Life-Cycle Costs of Steel Frame Buildings Subjected to Earthquake Loading

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Acknowledgements – Prof. G. Dela Corte

Mozarella di bufala
Acknowledgements – Prof. M. D’Aniello & Prof. R. Landolfo (Special Photos tomorrow*)
Motivation – Collapse Risk Quantification
-Low-Probability of Occurrence Seismic Events

Taiwan 2018

Hyogoken-Nanbu 1995
Motivation

-Earthquake-induced Losses of Code-Conforming Steel Buildings

☆ Frequently occurring seismic events:
  ☆ damage to non-structural content

☆ Low-Probability of occurrence seismic events:
  ☆ Hopefully “no collapse” but likely “residual deformations”

Source: Bruneau et al. (2011)

Source: Kumamoto 2016, Japan
Motivation
-Earthquake-induced Loss Assessment

Source: FEMA P58
Overview of PBEE Methodology

\[ \lambda(DV) = \int_{\text{all IMs}} \int_{\text{all EDPs}} \int_{\text{all DMs}} G(DV|DM) dG(DM|EDP) dG(EDP|IM) d\lambda(IM) \]

Motivation
-Impact of Numerical Model Representation

Historically, "bare frame" models have been utilized for nonlinear response history analysis of frame buildings (e.g., Composite action, gravity framing is ignored).
Motivation
-Impact of Numerical Model Representation

- Seismic performance assessment: typically with "bare-frame" models
- Composite action, gravity framing typically ignored
Problem Statement
Comprehensive Loss Assessment of Steel Frame Buildings

Steel Special Concentrically Braced Frames  Steel Special Moment Frames

Images courtesy of Prof. M. Engelhardt
Objectives and Scope

✧ Utilize loss metrics in order to quantify the seismic-induced losses in steel frame buildings designed in seismic regions.
✧ Assess the effect of analytical model representation of a steel frame building on earthquake-induced losses under various seismic intensities.
✧ Quantify the effect of residual deformations on the loss assessment of steel frame buildings with steel MRFs and SCBFs.
✧ Assess the effect of seismic design parameters (e.g., SCWB ratio) on the earthquake-induced losses of steel frame buildings in highly seismic regions.
Overview of Loss Estimation Methodology

\[
E[L_T|IM] = E[L_T|NC \cap R, IM] \cdot P(\text{NC} \cap R|IM) + E[L_T|NC \cap D] \cdot P(\text{NC} \cap D|IM) + E[L_T|C] \cdot P(C|IM)
\]

- Loss given that collapse does not occur and the building will be repaired
- Loss due to building demolition given no collapse but due to large residual deformations
- Loss when collapse occurs

\( E[L_T|IM] \): Expected total repair costs conditioned on seismic intensity \( IM \).

\( P(\text{NC} \cap R|IM) \): Probability of having no-collapse given \( IM \)

\( P(\text{NC} \cap D|IM) \): Probability of having no-collapse given \( IM \) but the building will be demolished.

\( P(C|IM) \): Probability of having collapse given \( IM \).

\( P(D|\text{NC}, IM) = \int_0^\infty P(D|\text{RSDR})dP(\text{RSDR}|\text{NC}, IM) \)

Source: Ramirez and Miranda (2013)
Example: Steel Frame Buildings with MRFs

Archetype office steel buildings (2- to 20-stories) with perimeter steel special moment frames designed in Urban California (IBC 2009, AISC-2010)

Steel Frame Buildings with Concentrifically Braced Frames

Archetype office steel buildings (2- to 12-stories) with perimeter steel special concentrically braced frames designed in Urban California (IBC 2009, AISC-2010)

(Sources: NIST 2010)
Seismic Hazard in Design Location of Interest

Source: National Seismic Hazard Map (USGS 2008)
Fragility and Cost Distribution Functions

✧ To compute realistic loss estimations for steel frame buildings architectural layouts were developed.
✧ Steel frame buildings with SMFs: rectangular footprint of 14,000 ft²
✧ Cost estimates were developed based on the RS Means Cost Estimating Manuals.
✧ Non-structural components (both drift- and acceleration-sensitive) were considered to compute the replacement cost estimates per building.
✧ Structural components (e.g., beam-to-column connections, columns, slabs, base plates, etc) were also considered.
✧ Base case replacement cost was estimated to be $250/ft².
### Fragility and Cost Distribution Functions (3)

- **Examples of Damageable Components**

<table>
<thead>
<tr>
<th>Assembly description</th>
<th>Damage state</th>
<th>Unit</th>
<th>EDP</th>
<th>( x_m )</th>
<th>( \beta )</th>
<th>( x_m ) ($)</th>
<th>( \beta )</th>
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</table>
Fragility and Cost Distribution Functions (2)
-Examples of Damageable Components and Damage States

Steel Frame Buildings with Moment Resisting Frames
-Modeling of Composite Action and Interior Gravity Framing

Steel Frame Buildings with Moment-Resisting Frames

-Modeling of steel columns

Source: Suzuki and Lignos (2015)*

Steel Frame Buildings with Special Concentrically Braced Frames
-Modeling of Steel Braces: Flexural Buckling and Fracture due to Low-Cycle Fatigue

Calibrated with over 270 tests from steel braces

\[ \varepsilon_0 = 0.748 \left( \frac{kL}{r} \right)^{-0.399} \left( \frac{D}{t} \right)^{-0.628} \left( \frac{E}{F_y} \right)^{0.2} \]

Source: Karamanci and Lignos (2014)*

Steel Frame Buildings with Special Concentrically Braced Frames
-Modeling of Steel Braces: Flexural Buckling and Fracture due to Low-Cycle Fatigue

*Source: Karamanci and Lignos (2014)*

Tracing Sidesway Collapse of Frame Buildings

- Example of definition of dynamic collapse due to earthquake shaking
Collaps Risk of Steel Frame Buildings with MRFs
-Ground Motion Sets and Process to Trace Collapse

Ground Motion Set from FEMA P695
Far-Field Set of 44 Ground Motions

Incremental Dynamic Analysis
to Trace Dynamic Instability

Source: Elkady and Lignos (2014)*

Evaluating the Collapse Risk of Steel Structures

-Collapse Metric: Mean Annual Frequency of Collapse, $\lambda_c$

Collapse Fragility Curves

Hazard Curves for Site Location

$$\lambda_c = \int_0^\infty (P_c|Sa) \cdot \left| \frac{d\lambda_{Sa}(Sa)}{d(Sa)} \right| d(Sa)$$

$$P_{\text{collapse}}(\text{in } t \text{ years}) = 1 - \exp(-\lambda_c t)$$

(e.g., assume building life expectancy $t=50$ years)

Source: Eads et al. (2013)*

Collapse Risk of Steel Frame Buildings with Concentrically Braced Frames

Source: Hwang and Lignos (2017)*

Collapse Mechanisms of steel CBFs

Bare Frame Models

Collapse Mechanism I
14% of collapses (6/44)

Collapse Mechanism II
23% of collapses (10/44)

Collapse Mechanism III
32% of collapses (14/44)

Collapse Mechanism IV
9% of collapses (4/44)

Collapse Mechanism V
14% of collapses (6/44)

Collapse Mechanism VI
7% of collapses (3/44)

Collapse Mechanism VII
2% of collapses (1/44)

Models with Gravity Framing

Collapse Mechanism I
41% of collapses (18/44)

Collapse Mechanism II
20% of collapses (9/44)

Collapse Mechanism III
18% of collapses (8/44)

Collapse Mechanism IV
20% of collapses (9/44)

Source: Hwang and Lignos (2017)*

Normalized Loss Vulnerability Functions
-Utilization of Bare Frame Analytical Models

\[ S_a(T_1, 5%) / S_a(T_1, 5%) \text{ @ DBE} \]

Source: Hwang and Lignos (2017)*

Expected Losses Conditioned on Seismic Intensity

- Utilization of Bare Frame Analytical Models

✧ Hazards: Service Level, Design Basis (DLE) & Maximum Considered Event (MCE)
✧ Minimum monetary loss due to business interruption is not considered

Source: Hwang and Lignos (2017)*

**Expected Losses Conditioned on Seismic Intensity**

- Effect of Analytical Model Representation: Steel MRFs

Earthquake-induced loss assessment at discrete levels of intensity may be over-conservative when it is based on “bare frame” model representations of the building.

Expected Losses Conditioned on a **Single Seismic Intensity** - Effect of Numerical Model Representation on Losses

Illustration: 6-story Steel Frame Building with CBFs

Source: Hwang and Lignos (2017)*

Expected Losses Conditioned on Seismic Intensity
Effect of Strong-Column-Weak-Beam Ratio on Expected Losses

✧ Hazards: Service Level, Design Basis (DLE) & Maximum Considered Event (MCE)
✧ Minimum monetary loss due to business interruption is not considered

Expected Annual Losses \((EAL)\) as a Loss Metric

\(EAL\) weights all possible levels of the seismic hazard by taking into account their probability of occurrence.

\[
E(L_T) = \int_0^\infty E(L_T|IM) d\lambda(IM) = \int_0^\infty E(L_T|IM) \left|\frac{d\lambda(IM)}{dIM}\right| dIM
\]
Expected Annual Losses (EALs)

- Collapse Loss
- Structural Repair Loss
- Nonstructural Repair Loss (Acc)
- Nonstructural Repair Loss (Drift)
- Demolition Loss
- Total Loss

**SCWB > 1.0**

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**SCWB > 1.5**

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**SCWB > 2.0**

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Expected Annual Losses – Steel CBFs

Source: Hwang and Lignos (2017)*

Concluding Remarks

✧ Gravity framing system reduces the collapse risk of up to 75%.

✧ At frequently occurring seismic events:
  ✧ damage to non-structural content dominates losses regardless of the selected numerical model and lateral load resisting system

✧ Earthquake-induced loss estimates at discrete seismic intensities:
  ✧ overestimated when building EDPs are based on “bare-frame” models (Losses due to demolition over predicted ~ by a factor of 2).

✧ Expected Annual Losses as a loss-metric:
  ✧ Minor dependence on numerical model representation.
  ✧ Main contributors: Repairs due to acceleration sensitive components followed by repairs due to steel brace buckling.
Thank you for your kind attention!

For more information visit: resslab.epfl.ch