Phasing out of Conventional Ductile Seismic Design: An overview of research toward a next generation of seismic resistant structures

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Christchurch, 2011
*minutes after M6.3 earthquake*

- Limited number of deaths (most in one poorly designed building)
- But, more than $30 Billion in losses
- 80% of the tallest 50 buildings in Christchurch have or will be demolished even though they met their design goal or preserving life during a design level earthquake.
- Estimated that it will take at least two decades to recover fully
Ductile Design = Damage to main structural elements through inelastic yielding and residual deformations

Can Lead to total Loss of Buildings even if they respond as expected and as intended by current modern seismic codes
14-storey Building in Sendai-City
Possible Practical Limits for Residual Drifts

- Permissible out of plumb for new construction = 0.2% drift
- Re-alignment most likely required for residual drifts greater than 0.5%
- Total loss of structure if residual drift is of the order of 1% or greater

McCormick et al. (2008) – Study done on real buildings with post earthquake residual deformations ---- concluded that in Japan less expensive to rebuild a structure than to repair it when residual drifts greater than 0.5%.
Residual Deformations of Steel Structures designed according to ASCE-7 (05)
Erochko et al, 2010 – ASCE Journal of Structural Engineering

Results from 20 Spectrum Compatible Records
Some research towards the development of resilient seismic-resistant systems in Canada

- **Steel frames (MRF and EBF) with replaceable nonlinear links**
- **Braces with Yielding Connectors**
- **Self-Centering Bracing (SCED) Systems**
- **Base Rocking Steel frame systems (with higher mode control)**
- **Damped Coupling Beams for high-rise buildings**
Welding Replacement Technique
Steel Deck in place to simulate accessibility constraints during replacement – repair carried out with 0.5% residual drift imposed on frame

Replacement Welded Link

Welding on site
Recent Implementations of replaceable EBF fuses in Christchurch, NZ

Brace Equipped with Yielding Connector

Two Castings are Welded to the Brace Member with Fillet Welds

Standard Brace and Bolted Connection

Splice Plate Assembly with Slotted Holes Connects the Yielding Fingers to the Corner Gusset

Connector and brace combine in series to give stiffness allowing for independent control of stiffness and yield load (by changing brace section but or connector)
Repeatability of Castings

YBS-1 and YBS-4 Were Manufactured 8 Months Apart

![Graph showing brace axial force versus axial brace displacement with curves for YBS-1 and YBS-4]
Whistler, British Columbia
Self-Centering Energy Dissipative Brace

**No Load**
- Tendon Anchor
- Outer Member
- Inner Member
- End Plate
- Hysteretic, Viscous or Shape Memory Alloy Energy Dissipation

**Tension**
- Brace Strain = +δ
- Outer Member Force = F
- Tendon Force = \( P - F \)
- Inner Member Force = \( F \)
- Tendon Strain = +δ

**Compression**
- Brace Strain = -δ
- Outer Member Force = \( P \)
- Tendon Force = \( P - F \)
- Inner Member Force = \( P \)
- Tendon Strain = +δ

Hysteretic Response
- With Hysteretic Damper
- Yield/Slip Force = \( F \)
Telescoping SCED Brace (T-SCED Brace)

**Tension**
Brace Strain = +2\(\delta\)

Outer Member Force = \(F\)
Strain = +2\(\delta\)

Intermediate Member Force = \(P - F\)

Tendon Force = \(P - F\)
Tendon Strain = +\(\delta\)

Hysteretic Response
With Hysteretic Damper
Yield/Slip Force = \(F\)

**Compression**
Brace Strain = -2\(\delta\)

Outer Member Force = \(P\)
Strain = -2\(\delta\)

Intermediate Member Force = \(P - F\)

Tendon Force = \(P - F\)
Tendon Strain = +\(\delta\)
Self-Centering Base-Rocking Systems

• Rocking of structures (unintended in the past) has allowed for many seismically deficient structures to survive earthquakes

• Primarily a result of deficient foundations that allowed structures to uplift

• Can be engineered as the intended response to provide self-centering undamaged seismic response
Rocking Structures with Engineered Higher Mode Control Systems
Test Concept

concentrically braced frame

mass system

upper rocking joint
  i) clamped shut
  ii) free to rock

first-storey brace
  i) conventional
  ii) SCED

base rocking joint

shake table
First-storey brace
Expected Seismic Performance
This building performed as designed according to Current National Building Codes

This building was decommissioned (LATBSDC 2010)
Viscoelastic Coupling Damper (VCD)

• Replace concrete link beams with dampers

• Multiple layers of high damping Viscoelastic material (VE) sandwiched between steel plates

• Adds distributed damping for both wind and earthquakes

Developed at University of Toronto in collaboration with Yolles Partnership

• US Patents #7,987,639, 8,516,753, 8,881,491
• Canadian Patents #2,634,641, 2,820,820
• Chinese Patent #200680040409.X
• Korean Patent #10-2008-701296
• 9 Int. Patents Pending
Kinematics of Coupling Damper

- Walls rotate about centerline causing large shear deformations in between ends of walls
- Coupling Damper VE Material undergoes shear deformation
- Added Damping (equivalent VE behavior) under wind and DLE events
- Viscoelastic-plastic behavior under Maximum Credible Earthquakes
## Performance Based Wind and Seismic Design

<table>
<thead>
<tr>
<th>VCD Performance Targets</th>
<th>All Wind Loads</th>
<th>Frequent / Design Level Earthquakes</th>
<th>Maximum Credible Earthquakes</th>
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<tbody>
<tr>
<td><strong>Added Damping</strong></td>
<td><strong>Accelerations</strong>&lt;br&gt;- Drifts&lt;br&gt;- Velocities&lt;br&gt;- Forces</td>
<td><strong>Equivalent performance</strong> to ductile structure</td>
<td>Advantage:&lt;br&gt;- <strong>VCDs easily inspected</strong> and <strong>replaced</strong> if fuses have activated</td>
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<td><strong>Behaviour</strong></td>
<td><strong>Viscoelastic Response</strong>&lt;br&gt;- No damage</td>
<td><strong>Viscoelastic-Plastic Response</strong>&lt;br&gt;- Fuses <strong>activate</strong></td>
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<td><strong>Performance Benefits</strong></td>
<td><strong>More cost-effective</strong> design&lt;br&gt;- Increased sellable space&lt;br&gt;- Material reduction</td>
<td><strong>Much less damage</strong>&lt;br&gt;- <strong>Reduces downtime and repair costs</strong> after EQ</td>
<td></td>
</tr>
</tbody>
</table>

- Added Damping reduces:
  - Accelerations
  - Drifts
  - Velocities
  - Forces

- Added Damping has the following benefits:
  - More cost-effective design
  - Increased sellable space
  - Material reduction

- Added Damping ensures equivalent performance to ductile structures.

- Advantage:
  - VCDs easily inspected and replaced if fuses have activated.

- Behaviour:
  - Viscoelastic Response:
    - No damage
  - Viscoelastic-Plastic Response:
    - Fuses activate

- Performance Benefits:
  - More cost-effective design
  - Increased sellable space
  - Material reduction
  - Much less damage
  - Reduces downtime and repair costs after EQ
Wind and EQ (integrated) Design Philosophy

Viscoelastic Response: Added Damping
- Wind and low level earthquakes

Viscoelastic-Plastic Response:
- Maximum Credible Earthquake

Hysteretic Envelope

Ultimate Capacity designed for ductility

Displacement
VCD vs Current Practice
Maximum Credible Earthquake Response

- **Dampers and walls protected**

- **Damper fully replaceable if required**

- **Enhanced seismic performance compared to coupling beams**
Some Concluding Thoughts

• The earthquake engineering community may want to consider moving away from using ductile structural systems.

• In most cases the initial construction cost of advanced systems is very similar to that of conventional systems (a few percent greater than total initial cost of project).

• Owners need to be better educated about potential seismic damage by structural engineers.

• Significant research efforts have to be steered in this direction at all levels to achieve this shift in seismic engineering.

• Leaders in industry must take part and support this effort if we want to accelerate this shift.
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In Memoriam

Professor Nigel Priestley
1943-2014