Seismic Design of Masonry
The Theory, The Codes and The Practice

John G Tawresey
KPFF Consulting Engineers [Retired]
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The Theory, The Codes and The Practice

John G. Towneley
KPFF Consulting Engineers [Retired]

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Contents:

1. The Theory [ASD and SD]


3. The Examples

Trial Design 4
Seven Story Apartment Building
Size: 76,500 S.F
Seven Story Apartment Building
Design Problem Statement:
- Design the wall J of the apartment at the base and the 5th floor.
- Complete the design questionnaire at the end of the problem.
- Assume a rigid diaphragm.
- Assume the wall is a special reinforced masonry shear wall.

Materials:
- Concrete Masonry (different strengths can be used at the base and 5th floor).
- Grade 60 reinforcement.

Design Code:
- 2006 IBC and ACI 530.1-05/ASCE 6-05/TMS 602-05 (2005 MSJC) Strength

Design Loads:
- Seismic Design Category D, \( R = 5.0, \Omega_0 = 3.0, C_d = 3.5, T = .50 \) sec. SDS = 1.12.
- SD1 = .68

Dead and live loads given.
Dead load includes partition and wall weight. The axial load is due to minor coupling in the model. It is not the Ev (vertical earthquake load).

Fee Paid = $750.00
Average = 8.4 hours
2 hour minimum to 16 hours max

Average $ 89.28/hour
Experience varied from 2 to 30 years
Most Masonry Design is about bending plus compression in walls – in-plane or out-of-plane

\[ W, H, L \]

In-Plane

\[ b \Rightarrow W \]
\[ d \Rightarrow L \]

Out-of-Plane

\[ b \Rightarrow L \]
\[ d \Rightarrow W \]

Contents:

1. The Theory


3. The Examples
Tragans Column

If the column walls are .83 ft [10 in] thick, will the tower tip over in a 36 psf wind load applied to the projected area?

- Neglect the weight above the 88.32 ft
- Consider the base at the bottom of the 88.32 ft
- Assume the column is constructed of marble weighing 150 pcf

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If the column walls are .83 ft [10 in] thick, will the tower tip over in a 36 psf wind load applied to the projected area?

Neglect the weight above the 88.32 ft

Consider the base at the bottom of the 88.32 ft

Assume the column is constructed of marble weighing 150 psf

Projected Area:
88.32x12 = 1060 ft²

Wind Load:
1060x36 = 38,200 Lb

Center of Pressure:
Assume located at the mid-height
\( H = \frac{88.32}{2} = 44 \) ft

Overturning Moment:
38,200x44 = 1,681,000 lb-ft

The wind is pushing to overturn the column

Column Weight
3.14x(62-5.172) x 88.3 x 150 = 385,600 lbs

Resisting Moment comes from gravity:
\[ M = \frac{W \cdot H}{2} \]

Resisting Moment:
385,600x6 = 2,313,000 lb-ft

Assume the weight acts at the center of the circular cross section.
The center of mass would need to be calculated using the first moment of inertia.

Since the resisting moment exceeds the overturning moment, the column remains upright.
Tragans Column

\[
\frac{P_{LM} + P_{DM}}{P_{LM}} = 1.4
\]

Overturning moment/resisting moment = F.S.

\[
\frac{2,313,000}{1,681,000} = 1.4
\]

\[
M/PL = \frac{1}{2.8}
\]

\[
Pd/M = 1.4
\]

F.S. = 1.4

\[
Pd/M = 1.5
\]

F.S. = 1.5

\[
Pd/M = 1.0
\]

F.S. = 1.0

How much additional axial load is required to reach a F.S. of 1.5?

\[
\frac{M}{PL} = \frac{1}{3.0}
\]

\[
3*681,000/12 = 420,200 \text{ lbs}
\]

Dead load = 385,600 lbs

Added = 420,000 - 385,600 = 34,400 lbs

1 No. 7 bar

Use 0.9 load factor

\[
420,000 - 0.9*385,600 = 73,000 \text{ lbs}
\]

212% increase
Expected Utility Theory Vs Prospect Theory

- Instabilities around 0
- Gains and losses are not symmetrical
- “Losses loom larger than gains”
- Estimates people tend to dislike losses about twice as much as they like equivalent gains

“Aggregate Losses; Segregate Gains”

Contents:

1. The Theory [ASD and SD]
3. The Examples

The Problem – Seismic Design of Walls
The Problem – Seismic Design of Walls

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The Problem – Seismic Design of Walls

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The Problem – Seismic Design of Walls

Bending + Compression

Cracked Section – Masonry/Concrete reinforced

The Problem – Seismic Design of Walls

Add axial load at L [trim steel].

75k at L results in F.S. of 1.5
Requires 1.2 in² of reinforcement.

The Equations:

The Assumptions

The Variables and Solution for the Unknowns

The Limits
The Equations - Assumptions:

Plane Sections Remain Plane [Special Case of an Isotropic Material]

Strains are Compatible

Stress and Strain are Related

\[
\begin{bmatrix}
\sigma_{xx} \\
\sigma_{yy} \\
\tau_{xy}
\end{bmatrix} =
\begin{bmatrix}
S_{11} & S_{12} & S_{13} \\
S_{21} & S_{22} & S_{23} \\
S_{31} & S_{32} & S_{33}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{bmatrix}
\]

The Equations - Assumptions:

Hooks Law

\[
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{bmatrix} =
\begin{bmatrix}
1 & -\nu & -\nu \\
-\nu & 1 & -\nu \\
-\nu & -\nu & 1
\end{bmatrix}
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\tau_{xy}
\end{bmatrix}
\]

The Equations - Assumptions:

Hooks Law – Isotropic Material

\[
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{bmatrix} =
\begin{bmatrix}
1 & -\nu & -\nu \\
-\nu & 1 & -\nu \\
-\nu & -\nu & 1
\end{bmatrix}
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\tau_{xy}
\end{bmatrix}
\]
2.1 The Equations - Assumptions:

Hooks Law – Plane Sections Remain Plane

\[ \epsilon_{xx} = \frac{1}{E} \sigma_{xx} \]
**The Equations - Assumptions:**

**Strains are Compatible**

The strain in the masonry/concrete equals the strain in the reinforcement.

---

**The Equations - Assumptions:**

Stress and Strain are Related

![Graph of Stress and Strain](image)

**ASD** **SD**

\[ \varepsilon_{ms} = k_d \varepsilon_{s} \]

ASD ASD ASD

Strain Strain Strain
The Equations - Assumptions:

Stress and Strain are Related

The Variables and Solution for the Unknowns

Knowns:

- Guess and Check: \( A, L, b, d \)
- Loads: \( M, P \) and \( V \)

Unknowns:

- Stresses: \( k, f_b, f_s \) or \( k, \varepsilon_m, \varepsilon_s \)
The Variables and Solution for the Unknowns

Equations:

Plane Sections Remain Plane

\[ \sum F = 0, \text{ Internal to external} \]
\[ \sum M = 0, \text{ Internal to external} \]

\[ \varepsilon_m = \frac{k}{\varepsilon_s (1 - k)} \]

Limits: The Steel Strain is 0

\[ k = 1.0 \quad \text{and} \quad k = 1.0 \]

\[ \frac{M}{P_d} = \left( \frac{2}{3} - \Delta \right) \quad \frac{M}{P_d} = [1 - k_s - \Delta] \]
The Variables and Solution for the Unknowns

Equations:

Limits: Stress in the steel – Special Case for SD

\[ F_s < f_y \]

\[ k = \frac{\sigma_s}{\varepsilon_s + \frac{P}{F_k}} \]

\[ M = \frac{k_k'k_2kd\varepsilon_{m}'}{2} \left( 1 - \frac{2k_k'}{2} \right) - \Delta \]

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The Variables and Solution for the Unknowns

Equations:

Limits: Wall is not Cracked

\[ k = \frac{L}{d} \]

\[ \frac{M}{Pd} = \left( 1 - \frac{L}{3d} - \Delta \right) \]

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The Variables and Solution for the Unknowns

Equations:

\[ \Sigma F = 0, \text{ Internal to external} \]

\[ E_u\varepsilon_{u_{m}}\frac{bd^2}{2} - E_iA_i\varepsilon_i = P \]

\[ k_k'k_2k'd\varepsilon_{m}' = f\left(\varepsilon_i\right)A_i + P \]

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The Variables and Solution for the Unknowns

**Equations:**

\[ \sum F = 0, \text{ Internal to external} \]

\[ F = \frac{P}{E_{md}} \]

\[ n = \frac{E_{md}}{E_{x}} \]

Add a limit: Steel yielding

\[ e_{x}E_{x} = F_{y} \]

\[ k' = \left(2n_{p} + \frac{2}{E_{ps}}\right)k - \left(2n_{p} + \frac{2}{E_{ps}}\right) > 0 \]

\[ k = \frac{(A_{s}F_{y} + P)}{2k_{p}k_{b}df_{m}} \]

**The Variables and Solution for the Unknowns**

**Equations:**

\[ \sum M = 0, \text{ Internal to external} \]

Add a limit: Steel yielding

\[ M - \frac{Pd^{2}}{2} - k_{1}dA_{s}F_{y} \left[1 - \frac{1}{2}k_{1}dA_{s}F_{y}\right] \]

\[ M = A_{s}F_{y} \left[1 - \frac{2k_{1}dA_{s}F_{y}}{2} + \frac{2k_{1}dA_{s}F_{y}}{2} - A_{s}F_{y}\right] \]

**ASD**

Steel is compression/tension uncracked

Steel is compression/tension cracked

Steel is tension

Steel is compression/section cracked

Steel is compression/section uncracked
The Variables and Solution for the Unknowns

2.2 The Variables and Solution for the Unknowns
Ductility Requirements and the Codes

Axial Load is the same as reinforcement

Masonry ASD

\[ \rho_{\text{max}} = \frac{nf_y}{2f_y \left( n + \frac{f_y}{f_{yw}} \right)} \]

Ductility Requirements and the Codes

Axial Load is the same as reinforcement

Masonry ASD

\[ \rho_{\text{max}} = \frac{0.644\varepsilon'_{\text{ue}} \left( \frac{\varepsilon_{\text{ue}}}{\varepsilon_{\text{ue}} + \alpha \varepsilon_{\text{y}}'} \right)}{1.25f_y} \]

Ductility Requirements and the Codes

Axial Load is the same as reinforcement

Concrete

<table>
<thead>
<tr>
<th>( n )</th>
<th>( f_y )</th>
<th>( f_{yw} )</th>
<th>( A_f )</th>
<th>( \rho )</th>
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<tbody>
<tr>
<td>3</td>
<td>25 ksi</td>
<td>64 ksi</td>
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<td>0.005</td>
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</tbody>
</table>

Handout Page 19
What is wrong with this detail?

2 No. 5 @ 6" O.C.

One More Thing – Distribution of Loads

Distribution of Loads
**Distribution of Loads - Flexure**

\[ \delta_y = \frac{6EI}{L^2} \int x \, dx \]

\[ \delta_y = \frac{6EI}{L^2} \int x \, dx \]

\[ \delta_y = \frac{6EI}{L^2} \int x \, dx \]

**Distribution of Loads - Shear**

\[ \frac{dy}{dx} = \frac{P}{GTL} \]

\[ y = \frac{P}{GTL} \int dx = \frac{PH}{GTL} \]

\[ y = \frac{P}{GTL} \int dx = \frac{PH}{GTL} \]

**Distribution of Loads – Flexure Plus Shear**

\[ \delta_y = \frac{P}{EI} \left[ \frac{H^3}{L} + 2.6 \frac{H}{L} \right] \]
Contents:

1. The Theory [ASD and SD]


3. The Examples
Codes

1405.2 Load combinations using strength design or load and resistance factor design. Where strength design or load and resistance factor design is used, buildings and other structures, and portions thereof, shall be designed to resist the most critical effects resulting from the following combinations of factored loads:

\[ 1.6(D + F) \]  
\[ (Equation \ 16-1) \]

\[ 1.6(D + F) + 1.0(L + H) + 0.5(L, \ or \ S \ or \ R) \]  
\[ (Equation \ 16-2) \]

\[ 1.6(D + F) + 1.0(L, \ or \ S \ or \ R) + 1.6H + 0.75L, \ or \ 0.53H \]  
\[ (Equation \ 16-3) \]

\[ 1.6(D + F) + 1.0W + 1.6H = 0.5(L, \ or \ S \ or \ R) \]  
\[ (Equation \ 16-4) \]

\[ 1.6(D + F) + 1.0E = f LL + 1.6H + f LS \]  
\[ (Equation \ 16-5) \]

\[ 0.8D + 1.0E \times 1.6H \]  
\[ (Equation \ 16-6) \]

\[ 0.8(D + F) + 1.0E \times 1.6H \]  
\[ (Equation \ 16-7) \]

where:

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Codes

1405.3 Load combinations using allowable stress design.

1060.3.1 Basic load combinations. Where allowable stress design (working stress design, as permitted by this code), is used, structures and portions thereof shall resist the most critical effects resulting from the following combinations of loads:

\[ D + F \]  
\[ (Equation \ 16-8) \]

\[ D + H + F + L \]  
\[ (Equation \ 16-9) \]

\[ D + H + F + 1.6L, \ or \ S \ or \ R \]  
\[ (Equation \ 16-10) \]

\[ D + H + F + 0.75D, \ or \ 0.75L, \ or \ S \ or \ R \]  
\[ (Equation \ 16-11) \]

\[ D + H + F + 0.64 \times \sigma \]  
\[ (Equation \ 16-12) \]

\[ D + H + F + 0.75D(\phi) \times 0.75D, \ or \ 0.75L, \ or \ S \ or \ R \]  
\[ (Equation \ 16-13) \]

\[ D + H + F + 0.75 \times 0.7 \times \sigma + 0.75 \times 0.75 \times \sigma \]  
\[ (Equation \ 16-14) \]

\[ 0.62D + 0.64 \times \sigma \]  
\[ (Equation \ 16-15) \]

\[ 0.64(D + F) + 0.9(12) \times \sigma \]  
\[ (Equation \ 16-16) \]

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Codes

IBC 2012 Section 1605.3

5. In Equation 16-16, 0.6 \( D \) is permitted to be increased to 0.9 \( D \) for the design of special reinforced masonry shear walls complying with Chapter 21.
Codes

ASCE 7 -10 Section C2.4.1

Exception 3, given for special reinforced masonry walls, is based upon the combination of factors that yield a conservative design for overturning resistance under the seismic load combination:

1. The basic allowable stress for reinforcing steel is 40% of the specified yield.
2. The minimum reinforcement required in the vertical direction provides a protection against the circumstance where the dead and seismic loads result in a very small demand for tension reinforcement.
3. The maximum reinforcement limit prevents compression failure under overturning.

Of these, the low allowable stress in the reinforcing steel is the most significant. This exception should be deleted when and if the standard for design of masonry structures substantially increases the allowable stress in tension reinforcement.

Codes

1095.3.2 Alternative basic load combinations. In lieu of the basic load combinations specified in Section 1095.3.1, structures and portions thereof shall be permitted to be designed for the most critical effects resulting from the following combinations. When using these alternative basic load combinations that include wind or seismic loads, all dead load components are considered to be increased or decreased proportionately.

\[ D + L + (S_1 + S_2) \] (Equation 10-17)
\[ D + L + 0.6 a W \] (Equation 10-16)
\[ D + L + 0.6 a W + S_2 \] (Equation 10-19)
\[ D + L + 0.6 a W + S_2 \] (Equation 10-20)
\[ D + L + 0.6 a W + S + E_1 + 4 \] (Equation 10-21)
\[ 0.9 D + E_1 + 4 \] (Equation 10-22)

Codes – ASCE 7

2.1 GENERAL [ASCE 7 2005]

Buildings and other structures shall be designed using the provisions of either Section 2.3 [SD] or 2.4 [ASD]. Either Section 2.3 or 2.4 shall be used exclusively for proportioning elements of a particular construction material throughout the structure.

2.1 GENERAL [ASCE 7 2010]

Buildings and other structures shall be designed using the provisions of either Section 2.3 [SD] or 2.4 [ASD]. Where elements of a structure are designed by a particular material standard or specification, they shall be designed exclusively by either Section 2.3 or 2.4.
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2.1 GENERAL [ASCE 7 2010]
Buildings and other structures shall be designed using the provisions of either Section 2.3 [SD] or 2.4 [ASD]. Where elements of a structure are designed by a particular material standard or specification, they shall be designed exclusively by either Section 2.3 or 2.4.
Ground Motion Soil

\[ S_{MS} = F_a S_s \]

\[ S_{M1} = F_v S_1 \]

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<th>0.25</th>
<th>0.5</th>
<th>0.75</th>
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<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>C</td>
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Ground Motion Soil

\[ S_{MS} = F_a S_s \]
\[ S_{M1} = F_v S_1 \]

Seismic Design Category Occupancy

Select Seismic Use Group

<table>
<thead>
<tr>
<th>Seismic Importance Factor</th>
<th>III</th>
<th>II</th>
<th>I</th>
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<tbody>
<tr>
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Seismic Design Category

Design Category based on Sds

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Design Category based on Sd1

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<td>&gt; 2</td>
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</table>
Inelastic Force –Deformation Curve

Base Shear – Equivalent Lateral Force Method

\[ V = C_s W \]

\[ C_s = \frac{S_{DS}}{R \left( \frac{R}{T} \right)} \]

\[ C_{s(\text{min})} = \frac{S_{DS}}{T} \]

\[ C_{s(\text{max})} = 0.044 S_{DS} I_{E} \]

Seismic Design Category Irregularities

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<th>Type</th>
<th>Remarks</th>
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</table>
How Do I Find the Seismic Load in a Masonry Wall?

- Ground Motion $S_s$ and $S_l$
- Design Response Spectrum $S_{DS}$ and $S_{DS1}$
- Soil $S_{SAS}$ and $S_{SM1}$
- Occupancy Importance $I_{E}$
- Linear Elastic Base Shear
- Seismic Design Categories
- Element Forces

Scale the base shear

Codes

Distribution of Loads

- Computer analysis normal today

Uncoupled

Coupled

Design of Elements

- Load combinations, strength design (IBC 2012)

$1.2D + .5L + E$  
Formula 16-5

$.9D + E$  
Formula 16-6

$E = \rho Q_k + .2S_{SD}D$  
Equation 12.4-5 [ASCE 7]

$E = \rho Q_k - .2S_{SD}D$  
Equation 12.4-6 [ASCE 7]
Design of Elements

- Load combinations, allowable stress design (IBC 2012)

\[ D + L + S + 0.7E \]
\[ 0.6D + 0.7E \]
\[ E = \rho Q_e + 0.2S_{sd} \]
\[ E = \rho Q_e - 0.2S_{sd} \]

Design of Elements

- Load combinations, alternative allowable stress design (IBC 2012)

\[ D + L + S + E/1.4 \]
\[ 0.9D + E/1.4 \]
\[ E = \rho Q_e + 0.2S_{sd} \]
\[ E = \rho Q_e - 0.2S_{sd} \]
**Codes**

### Structural Frame
- **Operational Level Immediate Occupancy Level Life Safety Level Collapse Prevention Level**
  - Operational Level: Minor or no damage to the structural frame. Minor damage to structural frame.
  - Immediate Occupancy Level: Minor damage to structural frame. Does not interfere with immediate use. Does not interfere with long-term use.
  - Life Safety Level: Structural frame is permanently damaged. May not be repairable.
  - Collapse Prevention Level: Structural frame is near collapse.

### Cladding
- **Operational Level Immediate Occupancy Level Life Safety Level Collapse Prevention Level**
  - Operational Level: Little or no cladding damage. Operations not interrupted for repair.
  - Immediate Occupancy Level: Minor cladding damage. Does not interfere with immediate operations, but may require future repair.
  - Life Safety Level: Damage to cladding but cladding remains on the building. Cladding may have to be replaced.
  - Collapse Prevention Level: Extensive loss of cladding.

### Windows
- **Operational Level Immediate Occupancy Level Life Safety Level Collapse Prevention Level**
  - Operational Level: No window damage.
  - Immediate Occupancy Level: Minor or no window damage.
  - Life Safety Level: A few windows may be broken.
  - Collapse Prevention Level: Extensive broken windows.

### Doors
- **Operational Level Immediate Occupancy Level Life Safety Level Collapse Prevention Level**
  - Operational Level: No jamming of doors.
  - Immediate Occupancy Level: Some doors jammed.
  - Collapse Prevention Level: Extensive jamming of doors and blocking of exits.

### Walls
- **Operational Level Immediate Occupancy Level Life Safety Level Collapse Prevention Level**
  - Operational Level: Little or no damage to walls. Operations not interrupted for repair.
  - Immediate Occupancy Level: Minor damage of walls. Requires repair in the future.
  - Life Safety Level: Extensive damage of walls, many not repairable.
  - Collapse Prevention Level: Extensive damage of walls, many not repairable.

### Mechanical and Electrical Systems
- **Operational Level Immediate Occupancy Level Life Safety Level Collapse Prevention Level**
  - Operational Level: No damage to mechanical and electrical systems. Operational in all locations. Power and utilities remain available.
  - Immediate Occupancy Level: Minor damage of mechanical and electrical systems. Operational in all locations. Power and utilities remain available.
  - Life Safety Level: Moderate damage of mechanical and electrical systems. May not be functional for several days. Power and utilities may be unavailable.
  - Collapse Prevention Level: Extensive damage of mechanical and electrical systems, not repairable.

### Elevators
- **Operational Level Immediate Occupancy Level Life Safety Level Collapse Prevention Level**
  - Operational Level: Elevators functional.
  - Immediate Occupancy Level: Moderate damage of elevators. May not be functional for several days. Power and utilities may be unavailable.
  - Life Safety Level: Extensive damage of elevators, repairable.
  - Collapse Prevention Level: Extensive damage or elevators, not repairable.

### Computers and Data Storage
- **Operational Level Immediate Occupancy Level Life Safety Level Collapse Prevention Level**
  - Operational Level: Fully functional. No loss of data.
  - Immediate Occupancy Level: Minor damage, requiring repairs. Data may be lost. Down time depends on availability of parts and repair services.
  - Life Safety Level: Extensive damage, not repairable.
  - Collapse Prevention Level: Extensive damage, not repairable.

### Sensitive Equipment
- **Operational Level Immediate Occupancy Level Life Safety Level Collapse Prevention Level**
  - Operational Level: No damage to sensitive equipment.
  - Immediate Occupancy Level: Minimal damage, requiring repairs. Data may be lost. Down time depends on availability of parts and repair services.
  - Life Safety Level: Moderate damage, not repairable.
  - Collapse Prevention Level: Extensive damage, not repairable.

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**ACI**
- **(ACI 530-13)**
- **(ACI 530.1-13)**

**Lead sponsor**
- **TMS**
- **(TMS 402-13)**
- **(TMS 602-13)**

**ASCE**
- **(ASCE 5-13)**
- **(ASCE 6-13)**

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March 13, 2017

International Masonry Institute - Hawaii
Codes

Code and Specification

TMS 402 “Code”
• Design provisions
• QA program in accordance with the Specification
 • Section 1.4 invokes the Specification by reference.

TMS 602 “Specification”
• Verify compliance with specified $f'_m$
• Comply with specified products and execution
• Comply with required level of quality assurance
March 13, 2017 International Masonry Institute - Hawaii

Revised values for compressive strength of masonry units:
Concrete masonry units of 2000 psi in type M or S mortar have a compressive strength of 2000 psi.

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Starting with the 2008 MSJC code/specification, self-consolidating grout is permitted:
- SCG penetrates voids and surrounds reinforcement without requiring mechanical vibration for consolidation.

Codes – and the Structural Engineers Negligence

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