Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte
Band: 73/1/73/2 (1995)

Artikel: Seismic repair and upgrade of a steel braced frame building
Autor: Bonneville, David R. / Kelly, Dominic J. / Bartoletti, Stacy J.
DOI: https://doi.org/10.5169/seals-55171

Seismic Repair and Upgrade of a Steel Braced Frame Building

Réparation et consolidation d'un immeuble à ossature en acier endommagée par un séisme

Reparatur und Ertüchtigung eines erdbebengeschädigten Stahlgeschossbaus

David R. BONNEVILLE
Vice President
Degenkolb Engineers
San Francisco, CA, USA

Stacy J. BARTOLETTI
Structural Designer
Degenkolb Engineers
San Francisco, CA, USA

Dominic J. KELLY
Project Engineer
Degenkolb Engineers
San Francisco, CA, USA

Stephen G. JIRSA
Structural Designer
Degenkolb Engineers
San Francisco, CA, USA

SUMMARY

A modern four-story steel braced frame office building was structurally damaged in the 1994 Northridge, California, earthquake. The building, which was repaired and upgraded, provided an excellent opportunity to study the performance of a typical chevron braced frame system and to compare it analytically with other braced frame options. Linear and simplified nonlinear (static pushover) analyses were conducted on three different braced frame configurations, including the original system and the replacement system.

RÉSUMÉ

Un bâtiment moderne à ossature métallique de quatre étages, prévu pour des bureaux, a subi des dommages structuraux en 1994 lors du tremblement de terre de Northridge en Californie. La réparation et la consolidation de ce bâtiment ont permis de procéder à la comparaison analytique du comportement d'un système typique de cadre en treillis par rapport à celui de diverses autres ossatures du même genre. Il a été fait appel à des calculs statiques linéaires et non linéaires, en prenant en compte les effets de forces horizontales sur trois structures en portique raidies de manière différente, entre autres celle construite initialement et celle résultant de la solution adoptée pour la réparation.

ZUSAMMENFASSUNG

Ein modernes viergeschossiges Bürogebäude in Stahlbauweise wurde im Northridge-Erdbeben vom Januar 1994 in Kalifornien an tragenden Teilen beschädigt. Bei der Reparatur und Ertüchtigung ergab sich eine exzellente Gelegenheit, das Verhalten unterschiedlicher Ausfachungssystem auf analytischem Wege zu vergleichen. Dazu wurden lineare und statisch-nichtlineare Berechnungen, unter Horizontalkräften, an drei unterschiedlich ausgesteiften Rahmentragwerken, darunter das ursprüngliche und das ausgeführte Sanierungskonzept durchgeführt.

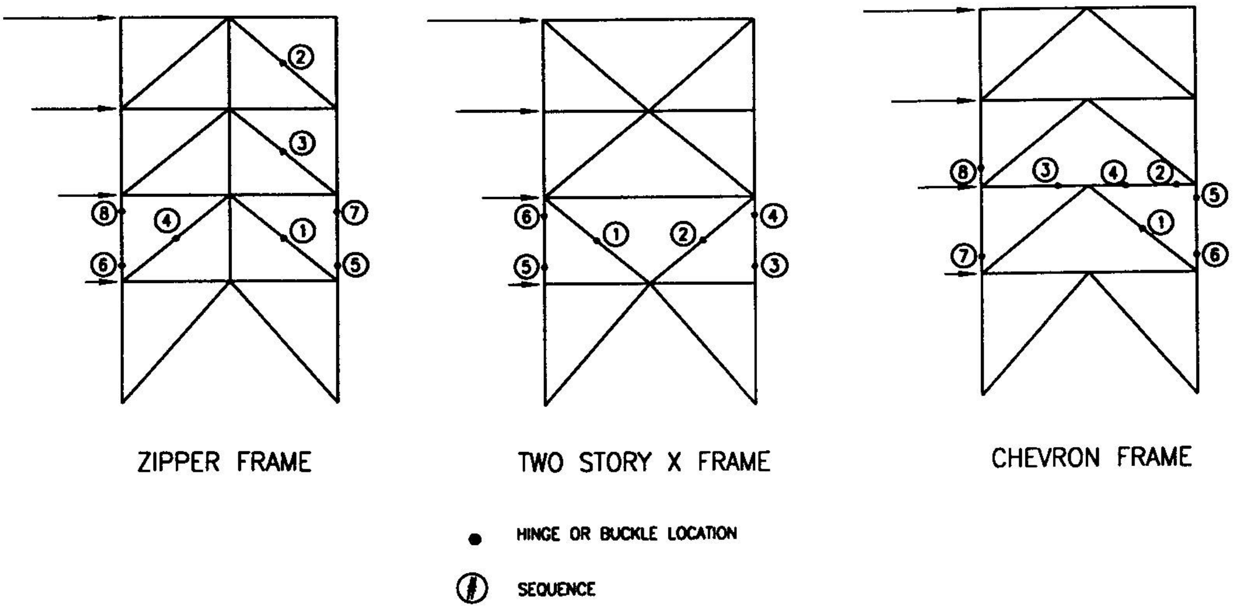
1. INTRODUCTION

The 1994 Northridge, California earthquake demonstrated the susceptibility of modern steel braced frame buildings to structural damage. An excellent example of ordinary, non-ductile, concentric braced frame (CBF) damage was provided by a four-story building in North Hollywood. This building, designed in accordance with recent seismic code provisions, suffered substantial damage in the Northridge earthquake and was repaired and strengthened in the following months. The authors were involved in the post-earthquake investigation, design of repair and strengthening, and construction administration. The building is particularly useful for study purposes since its structural system is typical of CBF's designed in accordance with U.S. Building Code requirements from the 1970s to the present.

The investigation of the subject building provided valuable insights into seismic performance from two standpoints: brace design and detailing, and braced frame configuration. Structural damage as well as design and detailing issues related to steel tube braces were previously discussed by Bonneville and Bartoletti [1]. This paper addresses braced frame configuration issues. During the repair and upgrade design, it was found analytically that post-buckling performance is affected substantially by the braced frame configuration. Therefore, the original analysis has been supplemented with additional studies, as described herein.

2. ANALYSIS APPROACH

Three braced frame configurations, based on the original building dimensions, have been studied. These include the original chevron configuration, a two-story X configuration, and a modified chevron configuration known as a zipper system [2]. For each configuration, a simplified nonlinear (static pushover) analysis [3] was conducted using the program SNAP-2DX [4]. This program was considered most appropriate for the analysis because it models nonlinear brace behavior more accurately than other software available. In the analysis, the structure is "pushed" to failure by incrementally increasing the static lateral loads until an instability forms. The static pushover analysis is a relatively simple way to determine progression of failure and relative deformations in a lateral system. In order to assess the affect of beam-column connections on the ductility of the braced frames, both fixed and pinned beam-column connections were analyzed for each frame configuration. The analyses were terminated when a complete mechanism formed in the frames and not necessarily at the point of collapse. Figures 1 and 2 show results for frames with fixed and pinned beam-column connections respectively. At the top of the figures, the three frame configurations are shown with the sequence of hinging and buckling of the members. Below, load versus deflection relationships are shown.



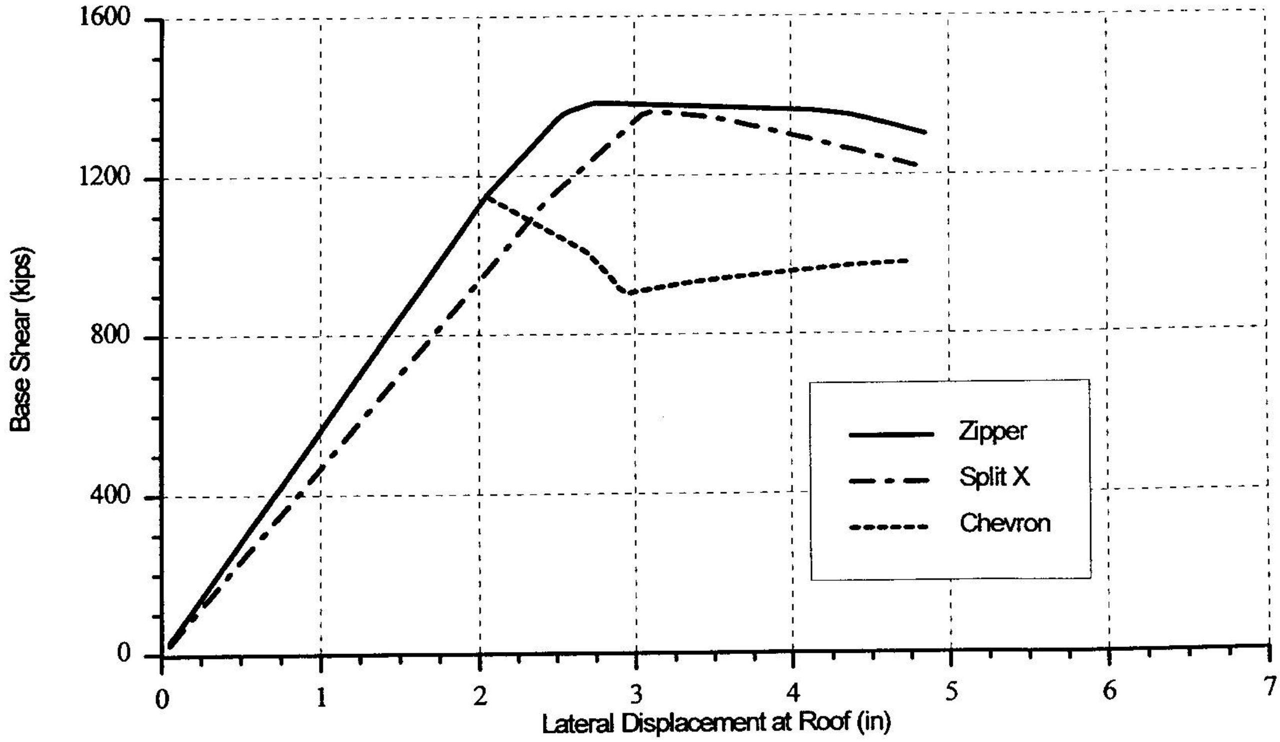


Figure 1 : Load vs Deflection - Fixed Girder to Column Connections

3. RESULTS OF ANALYSIS

3.1 Chevron Configuration

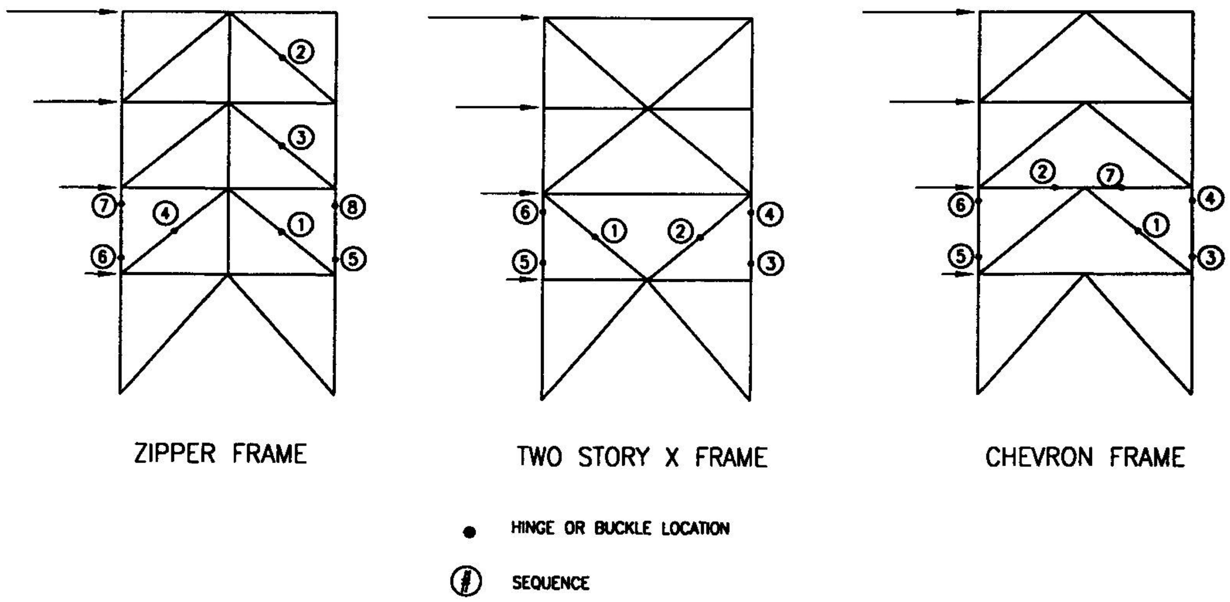
It should be noted that for the subject building, the ground level braces in all configurations were designed to be relatively stronger than the upper floors and, as a result, buckling occurs at the second level. Chevron brace configurations are generally thought to perform poorly in seismic events, thus the UBC [5] requires the brace members to be designed for 1.5 times the otherwise prescribed seismic forces. This requirement reflects the reduction in capacity that occurs for a bay of chevron bracing once the first brace buckles. For the frame studied, the capacity reduced by 20% for rigid beam-to-column connections and 30% for pinned connections. It was found that the post buckling strength and stiffness is highly dependent on the size of the beam intersected by the braces, which must resist the unbalanced vertical component of force between the tension and buckled compression brace. Improved performance can be obtained by using a beam strong enough to meet the UBC provision for special concentrically braced frames with a chevron configuration.

3.2 Two-Story X Configuration

The two-story X configuration was included in the analysis because it is a commonly used lateral system intended to alleviate the problems associated with the chevron system. When one brace buckles, lateral loads are transferred to other brace members rather than forcing the beam to resist the unbalanced vertical force in bending. In the analyses performed, the two-story X frame had a lower elastic stiffness than the other two configurations due to the distribution of overturning forces in the columns and, like the chevron, all yielding occurred in one story. In both the pinned and fixed configurations, a story mechanism formed through buckling and tension yield of the second floor braces followed by hinging of the second floor columns. After initial yield, the frame had additional capacity and reached a maximum capacity close to the maximum capacity of the zipper frame.

3.3 Zipper Configuration

The zipper braced frame is the system used for retrofit of the subject building. The design, based on research done by Khatib, Mahin, and Pister [2], is a modified chevron frame which utilizes vertical members at the beam midspans to redistribute lateral loads up the height of the frame. Figures 1 and 2 show that the zipper frame and chevron frame have identical elastic stiffness. However, while the capacity of the chevron frame drops off immediately after first yield, the capacity of the zipper increases until all three braces above the ground floor have buckled. Then, the second story tension brace yields and hinges form in the second floor columns to form a soft story. As seen with the other two configurations, the pinned condition has slightly less stiffness after first yield and a longer yield plateau as hinges form in the columns. In addition, the zipper



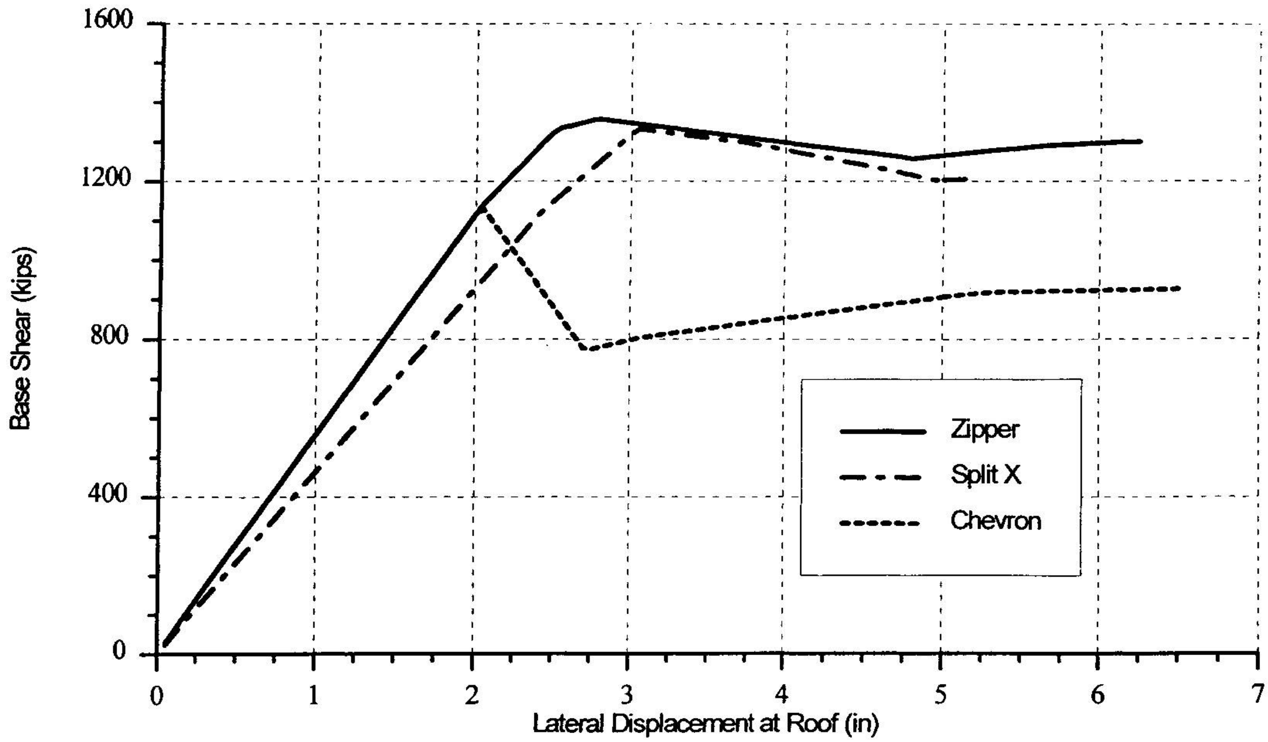


Figure 2 : Load vs Deflection - Pinned Girder to Column Connections

frame maintains greater lateral capacity than both the chevron or the two-story X configuration.

4. CONCLUSIONS

In comparing the different frames, it appears that the zipper and two-story X have similar maximum capacities and both have additional strength after the first yielding event occurs. However, the buckling of several braces up the height of the zipper acts to dissipate energy and distribute lateral deflections more effectively than the two-story X and chevron configurations. Ultimately, a soft story mechanism forms in each of the three frames through column hinging regardless of beam-column fixity. While the pinned frames were more flexible and formed mechanisms at higher lateral displacements, the frames with moment connections will absorb more energy under cyclic loading and have less inter-story drift.

It should be noted that the analyses show the load-deformation behavior of a single bay braced frame. The effects of load redistribution or stiffness of adjacent frame bays are not included in the study. In addition, the nonlinear behavior of the braced frames is sensitive to member sizes and material strengths. Much additional research is required to more comprehensively understand the nonlinear behavior of braced frame structures.

5. REFERENCES

1. BONNEVILLE D. and BARTOLETTI S., Northridge Building Case Studies Project, Chapter 2.3, Concentric Braced Frame. Report prepared by Rutherford and Chekene under contract to California Seismic Safety Commission, 1995.

2. KHATIB I., MAHIN S., PISTER K., Seismic Behavior of Concentrically Braced Frames. Report No. UCB/EERC - 88/01, Earthquake Engineering Research Center, University of California, Berkeley, January 1988.

3. DEPARTMENTS OF THE ARMY, THE NAVY, AND THE AIR FORCE. Seismic Design Guidelines for Essential Buildings, TM S-809-10-1/NAVFAC p-355.1/AFM 88-3, Chapter 13, December 1986.

4. RAI D., GOEL S., FIRMANSJAH J., SNAP-2DX - Users Guide, Department Of Civil And Environmental Engineering, University Of Michigan, Ann Arbor.

5. INTERNATIONAL CONFERENCE OF BUILDING OFFICIALS, Uniform Building Code, 1994 Edition, I.C.B.O., Whittier, California.