9th US National and 10th Canadian Conference on Earthquake Engineering: *Reaching Beyond Borders*

toronto july 25-29, 2010

9ième Conférence Nationale Américaine et 10ième Conférence Canadienne de Génie Parasismique: *Au delà des Frontières*

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SEISMIC RETROFIT OF A CITY HALL USING BUCKLING RESTRAINED BRACES BASED ON NONLINEAR ANALYSES INCLUDING SOIL-STRUCTURE INTERACTION

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ABSTRACT

This paper describes the seismic retrofit of the Huntington Beach City Hall Administration Building located in Huntington Beach, California. The existing 6-story 71,000 square foot structure was constructed circa 1971 and is located in close proximity to the Newport-Inglewood fault. The lateral system for the building consists of a non-ductile reinforced concrete beam-column moment frame system in each of the principal building directions. The building is supported on a pile foundation system. A preliminary evaluation of the building revealed several seismic deficiencies, including the following: (1) non-ductile detailing, such as strong beam-weak column configurations and lack of column and beam confinement reinforcement, (2) flexible lateral system with excessive building deflections, and (3) inadequate shear capacity of the beam-column joints.

After considering several alternate retrofit schemes, which included adding exterior and/or interior concrete shear walls and exterior conventional steel braced-frames, a seismic retrofit solution was selected that included the addition of exterior buckling restrained steel braces within a reinforced concrete beam-column frame. The retrofit scheme was designed and evaluated according to a performance-based approach that meets "Life Safety" performance for a design-basis (500-yr) earthquake. A three-dimensional nonlinear computer model was developed capable of capturing the nonlinear behavior of the buckling-restrained braces and the elements of the existing concrete beam-column frame system. The nonlinear interaction between the pile foundations and the surrounding soil and the nonlinear behavior of the soil pressure on the basement walls was explicitly included in the computer model. The seismic performance of the retrofitted building was investigated by time history analyses using seven sets of ground motion records. The results from the nonlinear analyses were used for the seismic design and performance validation of the retrofit scheme.

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Introduction

The Buckling Restrained Brace Frame (BRBF) system is a specialized version of the conventional concentrically braced frame. In traditional concentric brace frames, the hysteretic behavior of braces buckling in compression is characterized by significant degradation of strength and stiffness during cyclic loading. The braces of a BRBF are constructed by encasing core steel plates within a mortar-filled hollow steel tube or pipe, such that buckling is prevented. The steel core plates are overlaid by a de-bonding material that effectively de-couples the axial strength and stiffness from the flexural buckling behavior of the brace. By preventing buckling of the braces, this allows the braces to yield in tension and compression thereby dissipating energy through stable non-degrading hysteretic behavior. Furthermore, the buckling restrained braces do not exhibit the large deformations associated with buckling in conventional concentric braced frame systems. The behavior of the BRBF system has proven itself to be such a desirable lateral force resisting system that it is, for the first time, a recognized lateral force resisting system in the 2006 International Building Code (IBC). The IBC provides a response modification coefficient, "R", equal to 8.0 for a building frame system utilizing the BRBF system with moment resisting beam-column connections, comparable to that of the most ductile building frame systems, such as the special moment resisting frame system and the eccentrically braced frame system. The seismic retrofit of the Huntington Beach City Hall Administration building utilizes a BRBF system to provide additional stiffness and ductility to the existing lateral force resisting system of the building.

Building Description

The Huntington Beach City Hall Administration building is a 6-story existing concrete office building located in Huntington Beach, California. This building was the subject of a previous paper by Huang, et al. (2007). The existing 71,000 square foot structure was constructed circa 1971 and is located in close proximity to the Newport-Inglewood fault. The building is of cast-in-place concrete construction with a 4-1/2" pan-joist floor system with girders and columns as the vertical load carrying system. The lateral system for the building consists of a non-ductile reinforced concrete beam-column moment frame system in each of the principal building directions with concrete shear walls at the stairwells. The building is supported on a pile foundation system.

Seismic Concerns

A preliminary evaluation of the building revealed several seismic deficiencies, including the following: (1) non-ductile detailing, such as strong beam-weak column configurations and lack of column and beam confinement reinforcement, (2) flexible lateral system with excessive building deflections, (3) inadequate shear capacity of the beam-column joints, (4) inadequate strength of the shear walls at the stairwells, and (5) inadequate strength of the existing foundation system for resisting horizontal shear and vertical load demands due to seismic forces.

Seismic Retrofit Performance Objectives

The seismic retrofit of the Huntington Beach City Hall Administration Building is a voluntary seismic upgrade that is intended to improve the seismic performance of the building by addressing the structural seismic deficiencies such that it is capable of meeting the Life Safety level of seismic performance for the BSE-1 level earthquake, as defined in the FEMA-356 (2007) document. The BSE-1 level earthquake is defined by FEMA-356 as an earthquake that approximately has a 10% probability of being exceeded in 50 years, or alternately a 475-year return period earthquake. Life Safety performance means that significant damage to the building will occur and there will be some margin against partial or total collapse which gives the occupants of the structure an opportunity to evacuate safely.

Seismic Ground Shaking Hazard

A seismic hazard analysis was performed in order to develop the horizontal component of the 5% damped acceleration response spectrum corresponding to the BSE-1 (i.e. 500-year return period or 10% probability of exceedance in 50 years) seismic hazard level at the building site. Seven sets of ground motion time histories were developed for the BSE-1 earthquake level. Each set contains time histories for two orthogonal horizontal directions. The time histories were selected from appropriate recorded events with consistent local geology, magnitude, fault distance and source mechanism. The records were scaled by constant factors such that the average SRSS of the horizontal components was not less than 1.4 times the design response spectrum in a period range between 0.1 and 4.0 seconds.

Seismic Retrofit Solution

After considering several alternate retrofit schemes, which included adding exterior and/or interior concrete shear walls, exterior conventional steel braced-frames, and viscous dampers, a retrofit scheme was selected which included the addition of exterior buckling restrained steel braced frames. The new buckling restrained braces were incorporated into a new concrete beam-column frame connected to one-bay at the exterior of the building on three sides of the building and a new bay is added on the west side of the building. A rendering of the building after the retrofit is shown in Figure 1.

The proposed seismic upgrade consists of adding new exterior BRBF's to improve the overall lateral load resisting capability of the building, as well as its stiffness against deflection. Due to the non-ductile nature of the existing perimeter concrete moment frames, the estimated deformation of the existing building during a major earthquake was considered to be excessive. The new BRBF's would provide the necessary stiffness, strength, and ductility required in the event of a strong seismic disturbance at the site. The new BRBF's consist of the following components:

- New exterior 24”x24” concrete columns with steel reinforcement epoxy dowels to the existing exterior concrete columns.
- New exterior concrete beams, 24” wide and matching the depth of the existing perimeter concrete beams, typically 36”. The new concrete beams will have steel reinforcement epoxy dowels to the existing perimeter concrete beams to transfer the seismic shear into the new frame.
- New buckling restrained braces (manufactured by Nippon Steel in Japan) having a design axial capacity of between 490 and 770 kips and connected to the new concrete beams and columns.
- Strengthening of the slab-on-grade in the basement for unloading of the horizontal seismic load.
- New one bay interior basement wall and buttress wall below slab-on-grade with new piles under the added BRBF bay on the west side of the building

The introduction of the exterior BRBF's effectively addresses all of the seismic deficiencies of the existing building. Unlike conventional brace frame systems, the confining encasement provided around the steel core prevents buckling of the braces and instead allows for ductile compression yielding which provides stable energy dissipation characteristics and non-degrading stiffness and strength behavior. This is a particularly attractive feature of the BRBF system for this building since the existing lateral system is comprised of non-ductile concrete moment frames with poor energy dissipation capacity. The use of braces minimizes obstruction to office views and provides openness to allow for natural light and is less expensive and less intrusive than a conventional concrete shear wall scheme. In addition, the buckling-restrained braces do not exhibit large deformation associated with buckling of conventional braces, which was a very important consideration on this project due to the exterior application of these braces. The construction of the BRBF system at the perimeter of the building was extremely advantageous because it did not utilize occupied space of the building.

Nonlinear Analyses

A three-dimensional nonlinear analysis model of the existing building and retrofit elements was created using the SAP-2000 computer program. The computer model is shown in Figure 2. The building floor slabs were modeled as semi-rigid diaphragms to provide for a more accurate distribution of the seismic load. Mass was assigned to each diaphragm in the horizontal and in-plane rotational degrees-of-freedom. Expected gravity loads were applied to the model as a pre-loading prior to any of the dynamic analyses.

The beams and columns of the existing structure and the beams, columns and braces of the new BRBF's were modeled using nonlinear elements. Nonlinear soil springs were used to model the soil/pile behavior. The shear walls, floor slabs and slab-on-grade were modeled as linear elastic elements since these components were not expected to undergo significant ductility demands. A stress check on these elements was performed externally to ensure elastic behavior. The existing concrete beams were modeled with flexural hinges at the ends and the concrete beams that are part of the new BRBF's were modeled with P-M hinges to account for the axial loads induced by the braces in the chevron configuration. Frame columns are modeled using P-M-M hinges. The new buckling-restrained braces were modeled as non-linear axial elements with appropriate brace axial capacity in tension and compression.

Pile groups, pile caps and basement walls were considered in modeling of the foundation system. The foundation stiffness and strength was modeled using nonlinear soil springs, with separate springs being used to represent the lateral and vertical stiffness and strength of the piles. For downward loading, the total length of the piles was used to determine the vertical stiffness and strength of piles. For upward loading, only the reinforced length of the pile was used for the strength of the pile and only the reinforcement was considered for the tension stiffness. In the horizontal direction, the strength and stiffness of a pile group was determined by an analysis of the piles using nonlinear soil springs. Passive pressure on the pile caps and basement walls was modeled by soil springs based on the passive pressure mobilization curve per FEMA-356.

Results

The seismic performance of the retrofit building was investigated by time history analyses using seven sets of ground motion records developed for the 500-year BSE-1 earthquake at the building site. Two analyses were performed for each set of ground motion time histories. Each set of ground motions were applied to the non-linear model, first in one configuration and then the pair of the horizontal ground motions were rotated by 90 degrees for another analysis. The retrofit scheme was designed and evaluated according to a performance-based approach that meets "Life Safety" performance for a Design-Basis (500-yr) earthquake. In order to meet this level of seismic performance, the retrofit schemes were designed to limit the inter-story drift response obtained from the nonlinear analyses to a target inter-story drift of 1%.

Figure 3 shows the maximum story drifts in both directions for the retrofit. These results indicate that the BRBFs will significantly increases the building stiffness by reducing the expected story drifts to about 0.8% or less. Figure 4 shows the distribution of story shear to the existing and new retrofit elements in the north-south direction. The story shear distribution indicates that the addition of the BRBF system is beneficial in reducing the demands on the existing non-ductile concrete moment frame and that approximately 70% of the total story shear is resisted by the new frames.

A two-step procedure was followed for evaluation of the existing pile foundation system. In the first step the maximum pile cap movements and the maximum compression and tension loads on individual piles were obtained from the nonlinear analysis of the structure. Figure 5 shows the summary of such results for the pile foundation system for the earthquake loading in the east-west direction. In the second step, the nonlinear behavior of the pile structural component and the passive resistance of the soil along with the axial-flexure interaction effect on the strength and stiffness of the piles were explicitly modeled using the PERFORM-2D analysis software. Figure 6 shows the nonlinear static pushover curves of the piles for a range of axial loading. Using these curves it was proved that the piles maintain their stability without strength degradation of the flexural hinges or shear failure at the levels of deformation and axial loading presented in Figure 5.

The construction of the seismic retrofit scheme presented in this paper was completed in January 2010. The building remained fully operational during the entire construction as planed. Figure 7 shows the view of a newly added BRB through an existing window. Figure 8 is a close picture of the BRBF elevation taken during construction.

Conclusions

This paper describes the innovative seismic retrofit of an existing reinforced concrete building in which buckling restrained braced frames added to the exterior of the building were used to mitigate the seismic deficiencies. The explicit non-linear modeling of the soil-pile interaction allowed a better understanding of the building response including the superstructure. The case study building had a variety of seismic deficiencies, including the following: (1) non-ductile concrete detailing, (2) flexible lateral systems with excessive building deflections, and (3) inadequate strength of the existing foundation system. A performance-based verification of the design of the retrofit scheme was conducted using a three-dimensional nonlinear analysis of the retrofit building. The selection of the exterior application of a buckling-restrained braced-frame system provides several advantages compared to other conventional retrofit schemes, such as the addition of reinforced concrete shear walls or conventional steel braced frames, including: (1) Provides partial views from existing windows, (2) Requires significantly less demolition than an interior scheme, (3) More cost-effective than an interior solution, (4) Reduces building drift and demands on the non-ductile concrete lateral system, (5) Mitigates issues related to excessive stress in the existing structural elements, and (7) Buckling-restrained braces do not exhibit strength degrading and aesthetically unacceptable post-buckling deformations.

References

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Figure 1. Building after retrofit

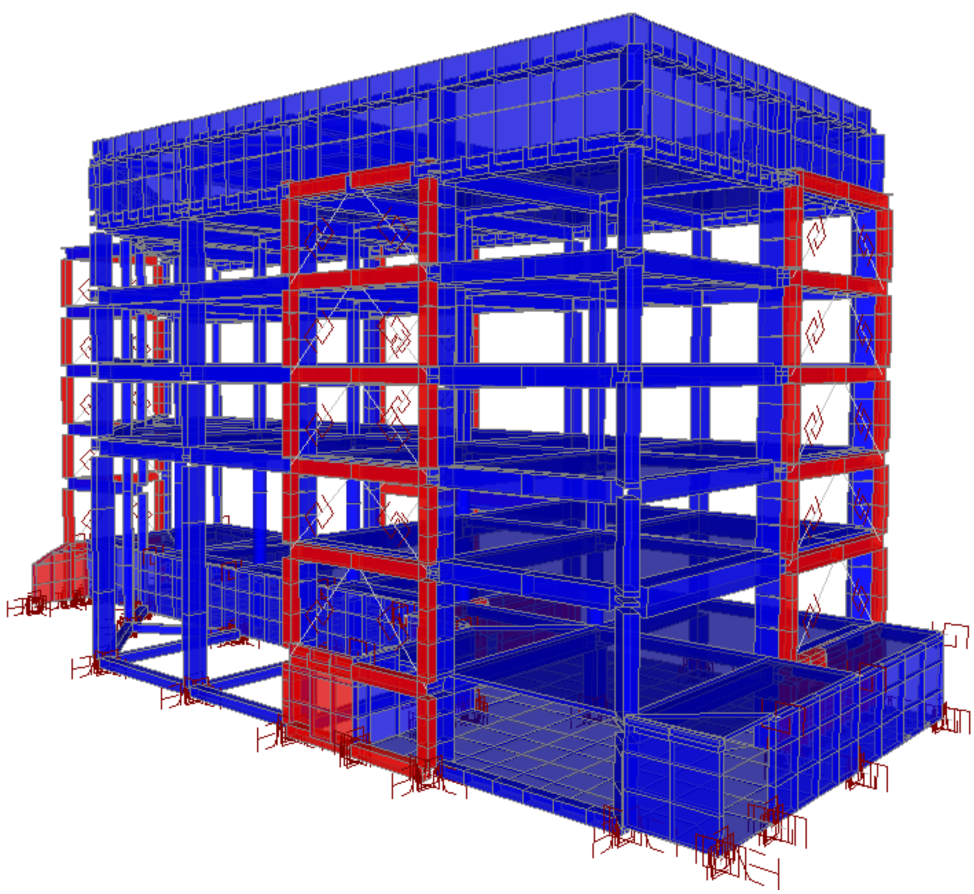

Figure 2. Computer model of building

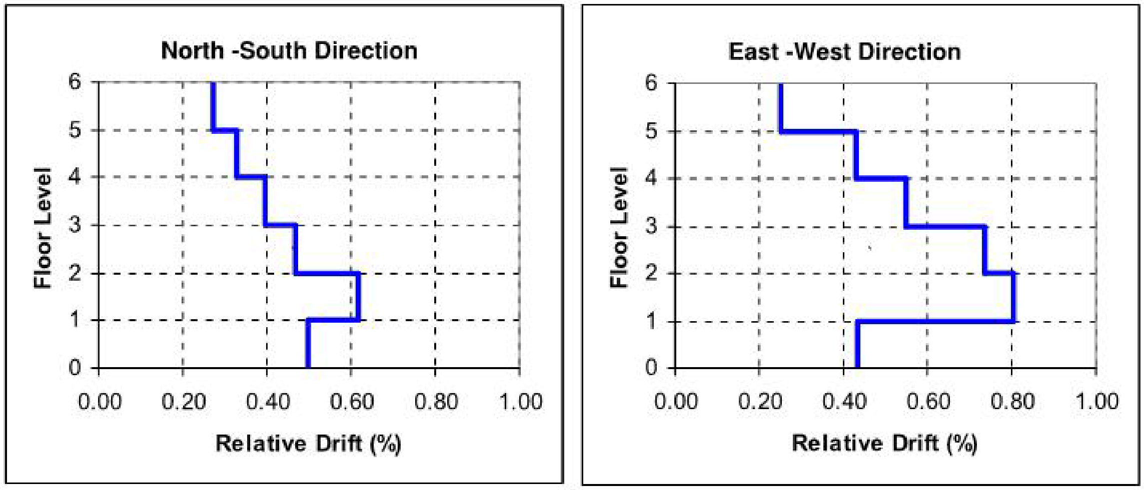

Figure 3 Maximum story drift in NS and EW directions – average of 7 EQ records

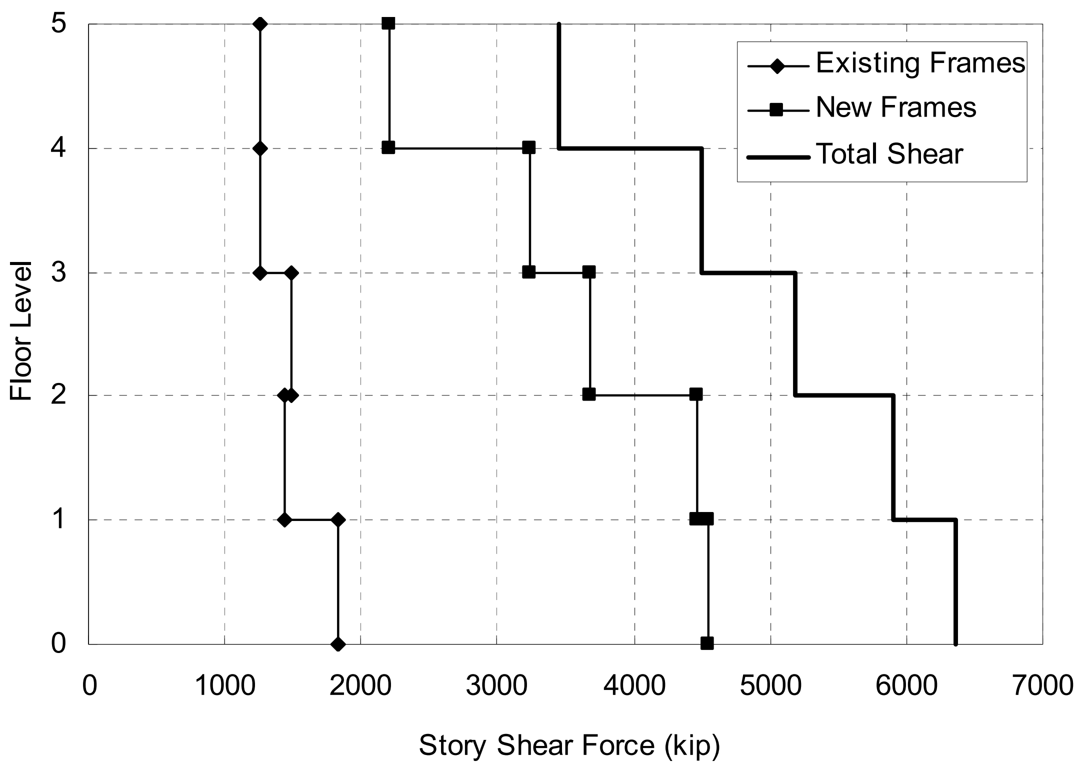

Figure 4. Story shear distribution for retrofit building in N-S direction

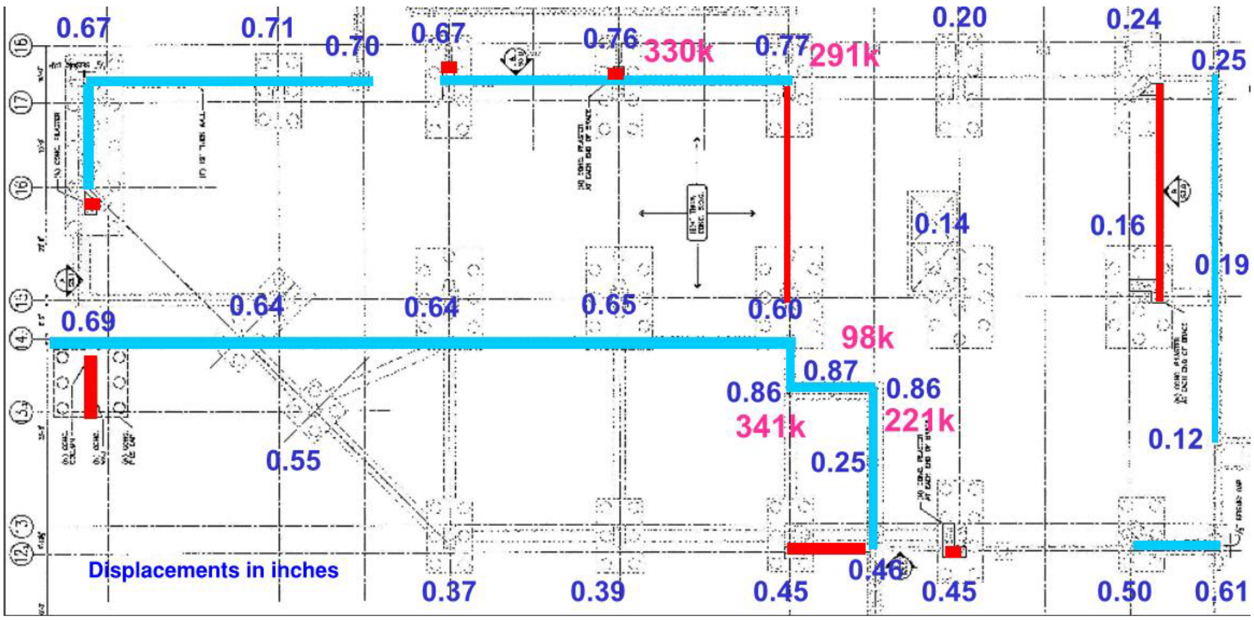

Figure 5. Summary of pile cap movements and critical compression loads on the individual piles

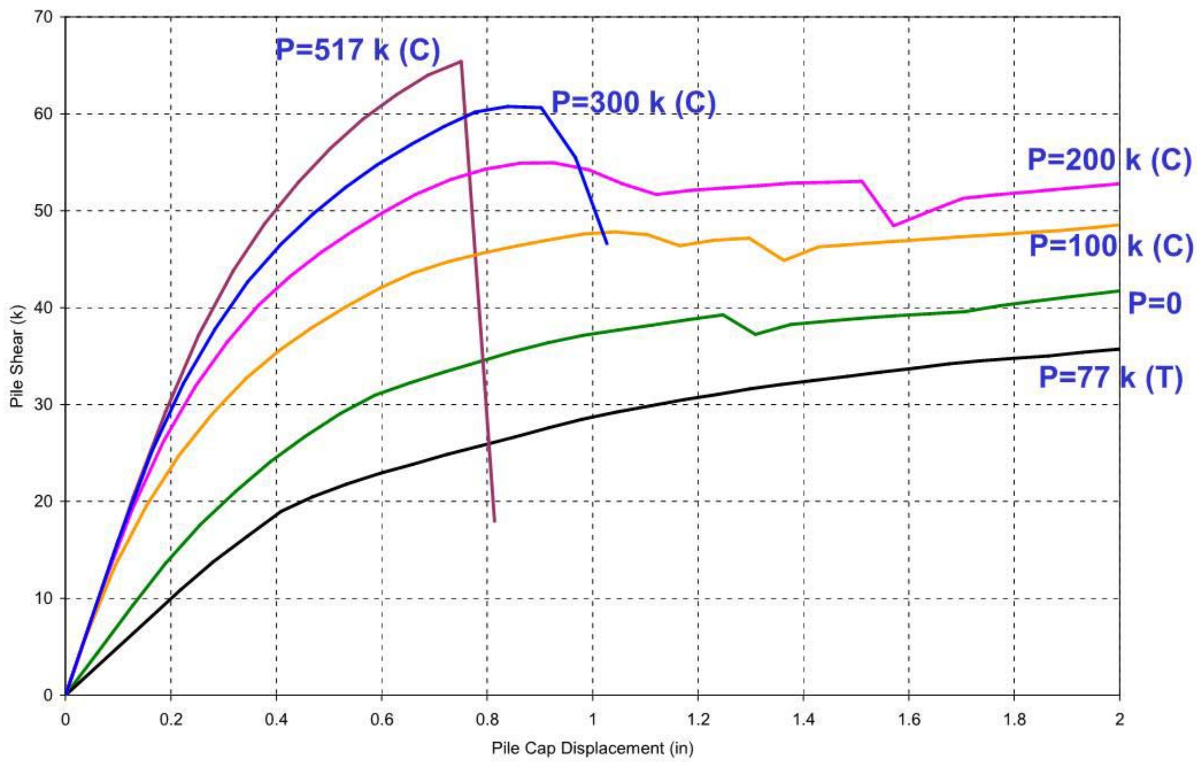

Figure 6. Pushover curves of piles for different values of axial loading

Figure 7. A view of BRBs through an existing window after construction

Figure 8. A picture of BRBF members taken during construction