HYBRID SIMULATION OF SEISMIC RESPONSES OF SEMI-RIGIDLY JOINTED STEEL FRAMES

by

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ABSTRACT

This paper presents the results from monotonic loading tests, cyclic loading tests and pseudo-dynamic tests on semi-rigidly jointed steel frames. There are two types of test specimen used as semi-rigid connections: split-tee type and angle type. In the pseudo-dynamic tests, the applicability of sub-structuring techniques to the earthquake response simulation on semi-rigidly jointed 2-story steel frames is demonstrated, and the influence of pinching effects in the restoring force characteristics on the global response of semi-rigidly jointed steel frames is discussed.

INTRODUCTION

Welded connections are widely used in beam-to-column connection of steel frame as rigid connections. But some diaphragms should be welded to the joints to obtain sufficient rigidity and strength, and it is observed in the recent earthquake damage, that the strain concentration in the vicinity of the weld may cause the fracture when loaded by severe earthquakes. Instead of such a welded rigid connection, another details semi-rigidly connected by cleats and mechanical fasteners are sometimes used in European and American countries. In Japan, however, these types of semi-rigid connection are not so popular except systematically prefabricated low-rise residential buildings, usually braced frames. The reason is that the structural design of middle-rise unbraced frame is mainly controlled by drift limitation, and the usage of semi-rigid joints will make it more stringent. Even with this demerit, the fabrication error of members can be easily absorbed with such a detail, and the construction and quality controls become easier. Furthermore, there are various combinations of connection stiffness and strength available corresponding to various types of semi-rigid details, and then it is possible to control the collapse mode and the energy absorption capacity of frames to a severe earthquake by an appropriate use of semi-rigid connections. In addition, stiffness and strength of semi-rigidly jointed frames can be enhanced by adding earthquake resisting elements like braces to dissolve the demerit mentioned above.

In this study, two types of semi-rigidly jointed beam specimens are fabricated and tested: one is connected by split-tees and the other is connected by top, seat, and double web angles. Quasi-static loading tests are performed to identify the restoring characteristics including pinching effect, and pseudo-dynamic tests are carried out to demonstrate the applicability of

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sub-structuring technique to the earthquake response simulation on semi-rigid jointed 2-story steel frames. In this paper, the results of monotonic and cyclic loading tests as well as the earthquake response simulation on semi-rigidly jointed 2-story frame are presented.

BRIEF DESCRIPTION OF QUASI-STATIC LOADING TESTS

The setup for testing is shown in Fig.1, where a test specimen composed of a beam and a connection is loaded as a cantilever beam. The lower end of beam is jointed to base block through a semi-rigid joint, and the other end is the pinned end loaded by an actuator. Two types of joint details are used as follows:

(A) Split-tee type: Fig.2 shows the details of connection. These split-tees are made of JIS steel grade SS400 and cut from rolled H-shaped section, H-150×150×7×10. Four high-strength bolts are used in each of web and flange of tee. Pretension in high-strength bolts is about 11.4 ton, and bolt-hole clearance is 2.0 mm.

(B) Angle type: Fig.3 shows the details of connection. In this case, top and seat flange angles and double web angles are used, which are made of JIS steel grade SS400 rolled angle, L-75 ×75×9×8.5. As for the mechanical fasteners, the same high-strength bolts are used in the same conditions with the split-tee type.

Each type of joint detail is used both in monotonic and cyclic loading tests. The beams to be connected are commonly made of JIS steel grade SS400 rolled H-shaped section, H-250×125× 6×9.

RESULTS OF LOADING TESTS

The inelastic behaviors of split-tee type and angle type observed in the monotonic loading tests are shown in Fig.4. The vertical axis represents for the ratio of moment of beam end to fully-plastic moment of beam, while the horizontal axis represents the rotation angle of beam including rotation of joint. Initial slippage of bolted joints occurs in the early stage of plastic range. In the case of angle type, the restoring characteristics are similar to a bilinear curve, and in the case of split-tee type, tangent stiffness after yielding decreases slightly when the specimen comes close to the ultimate state. The slip coefficient measured from the tests is around 0.39.

Fig.5 shows hysteresis behaviors observed in the cyclic loading tests. As for the initial slip loads, they almost agree with the slip loads measured from the monotonic loading tests. The end moment, M/M_p, is kept less than 0.8 during all the tests, and the beams stay in elastic range. The inelastic energy absorption is done by split-tees and angles completely, and deformation concentrates at the semi-rigid joint. The split-tee type has larger yield strength and less stringent pinching effect than those of the angle type. The relationship between slip resistance and loading cycle is shown in Fig.6, where the vertical axis is the value of M_s/M_{so}. M_s denotes the slip resistance observed at each loading cycle, and M_{so} denotes that of monotonic loading test. In the case of split-tee type, the level of slip resistance gradually decrease, according with the loading cycles and rotation amplitudes, to 60% of initial slip resistance finally. Fig.7 shows the rotation range when pinching is observed. The ratio of the pinching range to the whole rotation amplitude, L_s/A, are plotted to the ratio, A/A_c, where A denotes rotation amplitude at each loading cycle and A_c denotes the pinching range corresponding to bolt-hole clearance. The relationship shown in the figure looks like approximately linear, and then the pinching range L_s can be expressed by a quadratic function of the rotation amplitude A .

BRIEF DESCRIPTION OF EARTHQUAKE RESPONSE TESTS

The models for testing are shown in Fig.8, model B is different from model A by adding fictitious braces as earthquake resisting elements, the 2-story moment frames are composed by using split-tee or angle type semi-rigid joints. Four earthquake response tests are performed, each model with split-tee type connections and angle type connections. In these tests, sub-structuring pseudo-dynamic test techniques are applied, and the columns are assumed as elastic elements and simulated in computer as fictitious structures. The beams and their connections are extracted for loading tests performed in parallel with analysis. In the case of model B, the fictitious braces are simulated by using slip model. The contribution of these braces in strength is taken as 0.5, which is the ratio of strength of braces to that of the whole system. The testing system is shown in Fig.9. Being as loading apparatus, the actuators and the controller are connected to the computer through two kinds of interface boards (Analog to Digital and Digital to Analog). In the test, the value of load is read from the load cell attached to the actuator and feed back to the computer system as beam restoring force so that the hybrid response analysis can be performed on a whole structural system including fictitious elements. The beam specimens and the semi-rigid connection details (split-tee or angle type) are the same as in the quasi-static loading tests. The moment of inertia of fictitious column is assumed to 2.8 times of beam specimen (I_c=10125cm^4) and mass of each story is assumed to be 15.0/980 toncm^{-1}sec^2 and concentrated at each node. The average value of initial elastic stiffness of split-tee type and angle type, both measured from the quasi-static loading tests, is around 850 t·m/rad. The fundamental natural period of the unbraced frame becomes 1.0 sec if based on this average stiffness value. The natural periods based on actual stiffness K of each details are:

(a) Split-tee type, K=1000t·m/rad. Model A: T_1=0.94sec, Model B: T_1=0.54sec

(b) Angle type, K=720t·m/rad. Model A: T_1=1.08sec, Model B: T_1=0.66sec

EQUATION OF MOTION

The equation of motion and the attendant equilibrium equation of 2-story moment frame can be formed as

$$[M]\begin{Bmatrix}\ddot{x}_1\\ \ddot{x}_2\end{Bmatrix}+[K_1]\begin{Bmatrix}x_1\\ x_2\end{Bmatrix}+[K_2]\begin{Bmatrix}\theta_1\\ \theta_2\end{Bmatrix}+[K_3]\begin{Bmatrix}R_1\\ R_2\end{Bmatrix}=-\begin{Bmatrix}m_1\ddot{y}\\ m_2\ddot{y}\end{Bmatrix} \quad (1)$$

$$[K_4]\begin{Bmatrix}\Delta x_1\\ \Delta x_2\end{Bmatrix}+[K_5]\begin{Bmatrix}\Delta\theta_1\\ \Delta\theta_2\end{Bmatrix}+\begin{Bmatrix}\Delta M_{b1}\\ \Delta M_{b2}\end{Bmatrix}+\begin{Bmatrix}M_{u1}\\ M_{u2}\end{Bmatrix}=\begin{Bmatrix}0\\ 0\end{Bmatrix} \quad (2)$$

in which X_i=displacement of i story; θ_i=beam end rotation angle including deformation of a beam; R_i=restoring force of braces of i story, but in the case of model B, R_i=0; M_{bi}=beam end moment of i story; M_{ui}=unbalance moment of i joint in the last step that is calculated from actual moment of beam end measured by loading test. The Central Difference Method is utilized for numerical integration of the response analysis. In this testing, when loading of n step is completed and put forward to $(n+1)$ step, $\{x\}_{n+1}$ can be calculated from equation (1) while $\{M$

$b\}_{n+1}$ is necessary for calculating $\{\theta\}_{n+1}$ from equation (2). Nevertheless, it is impossible to proceed loading because $\{\theta\}_{n+1}$ is unknown. Accordingly, the relationship between $\{\Delta Mb\}$ and $\{\Delta\theta\}$ need to be predicted. Here, a bilinear model is adopted to predict the restoring of specimen. Unbalance moment due to this prediction error will be dissolved in the next step as shown in equation (2). The NS component recorded at El Centro in 1940 has been used as input earthquake wave, where duration is 10 sec and the input level was magnified to 550 gal.

RESULTS OF EARTHQUAKE RESPONSE TESTS

Fig.10 shows the time histories of displacement, and the results of completely numerical analysis are also plotted in dotted line. In the analysis, a skeleton-shift hysteresis model was used for simulating the hysteresis behavior of semi-rigidly connected beam. The parameters are assigned based on the results of quasi-static loading tests, and the influence of pinching of restoring characteristic is not taken into account in the completely numerical analysis. In the case of split-tee type, the maximum displacement response of completely numerical analysis is 20% smaller than the tests. In the case of angle type, the value is over 40% and the unbraced moment frame (model A) in the tests begins to collapse at around 4.5 sec, it looks much different from completely numerical analysis because a significant pinching effect occurs in the hybrid test. In the tests of braced frame (model B), the braces are useful for resisting earthquake loading, and the displacement response turn to half of the case of unbraced frame.

The hysteresis behavior of joint including beam deformation is shown in Fig.11 and Fig.12. Slip of bolt frequently occur at the stage of loading level is 60% of initial slip resistance, and pinching loop has been formed. The earthquake energy is completely absorbed by deformation of connections in the case of model A. In the case of model B, the braces absorbs 30~40% of whole earthquake energy. The measured restoring characteristics look much different from the bilinear model used as predictor. But the unbalance moment at the node caused by error of prediction is stable as shown in Fig.13, and it is kept within a small value except at the moment of bolt slip.

CONCLUDING REMARKS

The following conclusion are drawn from the simulation:

(1) Sub-structuring techniques in pseudo-dynamic testing is useful to simulate earthquake response of structural system affected by the local non-linear behaviors like semi-rigid joints.

(2) The local pinching effect at the semi-rigid joints sometimes affects considerably on the global response of the frame. and then it shall be considered properly in the mathematical modeling.

(3) With the presence of moderate non-linearity induced by the semi-rigid joints tested herein, a hybrid test can be performed successfully even with a simple bilinear predictor for unknown specimen resistance, as long as an effective corrective algorithm is employed to remove the moment imbalance at the nodes.

(4) The brace as earthquake resisting element in the semi-rigidly jointed steel frame is useful to absorb earthquake energy and reduce the displacement response of frame.

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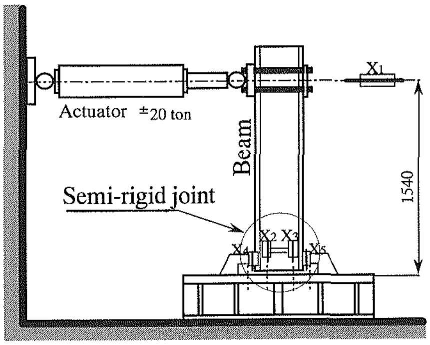


Fig.1 Test setup

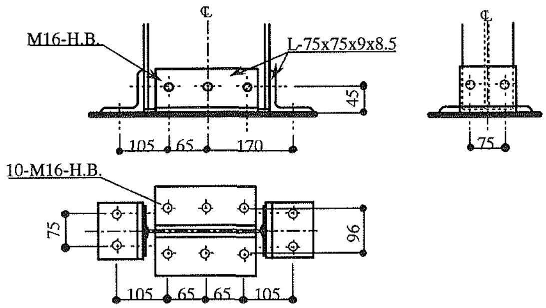


Fig.2 Semi-rigid joint with top, seat and side angles

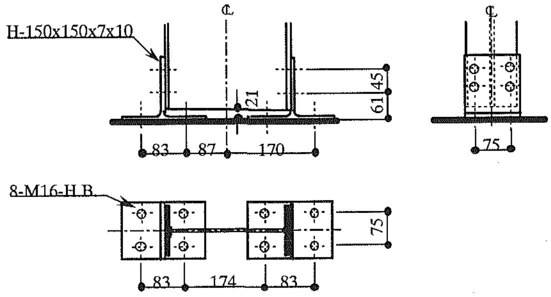


Fig.3 Semi-rigid joint with split-tees

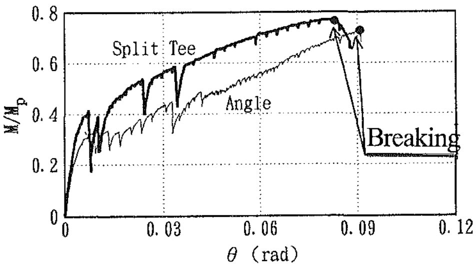
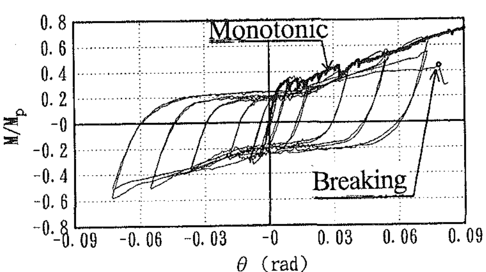
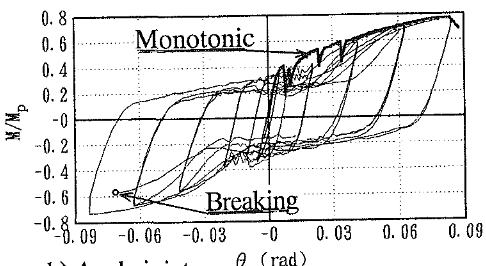


Fig.4 Monotonic loading tests



a) Split-tee joint



b) Angle joint

Fig.5 Cyclic loading tests

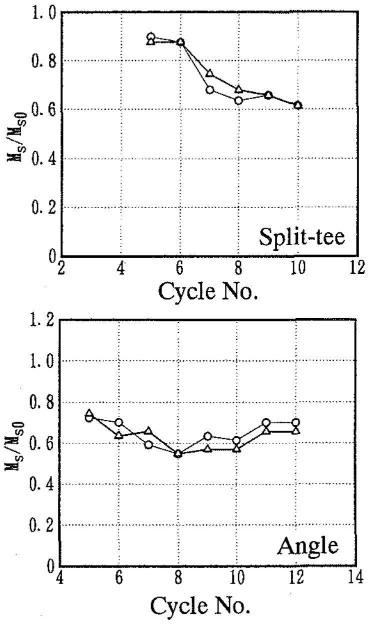


Fig.6 Joint resistance during pinching is observed

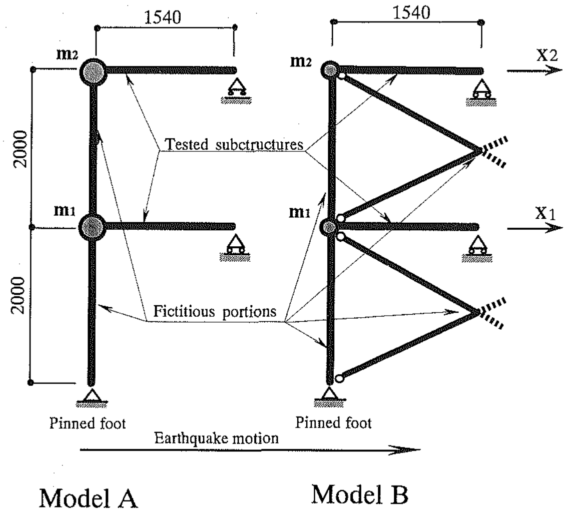


Fig.8 Frame model for hybrid test

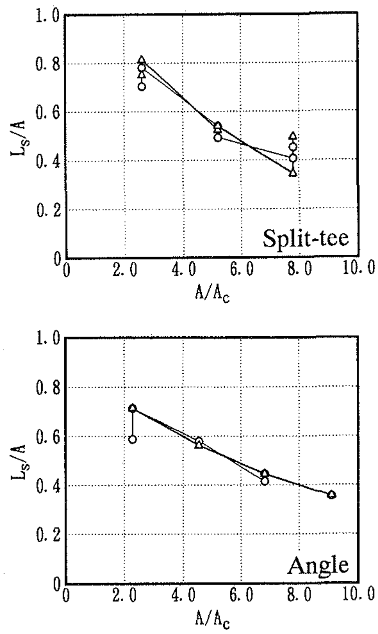


Fig.7 Rotation range during pinching is observed

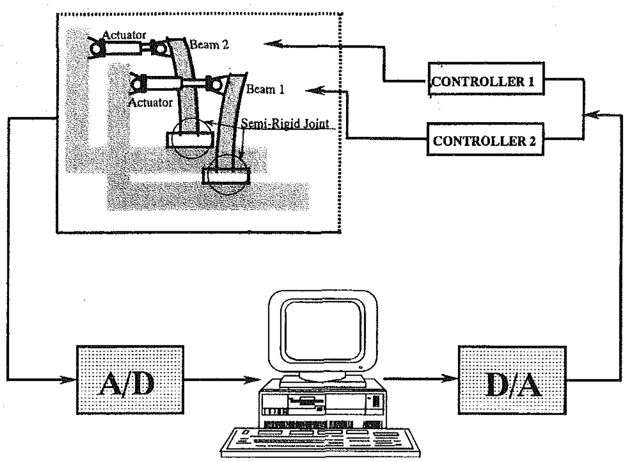
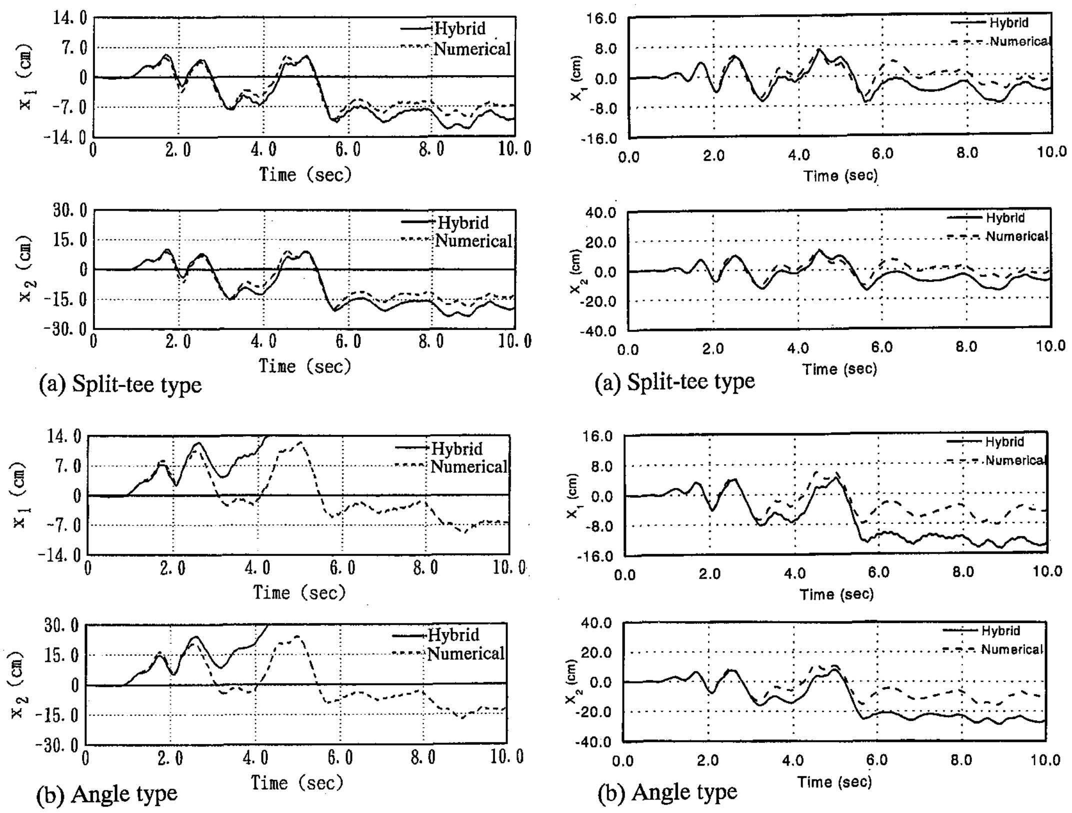


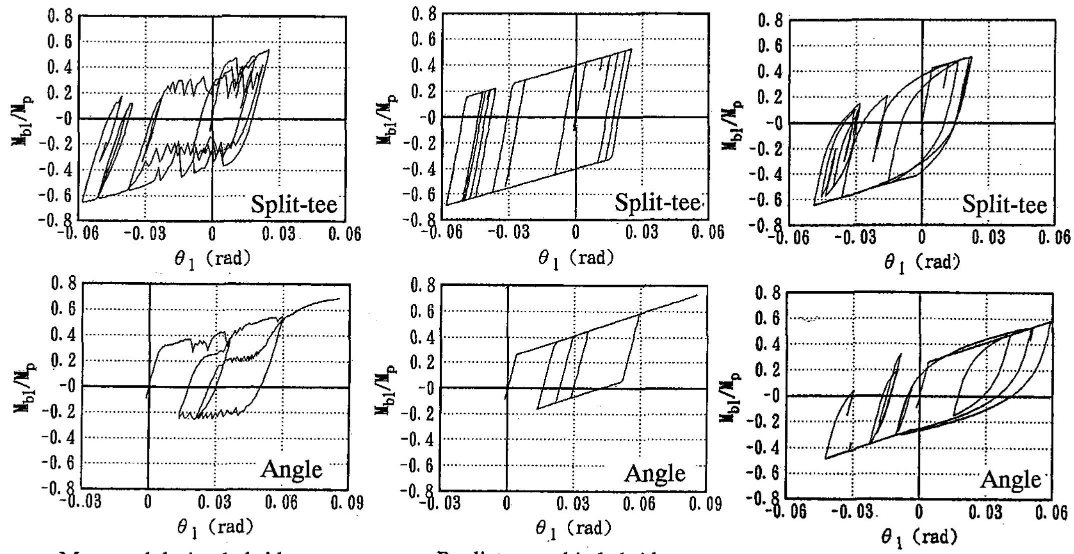
Fig.9 Hybrid testing system



Model A: Unbraced frame

Model B: Braced Frame

Fig.10 Time histories of simulated responses

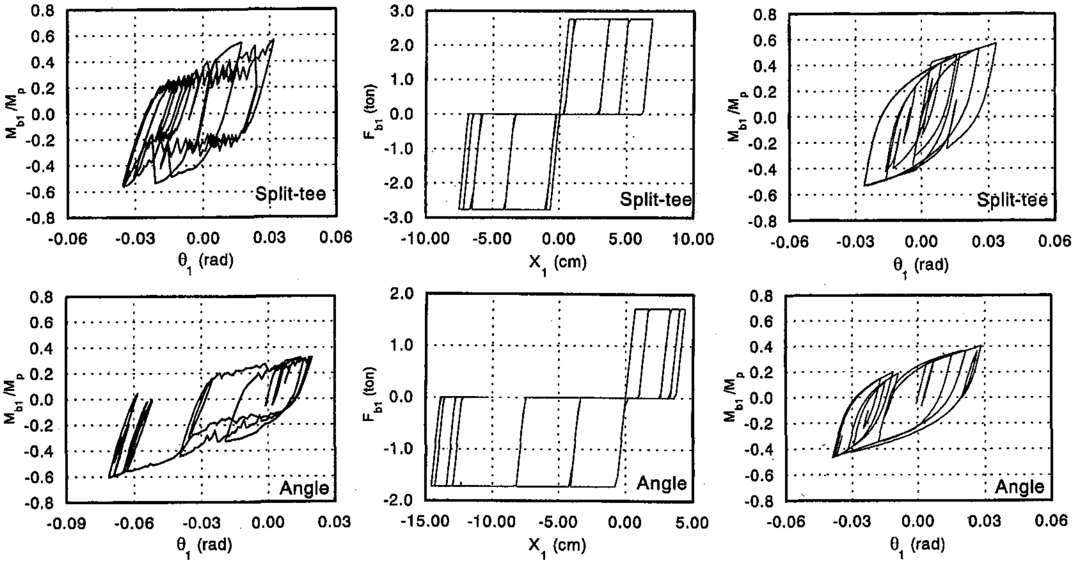


Measured during hybrid test

Predictor used in hybrid test

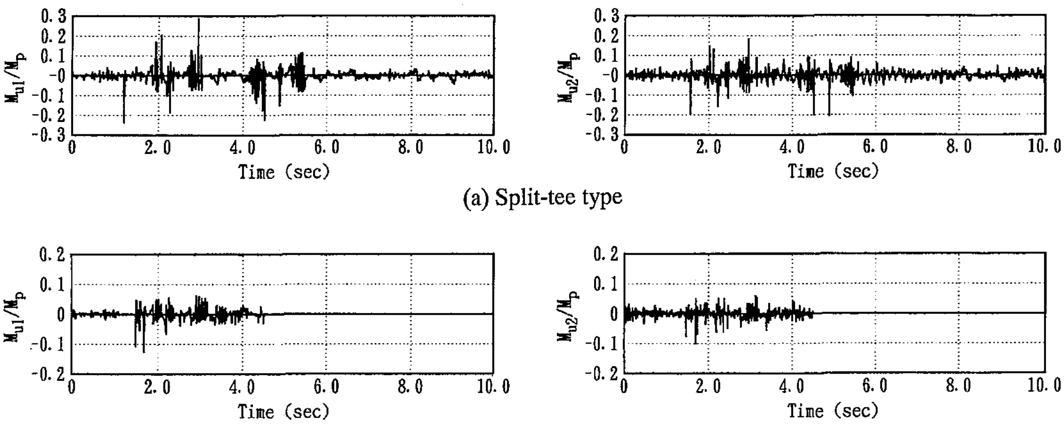
Completely numerical

Fig.11 Hysteresis loops of model A



Measured during hybrid test | Restoring force of brace | Completely numerical

Fig.12 Hysteresis loops of model B



(a) Split-tee type

(b) Angle type

Fig.13 Nodal moment in balance observed during hybrid test