Quantitative Assessment of Code Provisions for Vertical Irregularities in Frame Buildings

ATC-123: Improving Seismic Design of Buildings with Configuration Irregularities

D. Jared DeBock: CSU, Chico
Katie Fitzgerald Wade: Haselton Baker Risk Group
Dustin Cook: CU Boulder and Haselton Baker Risk Group
Curt B. Haselton: CSU, Chico and Haselton Baker Risk Group
Michael Valley: Magnusson Klemencic Associates
Thomas Sabol: Englekirk Structural Engineers
Objectives

1. Asses ASCE/SEI 7-16 provisions guarding against collapse in irregular buildings
2. Consider whether additional irregularities should be recognized
Table 12.3-2 Vertical Structural Irregularities

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Reference Section</th>
<th>Seismic Design Category Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a.</td>
<td>Stiffness-Soft Story Irregularity</td>
<td>Table 12.6-1</td>
<td>D, E, and F</td>
</tr>
<tr>
<td>1b.</td>
<td>Stiffness-Extremely Soft Story Irregularity</td>
<td>Table 12.6-1</td>
<td>D, E, and F</td>
</tr>
<tr>
<td>2.</td>
<td>Weight (Mass) Irregularity</td>
<td>Table 12.6-1</td>
<td>D, E, and F</td>
</tr>
<tr>
<td>3.</td>
<td>Vertical Geometric Irregularity</td>
<td>Table 12.6-1</td>
<td>D, E, and F</td>
</tr>
<tr>
<td>4.</td>
<td>In-Plane Discontinuity in Vertical Lateral Force-Resisting Element Irregularity</td>
<td>Table 12.6-1</td>
<td>D, E, and F</td>
</tr>
<tr>
<td>5a.</td>
<td>Discontinuity in Lateral Strength-Weak Story Irregularity</td>
<td>Table 12.6-1</td>
<td>D, E, and F</td>
</tr>
<tr>
<td>5b.</td>
<td>Discontinuity in Lateral Strength-Extreme Weak Story Irregularity</td>
<td>Table 12.6-1</td>
<td>D, E, and F</td>
</tr>
</tbody>
</table>
- Weight (Mass) [V2]
- Soft/Weak Story [V1/V5]
- Strong-Column/Weak-Beam (SCWB)
- Gravity Induced Lateral Demand (GILD)
Summary of Findings

- Irregularities do not reduce collapse performance significantly if designed for.
Assessment Method

- Collapse performance according to FEMA P695 nonlinear response history analysis (NRHA)
- Collapse margin ratio (CMR): $\frac{S_{a_{\text{collapse}}}}{S_{a_{\text{MCE}}}}$
- Adjusted Collapse Margin Ratio
- Relative to baseline/regular building: ACMR/ACMR_{Baseline}
Weight (Mass) Irregularity [V2]

- ELF prohibited in seismic design categories (SDC) D, E, F

Irregular:

\[ M_i > 1.5M_{i+1} \]

or

\[ M_i > 1.5M_{i-1} \]
Weight Mass Irregularity [V2]

- System: Steel and reinforced concrete (RC) Special Moment Frames (SMF)
- Stories: 3-20
- Mass ratio (MR): 150% - 300%
Weight Mass Irregularity [V2]

- Steel Special Moment Frame
Weight Mass Irregularity [V2]

- Steel Special Moment Frame
Steel Special Moment Frame
Weight Mass Irregularity [V2]

- RC Special Moment Frame
Weight Mass Irregularity [V2]

- Conclusions and Recommendations:
  - Performance may decrease in mass irregular buildings, but remains in an acceptable range
  - The prohibition on ELF for Mass Irregular buildings be removed
Soft Story Irregularity

- ELF prohibited in seismic design categories (SDC) D, E, F

Irregular:

\[
\begin{align*}
K_i &< 0.7K_{i+1} \\
K_i &< \frac{0.8}{3}(K_{i+1} + K_{i+1} + K_{i+1})
\end{align*}
\]
Soft Story Irregularity [V1]

- Soft Story Irregularity
  - ELF prohibited in SDC D, E, F

- Extreme Soft Story Irregularity
  - ELF prohibited in SDC D, E, F
  - Prohibited in SDC E, F

Extremely Irregular:

\[ K_i < 0.6K_{i+1} \]

or

\[ K_i < \frac{0.7}{3} (K_{i+1} + K_{i+1} + K_{i+1}) \]
Weak Story Irregularity [V5]

- Weak Story Irregularity
  - Prohibited in SDC E, F
- Extreme Weak Story Irregularity
  - Prohibited in SDC D, E, F
  - $\leq 2$ stories
  - $\leq 30$ feet

Irregular:

$\text{Strength}_i < 0.8\text{Strength}_{i+1}$

Extremely Irregular:

$\text{Strength}_i < 0.65\text{Strength}_{i+1}$
Soft/Weak Story Irregularity [V1/5]

- System: Reinforced concrete (RC)
  - Special Moment Frames (SMF)
  - Ordinary Moment Frames (OMF)
- Stories: 4-20
- Stiffness/Strength ratio: 0.6-0.8
Soft/Weak Story Irregularity [V1/5]

1. Increased story height
2. Increased story above strength
Soft/Weak Story Irregularity [V1/5]

1. Increased story height
2. Increased story strength above
Soft/Weak Story Irregularity [V1/5]

1. Increased story height
2. Increased story strength above

![Graph showing ACMR/ACMR baseline and different story types over Story Strength Ratio.]
Soft/Weak Story Irregularity [V1/V5]

Conclusions and Recommendations:
- The prohibition on extreme weak story irregularities in SDC D may be overly conservative.
- Further study on weak/soft stories in SCD E & F
- Further study comparing ELF and MRS designs
Strong-Column/Weak-Beam [V6]

- Material Standards
  - ACI
  - AISC

Irregular:

\[
\frac{\sum M_c}{\sum M_b} < \text{Target SCWBR}
\]
Strong-Column/Weak-Beam [V6]

- System: Reinforced concrete (RC) and steel
  - Special Moment Frames (SMF)
  - Ordinary Moment Frames (OMF)
- Stories: 3-20
- SCWBR: 0.4-2.0
  - Design min.
  - Exact
  - Stepped
Strong-Column/Weak-Beam [V6]

- RC Special Moment Frames
Strong-Column/Weak-Beam [V6]

- RC Ordinary Moment Frames
Strong-Column/Weak-Beam [V6]

- RC Special Moment Frames (stepped)
Strong-Column/Weak-Beam [V6]

- RC Special Moment Frames (stepped)
Conclusions and Recommendations:
- Collapse performance increases with increasing SCWBR
- The advantage of increased SCWBR may be economically achieved by varying the SCWBR along the height of the building.
Gravity Induced Lateral Demand [V7]

- System: Reinforced concrete (RC) and steel
  - Special Moment Frames (SMF)
  - Ordinary Moment Frames (OMF)
- Stories: 20

\[ Q_G = \text{Gravity induced story shear} \]
\[ Q_V = \text{Story shear capacity} \]
\[ GILD = \frac{Q_G}{Q_V} \]
Gravity Induced Lateral Demand [V7]

- Steel Special Moment Frame (SMF)

![Graph showing GILD Ratio vs ACMR/ACMR baseline for SMF-20Stories-Floor1, SMF-20Stories-Floor7, and SMF-20Stories-Floor14.](image)
Gravity Induced Lateral Demand [V7]

- Steel Ordinary Moment Frame (OMF)
Gravity Induced Lateral Demand [V7]

- RC Moment Frames (SMF and OMF)
  - No GILD design
Gravity Induced Lateral Demand [V7]

Conclusions and Recommendations:
- GILD does not significantly affect collapse performance when designed for
- Preliminary finds suggest that GILD does not need to be incorporated into ASCE 7, but further study is recommended
Vertical Irregularities

- Potential negative effects of vertical irregularities examined here are generally insignificant for moment frame buildings
- ELF designed buildings tend to perform better than MRS designed buildings
Questions?
ATC (2015). *Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14)*. American Concrete Institute, ACI Committee 318.


ATC (2016). *ATC 114: Development of accurate models and efficient simulation capabilities for collapse analysis to support implementation of performance based seismic engineering*. Prepared by ATC for NIST.


