Seismic performance of hollowcore

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Summary

- Earthquakes
- Development of seismic design
- Seismic load
- Earthquake resistant buildings
- Design of hollowcore diaphragms
- Topping?
- Potential failure modes
Earthquakes of 20th Century
Earthquake casualties & economic losses

- Twentieth century global earthquake fatalities, by decade

- Trend of worldwide economic and insured losses (from Munich Reinsurance)
Development of seismic design

- 1920’s & 1930’s several major earthquakes occurred
  - Japan: 1925 Kanto earthquake
  - USA: 1933 Long Beach earthquake
  - New Zealand: 1932 Napier earthquake

Structures designed to lateral wind loads performed better

- Structures designed for lateral inertia forces
- 10% of building’s weight uniformly distributed
Development of seismic design

- 1940’s & 1950’s
  - Significance of structural dynamic characteristics

- 1960’s
  - Period-dependent design lateral force levels
  - Concept of DUCTILITY

- 1970’s & 1980’s
  - CAPACITY DESIGN
  - Displacement-based design
Development of seismic design

- **Common seismic design procedures:**
  - Equivalent lateral forces (ELF)
  - Modal spectral analysis

\[
F_b = \gamma S_d(T_1) m \lambda
\]

\[
F_i = F_b \frac{m_i Z_i}{\sum_{i=1}^{n} m_i Z_i}
\]

- ELF
- Modal analysis
Seismic map of Europe
Seismic map of Europe

- **Romania**
  - Constant increase of seismic demand
  - Target reference return period: 225 years → 475 years

- Evolution of spectral shape
- Evolution of the design base shear for a 13 story RC frame building
Seismic map of Europe

- **Norway**
  - 2004: new series of standards
  - Introduction of seismic design provisions
  - National Annex to EC8
  - Common approach: ductility class low
The Netherlands
- Globally - non-seismic area
- Groningen area: shallow earthquakes caused by gas drilling
- 2014 draft version of the seismic design standard
Seismic load

[Diagram showing seismic waves attenuating as they travel from the fault to the building site.]

Spectral acceleration $S_a$ [m/s²]

Period $T$ [s]

- $S_a(T = 0.3 \, s)$
- $S_a(T = 1.0 \, s)$

Elastic demand spectrum (damping $\xi = 5\%$)
Seismic load

- **EC8 seismic response spectra**
  - Horizontal spectra
    - Seismic design $\Rightarrow a_g S \geq 0.05 g$
    - Type 1
    - Type 2
    - Elastic spectrum $\Rightarrow q \Rightarrow$ design spectrum
  - Vertical spectra
    - Seismic design $\Rightarrow a_{vg} \geq 0.25 g$
    - Elastic spectrum $\Rightarrow q < 1.5$ (overstrength)

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>$a_{vg}/a_g$</th>
<th>$T_B(s)$</th>
<th>$T_C(s)$</th>
<th>$T_D(s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>0.90</td>
<td>0.05</td>
<td>0.15</td>
<td>1.0</td>
</tr>
<tr>
<td>Type 2</td>
<td>0.45</td>
<td>0.05</td>
<td>0.15</td>
<td>1.0</td>
</tr>
</tbody>
</table>

- Type 1 elastic response spectra
- Type 2 elastic response spectra
Earthquake resistant buildings

- Conceptual design – EC8
  - Structural simplicity
  - Uniformity
  - Symmetry
  - Redundancy
  - Bi-directional resistance & stiffness
  - Torsional stiffness
  - Diaphragmatic behaviour at storey level
  - Adequate foundation
Earthquake resistant buildings - ductility

a) Hysteretic force-deformation behavior from tests

b) Backbone representation of hysteretic behavior

- Ductile (deformation controlled)
- Semi-ductile
- Brittle (force controlled)
Earthquake resistant buildings

- Conceptual design – EC8

  - Basic value of the behaviour factor, $q$

<table>
<thead>
<tr>
<th>Structural type</th>
<th>DCM</th>
<th>DCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame, dual, coupled wall systems</td>
<td>$3.0\alpha_u/\alpha_1$</td>
<td>$4.5\alpha_u/\alpha_1$</td>
</tr>
<tr>
<td>Uncoupled wall systems</td>
<td>3.0</td>
<td>$4.0\alpha_u/\alpha_1$</td>
</tr>
<tr>
<td>Torsionally flexible systems</td>
<td>2.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Inverted pendulum systems</td>
<td>1.5</td>
<td>2.0</td>
</tr>
</tbody>
</table>

$q = \frac{d_u}{d_1}$
Earthquake resistant buildings

- **Capacity design method**
  - Designated elements suitably designed for energy dissipation
  - All other structural elements provided with sufficient strength

- **Preferred ductile mode of failure**

- Ductile mode of failure
- Story mechanism – early collapse
Earthquake resistant buildings

Concrete Core Wall without Openings (Cantilever Wall)

Concrete Core Wall with Openings (Coupled Wall)

Gravity Framing

Floor Diaphragms at and Below Grade Transfer Forces from Core Wall to Perimeter Retaining Walls

Plastic Hinge Locations at Coupling Beams and Base of Wall

Flexural Plastic Hinge Location, Detailed for Ductility

Below-Grade Perimeter Retaining Walls

Foundation
Earthquake resistant buildings

- Failure of confinement in columns – 1985 Mexico earthquake
- Failure due to discontinuity of vertical resisting elements – 1972 San Fernando earthquake
Earthquake resistant buildings

- Regardless of the ductility class of the structure
  - Foundations
  - Floors
  - Connections

ELASTIC RANGE DIAPHRAGMS
Diaphragms - Eurocode8

- **Solid reinforced concrete slab**
  - Minimum thickness $\geq 70$ mm
  - Reinforced in both horizontal directions
  - Explicit verifications required only in DCH

- **Cast-in-place topping on a precast floor**
  - Provides alone the required diaphragm stiffness and resistance
  - Composite section
Diaphragms - Eurocode8

- **Precast slabs**
  - Appropriate topping → drastically improves the rigidity of the diaphragm
  - Thickness of topping ≥ 40 mm if span ≤ 8 m
  - Thickness of topping ≥ 50 mm if span > 8 m
  - Mesh reinforcement connected to vertical resisting elements
  - Ties → system of reinforcement
  - Friction forces neglected
Diaphragms – USA (ACI)

- General provisions
  - Prevention of boundary reinforcement (ties) from buckling
    - Increased spacing in between bars
    - Confinement with transverse reinforcement

- Precast slabs with cast-in-place topping
  - Composite section
  - Independent elements
  - Topping slabs acting compositely – thickness ≥ 50mm
  - Non-composite topping – thickness ≥ 65mm
Diaphragm – New Zealand (NZS)

- General provisions
  - Designed to remain elastic
  - Designed to forces associated with overstrength development

- Precast slabs with cast-in-place topping
  - It is recommended to rely on reinforced topping of at least 50 mm
  - Elements with camber
  - Minimum cover at lapped splices
  - Mesh $\rightarrow$ rebars

thickness $\geq$ 65mm
Design loads for diaphragms

- **EC8**
  - Shear forces $\rightarrow$ overdesign factor $\gamma_{Rd} = 1.1 - 1.3$

- **ASCE**
  - Collectors are designed to remain elastic (overstrength factor $\Omega_0 = 2 - 3$)

$$F_{px} = \frac{\sum_{i=x}^{n} F_i}{\sum_{i=x}^{n} w_i} w_{px}$$

- **NZS**
  - capacity design
  - $\gamma_{Rd} \times \text{seismic loads} < \text{design loads (F}_{Ed} < \text{elastic seismic forces (q=1)}$
Design of diaphragms

- Deep beam model

Simply supported case

Horizontal loading

Shear force diagram

Bending moment diagram

Shear core

Shear wall
Design of diaphragms

- Strut and tie model
Design of diaphragms

- 3D mathematical model & seismic analysis
Design of HC diaphragms

- Diaphragm action with hollow core slabs
Design of HC diaphragms
Design of diaphragms – PCI provisions

- **Longitudinal joints**
  - Longitudinal shear transfer capacity of grouted keyways
  - Limited strength for longitudinal shear

\[ \phi V_n = \phi(0.08)h_n \ell \]

where

\[ \ell = \text{length of joint under consideration (in)} \]
\[ h_n = \text{net height of grout key (in)} \]
\[ \phi = 0.85 \]

- Grout strength exceeded
  - Reinforcement placed perpendicular to the longitudinal joints

\[ A_{vf} = \frac{V_u}{\phi f_y u} \]

where

\[ V_u = \text{factored applied shear} \]
Design of diaphragms – PCI provisions

- **Transversal joints**
  - Shear friction reinforcement for shear in the longitudinal joints
  - Drag strut with axial tension/compression

\[ A_s = \frac{T_u}{\phi f_y} \]

- Chord member where flexural tension is resisted

\[ A_s = \frac{M_{ul}}{\phi 0.8 h f_y} \]

where

- \( h \) = depth of the diaphragm
- \( \phi \) = 0.9
When is topping needed?

Gravity Loads

Building Drift

Moment from rotation of support beam

Axial load from elongation of parallel beams

Vertical Seismic loads

Down

Up
When is topping needed?
Potential failure modes

- Interaction of precast HC units with beams (frame systems)

Plan on part of floor

Corner rises due to drift

Displacement between hollow-core unit and beam in eccentrically braced bay

Hollow-core floor

Vertical deflection between beam and precast unit

Precast unit
Potential failure modes

- Interaction of precast HC units with beams (frame systems)
  - Differential displacement between HC and beam → splitting of the web
Potential failure modes

- Interaction of precast units with beams (frame systems)
  - Beam-slab interaction $\rightarrow$ up to 2x negative bending capacity
Potential failure modes

- Interaction of precast units with beams (frame systems)
  - Solution → flexible “linking” slab – allow differential movement
Potential failure modes

- Possible loss of support of hollow-core units
  - Movement of support relative to precast unit
  - Required support length should include elongations
Potential failure modes

- Negative moment failure near support
  - Unintended restraining effects
  - Flexural strength – starter bar > flexural strength – mesh
Potential failure modes

- **Positive moment failure near support**
  - Relative rotation beam-floor → close to support positive moment
  - Support – prestress is not fully developed
Potential failure modes

- Torsion
  - Differential deflection of supporting structure
Potential failure modes

- **Torsion**
  - Differential deflection of supporting structure
  - Torsional cracking moment must be checked
Thank you

References

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- EN 1998-1 : 2003
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