IMPROVED NONSTRUCTURAL SEISMIC DESIGN FORCE EQUATIONS

John Gillengerten – Chair, IT5 Nonstructural Components
## Seismic Design for Nonstructural Components

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Development of the Revised Force Equations

• In 2013, the National Institute of Standards and Technology (NIST) awarded a NEHRP “Earthquake Structural and Engineering Research” task order contract to the Applied Technology Council (ATC)

• A resulting report, NIST GCR 13-917-23, Development of NIST Measurement Science R&D Roadmap: Earthquake Risk Reduction in Buildings identified nonstructural issues as a top priority

• Resulted in the ATC-120 Project
ATC-120 Project Initial Phase

• Detailed Reviews of
  • Performance of nonstructural components and systems in past earthquakes,
  • History and evolution of nonstructural seismic design provisions and criteria
  • Current information on research and testing

• Develop recommendations

• Number 1 recommendation - Conduct Holistic Assessment of Current Code Design Approaches
ATC-120 Project Follow-up Phase

• A number of topics were studied, including:
  • Reviewed of ASCE/SEI 7-16 nonstructural design provisions
  • Performed analytical investigations to provide a fundamental understanding of the response of nonstructural components to earthquakes, proposed new design equations for horizontal forces
  • Recommended code changes and additional research
Factors Influencing Seismic Design of Nonstructural Components

- Ground shaking intensity, expressed in terms of peak ground acceleration (PGA)
  - Hazard Level
  - Site Conditions

- Component Properties
  - Component period
  - Inherent component damping
  - Component overstrength
  - Ductility (component and/or anchorage)
  - Component Importance

- Vertical location of component within the building or structure supporting the component

- Supporting Structure Properties
  - Building’s modal periods
  - Seismic force-resisting system (SFRS)
  - Ductility
  - Inherent damping
  - Configuration (such as plan and vertical irregularities)
  - Floor diaphragm rigidity
ASCE/SEI 7-16

2020 NEHRP Provisions

\[ F_p = 0.4S_{DS}W_p \left( \frac{a_p}{R_p} \right) \left( 1 + 2 \frac{z}{h} \right) \]

\[ F_p = 0.4S_{DS}I_pW_p \left( \frac{H_f}{R_\mu} \right) \left( \frac{C_{AR}}{R_{po}} \right) \]

PFA/PGA

Resonance, strength and ductility of component
New Design Coefficients

\[ F_p = 0.4 S_{DS} I_p W_p \left[ \frac{H_f}{R_\mu} \right] \left[ \frac{C_{AR}}{R_{po}} \right] \]

- \( H_f \) = factor for force amplification as a function of height in the structure;
- \( R_\mu \) = structure ductility reduction factor;
- \( C_{AR} \) = component resonance ductility factor that converts the peak floor or ground acceleration into the peak component acceleration;
- \( R_{po} \) = component strength factor.
Force Amplification Factor, $H_f$

- Function of structure approximate fundamental period $T_a$ and location in structure

\[ H_f = 1 + a_1 \left( \frac{z}{h} \right) + a_2 \left( \frac{z}{h} \right)^{10} \quad \text{or,} \]

\[ H_f = 1 + 2.5 \left( \frac{z}{h} \right) \]

where \( a_1 = \frac{1}{T_a} \leq 2.5 \)

\[ a_2 = \left[ 1 - \left( 0.4/T_a \right)^2 \right] \geq 0 \]

Figure 4-15 Sample equation for PFA/PGA for PCA > 0.9g.
Building global ductility, $R_\mu$

- Increased building ductility generally reduces nonstructural component response.
- This is captured by the variable $R_\mu$

$$R_\mu = (1.1R/\Omega_0)^{\frac{1}{2}} \geq 1.3$$

where $R$ and $\Omega_0$ for the building or supporting structure are obtained from Tables 12.2-1, 15.4-1, and 15,4-2
Building global ductility, $R_\mu$

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Lower Bound Cap on $R_\mu$:

- SDC D and higher, except the following
- Light-frame walls w/shear panels of other materials
- Steel OCBF, IMF
- Cold-formed steel special bolted moment frame
- Cantilever column systems
Treatment of nonbuilding structures

• Nonbuilding structures often utilize ordinary or intermediate lateral systems or are not similar to building systems at all
  - Low values of $R$ for nonbuilding structures might have been selected to facilitate adoption in the building standards
  - Low $R$ nonbuilding structures have performed well
  - Special systems would be cost-prohibitive

• For nonbuilding structures similar to buildings, the least conservative values of design coefficients (without regard to height limits) can be used for a given LFRS (i.e. intermediate moment frames)

• The calculated period, $T$ may be used in lieu of $T_a$ for the computation of $H_f$, force amplification with height
Component Design Coefficients

• The focus of the proposal was on including the influence of the supporting structure in the seismic design force equation
• Incorporate the notation for component design coefficients recommended in ATC-120
• Nonstructural components are assigned to one of three categories of component ductility, and whether they are likely to be in resonance

<table>
<thead>
<tr>
<th>Ductility Category</th>
<th>Assumed Component Ductility, $\mu_{comp}$</th>
<th>Resonance Likely CA/PFA ($C_{AR}$)</th>
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<td>Supported Above Grade Plane by a Structure</td>
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<td>High</td>
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<td>1.4</td>
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Assignment of $C_{AR}$ and $R_{po}$ Values

- Current design coefficients for nonstructural components are based on engineering judgement.
- The new design coefficients for classes of nonstructural components were assigned by IT-5, based on the properties of the components given in ASCE 7-16, using the following assumptions:
  - Components with $a_p=1$ are classified as unlikely to be in resonance.
  - Components with $a_p=2.5$ are classified as likely to be in resonance.
  - For components likely to be in resonance, those assigned an $R_p=1.5$ are classified as low ductility, $R_p=2, 2.5,$ and $3$ are classified as having moderate ductility, and those with $R_p=4.5$ or greater as having high ductility.
  - The component strength factor $R_{po}$ varied from 1.3 to 3, reflecting the level of reserve strengths associated with the component.
Distribution Systems

• Currently, bracing for pipes, ducts, and conduit is designed using the same design coefficients as the distributed system.

• In the 2020 Provisions, design of supports and system are considered separately.
Rooftop Structures and Equipment Supports

• Design requirements for rooftop structures were expanded
  • Currently no restrictions on design of penthouses and rooftop structures
  • New design coefficients are based on system R values from Chapters 12 or 15
  • Detail design is per Chapters 12 or 15

• Expanded requirements for mechanical and electrical component supports
  • Integral supports (i.e. lugs, saddles, short legs, etc.)
  • Support structures (i.e. braced and moment frames)
  • Platforms (multiple components supported on a single structure)
Changes to Design Practice

• The new equations require knowledge of the LFRS and height of the supporting structure

• Some engineers currently produce designs with little or no information on the structure
  • Default values for $R_\mu$ can be used if the structural system is unknown
  • Default formula available for determining $H_f$ is the height of the structure and lateral force-resisting system is unknown

• Practice will evolve if there are substantial advantages for providing the designer with information on the lateral force-resisting system of the structure

• If the information cannot be provided, the design force should be conservative, given the influence of the supporting building on component force demands
Adoption into ASCE/SEI 7-22

• The new procedures for calculation seismic forces for nonstructural components is being incorporated into the next edition of ASCE 7

• A number of enhancements and improvements to the procedures were incorporated into the ASCE 7 version
  • Including the structure importance factor $I_e$, when computing the building global ductility factor, $R_\mu$
  • Refinement of the design coefficients for high ductility piping systems
  • Improved the correlation between the component resonance ductility factor, $C_{AR}$, and the anchorage overstrength factor $\Omega_{op}$ for components unlikely to be in resonance
## Components at grade

<table>
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<th>No.</th>
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Items 2, 5, 21, and 22 currently governed by minimum force. Items 15 and 16 currently 10% over min. force.
The proposed design force $F_p$ averaged over all levels of the structure, normalized $F_p$ using ASCE 7-16:

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<th>8-sty Steel BRBF</th>
<th>8-sty Special RCSW (Bldg Frame)</th>
<th>2-sty Steel SCBF</th>
<th>2-sty SRMSW (bearing wall)</th>
<th>4-sty Light Frame</th>
<th>6-sty Steel SCBF</th>
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<td>0.81</td>
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<td>0.93</td>
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<td>2</td>
<td>0.83</td>
<td>0.91</td>
<td>1.11</td>
<td>1.22</td>
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<td>0.94</td>
<td>1.17</td>
<td>1.23</td>
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<td>1.15</td>
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<td>1.02</td>
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<td>0.98</td>
<td>1.04</td>
<td>1.05</td>
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<td>0.89</td>
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<td>0.86</td>
<td>0.88</td>
<td>0.96</td>
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NEW PROVISIONS FOR SEISMIC DESIGN OF DIAPHRAGMS

Kelly Cobeen, Wiss Janney Elstner Associates
Acknowledgements – PUC IT9

Voting members:

<table>
<thead>
<tr>
<th>Name</th>
<th>Company/Institution</th>
<th>Location</th>
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<tbody>
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<td>Emeryville, CA</td>
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<td>Cal Poly San Luis Obispo</td>
<td>San Luis Obispo, CA</td>
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<td>S. K. Ghosh Associates</td>
<td>Palatine, IL</td>
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<td>Johns Hopkins University</td>
<td>Baltimore, MD</td>
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<td>Engelkirk &amp; Sabol</td>
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<td>California Division of the State Architect</td>
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</table>

(1) Ben Schafer is primary contact and voting member for steel industry research projects. Matt Eatherton and Jerome Hajjar were alternates and active contributors to the work of IT9
Acknowledgements – PUC IT9
Corresponding members:

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<th>Location</th>
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<tbody>
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<td>SUNY University at Buffalo</td>
<td>Buffalo, NY</td>
</tr>
<tr>
<td>Andrew Shuck</td>
<td>WJE</td>
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</tr>
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<td>Bill Holmes</td>
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<tr>
<td>Bonnie Manley</td>
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<td>Norfolk, MA</td>
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<td>Hilti North America</td>
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<td>Maria Kolioi</td>
<td>Colorado State University</td>
<td>Fort Collins, CO</td>
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<tr>
<td>Matt Eatherton</td>
<td>Virginia Tech</td>
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</tr>
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<tr>
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<td>Seattle, WA</td>
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<td>Robert Tremblay</td>
<td>Polytechnique Montreal</td>
<td>Montreal, Canada</td>
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<td>Veronica Cedillos</td>
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<td>Steve Hobbs</td>
<td>Vulcraft</td>
<td>Tremonton, UT</td>
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<td>Tom Xia</td>
<td>DCI Engineers</td>
<td>Seattle, WA</td>
</tr>
<tr>
<td>Walt Schultz</td>
<td>Nucor</td>
<td>Norfolk, NE</td>
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</table>
3 Diaphragm Seismic Design Methods
Including 2020 NEHRP Provisions and ASCE 7-22

1. Basic Design (Sec. 12.10.1 and 12.10.2)
   a. Can be used for any structure or diaphragm system type EXCEPT precast concrete diaphragms in SDC C and above

2. Alternative Design Provisions for Diaphragms (Sec. 12.10.3)
   a. No limits on structure size or configuration
   b. Limits diaphragm system to those listed in Table 12.10-1 - precast concrete, cast-in-place concrete, wood, bare steel deck diaphragms, concrete filled metal deck systems

3. Alternative Diaphragm Design Provisions for One-Story Structures with Flexible Diaphragms and Rigid Vertical Elements (RWFD, Sec. 12.10.4)
   a. Limits structure size to one story, diaphragm geometry limits apply
   b. Limits structure vertical elements of SFRS to those deemed to be rigid
   c. Limits diaphragm system to wood structural panel on wood framing and bare steel deck
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   a. Limits structure size to one story, diaphragm geometry limits apply
   b. Limits structure vertical elements of SFRS to those deemed to be rigid
   c. Limits diaphragm system to wood structural panel on wood framing and bare steel deck

**WHY?**
- To better recognize:
  - Diaphragm influence on seismic response
  - Diaphragm force demands
  - Diaphragm ductility
- To improve diaphragm and structure seismic performance
2020 Provisions Starting Point

Alternative Design Method
• 2015 NEHRP/ ASCE 7-16
• Extensive Commentary

RWFD
• Simplified Design Program Study (funded by FEMA, administered by BSSC)
• 2015 NEHRP Part 3 Resource Paper
• FEMA P-1026 Guideline Document, published 2015
  (Bill Holmes, John Lawson, Dominic Kelly, Maria Koliou + others)
2020 Provisions Steel Research Collaboration

SDII – Steel Diaphragm Innovation Initiative (Eatherton, Hajjar, Easterling, Sabelli)

Advance the seismic performance of steel floor and roof diaphragms utilized in steel buildings through:

• better understanding of diaphragm-structure interaction,
• new design approaches, and
• new three-dimensional modeling tools that provided enhanced capabilities to designers utilizing steel diaphragms in their building systems.

SDII primarily focuses on the seismic design of diaphragms commonly used in steel mid-rise buildings.
2020 Provisions Steel Research Collaboration

RWFD: Advancing Seismic Provisions for Steel Diaphragms in Rigid Wall-Flexible Diaphragm (RWFD) Buildings, with NBM Technologies, Inc. (Meimand, Torabian, Eatherton, and Schafer)

Objective:
Validate alternative provisions for conventionally designed steel diaphragms in RWFD buildings.

Scope:
Small-scale testing and related efforts to develop an accurate and validated building scale model for NLRH analysis of steel diaphragms in typical RWFD buildings.
Alternative Diaphragm Design Provisions

( Sec. 12.10.3 )

FIGURE 12.10-7  Diaphragm Design Acceleration Coefficient Cpx for Buildings with Non-
Uniform Mass Distribution
Alternative Diaphragm Design Provisions

Drivers

Jose Restrepo and Mario Rodriguez

collection of analysis and testing data

on seismic forces in diaphragms

Multi-University project to develop

seismic design methodology for precast

concrete diaphragms (Fleishmann et al. 2012)

FIGURE 12.10-5 Comparison of Measured Floor Accelerations and Accelerations Predicted by Eq. 12.10-4 for a 5-Story Special MRF Building (Chen et al., 2013)

FIGURE C12.10-9 Relationships: (a) $\mu_{global} vs \mu_{local}$ and (b) $R_{dia} vs \mu_{global}$
Alternative Diaphragm Design Provisions

Part 1: Introduced new vertical distribution of diaphragm seismic forces for near-elastic diaphragm behavior

Part 2: Parameter $R_s$ modifies near-elastic forces based on diaphragm ductility and deformation capacity

$$F_{px} = \frac{C_{px}}{R_s} w_{px}$$

FIGURE 12.10-7 Diaphragm Design Acceleration Coefficient $C_{px}$ for Buildings with Non-Uniform Mass Distribution
Alternative Diaphragm Design Provisions
(2015 NEHRP ASCE 7-16)

Table 12.10-1 Diaphragm Design Force Reduction Factor, $R_s$

<table>
<thead>
<tr>
<th>Diaphragm System</th>
<th>Shear Controlled</th>
<th>Flexure Controlled</th>
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<tbody>
<tr>
<td>Cast-in-place concrete designed in accordance with Section 14.2 and ACI 318</td>
<td>-</td>
<td>1.5</td>
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<tr>
<td>Precast concrete designed in accordance with Section 14.2.4 and ACI 318</td>
<td>EDO 0.7</td>
<td>0.7</td>
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<tr>
<td></td>
<td>BDO 1.0</td>
<td>1.0</td>
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<tr>
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<td>RDO 1.4</td>
<td>1.4</td>
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<tr>
<td>Wood sheathed designed in accordance with Section 14.5 and SDPWS</td>
<td>3.0</td>
<td>NA</td>
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Alternative Diaphragm Design Provisions
(Added in 2020 NEHRP and ASCE 7-22)

Table 12.10-1 Diaphragm Design Force Reduction Factor, $R_s$

<table>
<thead>
<tr>
<th>Diaphragm System</th>
<th>Shear Controlled</th>
<th>Flexure Controlled</th>
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<tbody>
<tr>
<td>Bare steel deck diaphragm designed in accordance with Section 14.1.5 (Design per AISI S400)</td>
<td>With special seismic detailing 2.5</td>
<td>NA</td>
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<tr>
<td></td>
<td>Other 1.0</td>
<td>NA</td>
</tr>
<tr>
<td>Concrete-filled metal deck diaphragm designed in accordance with Section 14.1.6 (Design per AISC 341)</td>
<td>2.0</td>
<td>NA</td>
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Alternative Diaphragm Design Provisions

Bare Steel Deck Diaphragm Background and Basis

• Performance is driven by the performance of the deck profile and interaction with the sidelap and structural connections

• WR roof deck with appropriate connections has adequate ductility and deformation capacity to qualify as special seismic detailing
Alternative Diaphragm Design Provisions

Bare Steel Deck Diaphragm Basis of $R_s$ Derivation

- New cyclic shear (connection level) testing by Schafer and NBM Technologies
- Cantilevered diaphragm tests
- 3D building modeling by Schafer translating local ductility to global ductility
- Use of ATC-19 μ-R relations
Alternative Diaphragm Design Provisions

Concrete Topped Metal Deck Diaphragms Background and Basis

- 2020 NEHRP Part 3 resource paper discusses studies and likely values
- ASCE 7-22 adopted results
- Performance is driven primarily by diagonal cracking in the field of the diaphragm
- Performance can also be driven by shear transfer into collectors and vertical elements
Alternative Diaphragm Design Provisions

Basis of $R_s$ Factor for Concrete Topped Metal Deck Diaphragms

- Derived using method similar to ATC-19 considering overstrength and ductility
- Confirmed with limited FEMA P-695 numerical studies
RWFD Incorporation into ASCE 7-22

• New diaphragm design provisions in Section 12.10.4
• New *optional* two-stage approach to vertical element seismic forces in Section 12.2.3.4
RWFD Starting Point

Acknowledge and incorporate actual seismic response of RWFD buildings for diaphragm design.
RWFD Starting Point

Design to encourage distributed inelastic behavior for *improved seismic performance*

Amplified Shear Boundary Zone

Inelastic behavior is driven away from diaphragm edge and towards interior
**RWFD Starting Point**

*Optional* incorporation of actual seismic response of RWFD buildings for vertical elements – 2 stage analysis

---

Seismic Design Forces to Vertical Element

- Seismic design forces using $\text{Mass}_{\text{diaph}}$ & $\text{T}_{\text{diaph}}$
- Seismic design forces using $\text{Mass}_{\text{wall}}$ & $\text{R}$

---

![Graph showing spectral response acceleration vs. period for rigid wall and flexible diaphragm responses](image-url)

- Rigid Wall Response
- Flexible Diaphragm Response

---

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RWFD Limitations

- One-story structures
- All portions of the diaphragm must use RWFD design
- Wood structural panel diaphragms on wood framing or nailers, fastened in accordance with SDPWS tables
- Bare steel deck diaphragms designed in accordance with AISI S400 and AISI S310
- Toppings of concrete or similar not permitted
- Horizontal irregularities prohibited except reentrant corners
RWFD Limitations

- Diaphragm is rectangular or can be divided into rectangles
- Vertical elements permitted are:
  - Concrete, precast concrete or masonry shear walls,
  - Concentrically braced frames,
  - Steel and concrete composite braced frames,
  - Steel and concrete composite shear walls
RWFD Limitations
RWFD Limitations

SEISMIC DESIGN DIRECTION

A
50 FEET
SPAN 1

75 FEET

B
50 FEET

C

SEGMENT 1

COLLECTOR

CONCRETE OR MASONRY WALLS

SEGMENT 2

200 FEET – SPAN 2
• For $L_{\text{diaph}} < 100'$, shear from loading perpendicular to span shall be amplified to 1.5 times $F_{px}$
• For $L_{\text{diaph}} > 100'$, shear from loading perpendicular shall be amplified to 1.5 times $F_{px}$ for amplified shear boundary zone at each end of span for a distance equal to 10% of diaphragm span
RWFD – Example Impact on Wood Roof Diaphragm Design

Shear Nailing Zones - Proposed Design

Shear Nailing Zones - Conventional Design

Figure Credit: FEMA P-1026
RWFD – Diaphragm Seismic Design Forces

\[ F_{px} = C_{s-diaph} \times w_{px} \]

\[ C_{s-diaph} = \frac{S_{DS}}{R_{diaph}/I_e} \]

\[ C_{s-diaph} = \frac{S_{D1}}{T_{diaph} \times (R_{diaph}/I_e)} \]
RWFD – Diaphragm Seismic Design Forces

\[ R_{\text{diaph}} \]
\[ = 4.5 \text{ for wood structural panel diaphragms} \]
\[ = 4.5 \text{ for bare steel deck diaphragms that meet the special seismic detailing requirements of AISI S400} \]
\[ = 1.5 \text{ for all other bare steel deck diaphragms} \]

\[ T_{\text{diaph}} \]
\[ = 0.002 L_{\text{diaph}} \text{ for wood structural panel diaphragms, and} \]
\[ = 0.001 L_{\text{diaph}} \text{ for profiled steel deck panel diaphragms} \]

Determined for each rectangular segment of the diaphragm in each orthogonal direction [seconds]
RWFD – Diaphragm Seismic Design Forces

\[ C_{d-diaph} \]
- 3.0 for wood structural panel diaphragms
- 3.0 for bare steel deck diaphragms that meet the special seismic detailing requirements of AISI S400
- 1.5 for all other bare steel deck diaphragms

\[ \Omega_{0-diaph} \]
- 2

But need not exceed \( R_{diaph} \)
RWFD – Diaphragm Chords and Collectors

• Chords are designed using diaphragm $F_{px}$ forces
• Collectors are designed using diaphragm $F_{px}$ forces
• In SDC C to F, collectors and their connections to vertical elements are designed using diaphragm overstrength factor, $\Omega_0$
• Diaphragm overstrength factor need not be combined with the shear amplification of 1.5
• Strength level diaphragm deflection is amplified by $C_{d-diaph}$
NLRHA numerical studies using FEMA P-695 to study probability of collapse in MCE$_R$ as indicator of meeting building code performance target, as documented in FEMA P-1026

- Building footprint range: 100’x100’, 200’x400’, 400’x400’
- Heavy and light walls
- High and moderate seismic
- Conventional and proposed new design approach
Basis of Methodology – Bare Steel Deck Diaphragms

• NLRHA numerical studies using FEMA P-695. documented in FEMA P-1026

Supplemented by:
• Additional steel studies by Schafer et al.
• Separation of steel deck diaphragms into those with “special seismic detailing” and “all other”
Special Seismic Detailing for Bare Steel Deck Diaphragms

NESTED SIDE-LAP

1½" NOMINAL

2½" NOMINAL

6"

36" NOMINAL PANEL COVER

INTERLOCKING SIDE-LAP
Special Seismic Detailing for Bare Steel Deck Diaphragms

- Required in order to use $R_s = 2.5$ in Alternative Diaphragm Design Provisions of Sec. 12.10.3
- Required in order to use $R_{\text{diaph}} = 4.5$ in Sec. 12.10.4 RWFD Provisions

Provisions Include

- Prescriptive special seismic detailing - list of 8 requirements, mechanical fasteners only
- Structural Connection Qualification provisions
- Sidelap Connection Qualification provisions
- Special Seismic Qualification by Cantilever Diaphragm Test
- Special Seismic Qualification by Principles of Mechanics
RWFD Other Issues In Commentary

• Calculation of diaphragm deflections
• Wall P-delta stability
• Gravity system accommodation of diaphragm deflection
IT9 Part 3 Resource Papers

• Resource Paper 6 - Diaphragm Design Force Reduction Factor, $R_s$, for Composite Concrete on Metal Deck Diaphragms
• Resource Paper 7 - Development of Diaphragm Design Force Reduction Factors, $R_s$
• Resource Paper 8 - Calculation of Diaphragm Deflections Under Seismic Loading