RETROFIT OF A CIRCA – 1992 STEEL CONCENTRIC BRACED FRAME BUILDING – CASE STUDY

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Introduction

- In late 2016, Hohbach-Lewin took on the seismic upgrading of a tech-oriented company's campus cafe dedicated to serving approximately 3000 employees per meal.
- The goal of this project was to provide the existing circa-1991 concentrically braced frames with the necessary and minimally invasive retrofits required to bring the structure as close as practically possible to immediate occupancy, and life-safety occupancy performance objectives under BSE-1E and BSE-2E level earthquakes, respectively, given typical project constraints.
- This presentation explores the employed retrofit techniques and reasoning as well as issues encountered during the design and construction processes.
Definitions – ASCE 41

• Performance Objective
  • Immediate Occupancy – Limited post-earthquake structural damage where basic vertical and lateral force resisting systems of the building retain the majority of their post-earthquake strength and stiffness. Low risk of life-threatening injury as a result.
  • Life-Safety Occupancy – Significant post-earthquake structural damage where some margin against partial/total structural collapse remains. Severe damages do not result in large falling debris hazards. Injuries may occur during earthquake but life threatening injury as a result of structural damage is expected to be low.

Reference: ASCE 41 §C2.3.1.1, §C2.3.1.3
Ground Motions – ASCE 41 / USGS

- **Seismic Hazard Levels**
  - **BSE-2E (existing)** – Seismic activity with a 5% probability of occurring every 50 years (1000 Year Event). At site, 100% (s) 88% (1) of the BSE-2N (new) associated with the MCE.
  - **BS1-1E (existing)** – Seismic activity with a 20% probability of occurring every 50 years (250 Year Event). At site, 99% (s) 75% (1) of the BSE-1N (new) associated with 2/3 the MCE (DBE)

\[
\begin{align*}
S_{S,5/50} &= 1.402 \, \text{g} \\
S_{S,1.5/50} &= 0.546 \, \text{g} \\
S_{X5,BSE-2E} &= 1.262 \, \text{g} \\
S_{X1,BSE-2E} &= 1.310 \, \text{g}
\end{align*}
\]

Reference: ASCE 41 §2.4.1.1 - §2.4.1.4, USGS
Code Background

- **Circa-1991 Braced Frames**
  - **1988 UBC**—Ductility and capacity design concepts introduced. Braced frames were designed using strength based static analysis without considering post-buckling behavior or over strength capacity of the brace.
  - **UBC 1991 Designed Structure**
  - **Post-1994 Northridge EQ** – Damage due to this event highlighted that current code, at the time, was producing inadequate connections. Capacity design concepts were further developed in subsequent codes.

Building Description

- Constructed 1992 per 1991 UBC
- First floor 36,000 SF
- Second floor 11,000 SF
- Steel framing supporting concrete filled metal decking
- 9.5” structural slab over precast concrete piles
- 7 bays of SFRS in NS, 4 bays of SFRS in EW
- BFs of irregular geometry and opportunistically located

Reference: Client Specific Earthquake Preparedness Program (V. Rundorff, S.E)
Seismic Analysis

- Linear Static Procedure
  - Structure too irregular to assume first mode governs
- Non-linear static procedure
  - Pushover Analysis
  - Irregularity of structure returned unrealistic results
- Linear Dynamic Procedure
  - Modal Response Spectral Analysis
  - Combines displacements from different modes which translates to forces in braces.
  - Structure remains elastic in analysis

<table>
<thead>
<tr>
<th>Case</th>
<th>Mode</th>
<th>Period (sec)</th>
<th>UX</th>
<th>UY</th>
<th>Sum UX</th>
<th>Sum UY</th>
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<td>0.1298</td>
<td>0.7061</td>
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</table>

Reference: 3D LDP MRSA Model by V. Rundorff
CBF Performance
1988 vs. 1997

Pre-1988 CBF Vulnerabilities

- High b/t ratio leading to severe local buckling, significant degradation of compression strength and premature brace fracture
- Brace connections are typically weaker than brace
- No “hinge line” to allow out-of-plane buckling of the gusset plate
- No net section reinforcement

Reference: “Seismic Performance of New and Older CBF” (Lehman, Roeder, Hsiao, 2014)
Circa-1991 BF Typical Details

- Different brace HSS sizes correspond to different plate thickness, weld sizes, and weld lengths indicating that capacity design was used in determining braced frame construction.

<table>
<thead>
<tr>
<th>BRACED FRAME CONNECTION SCHEDULE</th>
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<tbody>
<tr>
<td>BRACE SIZE</td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>TS 6x6x1.4&quot;</td>
</tr>
<tr>
<td>TS 6x6x5/16&quot;</td>
</tr>
<tr>
<td>TS 6x6x3/8&quot;</td>
</tr>
<tr>
<td>TS 8x8x2/3/16&quot;</td>
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<tr>
<td>TS 8x8x1/4&quot;</td>
</tr>
<tr>
<td>TS 8x8x3/8&quot;</td>
</tr>
<tr>
<td>TS 8x9x5/8&quot;</td>
</tr>
<tr>
<td>TS 8x9x5/8&quot;</td>
</tr>
</tbody>
</table>

Reference: Original Structural Drawings
Circa-1991 BF Typical Details

Reference: Original Structural Drawings
Brace Vulnerabilities

VULNERABILITY A
BRACE-TO-GUSSET WELD UNABLE TO DEVELOP THE FULL TENSILE CAPACITY OF THE BRACE.

VULNERABILITY B
INADEQUATE BRACE AREA AT BRACE-TO-GUSSET CONNECTION SUSCEPTIBLE TO TEAR OUT

VULNERABILITY C
INSUFFICIENT LENGTH OF GUSSET CONNECTION TO ADJACENT COLUMN OR BASE PLATE

VULNERABILITY D
BRACE HAS INADEQUATE COMPRESSIVE CAPACITY OR LOCAL BUCKLING ISSUES DUE TO b/t

VULNERABILITY E
CHEVRON BRACE CONFIGURATION WILL POTENTIAL DELIVER UNBALANCED VERTICAL LOADS TO THE OVERHEAD BEAM DUE TO POST-YIELD/BUCKLING BEHAVIOR

VULNERABILITY F
EXISTING ANCHOR BOLTS UNABLE TO TRANSFER BRACE FRAME OVERTURNING FORCE COUPLE

Reference: Original Structural Drawings
VULNERABILITY A
BRACE-TO-GUSSET WELD UNABLE TO DEVELOP THE FULL TENSILE CAPACITY OF THE BRACE.

VULNERABILITY B
INADEQUATE BRACE AREA AT BRACE-TO-GUSSET CONNECTION SUSCEPTIBLE TO TEAR OUT

VULNERABILITY C
INSUFFICIENT LENGTH OF GUSSET CONNECTION TO ADJACENT COLUMN OR BASE PLATE

Reference: Original Structural Drawings
Upper Brace I Connection Retrofit

Lower Brace I Connection Retrofit

Reference: Original Structural Drawings
Net Section Reinforcement

Reference: “Steel Tips: Limiting Net Section Fracture in Slotted Tube Braces” (Yang, Mahin, April 2005)
VULNERABILITY D

BRACE HAS INADEQUATE COMPRESSIVE CAPACITY OR LOCAL BUCKLING ISSUES DUE TO b/t

Reference: Original Structural Drawings
5 KSI Concrete Fill

Solution 1

NOTE:
(2) GUSSET PLATE DIMENSIONS VERIFIED

Reference: Seismic Retrofit Details
**5 KSI Concrete Fill**

Reference: “Performance of Vulnerable and Retrofit CBF ...” (Simpson, Mahin, Lai 2015) & “Seismic Behavior of Hollow and Concrete-Filled Square Tubular Bracing Members” (Lee, Goel 1987)
VULNERABILITY E

CHEVRON BRACE CONFIGURATION WILL POTENTIAL DELIVER UNBALANCED VERTICAL LOADS TO THE OVERHEAD BEAM DUE TO POST-YIELD/BUCKLING BEHAVIOR

Reference: Original Structural Drawings
Unbalanced Beam Loading

Solution 1

Upper Brace IV Connection Retrofit

Brace IV Pile Cap Retrofit

Reference: Seismic Retrofit Details
Unbalanced Beam Loading

Solution 2

Brace VII X-Configuration Retrofit Construction

Brace VII Connection Retrofits

Reference: Seismic Retrofit Details
VULNERABILITY F

EXISTING ANCHOR BOLTS UNABLE TO TRANSFER BRACE FRAME OVERTURNING FORCE COUPLE

Reference: Original Structural Drawings
Inadequate Column Connection

Brace V/VI Column Base Retrofit Construction

Brace V/VI Column Base Retrofit

Reference: Seismic Retrofit Details
**Construction Schedule**

- **Preconstruction**
  - Oct 19 – Nov 22

- **Exploration Period**
  - Nov 16 – Dec 16

- **Retrofit Construction**
  - Dec 19 – Jan 18

## Submittals/Shop Drawings
- Oct 19 – Oct 25 (5d)
- Oct 26 – Oct 25 (5d)

## Structural Steel Fabrication
- Nov 2 – Nov 22 (15d)

## Exploratory Demolition
- Nov 16 – Nov 22 (5d)
- Nov 23 – Nov 30 (4d)

## Temporary Patches/Repairs
- Nov 22

## Engineering Review/Confirm.
- Nov 28 – Dec 16 (15d)

## Demolition of Finishes
- Dec 19 – Dec 27 (6d)
- Jan 3 (6d)

## Structural Steel Upgrades + Insp.
- Dec 28 – Jan 3 (6d)

## Repair Finishes + Pour Back at Columns
- Jan 6 – Jan 18 (8d)
Interview with Construction Manager

• Structure is the main café for the entire tech-oriented campus, it serves **3000 people per meal**, so shutting any part of the café down at any time was not possible
  • Mainly worked at night, on weekend, and holidays, significant construction (i.e. switching braces/configuration) occurred on holidays
  • Required work in very limited spaces (i.e. dishwasher room)
  • Structural work was completed really early, it was repairing finishes through a subcontractor that was the most time consuming because it wasn’t a “mass-produce” job, all finish reparations were relatively unique.

Reference: V. Rundorff
Interview with Construction Manager

- A lot of modifications had to be done to construction details due to the discovery phase of construction where existing conditions were analyzed by engineers involved.
- Menlo Park permitting process is very strict, all structural changes had to be submitted to the city in the form of an RFI.
- Retrofit construction was pretty minimal, “extra plates here and there,” concrete mix design involved several submittals because proper mix design had to be achieved to tweak strength, placement, and shrinkage.
- Contingencies built into plan

Reference: + V. Rundorff
Interview with Construction Manager

• What would the C.M do differently?
  • Have a better understanding of the design and permitting process
  • “If we have the design finished we can usually go get it done, but with retrofits you’re trying to do the best you can given the circumstances. Knowing about the difficulties you will encounter at first and incorporating them into planning would have saved time”
Conclusion

Pre-1988 CBF

- Minimally Invasive
- Cost Effective
- Time Efficient

Retrofitted Pre-1988 CBF

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Roof drift amplitude (in)</th>
<th>$\nu$ (kips)</th>
<th>$\nu^2$ (kips)</th>
<th>$\nu_{max}/\nu_{min}$</th>
<th>Event</th>
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</thead>
<tbody>
<tr>
<td>9</td>
<td>+0.5</td>
<td>336.7</td>
<td>232.1</td>
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<td>2F E (LB)</td>
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<td>9</td>
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<td>0.65</td>
<td>2F W (LB)</td>
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<tr>
<td>13</td>
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<td>2F W (Fr)</td>
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<tr>
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<td>-236.9</td>
<td>-117.9</td>
<td>0.30</td>
<td>2F E (Fr)</td>
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</table>

$^1$ Approximate base shear after significant drop in maximum $\nu$ in a half-cycle.

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Amplitude (in)</th>
<th>$\nu$ (kips)</th>
<th>$\nu^1$ (kips)</th>
<th>$\nu_{L}/\nu_{max}$</th>
<th>Event</th>
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<tbody>
<tr>
<td>9</td>
<td>+0.5</td>
<td>495.9</td>
<td>406.1</td>
<td>0.84</td>
<td>1F E (B)</td>
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<tr>
<td>11</td>
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<td>366.3</td>
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<td>0.69</td>
<td>1F E (LB)</td>
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<td>11</td>
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<td>0.74</td>
<td>1F W (B)</td>
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<td>0.29</td>
<td>1F E (Fr)</td>
</tr>
<tr>
<td>20</td>
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<td>174.1</td>
<td>159.3</td>
<td>0.33</td>
<td>W Col (Fr)</td>
</tr>
</tbody>
</table>

$^1$ Approximate base shear after significant drop in maximum $\nu$ in a half-cycle.

Reference: “Performance of Vulnerable and Retrofit CBF under Quasi-Static Cyclic Loading” (Simpson, Mahin, Lai 2015)
THANK YOU,

Questions?