COLLABORATIVE HYBRID EXPERIMENTS ON LARGE SCALE FRAME STRUCTURES AT NCREE

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ABSTRACT:
Four of the networked hybrid experiments are introduced in this paper. The first one is a Taiwan-USA-Japan joint research program. A full-scale three-story three-bay buckling restrained braced (BRB) frame with concrete filled tube (CFT) columns was tested in 2003 using pseudo-dynamic testing (PDT) procedures. Various types of BRB and steel beam-to-CFT column moment connections were investigated in this test. The second one is a Taiwan-USA collaborative substructure PDTs of a full-scale two-story BRB frame subjected to the bi-directional seismic ground motions were conducted in 2005. The performance and the design methodology of BRB-to-gusset plate connections were investigated. The third one is a collaboration of NCREE and Multidisciplinary Center for Earthquake Engineering Research (MCEER) of USA in 2006. A full-scale two-story one-bay steel-plate shear wall frame was pseudo-dynamic tested. The capacity design of columns and beams surrounding the steel-plate shear wall was studied. The design of the restrainers for the steel-plate shear walls was also verified. The last one is a Taiwan-USA cooperative research project, entitled "NEES-SR SG International Hybrid Simulation of Tomorrow's Braced Frames". A full-scale two-story steel concentrically braced frame (CBF) was tested under cyclically increasing lateral displacements. Test results confirmed that the two-story X-shape steel CBFs all have good energy dissipation characteristics. Tests also confirmed that both the 2t-linear and 8t-elliptical out-of-plane deformations of the gussets provide satisfactory ductility for the seismic resistant design of steel CBFs. The feature of specimen, test protocols, the details of PDTs as well as the key experimental results of the stated four collaborative hybrid experiments have been webcasted during the tests, and are presented in this paper.

KEYWORDS: Large-scale frame test, International collaboration, Hybrid tests

1. INTRODUCTION

The seismic performance of structures can be realistically evaluated through the large-scale experiments. Thus, the demand of large-scale structural tests has significantly increased in recent years. Nevertheless, due to the limited capacity of each individual laboratory, it has been found difficult and not very cost-effective to carry out such large-scale structural tests by one single research institute. Therefore, the hybrid experiments collaboratively conducted by several research institutes have become the trend of large-scale structural tests in modern test laboratories. Recently, several large-scale frame hybrid tests have been collaboratively conducted at the Center for Research on Earthquake Engineering (NCREE) in Taiwan. In this paper, four international collaborative frame tests are introduced. The first one is a hybrid test of full-scale three-story three-bay buckling restrained braced frame (BRB). This 3-story BRB frame was test in 2003, and this project is a USA-Japan-Taiwan collaborative research. The second one is a USA-Taiwan collaborative experiment study. In 2005, a full-scale two-story BRB frame was tested under the bi-directional seismic ground motions. The third one is collaboration of NCREE and Multidisciplinary Center for Earthquake Engineering Research (MCEER) of

USA in 2006. A full-scale two-story steel plate shear wall (SPSW) frame was constructed and tested in NCREE laboratory. The last project is experimental study of a full-scale two-story steel concentrically braced frame (CBF). This research is collaborated among NCREE and University of Washington, Seattle. The paper includes the information of specimen, test protocols and key experimental results of four collaborative hybrid experiments.

2. FULL-SCALE 3-STORY CFT/BRB FRAME

2.1. Information of specimen

This research is a collaborative research among Japan, USA and Taiwan. Measuring 12 meters tall and 21 meters long, the specimen used square and circular CFT columns as the two exterior and interior columns respectively (Fig. 1). In the tested CFT/BRB frames, only the two exterior beam-to-column connections in each floor are moment connections, all other beam-to-column connections are assumed not to transfer any bending moment. The BRBs are installed in the center bay. Square CFT columns are chosen for the two exterior columns and the two columns in center are circular CFTs. The material of all beams and columns is A572 Gr.50. The compression strength of the infill concrete in CFT columns is 35MPa. Three types of BRBs were adopted for the three different floors. The two single-cored unbonded braces (UBs), each consisting of a steel flat plate in the core, were donated by Nippon Steel Company and installed in the 2nd-story. The two BRBs installed in the 3rd-story were double-core constructed using cement mortar infilled in two rectangular tubes (Tsai et al. 2002), and the two all-metel BRBs in the 1st-story were also double-core but fabricated with detachable features (Tsai and Lin 2003a). The detail sketch of specimen is shown in Fig. 2.

2.2. Experimental Program

Two earthquake records were used in this test, those are TCU082EW (from the 1999 ChiChi earthquake) and LP89g04NS (from the 1989 Loma Prieta earthquake). This original test plan was to scale these two records to represent four separate pseudo-dynamic loading events, which were described as follow: (1) TCU082 scaled to represent a 50/50 hazard intensity, i.e., with a 50% chance of exceeding in 50 years, (2) LP89g04 scaled to a 10/50 hazard intensity, which represents the design basis earthquake, (3) TCU082 scaled to a 2/50 hazard, and (4 LP89g04 scaled to a 10/50 hazard – identical to loading (2). The records scaling is based on matching the spectral acceleration at one second period to the specified earthquake hazard levels. Some unexpected fractures occurred and interrupted the Test No.1 due to the buckling of the gusset plate in the first story. Then the test stopped and stiffeners were added at the free edges of all the gusset plates Then test resumed using the same ground. Fig. 3(a) shows the actual applications of the ground motions in the PDTs for the specimen. After all PDTs were conducted, there was not any fracture found in the BRBs. Thus, cyclic increasing uniform story drifts were imposed until the failure of the BRBs. Since the scheduled PDT and cyclic tests were completed with failures only in bracing components including the BRBs, UBs and the gusset plates, it was decided that Phase-2 tests be conducted after repairing the damaged components. It adopted the same two earthquake records but scaled to match the spectral acceleration at the first mode period to the specified earthquake hazard levels. The ground motion accelerations applied in Phase 2 PDTs are shown in Fig. 3(b). All the key analytical predictions and the experimental responses were broadcasted from a website: http://cft-brbf.ncree.gov.tw.

2.3. Key Experimental Observations and Results

As noted above, the scheduled PDT and cyclic tests in Phase-1 study were completed with failures except in bracing components (BRBs, UBs and the gusset plates). It was decided that Phase-2 tests be conducted after repairing the damaged components. Phase-2 tests not only allowed to make the best use of the 3-story, 3-bay frame but also aimed to investigate the performance of the stiffened gussets plates and the new BRBs. Before the Phase-2 tests, the laterally buckled gusset under the 3rd floor beam had been removed before installing a new one. In addition, stiffeners were welded at the free edges of the heat straightened gusset at all the brace to column joints (Figs. 4 and 5). Six new BRBs, two all metal double cored construction for the 1st story and four concrete filled double cored for the 2nd and 3rd stories have been installed. Figs. 6 and 7 present the roof experimental displacement time history, and the 1st inter-story drift versus story shear relationships obtained in Test No.5. The peak inter-story drift was about 0.025 radians. It is evident that the roof displacement and the brace hysteretic behavior simulated either by PISA3D are satisfactory.

3. FULL-SCALE TWO-STORY BRB FRAME SUBJECTED TO BI-DIRECTIONAL EARTHQUAKE LOADS

3.1. Information of specimen

This study is a USA-Taiwan collaborative research. Figure 8 shows the floor framing plan and 3-D perspective of prototype structure. The 2-story prototype building was located at Chiayi City with Soil Type I (hard rock site) and was first designed according to the story force distribution prescribed in the 2002 Taiwan Seismic Building Specifications (ABRI 2002). The design dead load (DL) of the floor was 6.89kN/m^2, and the design live load (LL) was 2.45kN/m^2 for each floor. The corresponding design base shears were about 20% in both directions. The specimen was 8m width and 4m height. A 2.28m wide concrete slab was used to develop the composite action of the beams. Assuming the BRBF was resist 75% design earthquake force, the cross-sectional areas of the BRB steel cores were 50 cm^2 and 33 cm^2 in the first and second floors, respectively. The details of the design procedures were documented by Tsai et al. (2006). Figure 9 show detail sketch of specimen. All members of the fame were A572 Gr.50. The beam-to-column joints of the BRB frame were pin-connected. Welded connections were used for the 1st-story BRB-to-gusset connections, and bolted connections with 10-24mm A490 bolts were adopted for those in the 2-story. The vibration periods were 0.69s and 0.57s in the longitudinal (MRF, noted as X-direction) and transverse (BRBF+MRF, noted as Y-direction) directions, respectively.

3.2. Experimental Program

This specimen was tested under bi-directional pseudo dynamic loads. The adopted bi-directional ground motion records (TCU076 and CHY024), which were scaled to three different hazard levels (2/50, 10/50 and 50/50), were chosen to maximize both the in-plane and out-of-plane inelastic deformational demands. Figure 10 shows the earthquake scenario of this experiment, including the earthquake intensities and sequence. In order to reduce the residual deformations cumulated after each event, the direction of the ground motions were reversed in the subsequent earthquake load event. All the key analytical predictions and experimental responses were broadcasted from a website: http://substructure-brbf.ncree.org.tw.

3.3. Key Experimental Observations and Results

Figure 11 shows the inter-story drift verse story shear relationships obtained in test SPDT No.3. The energy dissipation ability is evident in this test. Test results confirm that adding stiffeners at the gusset edges by the suggestions from the finite element buckling analysis of gusset joints can effectively increase the compressive stability of the gusset. Test results also confirmed that the buckling of the gusset plates could be completely avoided by adding the adopted gusset stiffeners. The peak experimental inter-story drifts reached 0.015 and 0.022 radians in longitudinal and transverse directions respectively in 2% probabilities of exceedance in 50 years, which well agreed with the analytical results of PISA3D. Test results also confirmed that PISA3D models predicted the lateral displacement and story shear of specimen frame well in these bi-directional PDTs.

4. FULL-SCALE TWO-STORY STEEL PLATE SHEAR WALL FRAME

4.1. Information of specimen

This experiment is a collaborative research among NCREE and MCEER. It is assumed that the lateral force resisting system (LFRS) of the two-story prototype building includes a perimeter steel welded moment frame (SWMF) and two SPSW frames in the transverse direction. Figures 12 to 13 indicate that the floor framing plan, the member sizes of the SWMF and the 3D perspective of the prototype structure. This two-story prototype building is located in East District in Chiayi City of Taiwan. The design dead load of the floor is 6.87kN/m^2, and the design live load is 2.45kN/m^2 for each floor. Based on the latest seismic force requirements for new buildings in Taiwan (ABRI 2002), the design base shear is about 22% weight of the structure for both directions. The building fundamental vibration periods are 0.52 and 0.72 seconds in the transverse and longitudinal directions, respectively. The SS400 grade steel was chosen for the steel plate shear wall. All the beams and columns in the LFRS are A572 GR 50 steel. The specimen is 4m wide and 8m high. The thickness of the steel plate for the first story wall is 3mm and for the second story is 2mm. The actual yield strengths for the steel plates are 335MPa (1F) and 338MPa (2F). The 2.24 m wide, 75mm thick concrete over 75mm deep metal deck concrete slab was established in both floors. Detailed member sizes are shown in Fig. 14. In order to reduce the buckling sounds and minimize the out-of-plane buckling of the steel panels, the specimen is restrained by three horizontal restrainers on both sides of the infill plate in each story.

4.2. Experimental Program

In the phase I tests, the specimen was tested using pseudo-dynamic test procedures and a Chi-Chi earthquake ground motion record scaled up to represent seismic hazards of 2%, 10%, and 50% probabilities of exceedance in 50 years. The original ground acceleration record is TCU082EW as shown in Fig. 15. After the three Phase I hybrid tests, it was found that the SPSWs had severely buckled and significantly cracked. However, no evident fracture was found in the boundary beams and columns. In addition, there was no any yielding or fracture observed on the steel tube restrainers. Thus, after the Phase I tests, it was decided to replace the damaged steel panels with the new ones. In Phase II tests, no any restrainer was used. The specimen was tested using pseudo-dynamic of 2/50 event and cyclic increasing story drift to failure. All the key analytical predictions and experimental responses were broadcasted from a website: http://exp.ncree.org/spsw.

4.3. Key Experimental Observations and Results

Figure 16 shows the hysteresis loops in first floor SPSW, and the energy dissipation of this specimen is confirmed. From test results, it is evident that the responses of the SPSWF can be accurately predicted using the strip model and the tension-only material property implemented in PISA3D computer program. The proposed capacity design method in this research can provide a conservative design of boundary frames. It appears that the use of restrainers in SPSWs can effectively reduce out-of-plane displacement and buckling sounds, and then improve the serviceability of SPSW system.

5. FULL-SCALE TWO-STORY CONCENTRICALLY BRACED FRAME

5.1. Information of specimen

This study is collaborative research between NCREE and UW. The specimen is made of a single bay, concentrically-braced two-story frame. The width and height of the said frame are 6.7 meters and 6.67 meters, respectively. The specimen is the first of a series of large scale frame tests being conducted in NCREE Laboratory. The specimen is single bay with the braces arranged in a two-story X-brace configuration. All beams and columns are A572 GR 50 steel. There were three phases in this experiment. The main differences among the three tests are the brace types (hollow structural or wide-flange section) and the design criteria adopted for the gusset plate connections. During the three tests, there was no any fracture of beams and columns. Thus, damaged braces and gussets were replaced at the end of each test. In the Phase I test, The A500 grade steel tubes were used for braces and the 8t-clearance gusset design detail was adopted. Wide-flange braces and the 8t-clearance gusset detail were adopted in the Phase II test. Finally, in the Phase III test, the A500 steel tube braces and the 2t-clearance gusset detail were used in specimen. The detailed dimension of the specimen is shown in Figure 17. The CBF specimen was tested under cyclically increasing story displacements, and the test loading protocol is shown in Fig. 18. All the key analytical predictions and experimental responses were broadcasted from a website: http://exp.ncree.org/cbf.

5.2. Key Experimental Observations and Results

Results of these three tests confirm that the two-story X-shape steel CBFs all have rather good energy dissipation characteristics (Fig. 19) up to a story drift of about 0.03 radians under the cyclically increasing lateral displacements. Large brace local buckling and out-of-plane displacements were observed on during each test. Tests confirm that both the 2t-linear and 8t-elliptical out-of-plane deformations of the gussets provide satisfactory ductility for the seismic resistant design of steel CBFs. Hollow structural sections braces fractured at a story drift smaller than that found in the test the CBF using wide flange sections.

6. CONCLUSIONS

Base on the test results and analytic study, conclusions and recommendations are made as follows:

(1) Test results confirm that the earthquake responses of the 3-story 3-bay CFT-BRB frame and members can be

satisfactorily predicted using both PISA3D.
(2) Stiffeners added along the free edges of the gusset plate are effective in preventing out-of-plane instability of the brace-to-column connections. However, it also introduces flexural demands on the BRBs. Further researches are required to study the BRB end connections.
(3) The BRB gusset plates can sustain cyclic BRB loads and bi-directional deformational demand when it is properly stiffened at the free edge of the gusset plate and designed according to the theory proposed by Whitmore (1952) and Thornton (1984).
(4) The responses of the SPSWF can be accurately predicted using the strip model and the tension-only material property implemented in PISA3D computer program.
(5) The use of restrainers can improve the serviceability of SPSWs, including the decline of out-of-plane displacement and buckling sounds.
(6) Results of these three tests confirm that the two-story X-shape steel CBFs all have rather good energy dissipation characteristics up to a story drift of about 0.03 radians under the cyclically increasing lateral displacements.
(7) Test results confirm that both the 2t-linear and 8t-elliptical out-of-plane deformations of the gussets provide satisfactory ductility for the seismic resistant design of steel CBFs.

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Figure 1 Three story CFT/BRB Frame

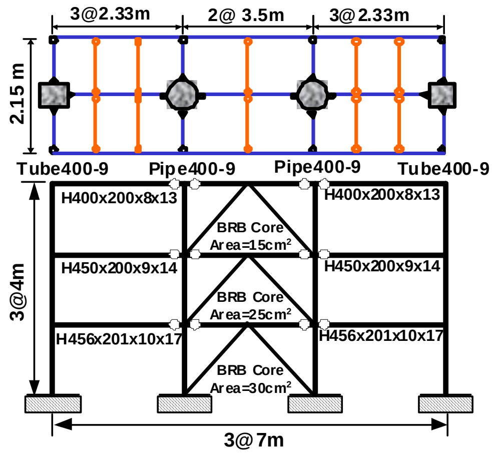
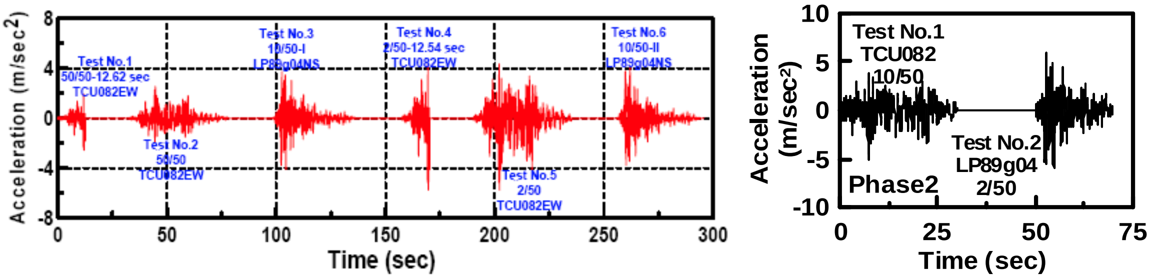


Figure 2 Plane and elevation view of CFT/BRB Frame



(a) (b)

Figure 3 (a) Phase 1 (b) Phase 2 ground acceleration time history in PDTs

Figure 4 Buckling of the gusset at the brace to column joint after Phase-1 tests

Figure 5 Added stiffeners at the free edges of the gusset at the brace to column joint before Phase-2 tests

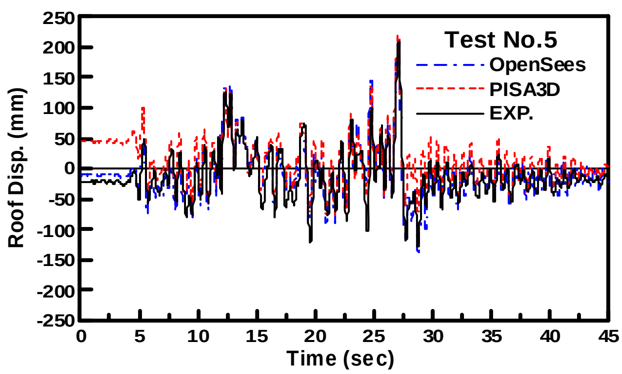


Figure 6 Roof displacement time history response of CFT/BRB Frame

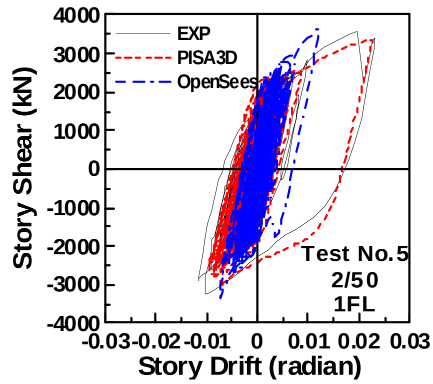


Figure 7 Story shear verse story drift response of CFT/BRB Frame

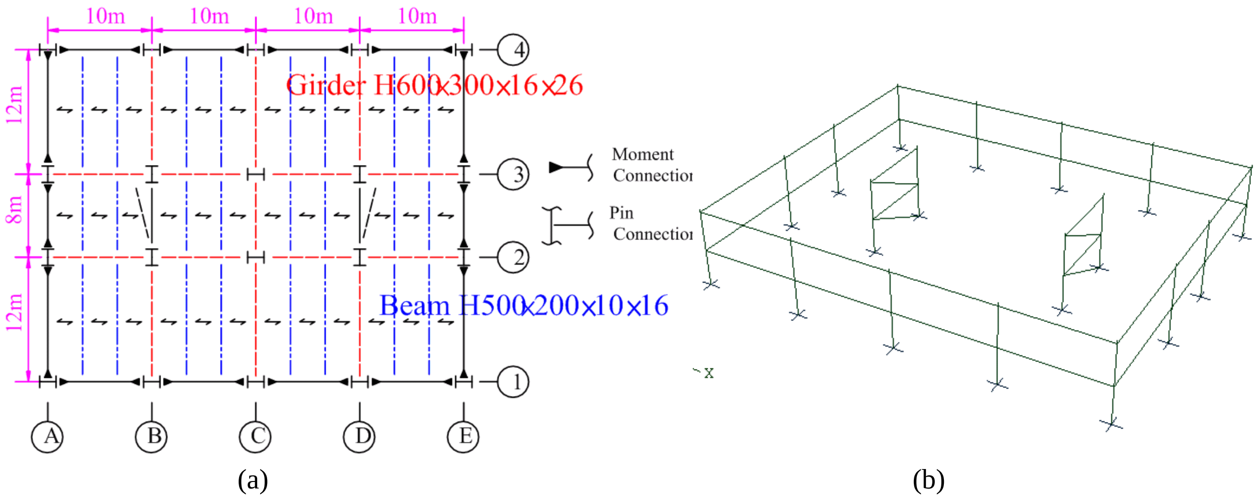


Figure 8 (a) Floor framing plan (b) PISA3D model of two-story prototype building (BRBF)

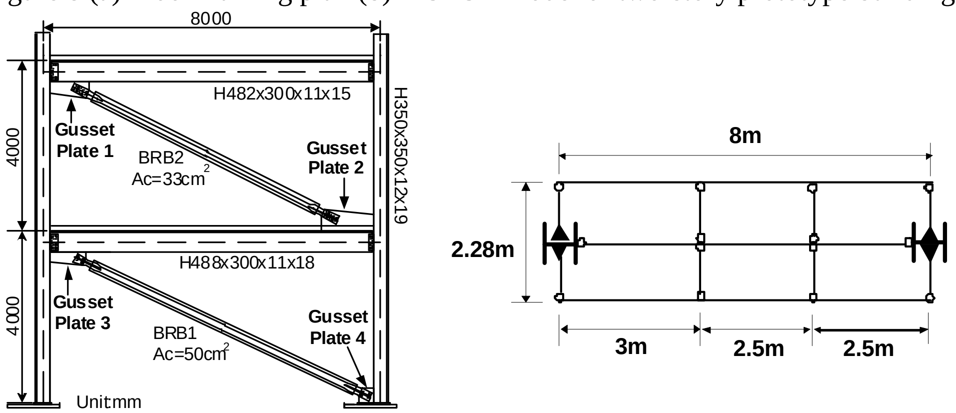


Figure 9 The detail sketch of two-story BRB frame

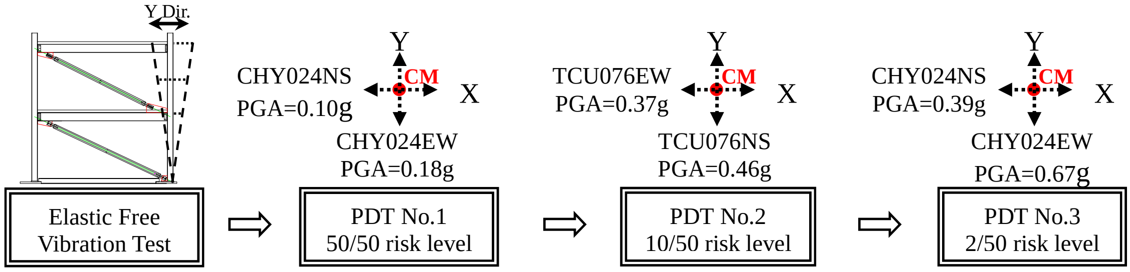


Figure 10 Earthquake sequence used in the experiment

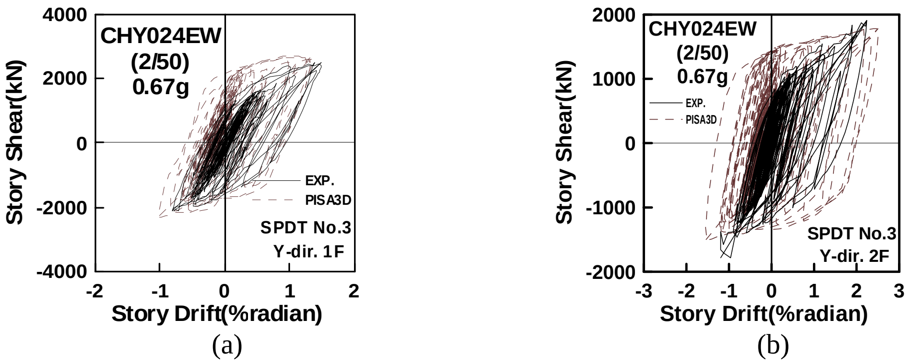
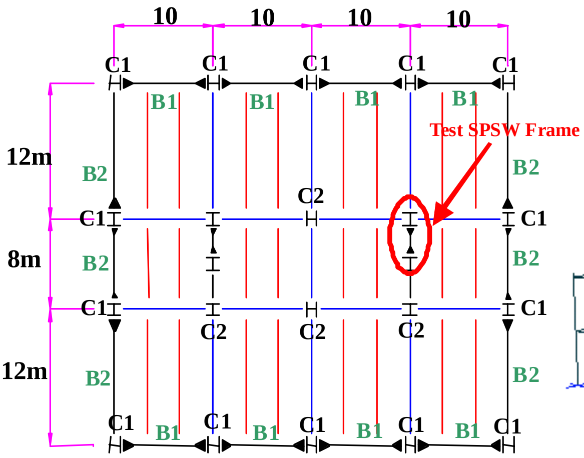


Figure 11 The story hysteretic responses at the in-plane (Y-direction) orientations in the (a) 1st story and (b) 2nd story in the SPDT No.3



Member	A572 GR50
C1	H400x400x20x35
C2	H400x300x18x26
B1	H600x200x16x26
B2	H600x200x12x20

Figure 12 Floor framing plan of two-story prototype building (SPSW frame)

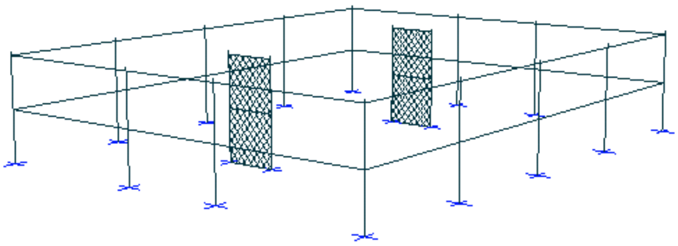


Figure 13 PISA3D analytical model of two-story prototype building (SPSW frame)

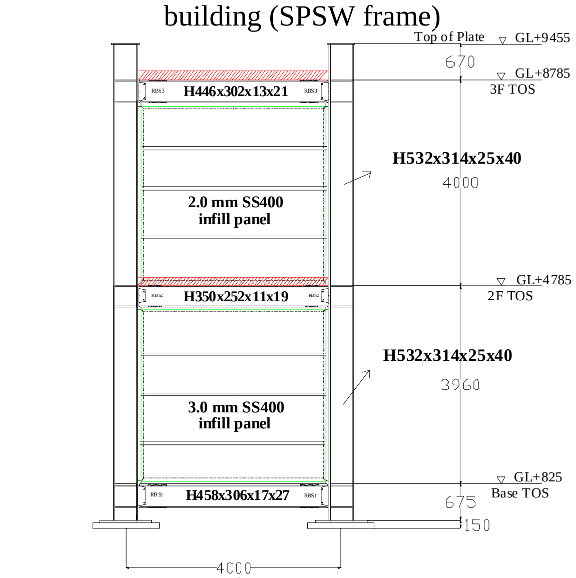


Figure 14 Detail sketch of two-story SPSW specimen

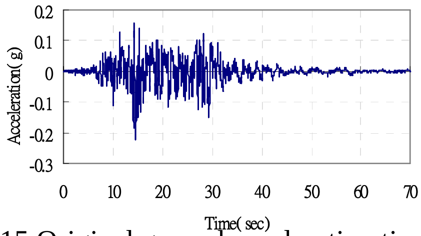


Figure 15 Original ground acceleration time history

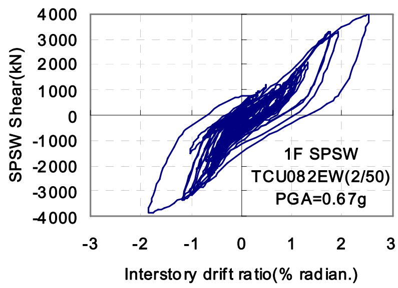


Figure 16 Hysteresis loops of 1F SPSW

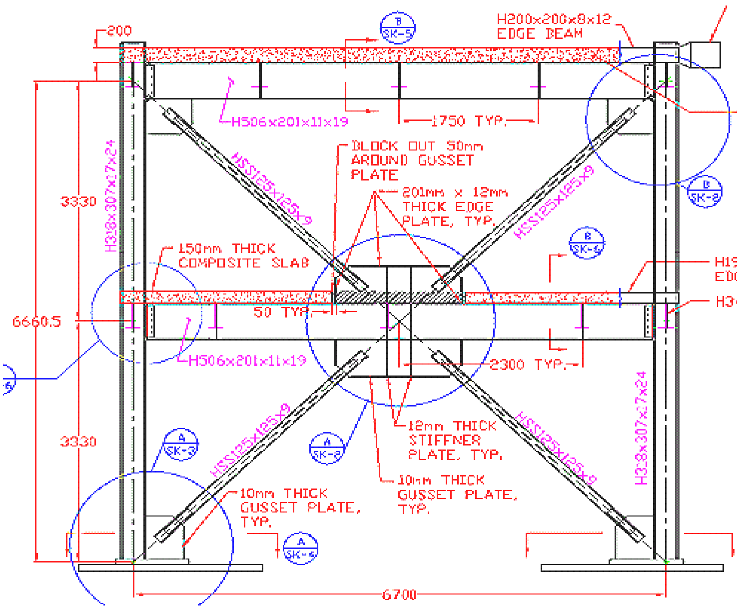


Figure 17 Detail sketch of two-story CBF specimen

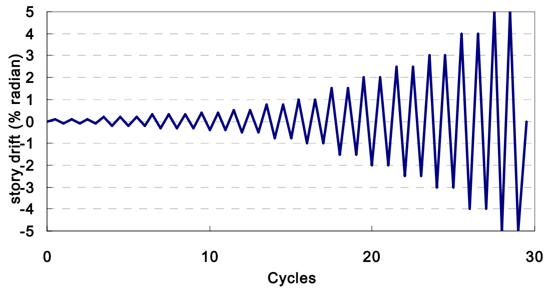


Figure 18 Test loading protocol

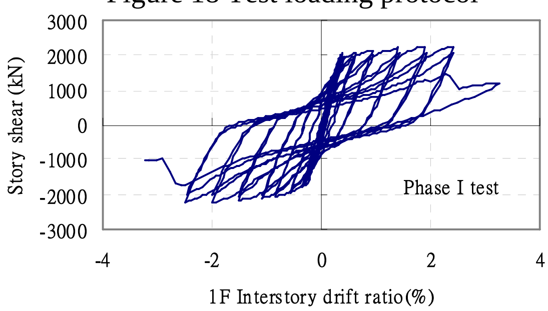


Figure 19 Story shear verse story drift ratio relationship