PSEUDO-DYNAMIC TESTS ON SERVICEABLE AND ROBUST STEEL FRAMES WITH THE COMBINATION OF HYSTERETIC DAMPERS AND SEMI-RIGID CONNECTIONS

Kenichi OHI[1], Seung-Jae LEE[2], Yosuke SHIMAWAKI[3] And Hideo KONDO[4]

SUMMARY

Steel semi-rigid connections composed of mechanical fasteners and split-tees, end plates, or angles are sometimes adopted in framing of steel building structures. However, moderate earthquakes occur so frequently in Japan, and then the displacement control from serviceability requirement is very stringent in the design of moment-resisting steel frames with such connections. This paper deals with a steel semi-rigid frame stiffened and damped by inter-story hysteretic dampers in order to meet the serviceability requirement during moderate earthquakes. The use of semi-rigid connection helps in turn to increase the robustness of structural system under an unexpected destructive earthquake like in Kobe, because welded connections might be broken in a brittle manner if the damper capacity would be exceeded. This paper presents a series of sub-structuring pseudo-dynamic tests on semi-rigid frames with inter-story dampers, and demonstrates the good performance of such a kind of structural system. It is demonstrated by a series of sub-structuring pseudo-dynamic tests that a combination of semi-rigid frame and inter-story hysteretic damper creates a fairly good structural system that satisfies not only the serviceability requirement under moderate earthquakes but also the robustness requirement under unexpected severe earthquakes.

INTRODUCTION

Steel semi-rigid connections composed of mechanical fasteners and split-tees, end plates, or angles are sometimes adopted in the framing of steel building structures. However, most of Japanese structural engineers are stick to the welded rigid connections, and the semi-rigid connections are scarcely adopted in steel moment resisting steel frames. The main reason is that moderate earthquakes occur so frequently in Japan, and that the displacement control from serviceability requirement is very stringent in the design of moment-resisting steel frames. This paper deals with a steel semi-rigid frame stiffened and damped by inter-story hysteretic dampers in order to meet the serviceability requirement during moderate earthquakes. Inelastic response of such a semi-rigid partial–strength frame combined with a hysteretic damper is simulated to a severe earthquake by sub-structuring pseudo-dynamic test technique.

The use of semi-rigid connection helps in turn to increase the robustness of structural system under such an unexpected destructive earthquake as experienced in Kobe, while welded connections might be broken in a brittle manner even if they are designed stiffer and stronger than semi-rigid partial-strength connections.

[1] *Institute of Industrial Science, University of Tokyo, Tokyo, Japan Email: ohi@cc.iis.u-tokyo.ac.jp*
[2] *Institute of Industrial Science, University of Tokyo, Tokyo, Japan*
[3] *Institute of Industrial Science, University of Tokyo, Tokyo, Japan*
[4] *Institute of Industrial Science, University of Tokyo, Tokyo, Japan*

This paper also simulates numerically inelastic responses of the other kind of damper-installed structural system, where connections are rigid but considerable deterioration in resistance occurs after yielding. Through the comparison of the two kinds of damper-installed systems, rigid and semi-rigid ones, the robustness of the structural system is discussed.

MATHEMATICAL MODELING OF LYP HYSTERETIC DAMPERS [K. Ohi et al., 1998]

As a hysteretic damper, a shear panel made of low-yield-point steel (LYP) is dealt with herein. The basic properties of such a damper was examined by the authors in the previous report [K. Ohi et al., 1998]. A mathematical model proposed in the report is also used herein in the following pseudo-dynamic test and numerical simulations. Fig. 1 shows an inelastic behavior of LYP shear panel damper supported by steel H-shaped stud under quasi-static loading. A mathematical model termed shifted skeleton model was adopted to simulate hysteresis loop of LYP steel as shown in Fig. 2. The validity of the model when used in numerical response analysis was also examined, as demonstrated in Fig. 3, through the comparison with sub-structuring pseudo-dynamic tests, where loading tests were performed only on the LYP shear panel damper supported by the stud, and other fictitious portions, surrounding frames, were assumed linear-elastic.

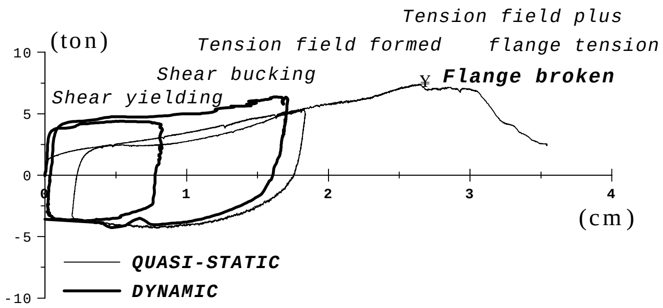


Figure 1: Inelastic Behavior of Shear-panel Low-Yield Point Steel Damper

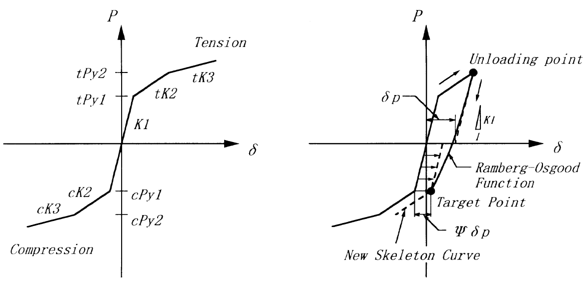


Figure 2: Shifted Skeleton Model for Hysteresis Loop of Steel

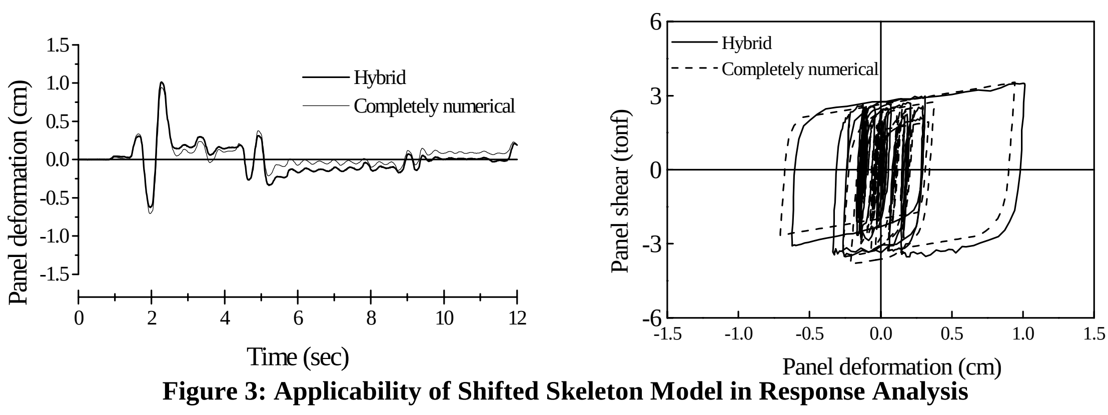


Figure 3: Applicability of Shifted Skeleton Model in Response Analysis

HYBRID RESPONSE OF SEMI-RIGID PARTIAL-STRENGTH FRAME COMBINED WITH HYSTERETIC DAMPERS

In this section an inelastic response is simulated of a damper-installed structural system connected by semi-rigid partial-strength connection. A cantilever H-shaped beam specimen semi-rigidly supported by split-tee connections was fabricated as a sub-structure specimen. The test setup used for such a sub-structure specimen is illustrated in Fig. 4, and the details of the split-tee connection are shown in Fig. 5. From the preliminary loading tests, the initial stiffness of the beam supported by this connection was found about 60% of that of completely fixed cantilever beam, and the yield strength was about 40 % of the beam full-plastic strength. Then this type of connection is categorized as a semi-rigid partial-strength connection.

Fig. 6 shows the whole frame model used in the hybrid simulation. The beam and connection specimens tested are connected to a fictitious rigid column with a pinned foot, and a fictitious inter-story damper system is installed in parallel with the frame. The behavior of the damper system is simulated by a shifted skeleton model mentioned in the previous section. The shifting parameter Ψ is set to 0.5 and the parameter n in the Ramberg-Osgood curve is set to 5. The ratio of initial yield resistance to the maximum resistance is taken 2.5 as a standard value of LYP steel. The resistance of the damper system is controlled by proportioning the damper itself, and the stiffness is controlled mainly by proportioning the supporting element. Then various combinations of stiffness and strength of damper system are possible and feasible in the actual designing. In this paper, a certain feasible combination shown in Table 1 is chosen, where relatively stiff supporting element is assumed.

A fictitious lumped mass is placed at the beam-to-column node, and the natural period in elastic range is set to as 0.9 seconds. The strength unit shown in Table 1 corresponds to about 150 gals in acceleration when divided by the assumed mass. A small amount of fictitious viscous damping as much as 0.001 of critical damping is considered to stabilize numerical integration. The N-S component of El Centro 1940 is used as the input ground motion with a modified PGA, 220 gals. The resistance of beam specimen measured from the loading test was combined with the fictitious resistance of damper system, and then used in the hybrid response analysis of the whole system. Varying axial force as well as bending were applied to the beam specimen, and the fictitious resistance of the damper system was considered to change the axial load.

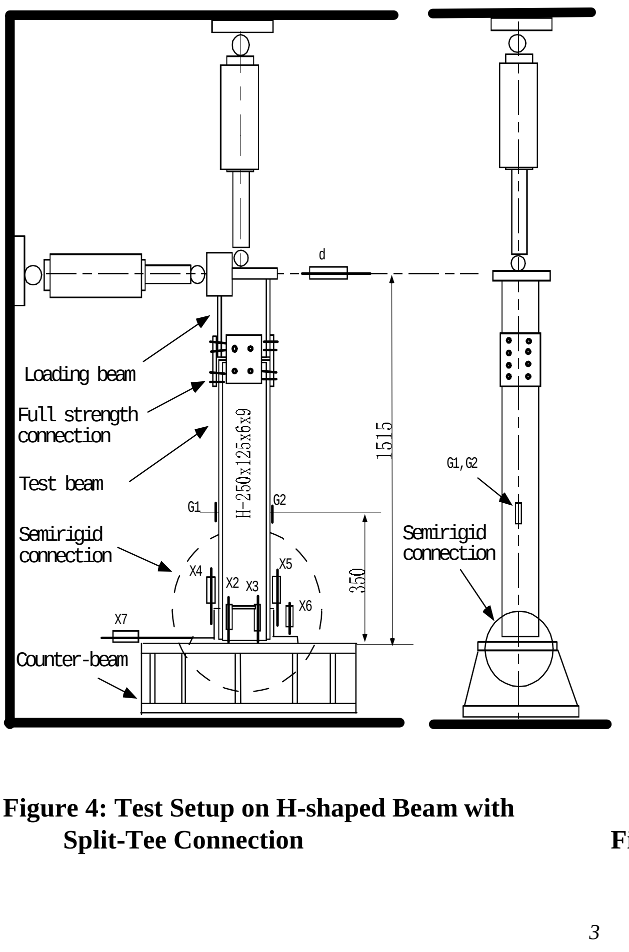


Figure 4: Test Setup on H-shaped Beam with Split-Tee Connection

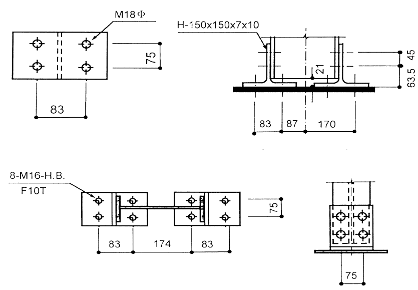


Figure 5: Details of Split-Tee Connection

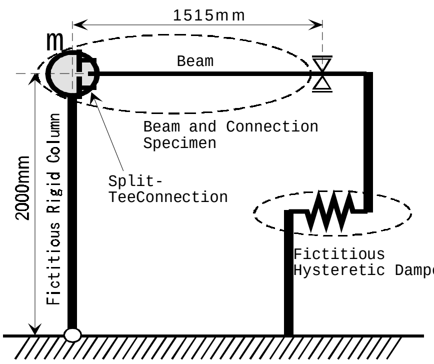
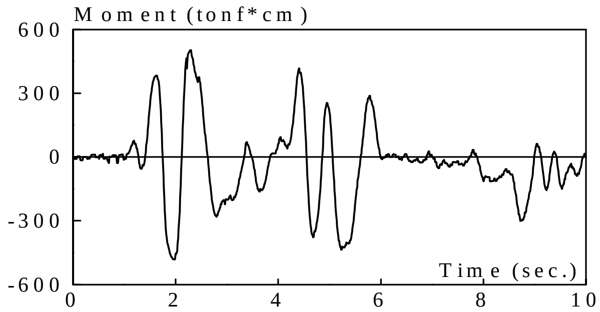
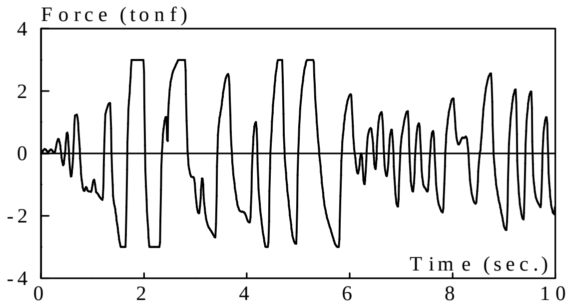


Figure 6: Frame Model Used in Hybrid Simulation

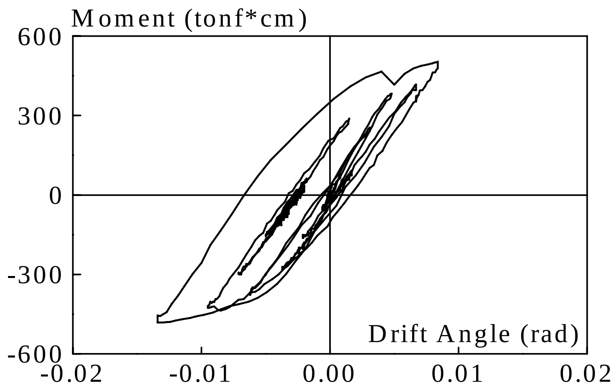
The results of the pseudo-dynamic test are shown in Figs. 7(1) through 7(4). The fictitious damper dissipated major part of earthquake energy input, and also the connection underwent yielding but no brittle failure occurred. No pinching was seen in the hysteresis loop of the connection, for yielding seemed to occur mainly at tee-flange plates. The peak response of drift angle remained within 0.015 radian, and the damage level was considerable but no serious problem was arisen about ultimate safety.



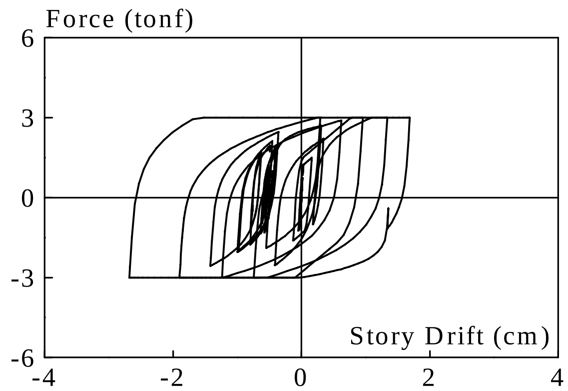
(1) Time History of Moment carried by Split-Tee Connection



(2) Time History of Axial Force applied to Split-Tee Connection



(3) Moment versus Drift Angle



(4) Fictitious Inelastic Behavior of Hysteretic Damper

Figure 7: Results of Hybrid Simulation

Table 1: Stiffness and Strength Proportions among Rigid Full-strength Frame, Semi-rigid Partial-strength Frame, and Damper System

	Initial Stiffness	Strength
Rigid Full-strength Frame (Fictitious)	1.0	1.0 (at Mp)
Semi-rigid Partial-strength Frame (Tested)	0.6	0.4 to >0.8 at max.
Damper System (Fictitious)	7.0	0.2 to 0.5 at max.

Note: The values for the rigid full-strength case are normalized to unit.

NUMERICAL SIMULATION ON ROBUSTNESS OF COMBINED SYSTEM

To demonstrate the advantage of the combined system of semi-rigid connection and hysteresis damper, some numerical simulation is performed on the other damper-installed system. In the alternative system, the rigid and full-strength connection, for example, welded connection with full-penetration, is assumed, but the beam resistance deteriorates after yielding. Bi-linear hysteresis models with negative tangent slope for the second branch is adopted for the beam inelastic behavior. Two levels of negative slopes are assumed, 10 % and 50% of the initial stiffness.

First the ground acceleration with 140 gals in PGA is applied to the two kinds of damper installed systems, semi-rigid partial strength and rigid full-strength. The beam in the rigid full-strength system remains in elastic range, while the semi-rigid partial strength connection underwent yielding. The thick dotted curve in Fig. 8(1) shows the semi-rigid partial strength response, and the thin dotted curve is for the rigid full-strength response. The predominant periods in these responses are not so different, because the same damper system is used to stiffen the two systems.

Next the input level is increased to 220 gals in PGA. The thick solid curve in Fig. 8(1) shows the semi-rigid partial-strength response already simulated in the previous section. On the other hand in the rigid full-strength system, the beam started to yield and the responses are shown as the thin solid curves in Fig. 8(1). Due to the deterioration of the beam resistance, the response of the rigid full-strength system is considerably magnified, and especially in the presence of the steep negative slope, the system is driven to the complete collapse.

Another case study is shown in Fig. 8(2). These responses are simulated commonly under the input level of 140 gals in PGA. The dotted curves are the same results with Fig. 8(1), while the solid curves in Fig. (8) are the responses with unexpected failure of damper system. The resistance of the damper system is assumed to disappear, once it reaches to the third branch in the skeleton curve. The thin solid curves show the responses of the rigid full-strength case, and they are driven to the complete collapse. The thick solid curve shows the semi-rigid partial-strength case, and it survives even if the damper system is broken.

CONCLUDING REMARKS

It is demonstrated by a sub-structuring pseudo-dynamic test and additional numerical simulations that a combination of semi-rigid partial-strength frame and inter-story hysteretic damper system creates a fairly good structural system that satisfies not only the serviceability requirement under moderate earthquakes but also the robustness requirement even if it is encountered by unexpected increase of input level or unexpected failure of damper system. The structural system of this kind is able to work as so-called ‘fail safe’ system in the presence of high uncertainty about earthquake load and structural resistance as well.

ACKNOWLEDGEMENT

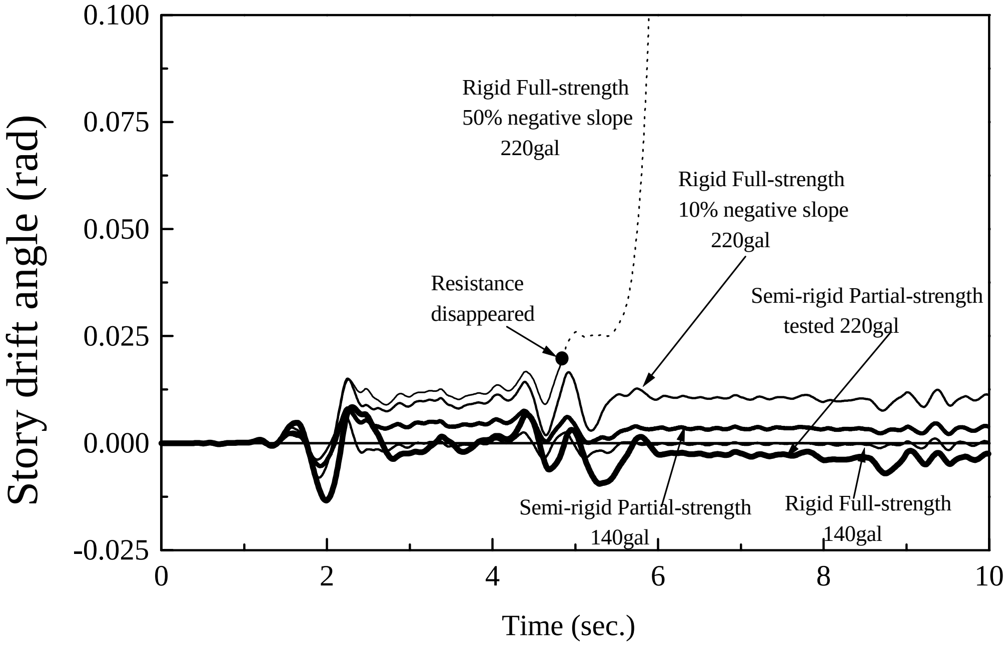
The authors would express their appreciation to the financial support of Ministry of Education, Science, Sports, and Culture, Japanese Government, Grant in Aid for Scientific Research(B)(2), No. 09450200, which made this work possible. Also the authors are grateful to Dr. X.-G. Lin, Lecturer of Osaka Institute of Technology, Dr. Z. Fu and Mr. N. Yamamoto, graduate students of University of Tokyo, for their assistance during the loading test.

REFERENCES

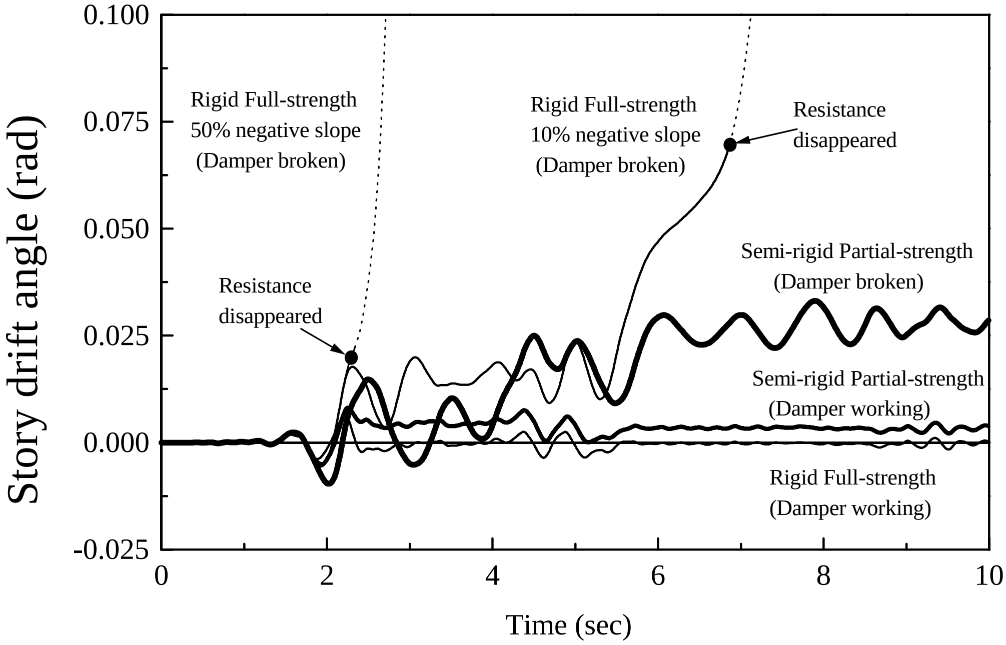
K. Ohi, Y. Shimawaki, S.J. Lee, N. Yamamoto (1998a), “Pseudo-dynamic Tests on Frames with Low-Yield-Point Steel Dampers”, Bulletin of ERS, IIS, University of Tokyo, No.31, pp.63-70.

K. Ohi(1998b), “Resistance Versus Resistance Reliability Concept in the Design of Steel Frames and Connections”, Structural Engineers World Congress, Elsevier Science Ltd., T104-4.

K. Ohi, X.G. Lin (1998), *Pseudo-dynamic Tests and Analysis on Semi-Rigidly Jointed Steel Frames,” Stability and Ductility of Steel Structures*, eds. T. Usami and Y. Ito, pp.131-140, Elsevier Science Ltd.



(1) Against Unexpected Increase of Seismic Input



(2) Against Unexpected Failure of Damper System

Figure 8: Robustness of Semi-rigid Partial-strength Frame Combined with Hysteretic Damper