Proceedings 7th U.S. National Conference on Earthquake Engineering. Boston, Massachusetts, July 2002.

APPLICATION OF THE UNBONDED BRACE IN MEDICAL FACILITIES

Eric Ko[1], Andrew Mole[1], Ian Aiken[2], Frederick Tajirian[2], Zigmund Rubel[3] and Isao Kimura[4]

ABSTRACT

Damage to medical facilities in the Loma Prieta and Northridge Earthquakes resulted in California legislating that all hospitals in the state meet tough new performance criteria by 2030. The new regulations will ensure that hospitals remain functional after a major earthquake. To achieve the enhanced performance objectives, engineers are increasingly considering new seismic structural technologies such as seismic isolation and passive energy dissipation systems.

For the new Kaiser Santa Clara Medical Center, the designer selected the Unbonded Brace (UBB), a type of buckling-restrained yielding steel brace, to achieve a high-performance seismic-resisting structural system. This project is the first application of the UBB in a medical facility requiring approval by the California Office of Statewide Health Planning and Development. Nonlinear pushover analyses were used to demonstrate the performance advantages of the UBB over the initially selected Eccentrically Braced Frame (EBF) system. Nonlinear time history analyses were carried out for Design Basis Earthquake (DBE) and Upper Bound Earthquake (UBE) demands. The largest calculated interstory drift ratio from the analyses was 1.5 percent, which was significantly less than the maximum UBE drift of 2.25 percent allowed by the design criteria.

Tests on two identical large-scale UBB specimens were carried out at the Pacific Earthquake Engineering Research Center at the University of California, Berkeley. A standardized loading history was applied to both specimens, followed by DBE and UBE displacement histories applied to one specimen, and a low-cycle fatigue history to the other. Both braces exhibited stable hysteretic behavior through all of the tests.

Introduction

The Kaiser Permanente Santa Clara Medical Center Replacement Project in Santa Clara, California (Fig. 1), is being constructed in two phases. Phase I consists of a 3-story hospital building with a full basement. The building is approximately 250 feet wide by 320 feet long, with a circular cutback at the northeast quadrant (Fig. 2). The lateral system

[1] Ove Arup and Partners, 901 Market Street, San Francisco, California 94103
[2] Seismic Isolation Engineering, Inc., P.O. Box 11243, Oakland, California 94611
[3] Anshen+Allen Architects, 901 Market Street, San Francisco, California 94103
[4] Nippon Steel Corporation, 2-6-3 Otemachi, Chiyoda-ku, Tokyo, 100-8071, Japan

comprises 10 bays of UBBs at each floor in the NS and EW directions. Columns are typically on a 28-foot grid, and the floor system comprises lightweight concrete fill over metal decking. The foundation consists of drilled piers with belled bottoms and straight shafts.

The UBB is a buckling-restrained yielding steel brace manufactured by Nippon Steel Corporation. The UBB consists of a yielding steel core plate surrounded by mortar and enclosed in a steel tube. A slip surface, or unbonding layer, separates the steel core from the surrounding mortar. Fig. 3 (left) shows a schematic of a UBB, and Fig. 3 (right) presents a typical UBB hysteresis loop. The UBB provides predictable, symmetric and stable hysteretic behavior without buckling.

The original design of the hospital was submitted to the California Office of Statewide Health Planning and Development (OSHPD) in 1996. During the review process the impact of the 1995 Kobe, Japan, earthquake became a concern for this project, specifically with regard to near-field ground motions. The building site is between two major faults, the San Andreas to the west and the Hayward to the east. Consequently, OSHPD requested that the seismic hazard assessment for the site be updated. This update resulted in an increase in the design earthquake peak ground acceleration of 50 percent (Kleinfelder 2000). During this time the Medical Center also went through programming adjustments that resulted in a 50 percent increase in the project gross floor area. Because of these factors, it was necessary to re-examine the design of the seismic lateral resisting system for the buildings.

Arup, having just completed the design of the first building in the U.S. to use UBBs, the UC Davis Plant and Environmental Sciences Building (Clark et al., 1999), presented a revised design with UBBs to the owner and the architect. The performance advantages of a UBB system over the initially selected Eccentrically Braced Frame (EBF) and a Special Concentrically Braced Frame (SCBF) system were demonstrated using nonlinear pushover analyses. The owner was also presented with the results of detailed nonlinear finite element analyses of an individual brace subjected to cyclic axial loading. The results obtained from these analyses were later verified by experimental testing. These presentations were followed by visits by OSHPD and owner representatives to the UC Davis project construction site, and ultimately resulted in the selection by the owner to use UBBs in their hospital buildings at the Santa Clara campus.

Design Procedure for Unbonded Braces

The UBB is a new type of bracing system in the U.S. A joint SEAOC and AISC Task Group has recently completed development of provisions for the design of structures incorporating buckling-restrained braces, but at the time of the design of the Kaiser Santa Clara campus, no design provisions were available. OSHPD required that the structural system be designed in accordance with the 1995 California Building Code, Vol. 2, Title 24, Part 2, and for the purposes of the project, that the UBB system be classified as an "Undefined Structural System". The seismic design criteria, the analytical procedure used in the design, as well as details of a full-scale testing program are presented in the remainder of the paper.

Seismic Design Criteria

The seismic design was based on two earthquake levels, a Design Basis Earthquake (DBE) and an Upper Bound Earthquake (UBE). The DBE was defined as having a 10 percent probability of exceedance in 50 years (475 year return period), and the UBE was defined as having a 10 percent probability of exceedance in 100 years (950 year return period). Site-specific response spectra were developed (Fig. 4), having peak ground accelerations of 0.6g and 0.8g, for the DBE and UBE, respectively. Maximum allowable interstory drift ratios for design were defined to be 1.25 percent for the DBE and 2.25 percent for the UBE.

Analytical Procedure

The design analyses were conducted using both linear and nonlinear structural models. A response spectrum analysis was conducted using a three-dimensional linear model developed in ETABS Ver. 6 (Computers & Structures, 1997). A force-reduction factor, $R_{w,}$ of 8 was used to initially calculate member forces. The linear results were subsequently validated using nonlinear time history analysis. Two computer programs were used for the nonlinear analyses–ETABS Ver. 6 and LS-DYNA (Livermore Software Technology Corp.).

ETABS analyses were used for "global" code compliance validation purposes, to check the brace strains and forces, and to verify the design story drift limits. The linear ETABS model was modified to include nonlinear characteristics for the UBBs. The beams and columns of the structure were modeled as linear elements while nonlinear link elements with bilinear stiffness properties were used to represent the UBBs (see Table 1).

Table 1 Unbonded Brace Nonlinear Properties

Story	**Core Area (in^2)**	**Elastic Stiffness (kips/in)**	**Yield Force (kips)**	**Stiffness Ratio (K_2/K_1)**
3	7.7	1191	288	.03
2	12.9	1714	485	.03
1	15.9	1951	598	.03

For each earthquake design level, three pairs of ground acceleration time histories were selected and scaled such that the square root of the sum of the squares (SRSS) response spectrum of each pair of motions did not fall below 1.3 times the 5 percent-damped design spectrum (Fig. 5).

The finite element software, LS-DYNA, was used to include the nonlinearities of the beams and columns and to perform parametric analyses that varied the UBB properties and the yield criterion. LS-DYNA uses explicit methods to calculate nonlinear structural behavior in the time domain rather than the implicit methods employed by most other structural analysis software, including ETABS. It is possible to model many types of nonlinearity, both constitutive and geometrical. All forces are calculated based on the deformed geometry, so there are no small displacement approximations and P-delta effects are directly included. A "seismic beam" element, developed by Arup, was used in the analyses and is now part of the standard LS-DYNA program. The element models post-yield behavior with lumped plastic hinges. The yield criterion, ψ, is based on the interaction of axial forces and moments on an individual section as defined by:

$$\psi = M_y^{\alpha} + M_z^{\beta} + 2N_x^2 - N_x^4 - 1.0$$

where M_y and M_z are the bending moments in the Y and Z directions, and N_x is the axial force in the element. Yield occurs when ψ is equal to zero.

The effect of varying the yield strength of the steel in the unbonded braces (from 34 ksi to 51 ksi) is examined using a two-dimensional LS-DYNA model consisting of a single braced frame (Fig. 6). Two percent additional damping was applied to the response at and around the fundamental period of the frame.

Since the form of the yield surface itself is a potential variable, additional analyses were also performed to investigate the effect of linear versus parabolic interaction. A post-yield stiffness of 2 percent was assumed for the UBBs. Tests show that UBBs exhibit larger post-yield forces in compression than in tension, and a 15 percent increase was included in the analyses to reflect this behavior.

Analyses to confirm the final design were performed with a 3D nonlinear model of the entire structure (Fig.7). This model used the same elements as the 2D frame, and applied ground motions in both horizontal directions. In order to model the correct distribution of structural mass and the vertical load on the frame columns, the diaphragms were modeled explicitly. Gravity columns were included to correctly distribute vertical load, but these were modeled as pin-ended so that they did not contribute to the overall lateral stiffness.

Analysis Results

The results of the nonlinear ETABS analyses are summarized in Fig. 8. The maximum interstory drift ratios for each time history pair were calculated for the DBE and UBE earthquakes. The maximum DBE drift was 1.2 percent, with 1.45 percent for the UBE, compared with the maximum allowable drift ratios of 1.25 and 2.25 percent, respectively. The maximum DBE and UBE story accelerations are also presented in Fig. 8. The maximum DBE accelerations are 0.8g at the second story and 1.26g at the roof, while the maximum UBE accelerations are 1.07g and 1.55g, respectively. It should be noted that the elastic structure has approximate predominant natural periods between 0.4 and 0.5 second. From the elastic 5 percent damped spectrum (Fig. 4), it can be seen that the peak DBE spectral acceleration in this period range is greater than 1.5g, and for the UBE greater than 2g. However, the calculated maximum roof acceleration for the DBE is only 1.26g, and for the UBE it is 1.5g. This reduction in accelerations is attributed to both the beneficial effect of energy dissipation by the UBBs, and the longer period of the yielding structure that is more accurately captured by the nonlinear analyses. These effects are seen to be greater for the UBE results than for the DBE. The maximum UBB forces are also shown in Fig.8.

The 3D LS-DYNA results further confirmed the excellent performance of the system. In all cases the calculated story drift ratios were less than the design criteria limits, and were similar in magnitude to the drift ratios calculated by ETABS. The maximum roof accelerations were calculated to be 1.13g for the DBE and 1.26g for the UBE. The analyses showed that for the DBE the beams and columns remained elastic and yielding was confined entirely to the UBBs, while for the UBE some beam and column yielding was observed. Where frame member yielding did occur, it occurred preferentially in the beams, and column yielding occurred only at the base of the frame.

The LS-DYNA 2D frame analysis results are summarized in Fig. 9. The results shown are for the parabolic yield surface analyses. Since there was no yielding of beams or columns at the DBE level, obviously there was no difference between the calculated responses for parabolic and linear yield surface models. For the UBE, the shape of the yield surface did not impact the story accelerations or brace forces, however there was some effect on the story drift ratios, with the linear model showing higher values.

The effect of the UBB yield strength can be seen in Fig. 9. As expected, reducing the yield stress of the UBB core plate from 51 ksi to 34 ksi results in increased drifts. For the UBE, the second and third story drift ratios increase by about 70 percent. The maximum calculated drift ratio is 2 percent, which is smaller than the allowable design limit (2.25 percent). The stronger braces also result in increased floor accelerations and maximum brace forces.

Full-Scale Testing

A full-scale UBB testing program was undertaken as part of the review and approval process by OSHPD. The program was developed with consideration given to previously published research results (Wada et al., 1988, Hasegawa et al., 1999, Nakamura et al., 1999) and the results of testing of full-sized UBBs carried out in support of the UC Davis project (SIE 1999).

Test Specimens and Test Program

Two identical UBB specimens were tested in the Structures Laboratory of the Pacific Earthquake Engineering Research Center at the Richmond Field Station of the University of California, Berkeley. The main purpose of the tests was to evaluate the behavior of UBBs of similar size and material to those designed for the hospital building, under repeated axial loads with increasing levels of strain. In addition, the tests also examined the behavior of UBBs subjected to simulated earthquake loading histories and low-cycle fatigue conditions.

Three sizes of UBBs are used in the hospital project. The design of the UBB test specimens was selected to be representative of the mid-size brace for the project and with consideration of the maximum capacities of the test facility. The test specimens, denoted as SP-1-1 and SP-1-2, had an overall length of approximately 14.75 ft. and a core area of 11.04 in^2. The core cross-section was cruciform (+) and was manufactured from JIS SN400B steel. The yield force of the brace was approximately 455 kips. SN400B steel is similar to ASTM A992/50, but with a yield stress approximately the same as ASTM A36. Tensile tests of three coupon specimens of the steel used to manufacture the core plates gave an average yield stress of 41.1 ksi, an average ultimate stress of 65.8 ksi. and an ultimate elongation of 33 percent. The end connection design details of the test specimens were the same as that for the building, with all bolts 1-inch diameter ASTM grade A490 and splice plates of JIS grade SM490A (approximately equivalent to ASTM A572/50). Direct Tension Indicators (DTIs) were used to ensure correct bolt tightening forces.

The *Brace Loading History* is shown in Fig. 10. It is expressed in terms of interstory drift, and the brace displacement and brace strain demands computed based on the building geometry and the designed brace dimensions. The maximum strain applied to the test specimens corresponded to a story drift ratio of 2.25 percent–the UBE-level story drift ratio limit established in the project design criteria. In addition to the sequence shown in Fig. 10, pre-yield displacement cycles of 0.25, 0.50, 0.75 and 1.0 times the yield displacement were also applied to both specimens.

Subsequent to the *Brace Loading History*, the two specimens were subjected to additional tests. Specimen SP-1-1 was subjected to a low-cycle fatigue test consisting of 31 tension-compression cycles at the DBE interstory drift ratio of approximately one percent (0.9 percent brace strain). Specimen SP-1-2 was subjected to two earthquake displacement histories. These were determined from the nonlinear ETABS analyses, and were the most severe DBE and UBE brace displacement histories.

Test Results

Force-displacement plots for all the *Brace Loading History* cyclic tests of specimens SP-1-1 and SP-1-2 are shown in Fig. 11. The results for both specimens are very similar. It should be noted that for SP-1-1, an error with the control system resulted in the maximum displacement in one direction exceeding the intended value (3.08 inches vs. the intended maximum of 2.75 inches). Both specimens exhibited stable hysteretic behavior over the entire range of displacement amplitudes without degradation in the measured properties. The core plate yield stress for specimen SP-1-1 was 40.9 ksi and for specimen SP-1-2 it was 40.7 ksi. There was less than 1 percent difference between the yield stress computed from these tests and that determined from the coupon test, indicating that coupon tests can be used to reliably predict the UBB yield force.

At the completion of the *Brace Loading History*, a low-cycle fatigue test was performed on specimen SP-1-1. The brace exhibited stable cyclic behavior for the entire test, which consisted of a total of 31 fully-reversed cycles (Fig. 12). The initial intent was to conduct the test to failure, which was anticipated to occur at about 20 cycles of loading. The test was ended after 31 cycles of loading, even though failure still had not occurred, so as to avoid damage to the test set-up or the instrumentation system.

At the completion of the *Brace Loading History,* two earthquake loading tests were performed on specimen SP-1-2. In the DBE test, the maximum brace displacement was 1.49 inches in compression, corresponding to a brace strain of 1.11 percent, and in the UBE test (Fig. 13) the maximum brace displacement was 1.86 inches in compression, corresponding to a brace strain of 1.38 percent. The specimen exhibited very predictable hysteretic behavior with no strength or stiffness degradation in either earthquake test.

Conclusions

The paper has illustrated the benefits of Unbonded Braces for the enhanced seismic safety of the Kaiser Santa Clara Medical Center. The UBB, with its stable and predictable energy dissipation capability, proved to be an ideal and cost effective solution for the project. The UBB made it possible to design the structure such that for the DBE level earthquake the gravity load-carrying system will remain elastic and yielding is confined to the UBB elements. At the UBE level the design ensures that only limited yielding occurs in the gravity system and story drift ratios are limited to less than 1.5 percent.

The results for the Brace Loading History tests showed that Unbonded Braces provide stable cyclic hysteretic behavior over the entire range of displacement amplitudes. The behavior of the braces in the additional tests indicated their resistance to fracture, even after severe loading, and their stable, predictable force-displacement characteristics, even under non-cyclic transient earthquake loading.

Since the introduction of the UBB in the U.S. with its first application at the UC Davis project, subsequent Arup projects, including the Kaiser Santa Clara Medical Center, have further demonstrated the merits of the UBB in achieving high-performance, cost-effective seismic designs. Arup believes that the UBB will continue to gain increased acceptance and the confidence of structural engineers for applications in both new buildings and retrofitted structures.

Acknowledgements

Much credit goes to the Kaiser Permanente project team for their substantial efforts in evaluating and selecting the Unbonded Brace for the new Kaiser Santa Clara Medical Center. The structural engineering design for the project was a result of the collaborative efforts of Arup's Advanced Technology Group in London and San Francisco, as well as Arup's offices in Tokyo and Los Angeles. The dedication of the structural engineering team, led by Sin-Tsuen Tong from Arup's office in San Francisco, is particularly recognized. The cooperative review and approval process conducted by OSHPD is appreciated, and contributed to the success of the project. The project team is grateful to Nippon Steel Corporation for sponsoring the testing program and contributing the test specimens. The efforts of David Maclam, Wes Neighbour and Don Clyde of the Structures Research Laboratory at the Pacific Earthquake Engineering Research Center, and Cameron Black, of the Department of Civil and Environmental Engineering of the University of California, Berkeley, in conducting the test program are appreciated.

References

Clark, P., Aiken, I., Kasai, K., Ko, E., and I. Kimura (1999). Design Procedures for Buildings Incorporating Hysteretic Damping Devices, *Proceedings*, 68th Annual Convention, SEAOC.

Computers & Structures, Inc., (1997), *ETABS Version 6*, Berkeley, California.

Hasegawa, H., Takeuchi, T., Iwata, M., Yamada, S., and H. Akiyama (1999). Experimental Study on Dynamic Behavior of Unbonded-Braces, *Journal of Technology Design*, No. 9, pp. 103-106, Architectural Institute of Japan, December.

Kleinfelder (2000). *Geotechnical, Geological Hazard, and Seismic Evaluation for the Ancillary and Medical Office Buildings at the Santa Clara Kaiser Site*.

Livermore Software Technology Corporation, *LS-DYNA, General Purpose Transient Dynamics Finite Element Program*, Livermore, California.

Nakamura, H., Maeda, Y., Taekuchi, T., Nakata, Y., Iwata M. and A. Wada (1999). Fatigue Properties of Practical-Scale Unbonded Braces (Part 1 & 2), *Proceedings*, AIJ Annual Meeting, Architectural Institute of Japan, September.

Nippon Steel Corporation (1999). *Plant & Environmental Sciences Replacement Facility, University of California, Davis, QA/QC Plan and Fabrication Manual of Unbonded Brace,* submitted to Ove Arup & Partners. California.

SIE, Inc. (1999). *Tests of Nippon Steel Corporation Unbonded Braces*, A Report to Ove Arup & Partners California, Ltd., submitted by Nippon Steel Corporation, Tokyo, Japan.

SIE, Inc. (2001). *Cyclic Tests of Nippon Steel Corporation Unbonded Braces,* A Report to Ove Arup & Partners California, Ltd., submitted by Nippon Steel Corporation, Tokyo, Japan.

Wada, A., Saeki, E., Takeuchi, T. and A. Watanabe (1988). Development of Unbonded Brace, *Quarterly 'Column'*, Nippon Steel Corporation, Winter.

Figure 1. Kaiser Santa Clara Medical Center

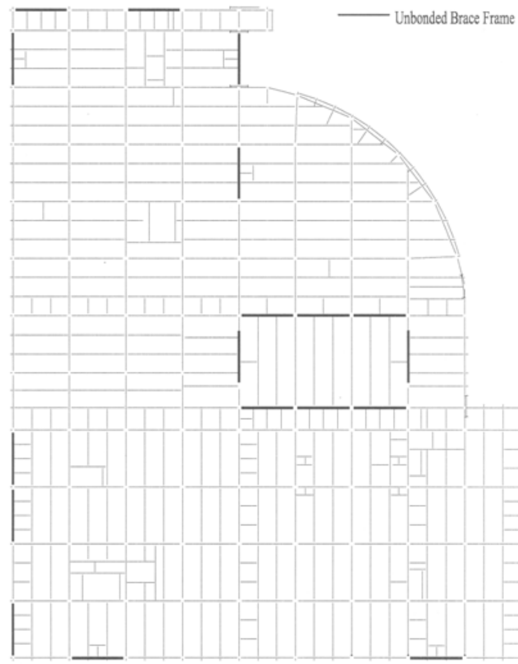

Figure 2 Typical Floor Framing Plan

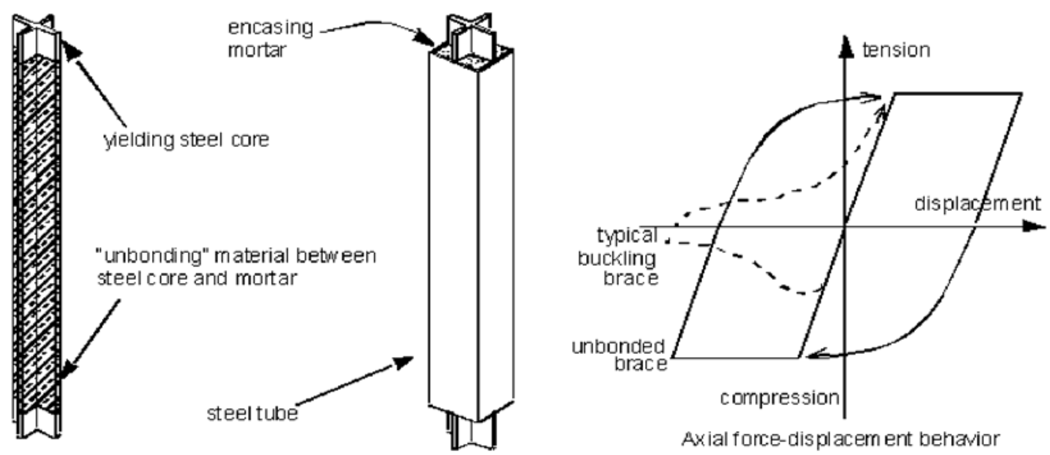

Figure 3 Unbonded Brace (left), and typical hysteresis loop (right)

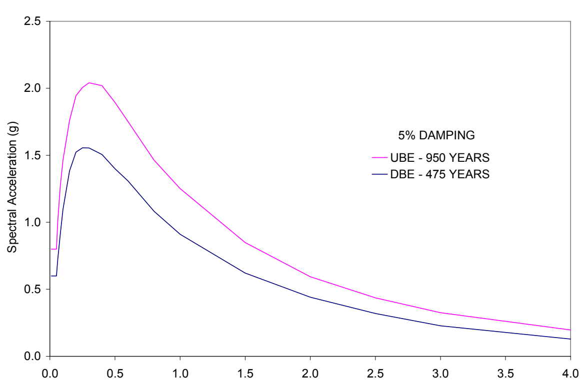

Figure 4 Site-Specific Design Spectra

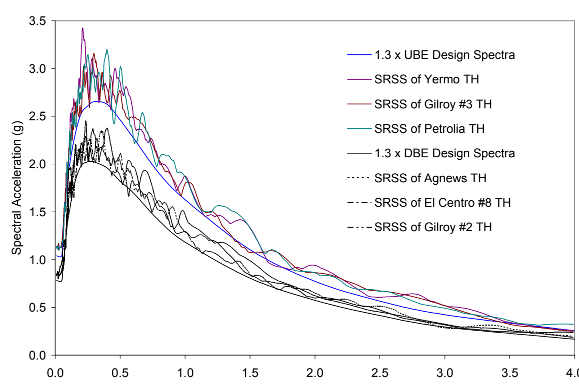

Figure 5 Comparisons of Time History Spectra

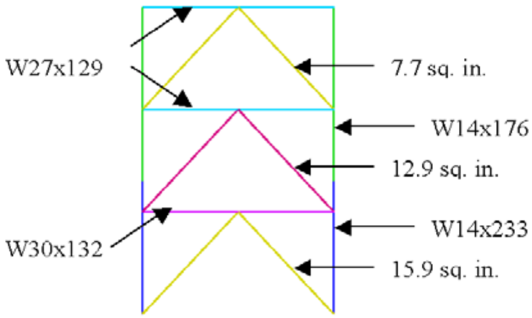

Figure 6 Typical UBB Frame used in 2D LS-DYNA Model

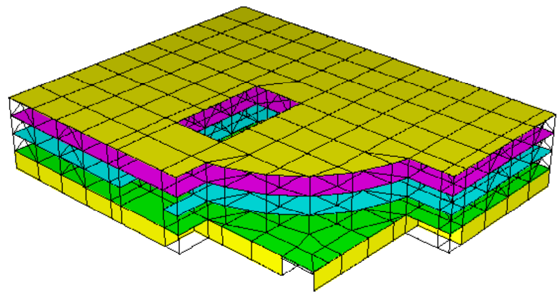

Figure 7 3D LS-DYNA Model

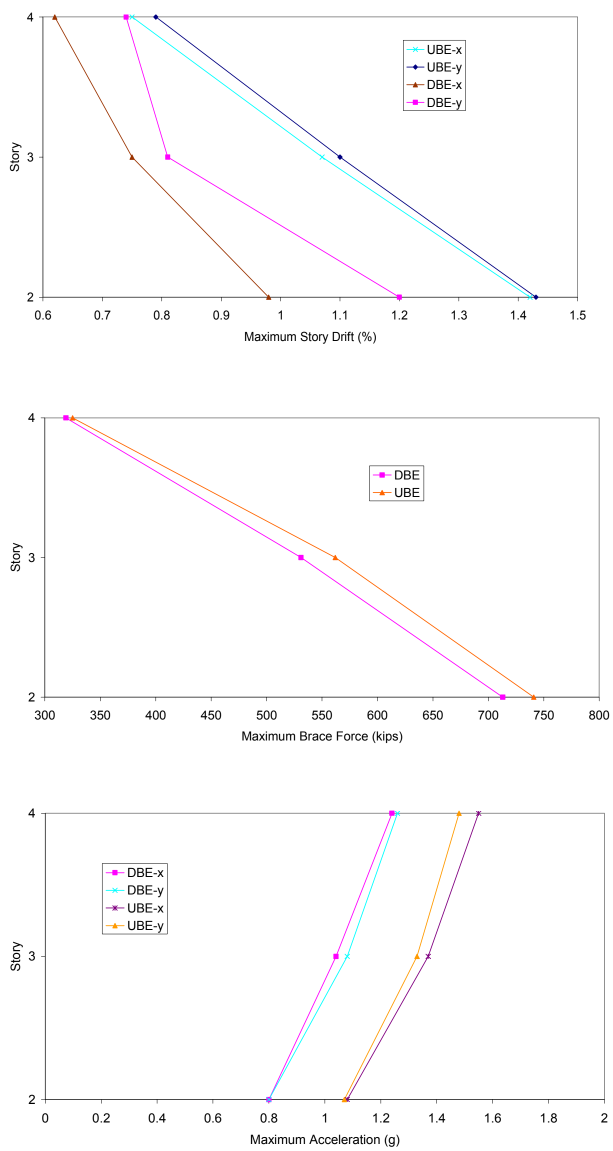

Figure 8 ETABS Nonlinear Results

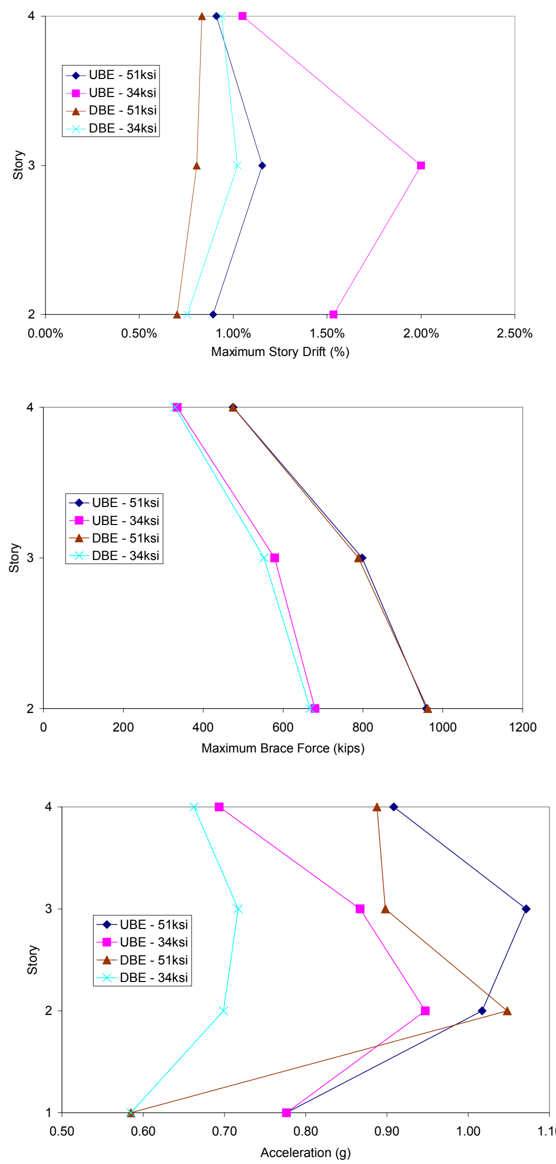

Figure 9 2D LS-DYNA Results

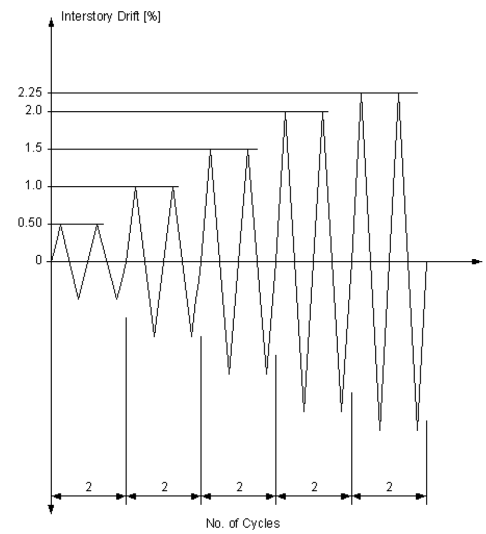

Figure 10   Brace Loading History
(pre-yield cycles not shown)

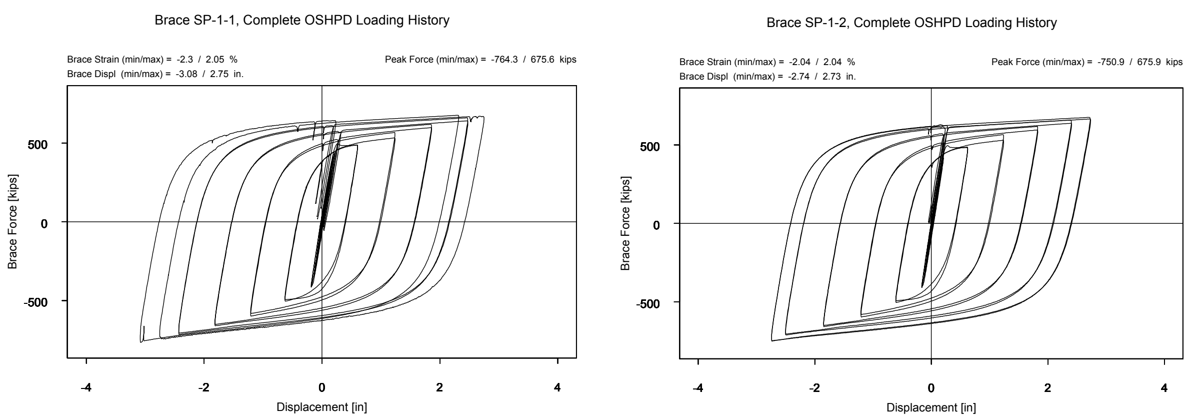

Figure 11   Force-Displacement Plots for Complete Brace Loading History

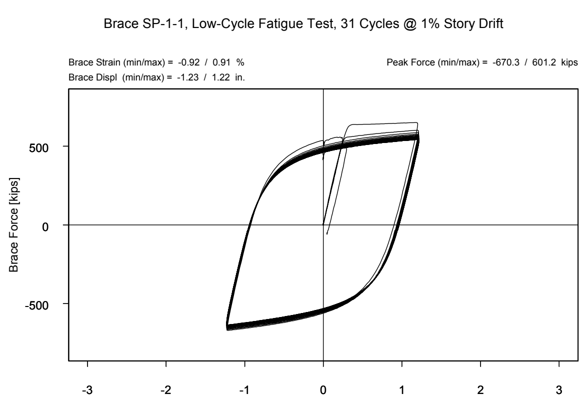

Figure 12   Low-Cycle Fatigue Test

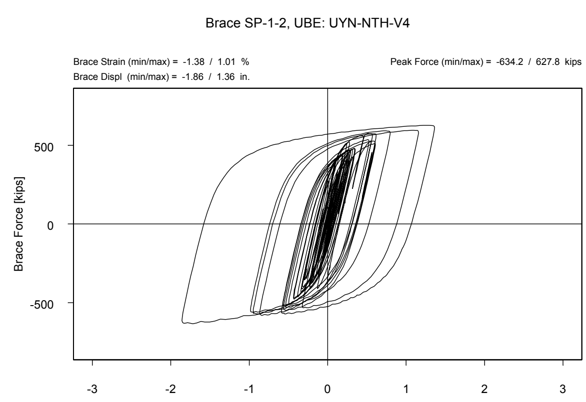

Figure 13   Plot for UBE Test