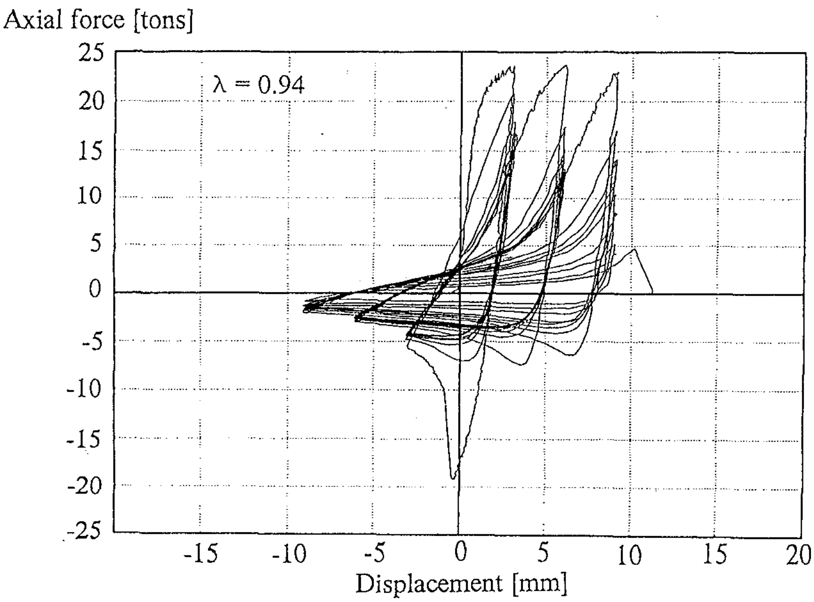


Fig. 5 Cyclic test results of brace members

Table 2 Parameters used in the analysis

CODE	λ	P_{Bt} (ton)	P_{Bc} (ton)	β_B	β_F	F_{1y}(ton) / F_{2y}(ton)	K_1(t/cm) / K_2(t/cm)	w_1(ton/g) / w_2(ton/g)	α_y	$\ddot{y}$ (cm/sec²)	T_1(sec) / T_2(sec)	K_s (t/cm)
A	1.88	21.3	1.76	0.9	0.1	2.13	6.71	0.267	0.0814	160	0.3	–
					–	–	–	–			–	
B	1.88	21.3	1.76	0.5	0.5	19.2	60.4	0.390	0.101	200	0.3	–
					–	–	–	–			–	
C	1.88	21.3	1.76	0.5	0.25	9.6	30.2	0.195	0.101	200	0.326	111
					0.25	9.6	30.2	0.195			0.155	
D	1.88	21.3	1.76	0.5	0.1	3.84	12.1	0.195	0.101	200	0.311	111
					0.4	15.35	48.4	0.195			0.157	
E	0.94	21.3	3.28	0.5	0.5	20.5	129.0	0.797	0.0523	100	0.3	–
					–	–	–	–			–	

w_1, w_2 : Weights of floors
$\ddot{y}$: Peak value of input acceleration
T_1, T_2 : 1st, 2nd natural period
K_s : Stiffness of floor
λ : Slenderness ratio of brace
$\beta_B = F_{By} / \Sigma F_y$
$\beta_F = F_{1y} / \Sigma F_y$ or $F_{2y} / \Sigma F_y$, $\Sigma F_y = F_{By} + F_{1y} + F_{2y}$
$\alpha_y = \Sigma F_y / g \Sigma m$

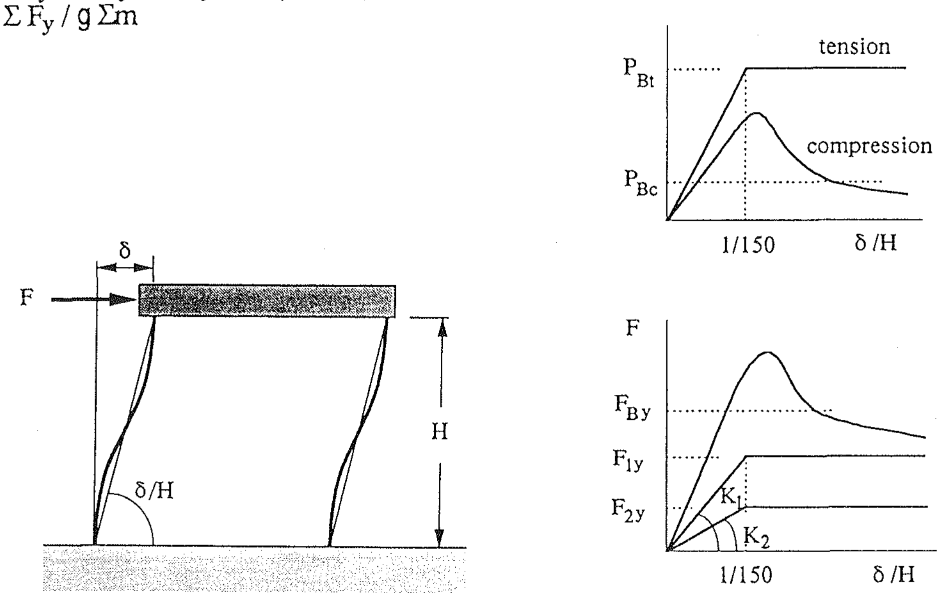


Fig. 6 Definitions of yield strength and stiffness

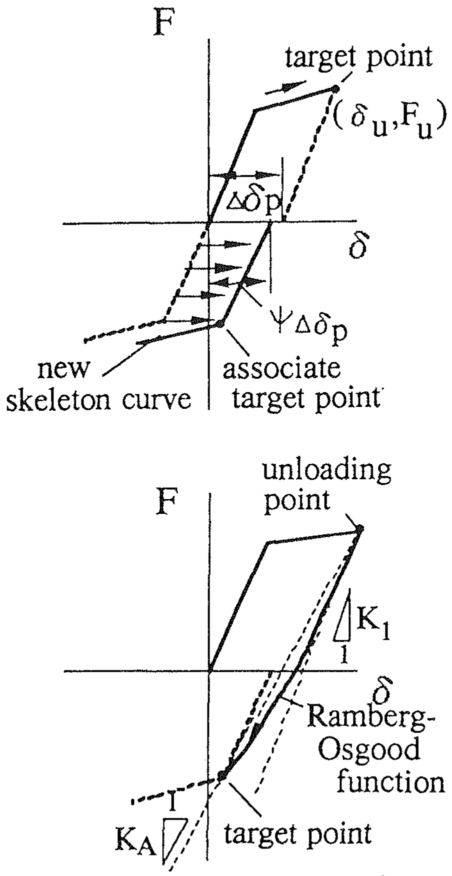


Fig. 7 Skeleton curve and hysteresis rule used in the analysis

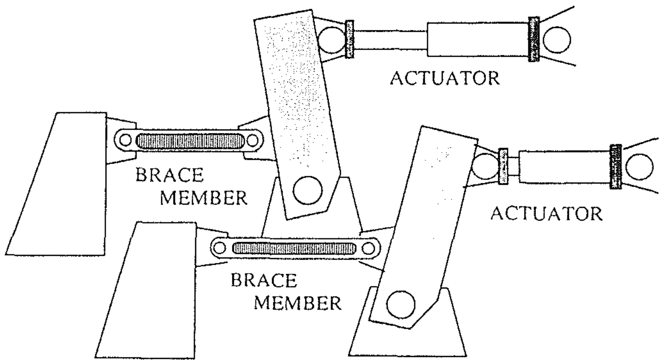


Fig. 8 Schematic view of test setup

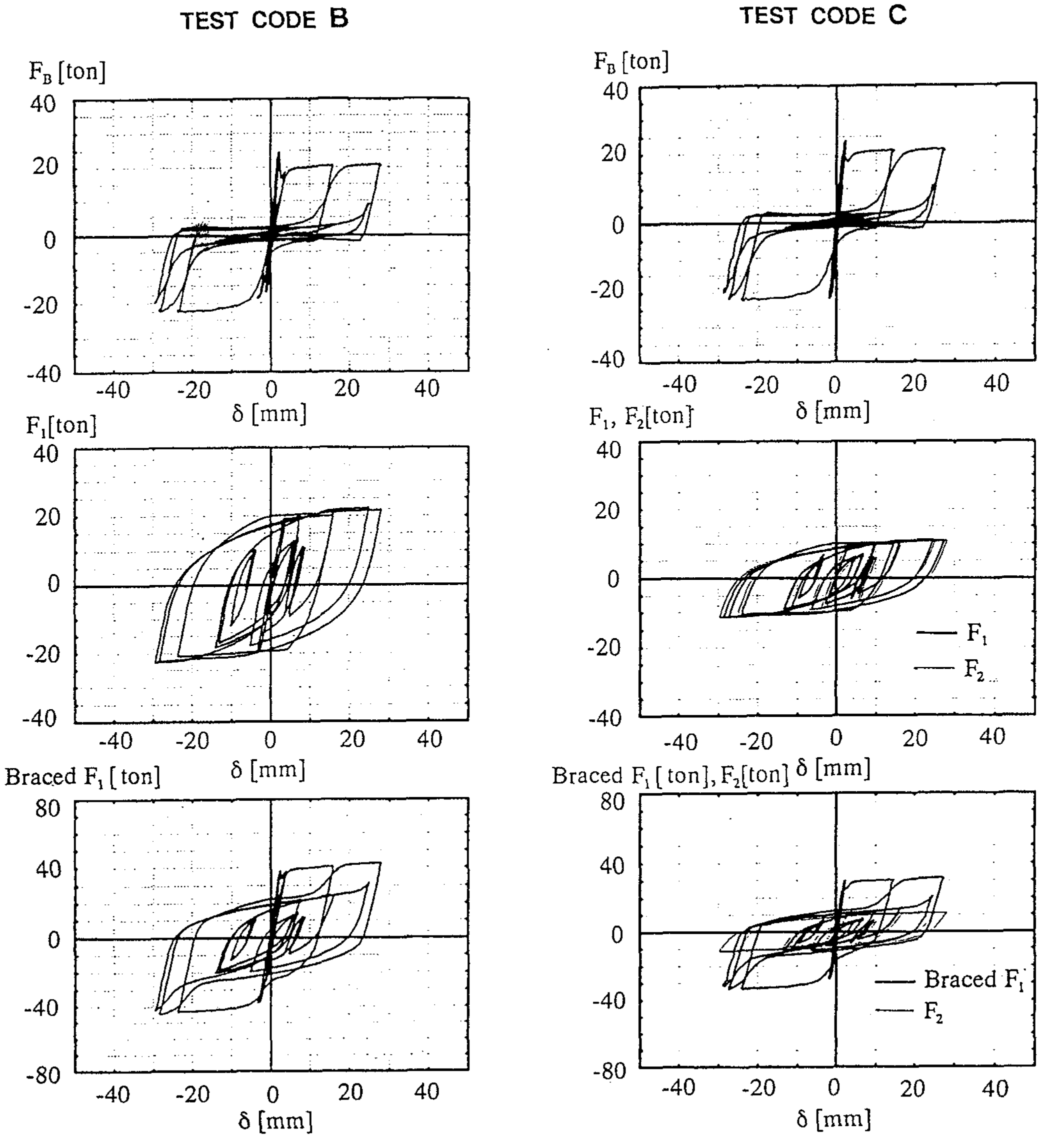


Fig. 9 Force vs. displacement relationship in testcode B and C

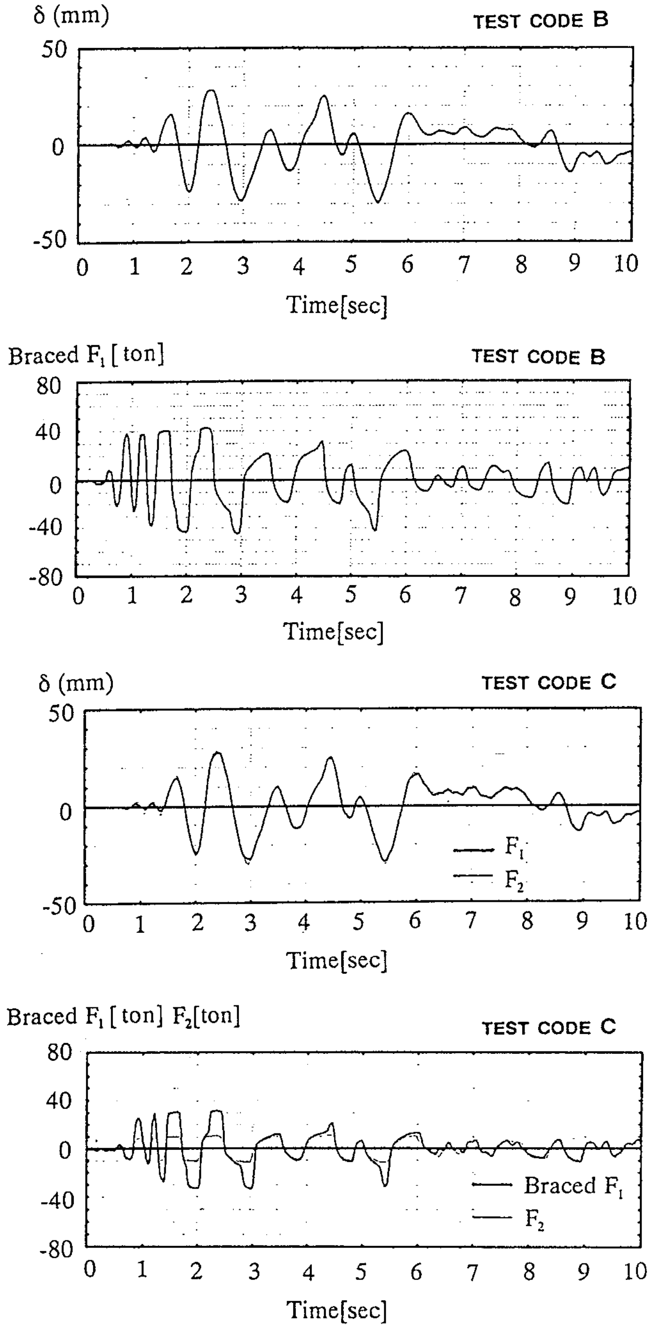


Fig. 10 Time histories of displacement and force in testcode B and C