Inelastic Seismic Design of Sheet Steel Roof Deck Diaphragms for Single-Storey Buildings

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Recent Advances in Cold-Formed Steel Design
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Single-Storey Steel Buildings

- **Industrial, commercial & recreational uses**
- **Often located in seismic zones in the east and west of North America**
- **Lateral resistance provided by:**
  1. Vertical cross-bracing in the perimeter walls
  2. Metal roof deck system (diaphragm)
- **Equivalent static force procedure may be used for design**
Roof Deck Diaphragm

- Cold-formed steel roof deck panels (38 & 76 mm deep)
- 0.76 & 0.91 mm most common thickness
- Nominal 230 MPa grade
- Deck-to-frame fasteners (welds, screws, powder actuated fasteners)
- Side lap fasteners (button punches, screws, welds, clinches)
- Carries gravity & lateral loads
Diaphragm Design Using Deep Girder Analogy

- Horizontal girder
- Diaphragm shear stiffness $G'$
- Diaphragm flexural stiffness $EI$
- Building stiffness also includes vertical braces
**Non Uniform Demand Across North America**

- **Saguenay (1988) typical earthquake East North America**
  - Ms 5.7, Chicoutimi-Nord (#16), R = 52 km
  - $a = 0.107 \text{ g}$, $v = 0.0151 \text{ m/s}$, $T_{0.05} = 12.1 \text{ s}$, $T_D = 17.1 \text{ s}$

- **Loma Prieta (1989) typical earthquake West North America**
  - ML 7.0, San Francisco, Diamond Heights (#58130), R = 98 km
  - $a = 0.113 \text{ g}$, $v = 0.143 \text{ m/s}$, $T_{0.05} = 3.44 \text{ s}$, $T_D = 9.42 \text{ s}$
Codes Allow Inelastic Response in Design

2005 NBCC: \( V_f = \frac{V_e}{R_d R_o} \)

- Ability to perform in the inelastic range necessary
Capacity Based Design Approach

- Collector Elements
- Bracing Connections
- Foundations
- Bracing Members
- Anchor Bolts
- Roof Diaphragm

- Ductile Elements: $V_U > V_{\text{DESIGN}}$
- Non Ductile Elements: $V_U > V_{U \text{ BRACING}}$

• Chain of Links
Modified Capacity Based Design Approach

Collector Elements  Bracing Connections  Foundations

Roof Diaphragm

Bracing Members

Anchor Bolts

V

Ductile Elements
$V_U > V_{\text{DESIGN}}$

Non Ductile Elements
$V_U > V_{U \text{ DIAPHRAGM}}$

Chain of Links
No Data on Seismic Inelastic Diaphragm Response

Monotonic
Connection Performance?

- **Typically the strength of the connectors controls the strength of the diaphragm**

- **Flexibility of the diaphragm is a function of the connection flexibility, deck warping and deck shear flexibility**
Connections

a) Button punch

b) Weld

c) Weld+washer

Screw

Nail

Weld+washer

Weld+washer

Weld+washer
Connection Tests

- Various welded deck-to-frame connections
- Screw, button punch, powder actuated connections
Diaphragm Tests - Phase I
Quasi-Static

- ATC-24 protocol
- Various connection combinations
- Results used to develop non-linear model
Realistic Loading Protocol Based on Actual Inelastic Response

Test No. 7
PAF - Screws
Ruaumoko (Carr 1996)
Wayne-Stewart Hysteretic Model
Analytical Study

- Four different buildings studied (15x30x5.4 m to 60x120x9.0 m)
- Equivalent static approach (NBCC)
- Design with $R_d = 2.0$ & $R_d = 3.0$ ($R_o = 1.67$)

- Two sites: Victoria BC and Quebec City QC
- 12 selected ground motion time histories
- Intra-plate and Cascadia for the west
- Inter-plate for the east
- Elastic, as well as inelastic roof design
Computed Period $T$

$$T = 2\pi \sqrt{\frac{(K_B + K_D) W}{K_B K_D g}}$$

$$K_D = \frac{\pi^2}{\frac{L^3}{\pi^2 EI} + \frac{L}{G'b}}$$

• Based on diaphragm and vertical brace stiffness
Typical Acceleration Time Histories for Eastern North America

- 1988 Saguenay, Les Éboulements 0°
- 1988 Saguenay, La Malbaie 63°
- 1985 Nahanni, Battlement Creek 270°
- Simulated M6.0 at 30 km
- Simulated M7.0 at 70 km
- 1985 Nahanni, Battlement Creek 0°
Typical Acceleration Time Histories for Western North America

- Simulated M6.5 at 30 km
- Simulated M7.2 at 70 km
- 1984 Morgan Hill, Gilroy #6 90°
- 1994 Northridge, Old Ridge Rd 90°
- 1965 Puget Sound, Olympia Test Lab 266°
- 1949 Western Washington, Olympia Test Lab 86°
- Simulated M8.5 Cascadia Earthquake

Intra-Plate

Cascadia
Satisfactory Performance

1994 Northridge, Castaic Old Ridge Rd 90°

Ground Accel. (g)

-0.4
-0.2
0
0.2
0.4

Drift (% hs)

-1.0
-0.5
0.0
0.5
1.0

Time (s)

0 5 10 15 20

Design No. 1: Rd = 2.0
Elastic Roof

Design No. 2: Rd = 3.0
Elastic Roof

Design No. 3: Rd = 3.0
Inelastic Roof

△ Bracing
△ Total
Loading Protocols

-15 -10 -5 0 5 10 15

East Rd = 3.0

-15 -10 -5 0 5 10 15

West Rd = 2.0

West Rd = 3.0

γ

0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 Time (s)

γ (x10³ rad)

1st segment 2nd segment 3rd segment

a) Short Duration (SD)  b) Long Duration (LD)
6.096 m
1500 kN Actuator
Specimen
Frame
Pin (typ.)
Hor. Reaction
Vert. Reaction (typ.)
Joist (typ.)
3.658 m
6.096 m
Diaphragm Tests
- Phase II
SD & LD Dynamic

- 11 Monotonic
- 12 Short Duration
- 4 Long Duration
- Various connection scenarios
Test Diaphragm Layout

- **Weld* side lap & weld* deck-to-frame**
- **Button punch side lap & weld deck-to-frame**
- **Screw side lap & PAF (nail) deck-to-frame**
- **Weld* side lap & PAF (nail) deck-to-frame**
Diaphragm Monotonic Test Results

Shear flow

Shear Rotation

\( \gamma (x10^{-3} \text{ rad}) \)

\( S (\text{kN/m}) \)

Test Results

1. WW-WW
2. WW-N
3. S-N
4. BP-W

(19)(22)(25)(37)
Connection Failures

Screw bearing & tilting

Nail bearing

Sidelap weld fracture

Sidelap weld bearing
Connection Failures

Weld fracture

Minor bearing distortion

Excessive bearing distortion

Excessive bearing distortion
Dynamic SD Load vs. Deformation and Time History Response

- \( t = 0.91 \) mm
- **Nail-Screw** - diaphragms could develop capacity up to end of test
- **Weld-Nail** - full sheet failure mode
- **Weld-Weld** - Side lap welds limit ductility
- **BP-Weld** - Strength degradation in 2\(^{nd}\) loading segment
Dynamic SD Load vs. Deformation and Time History Response

- $t = 0.91$ mm
- Nail-Screw - nail & screw bearing failure
- Weld-Nail - nail bearing failure perp. to flutes
- Weld-Weld - sudden loss in capacity with side lap shear failure
- BP-Weld - inadequate shear disp. Applied (56% of intended $\gamma$)
Dynamic SD Load vs. Deformation and Time History Response

- $t = 0.76 \text{ mm}$
- Nail-Screw – Ductile response
- Nail & screw bearing failure

- **BP-Weld** - Strength degradation in 1st loading segment
- **BP-Weld** - Shear capacity very limited in 2nd & 3rd segments
- Sudden shear fracture of unreinforced deck-to-frame welds
Dynamic LD Load vs. Deformation and Time History Response

- $t = 0.91 \text{ mm}$
- LD protocol contained 6 segments
- BP-Weld combination not tested due to poor performance in SD tests
Dynamic LD Load vs. Deformation and Time History Response

- \( t = 0.91 \text{ mm} \)
- Pinching observed due to bearing elongation at nail holes
- LD protocol provides no worse of a loading situation compared with SD
Overall Observations

- Based on this study preliminary seismic design recommendations can be made
- Long duration protocol ≈ greater demand
- Recommendations mainly based on SD diaphragm tests
- East $R_d = 3.0$ segment – limited damage and load degradation except for BP & weld diaphragm
- More extensive assessment of eastern demand is required
- Design requirements based on load protocols for west should also be used for the east at this time
Button Punch & Weld

- Curved profile at connection location - problematic for welding
- Weld & BP quality is variable
- Not suitable for weak diaphragm design in east or west North America
- Diaphragm design to remain elastic under seismic loading
- When elastic base shear < brace capacity use $R_d = 1.0$ & $R_o = 1.0$ for diaphragm
- Vertical braces – fuse elements ($R_d$ & $R_o > 1.0$)
**Weld* & Nail**

- Suitable for weak diaphragm design in east or west North America
- Welded side lap susceptible to loss of bond between weld metal and sheet steel
- $R_d = 1.5$
- $R_o = 1.0 / \phi$
- System was able to perform in the $R_d = 2.0$ range
- Overall sheet mode of failure causes high demand on all diaphragm edge connections
Weld* & Weld*

- Suitable for weak diaphragm design in east or west North America
- Welded side lap susceptible to loss of bond between weld metal and sheet steel
- $R_d = 1.5$
- $R_o = 1.0 / \phi$
- System was able to perform in the $R_d = 2.0$ range
- Outer edge joints must be stronger than the interior side lap connections to avoid concentration of inelastic demand* (applies to all systems)
Screw & Nail

- Suitable for weak diaphragm design in east or west North America
- Mech. Fasteners provide good reliability & predictability
- $R_d = 2.0$
- $R_o = 1.0 / \phi$
- System was able to perform in the $R_d = 3.0$ range
- Uncertainties remain - ground motions used & building response
- Pinching behaviour expected
- Sidelap behaviour needs improvement
Conclusions

• Steel roof deck diaphragm can be used as an energy dissipating element

• Proper connection design required to ensure adequate ductile performance

• Stated $R_d$ & $R_o$ values are preliminary

• Research should be extended to cover building performance, eastern North America seismic records, non-structural components, improved fastener design, panel end-laps, etc.
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