The Art of Designing Ductile Concrete in the Past 50 Years: The Impact of the PCA Book and Mete A. Sozen, Part 1

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DESIGN FOR CONTROLLING SHEAR STRENGTH DECAY IN RC MEMBERS: From Stirrups to Fiber Reinforcement

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OUTLINE

• State of affairs at time of publication of PCA Book (1961; 1963 ACI Code)

• Shear strength decay in RC flexural members (focused on beams)
  • Identification of phenomenon, causes, and mitigation methods (late 1960s – 1980)
  • From research to practice (1983 ACI Building Code)
  • 1990s
  • An alternative solution (2000s)

• Summary and recommendations
1961 – PCA Book
Shear design (beams):
• Capacity design introduced for the first time

\[ V_u = \frac{M_u + M_w}{L} + \frac{wL}{2} \]

1963 ACI Building Code
Shear design (beams):
• No decay of shear resistance recognized (no data available yet).
  However, peak shear stress limited to 6\( \sqrt{f_c} \)

\[ v_u = v_c + v_s \]
\[ v_c = 1.9\sqrt{f_c} \]
\[ v_s = \frac{Af_y}{h_wd} \]

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Within 4\( d \) from support:
\[ (A_v)_{min} = 0.15p h_wd \]
\[ s \leq d/2 \]
Within 2\( d \) from support:
Closed ties with 135° hooks at
\[ s_{min} = \min(d/2, 16\phi_b, 12 \text{ in}) \]

1963 ACI Building Code
Shear design (neglecting \( \phi \) factor):

\[ v_u = \frac{V_u}{b_wd} \leq 10\sqrt{f_c} \]
\[ s \leq d/2 \text{ for } v_u \leq 6\sqrt{f_c} \]
\[ s \leq d/4 \text{ for } v_u > 6\sqrt{f_c} \]
\[ v_c = 1.9\sqrt{f_c} + 2500p_w \frac{V_d}{M} \leq 3.5\sqrt{f_c} \]
\[ v_s = \frac{Af_y}{h_wd} \]

FLEXURAL MEMBERS UNDER LOAD REVERSALS
McCollister, Siess & Newmark (1954):
• Evaluated effect of loading in one direction on strength and ductility when loaded in reversed direction (one cycle)
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McCollister, Siess & Newmark (1954):
• Evaluated effect of loading in one direction on strength and ductility when loaded in reversed direction (one cycle)
• Sufficient transverse reinforcement to prevent shear failures

FLEXURAL MEMBERS UNDER LOAD REVERSALS

Burns & Siess (1962; 1966):
• Likely first comprehensive research on behavior of RC flexural members under load reversals
• Shear failures prevented ($V_c = 0$)
• Low shear stresses ($v_u \leq 3\sqrt{f_y}$)

FLEXURAL MEMBERS UNDER LOAD REVERSALS

• Shear strength decay phenomenon explicitly recognized

$v_u \approx 200$ psi; $v_s \approx 340$ psi; $a/d = 6$; $\Delta_{max} = 10\lambda_y = 11\%$ drift
$v_u \approx 400$ psi; $v_s \approx 420$ psi; $a/d = 3$; $\Delta_{max} = 10\lambda_y = 11\%$ drift

FLEXURAL MEMBERS UNDER LOAD REVERSALS

“…shear was the major factor governing behavior. The apparent shear failure was produced by abrasion over a surface formed by a combination of diagonal tension cracks and nearly vertical flexural tension cracks resulting from load reversals.”
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 “…higher deflection limits...reduced the number of cycles to failure...”

“Reducing the stirrup spacing increased significantly the number of cycles to failure...”

“Reduction of the shear span...resulted in failure in fewer cycles.”

Wight & Sozen (1973; 1975):
• Effect of axial load on shear strength decay evaluated

“...decay in shear strength is less in elements with higher axial loads, everything else being equal”

• Evaluation of change in shear resisting mechanisms
FLEXURAL MEMBERS UNDER LOAD REVERSALS

Wight & Sozen (1973; 1975):

“As this process [increase in permanent strain of stirrups] is repeated, the concrete section, which must ultimately provide the compressive thrust, becomes distorted. As a result, the shear strength decays.”

Wight & Sozen (1973; 1975):

“...if reinforced concrete elements are designed to resist earthquake effects by energy dissipation in the inelastic range, the transverse reinforcement must be designed to carry the entire shear.”

“...the use of closely spaced stirrups that are designed to carry all of the shear does not necessarily prevent shear failures...”

“...spacing of the stirrups should not exceed one-fourth of the effective depth.”

Popov, Bertero & Krawinkler (1972):

• Evaluated behavior of three RC beams under large shear reversals ($\sigma_s = 6\sigma_f$)

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• Degradation of shear resistance attributed to:
  • Deterioration of bond between stirrups and concrete
  • Loss of aggregate interlocking due to abrasion of cracked surfaces
Popov, Bertero & Krawinkler (1972):
- Evaluated behavior of three RC beams under large shear reversals ($\nu = 6\sqrt{\frac{f_{c}}{f_{y}}} $)
- Degradation of shear resistance attributed to:
  - Deterioration of bond between stirrups and concrete
  - Loss of aggregate interlocking due to abrasion of cracked surfaces

"...it appears to be advisable to neglect the shear resistance of the concrete, $V_{c}$, in the shear design of flexural members subjected to load reversals."

Scribner & Wight (1978; 1980):
- Evaluated effect of shear stress level and presence of intermediate longitudinal reinforcement on shear strength decay
- Intermediate reinforcement ($A_{i} = 0.25A_{s}$) was found most effective in members subjected to shear stresses between 3 and 6 $\sqrt{\frac{f_{c}}{f_{y}}}$ without intermediate bars
- $\nu_{u} = 3\sqrt{\frac{f_{c}}{f_{y}}}$; $\nu_{s} = 3\sqrt{\frac{f_{c}}{f_{y}}}$

with intermediate bars
- $\nu_{u} = 3.5\sqrt{\frac{f_{c}}{f_{y}}}$; $\nu_{s} = 3\sqrt{\frac{f_{c}}{f_{y}}}$

ACI BUILDING CODE
1983 ACI Code first to recognize shear strength decay in flexural members
- $V_{c} = 0$ (beams)
- $V_{u}$ based on member reaching expected moment capacity
- $V_{s}$ based on member reaching expected moment capacity
- Hoops required over 2σ from support
- $\sigma_{max} = \min(d/4; 8(d_{h})_{long}; 24(d_{h})_{hoop}; 12$ in)
- Every other longitudinal bar in outermost layers must be supported as for columns
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- $V_u$ based on member reaching expected moment capacity
- Hoops required over 2h from support
  - $s_{max} = \min(d/4; 8(d_{h,hoop} - 24(d_{h,hoop})/24 \text{ in})$
  - Every other longitudinal bar in outermost layers must be supported as for columns

These provisions have remained unchanged, except for the maximum allowed spacing, which was modified in 2011
- $s_{max} = \min(d/4; 6(d_{h,hoop} - 24(d_{h,hoop})/6 \text{ in})$

For all shear, keep $v_u \leq 3 \sqrt{f'}$
- If possible, keep $v_u \leq 3 \sqrt{f'}$
  - For $3 \sqrt{f'} \leq v_u \leq 6 \sqrt{f'}$, use intermediate longitudinal reinforcement (also enhances joint behavior)

ACI BUILDING CODE

Provisions in ACI Building Code are minimum requirements

If you want to stay out of trouble

KEEP SHEAR STRESSES LOW
ACI BUILDING CODE

- Provisions in ACI Building Code are minimum requirements
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**KEEP SHEAR STRESSES LOW**

- If possible, keep $v_u \leq 3\sqrt{f_c'}$.
- For $3\sqrt{f_c'} \leq v_u \leq 6\sqrt{f_c'}$, use intermediate longitudinal reinforcement (also enhances joint behavior)
- If $v_u > 6\sqrt{f_c'}$, say NO

1990s – Early 2000s

- Significant focus on defining relationship between $V_c$ and member deformation (primarily applied to columns): e.g., work at UC Berkeley, UC San Diego
- Substantial work also on estimating drift capacity of columns (e.g., Purdue Univ., UC Berkeley; Japan)

ADDRESING SHEAR STRENGTH DECAY AT THE MATERIAL LEVEL

Use of a material with higher tension and compression ductility should lead to a slower shear strength degradation with displacement cycles

**ADDRESING SHEAR STRENGTH DECAY AT THE MATERIAL LEVEL**

Fiber reinforced concrete with tensile strain-hardening behavior (HPFRC) and compression behavior similar to well-confined concrete

**HPFRC FLEXURAL MEMBERS UNDER DISPLACEMENT REVERSALS**

- RC member with closed hoops at $d/4$; $V_c = 0$
- HPFRC member **DID NOT** contain transverse reinforcement

**HPFRC FLEXURAL MEMBERS UNDER DISPLACEMENT REVERSALS**

- RC Member (4.0% drift)
- HPFRC Member (4.0% drift)

(Chompreda and Parra, 2005)
SUMMARY & RECOMMENDATIONS

• Shear strength decay is primarily affected by:
  • Displacement demand, shear stress level, axial load
  • Transverse reinforcement detailing (amount, spacing)

  “…the use of closely spaced stirrups that are designed to carry all of the shear does not necessarily prevent shear failures…” Wight & Sozen, 1975

• Best practice to stay out of trouble is to keep shear stresses low (< 3\(\sqrt{f_c}\)) and properly confine concrete core

• For moderate shear stress levels (between 3 and 6\(\sqrt{f_c}\)), consider use of intermediate longitudinal reinforcement

\[ v_C = 3.5\sqrt{f_c} \]
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- Best practice to stay out of trouble is to keep shear stresses low (< $3\sqrt{f_{c}}$) and properly confine concrete core
- For moderate shear stress levels (between $3\sqrt{f_{c}}$ and $6\sqrt{f_{c}}$), consider use of intermediate longitudinal reinforcement
- Increase of concrete ductility through addition of fibers could provide a way out in members subjected to large shear stress levels (> $6\sqrt{f_{c}}$)