Experimental Study of a Single Story-Single Bay Steel Moment Frame Subjected to Dynamic Loading

Kayo TANIGUCHI
Candidate for the Degree of Master of Engineering
Supervisor: Dr. Taichiro Okazaki
Division of Architectural and Structural Design

Introduction

The 1994 Northridge earthquake and 1995 Kobe earthquake reminded engineers that severe damage and potential collapse of steel buildings can happen. Seismic design provisions ensure ductile performance of steel moment resisting frames by adequate connection details and a strong column-weak beam proportion rule.

Major experiments are required to examine the damage process under exceedingly large ground motions leading to complete failure, or collapse, of building systems, and thereby to determine the safety margin against collapse. Such experiments, or shake table tests, require careful planning. Shimada. et al. [1] conducted a reduced scale shake-table test in preparation for a full-scale moment frame test at E-Defense in order to examine instrumentation schemes and the predictability of response. Kaneshiro. et al. [2] conducted a 1/3-scale shake-table test on a one bay-two story steel moment frame, with intentional damage introduced in the beam-to-column connections, to observe how fracture or damage of one beam end propagates to the entire structural system.

This paper reports a 1/3-scale shake-table test of a one bay-one story moment frame at the National Research Institute for Earth Science and Disaster Prevention (NIED) in Tsukuba in 2020 as a preliminary test of the main specimen (4 stories – 2 bays specimen conducted in 2021). The objective of the test was to verify that reduced-scale specimen, with simplistic details, behave similarly to real building systems and to validate the experimental method can be used for main test. A specific interest was to examine how the inertia force, produced by a large mass out of dimensional proportion, may be transferred to the specimen.

Test Plan

Specimen

As shown in Figure 1, the specimen had a plan of 1.5×2 m and height of 1.2 m. The columns were H-100×100×6×8 and the beams were H-150×75×5.5×7, both of SS400 steel. The columns were pinned at the shake table through a foundation beam. Table 1 lists the mechanical properties established based on tension coupon tests. A catching frame was placed beneath the moment frame to prevent damage to the shake table. Doubler plates were welded to the panel zones to avoid yielding of the column panels. Therefore, the expected energy dissipation mechanism was yielding at the top of the columns. Length was scaled to 1/3, but time was not scaled. The fundamental vibration period of the specimen was computed as 0.24 s. Large beams were fastened to the specimen above which steel plates were attached to supply mass. The total weight of the mass added to the specimen was 5750 kg.

Table 1. Material properties by coupon test

Location	Material	σ_y [N/mm^2]	σ_u [N/mm^2]
Column	SS400	319	447
Beam		349	471

Excitation

As listed in Table 2, the JMA Kobe NS motion recorded from the 1995 Kobe earthquake was repeated 9 times with amplitudes 10, 25, 50 and 100%. Figure 3 shows the target 100% motion in form of spectral acceleration (SA) versus spectral displacement (SD) relationship. The computed fundamental vibration period and computed plastic strength,

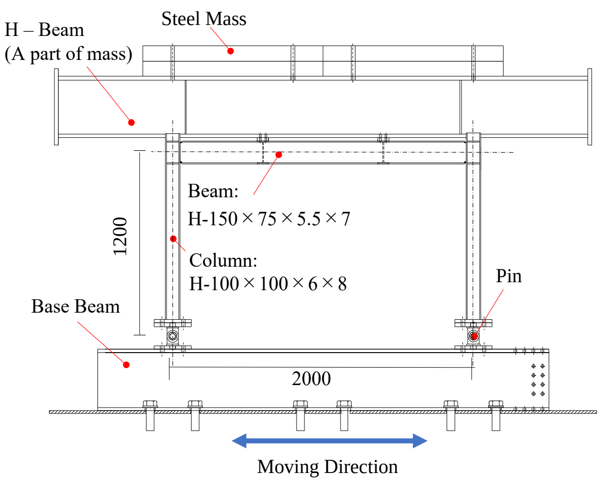

Fig. 1. Test specimen

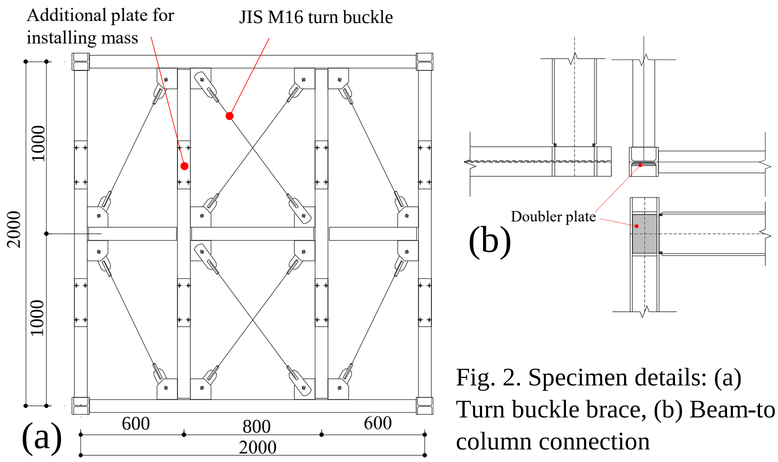

Fig. 2. Specimen details: (a) Turn buckle brace, (b) Beam-to column connection

Table 2. Excitation Plan

Test	Scale	Expected Behavior
1	10%	Elastic
2	25%	Elastic
3	50%	Elastic
4	10%	Elastic
5	100%	Plastic
6	10%	Plastic
7	100%	Plastic
8	100%	Plastic
9	10%	Plastic

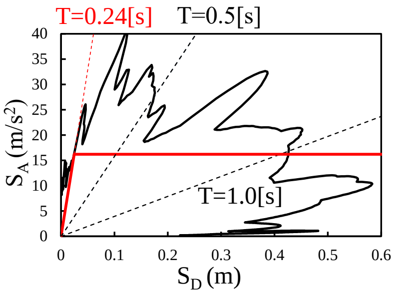

Fig. 3. SA – SD curve

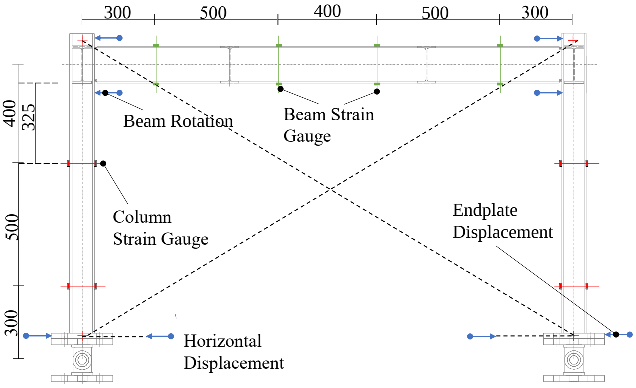

Fig. 4 Instrumentation plan

based on measured yield strength values, are indicated in the figure. The 10% motion was sufficiently small to keep the specimen elastic and was thereby used to compute the fundamental vibration period before and after the primary motions. The 50% motion was expected to subject the specimen near the proportional limit. The 100% motion was repeated three times. Under the 100% motion, the specimen was expected to yield but was not expected to develop substantial plastic deformation.

Instrumentation

Figure 4 shows instrumentation plan that involved 96 channels. Three dimensional accelerometers were placed on the middle of the mass and on the shake table. Story drift angle was measured in each plane by wire transducers and by subtracting slipping of endplate. Rotation of the beam end and shear deformation of the panel zone were measured by transducers. Restoring forces were measured by elastic strain gauges attached to the flanges of each column and beam at locations expected to remain elastic.

Initial Condition

Change in force distribution was measured in the column during the process of tightening the column endplates and placing the masses. Figure 5 shows the assumed axial force, shear force and bending moment diagrams in the system. Figure 6 shows the initial axial force after fastening all masses. Gravity load distributed evenly, and according to tributary area, to all columns. Because strain measurement was taken only at the columns, the force distribution in the beams needed to be estimated by mechanics.

Test result

As shown in Figure 7 for Test 5 (the first 100% motion), the acceleration record produced by the shake table closely matched the target motion. At the estimated fundamental period of the specimen, the produced motion was 5% greater than target.

Figure 8 shows the change in fundamental vibration period from the 10% motions (Tests 1, 4, 6, 9) using the zero-crossing method from response acceleration of the mass. The period elongated slightly from 0.263 s at the beginning to 0.275 s after the three 100% motions.

Figure 9 shows the story shear versus drift angle relationship from Test 3 (50% motion) and Test 5 (first 100% motion). The plastic strength of the system, based on measured yield strength, is shown in the figure. Test 3

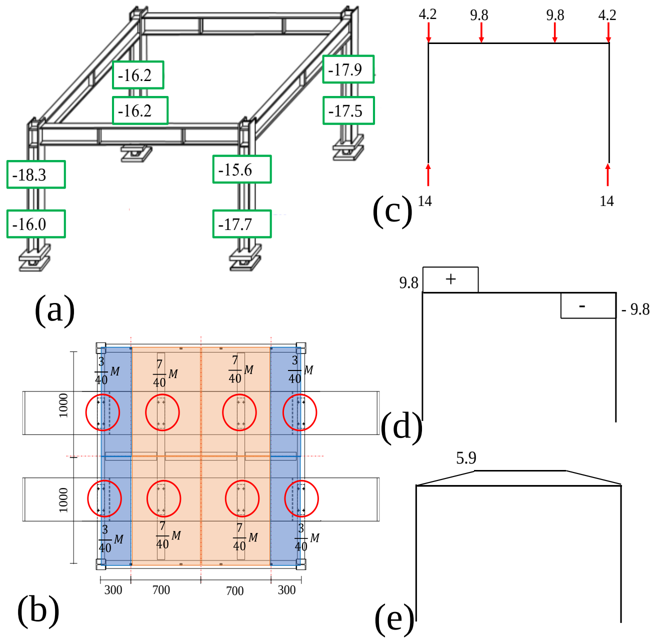

Fig. 5 Initial condition and assumptions before excitation: (a) Measured axial force of column, (b) Assumed mass distribution, (c) Assumed concentrate load, (d) Assumed shear force diagram

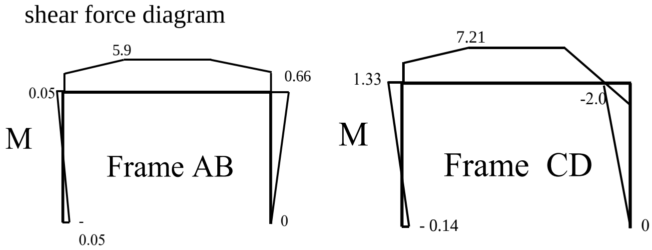

Fig. 6 Initial bending moment diagram combine assumption with measured axial force: (a) Frame AB, (b)

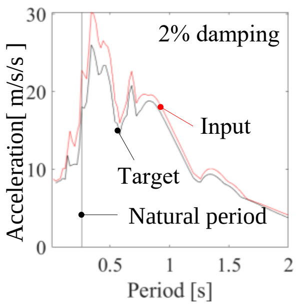

Fig. 7 Record of absolute acceleration response

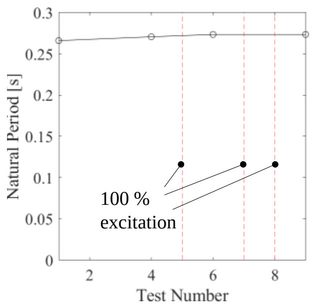

Fig. 8 The change in fundamental vibration period

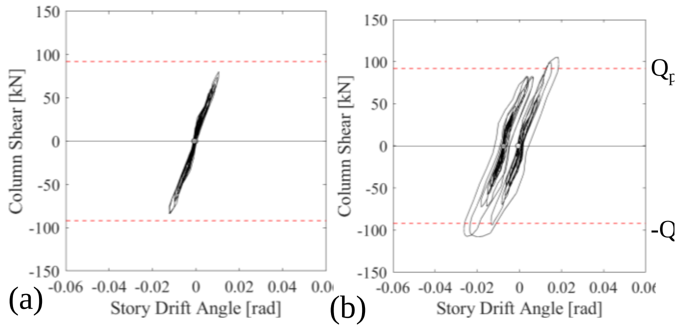

Fig. 9 Shear force and story drift angle relationship: (a) test 3, (b) test 5.

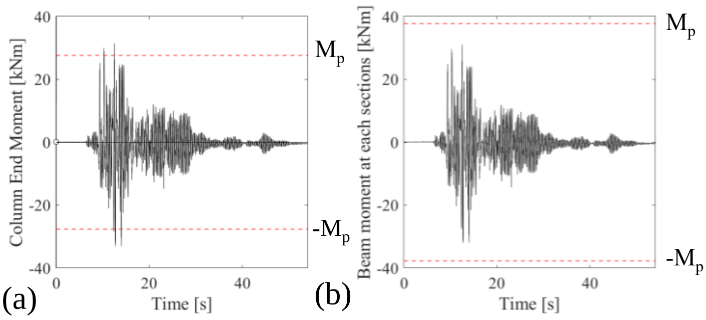

Fig. 10 Time history of nod moment: (a)Column (b) Beam.

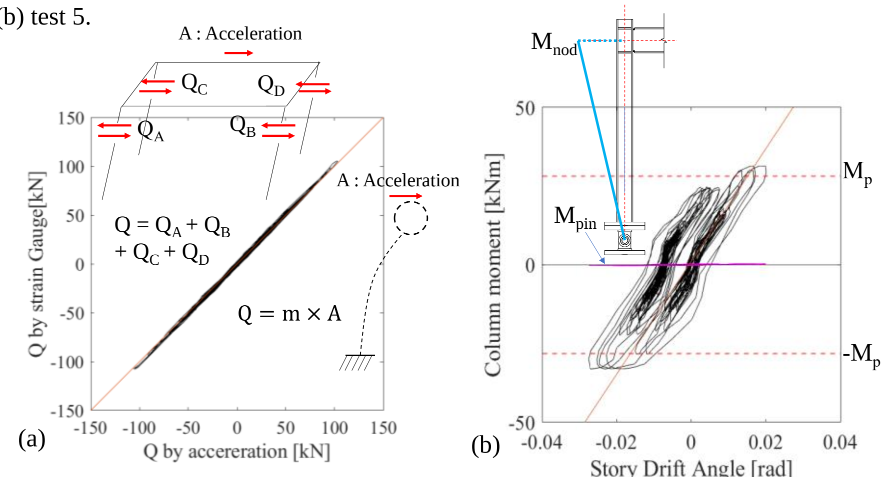

Fig. 12 Verification of forces: (a) Shear force by column shear and condensation models, (b) Relationship of column top moment and pin moment

produced a maximum story drift of 0.01 rad and the specimen remained elastic. Test 5 produced a maximum story drift of -0.263 rad and a residual deformation of 0.01 rad.

Figure 10 shows the time history response of the column end moment and beam end moment from Test 5. The plastic moment of the members, based on measured yield strength, are shown in the figure. As expected, the column exceeded the plastic moment, while the beam remained elastic.

Discussion

Verification of measurement

Figure 12 (a) compares the story shear force obtained for Test 5 (100% motion) by two methods: from strain measurement and equilibrium conditions, and from inertia, or multiple of mass and acceleration. The latter assumes that viscous damping is null. Story shear obtained from the two methods were almost identical. As shown in Figure 12 (b), the strain gauge measurement was also used to confirm that bending moment at the pin support was in fact very near zero.

Verification of torsion of mass

Fig. 2 indicates that the inertia force was transferred to the specimen through horizontal braces, placed in the same horizontal plane as the top flange of beams, and transverse floor beams. The line of action of the inertia force was substantially higher than the centerline of the beams. Therefore, an attempt was made to back calculate the force transferred to the beam. The transferred forces were simplified as a set of concentrated horizontal load, vertical load, and moment acting at each beam/column-to-floor beam joint, as shown in Figure 13 (b). The vertical force taken equal to the axial force in the column below. Figure14 shows the bending moment diagram sampled at the instant when the story shear was measured. Complete bending moment distribution may be derived for clear segments with two instrumented sections, namely the column and middle segment of the beam. The bending moment distribution in the outer segments of the beam was produced based on measurement at one section and assuming that the shear force equaled the shear force in the middle portion of the beam plus the initial shear shown in Figure 6 (d). The jump in value at the boundaries may be attributed to the concentrated moments shown in Figure 14. The initial bending moment as shown in Figure 6 (d) was deducted from transferred force because they were not generated by excitation. Figure 15 checked the inertia force and transferred force to the beam from 12 s to 15 s. The plots extracted the step when Figure 14 was shown. Transferred force had terrible noise, so it was filtered using moving average of 5 points.

The moments find in two different ways in the plot mentioned above were also evaluated by yielding moment of beams. Transferred force was 18.7 kNm and the inertial force was 42.7kN. The error 24.0 kNm divided by yielding moment 32kN is equal to 75.2 % where the resolution of the beam moment derived from strain gauge was 0.18 kNm. Moreover, the positive and negative peaks were also evaluated. Positive and negative peak differed 16.8 kNm and 14.3 kNm respectively. The error was evaluated in the same way and percentage was 52.5 % and 44.3 %. The transferred force was smaller than the inertia force, but they have similar behaviors.

Equivalent SDOF model

A single-degree-of-freedom model with bilinear properties was subjected to the recorded table motion. The model was provided with the aforementioned theoretical stiffness and plastic strength, and a secondary-to-post-yield stiffness ratio of 1/10000. The damping ratio was 1.5 %. Figure 16 compares the displacement response from shake-table test and model. Equivalent SDOF managed to capture the experiment with a certain degree of accuracy. However, the residual displacement of the SDOF was -5.0mm and of the experiment was -9.2mm. The model was undetermined by 54.3%.

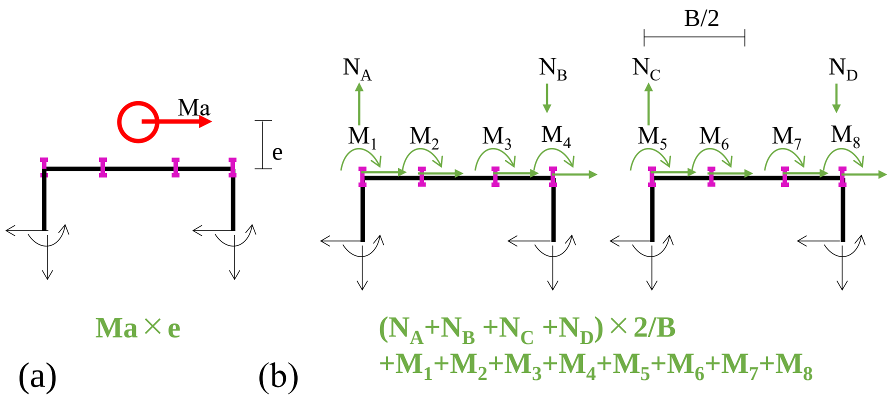

Fig. 13 Expected moment by ground motion: (a) Inertial force (b) Transferred force

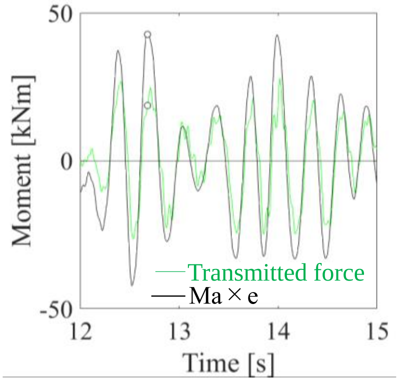

Fig. 15 Expected axial force by ground motion

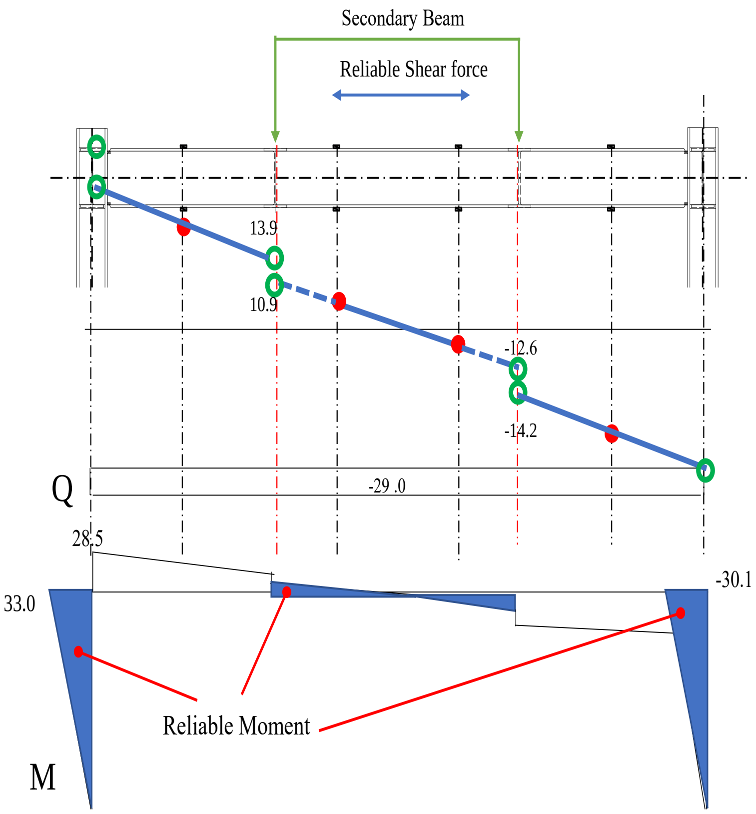

Fig. 14 Calculation method of torsional moment of secondary beam

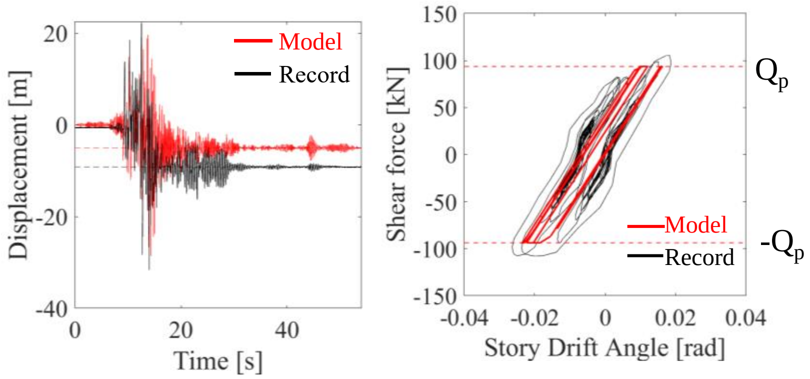

Fig. 16 Result of elastic – plastic analysis of single degree of freedom: (a) Displacement response, (b) Shear force and story drift angle relationship

Conclusions

A 1/3-scale, single story-single bay specimen was tested on a shake table as a preliminary test of the four stories-four bays specimen. Seismic performance and the experimental method were summarized below:

- The acceleration record produced by the shake table closely matched the target motion.
- As expected from material test, column reached M_p. On the other hand, beam remained elastic.
- Strain measurement was suitable.
- The bending moment at the pin support was in fact very near zero. The performance was required for the main frame.
- From initial strain of the column, weight of mass was distributed almost even to all the columns before excitation.
- Since the mass was tightened rigidly to the beam, the inertial force was transferred to the at each beam/column-to-floor beam joint. The inertia force, produced by a large mass out of dimensional proportion, matched the transferred force to a certain extent.
- The numerical simulation of the equivalent SDOF system, using a bilinear stress-strain relationship, fairly agreed with the experimental response.

The main test (4 stories – 2 bays specimen) was conducted in 2021 following the experimental method and the measurement was succeeded.

References

[1] Yuko Shimada, Motoki akazawa et al. *Shaking table test on collapse behavior of small-scale steel frame structure*. J. struct. Constr. Eng., AIJ, No.620, 125-132, Oct., 2007

[2] Yusuke KANESHIRO and Takashi HASEGAWA and satoru HIROSHIMA. *Shaking table test on seismic response of steel 2-story frame structure considering fracture at beam – end.* AIJ J. Technol. Des. Vol. 26, No.62, 147-152, Feb. 2020