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*Advancing concrete knowledge*

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

**ACI Fall 2012 Convention**
**October 21 – 24, Toronto, ON**

ACI
WEB SESSIONS

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


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University of Michigan


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## OUTLINE

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    - 1990s and early 2000s
    - An alternative solution (2000s)
- Summary and recommendations

## 1961 – PCA Book

Shear design (beams):

- Capacity design introduced for the first time

$$V_u = \frac{{M_u}^+ + {M_u}^-}{L} + \frac{wL}{2}$$

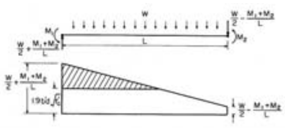


Fig. 6-1. Shear diagram for a beam at ultimate moment at both ends with the gravity load limited to the dead load plus fixed live load.

## 1961 – PCA Book

Shear design (beams):

- No decay of shear resistance recognized (no data available yet). However, peak shear stress limited to $6\sqrt{f_c'}$

$$v_n = v_c + v_s$$

$$v_c = 1.9\sqrt{f_c'}$$

$$v_s = \frac{A_v f_y}{b_w s}$$

## 1961 – PCA Book

Shear design (beams):

- No decay of shear resistance recognized (no data available yet). However, peak shear stress limited to $6\sqrt{f_c'}$
- Need for confinement reinforcement identified

Within 4*d* from support:

$$(A_v)_{min} = 0.15\rho\, b_w s$$

$s \le d/2$

Within 2*d* from support:

Closed ties with 135° hooks at
$s_{max}$ = min($d$/2, 16$\phi_b$, 12 in)

## 1963 ACI Building Code

Shear design (neglecting $\phi$ factor):

$$v_u = \frac{V_u}{b_w d} \le 10\sqrt{f_c'}$$

$$v_n = v_c + v_s$$

$$v_c = 1.9\sqrt{f_c'} + 2500\rho_w \frac{Vd}{M} \le 3.5\sqrt{f_c'}$$

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$$v_s = \frac{A_v f_y}{b_w s}$$

$s \le d/2$ for $v_u \le 6\sqrt{f_c'}$

$s \le d/4$ for $v_u > 6\sqrt{f_c'}$

$$(A_v)_{min} = 0.0015 b_w s$$

No modifications for earthquake-resistant design

## FLEXURAL MEMBERS UNDER LOAD REVERSALS

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- Evaluated effect of loading in one direction on strength and ductility when loaded in reversed direction (one cycle)

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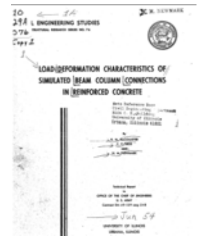
- Sufficient transverse reinforcement to prevent shear failures
- First use of $V_c$ = 0?



The spacing was either 4 or 6 in. and was chosen so that the stirrups would be capable of carrying all of the predicted maximum shear force at a unit stress not in excess of their yield point.

## 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 ($v_u \leq 3\sqrt{f_c'}$)

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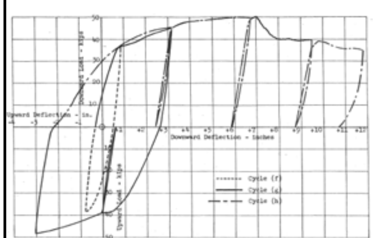
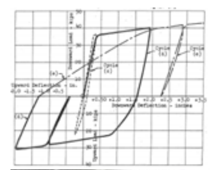
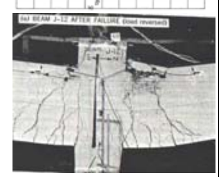


Beam J-7

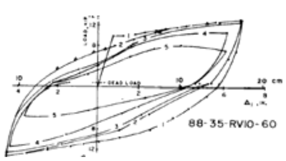




## FLEXURAL MEMBERS UNDER LOAD REVERSALS

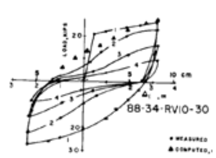
Brown & Jirsa (1970; 1971):

- Shear strength decay phenomenon explicitly recognized



$v_u \approx$ 200 psi; $v_s \approx$ 340 psi;

$a/d$ = 6; $\Delta_{max}$ = 10$\Delta_y$ ≈ 11% drift



$v_u \approx$ 400 psi; $v_s \approx$ 420 psi;

$a/d$ = 3; $\Delta_{max}$ = 10$\Delta_y$ ≈ 11% drift

## FLEXURAL MEMBERS UNDER LOAD REVERSALS

Brown & Jirsa (1970;1971):

*"…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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*"Reducing the stirrup spacing increased significantly the number of cycles to failure…"*

*"Reduction of the shear span…resulted in failure in fewer cycles."*

## FLEXURAL MEMBERS UNDER LOAD REVERSALS

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"*

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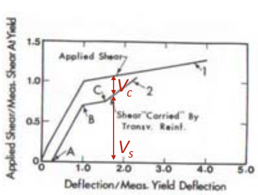


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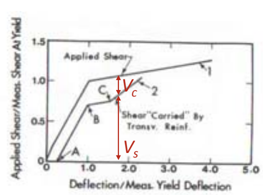


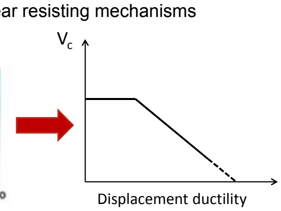

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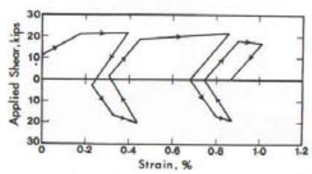
Wight & Sozen (1973; 1975):

*"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."*

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*"…spacing of the stirrups should not exceed one-fourth of the effective depth."*

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- Evaluated behavior of three RC beams under large shear reversals ($v_u \approx 6\sqrt{f_c'}$ )

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*"…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."*

## FLEXURAL MEMBERS UNDER LOAD REVERSALS

Scribner & Wight (1978; 1980):

- Evaluated effect of shear stress level and presence of intermediate longitudinal reinforcement on shear strength decay

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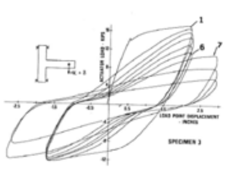
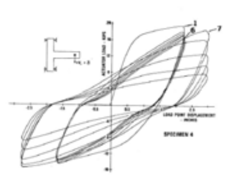
Scribner & Wight (1978; 1980):

- Intermediate reinforcement ($A_i \approx 0.25A_s$) was found most effective in members subjected to shear stresses between 3 and $6\sqrt{f_c'}$




*without intermediate bars*
$v_u = 3\sqrt{f_c'}$ ; $v_s = 3\sqrt{f_c'}$




*with intermediate bars*
$v_u = 3.5\sqrt{f_c'}$ ; $v_s = 3\sqrt{f_c'}$

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These provisions have remained unchanged, except for the maximum allowed spacing, which was modified in 2011

  - $s_{max}$ = min($d$/4; 6$(d_b)_{long}$; 24$(d_b)_{hoop}$; 6 in)

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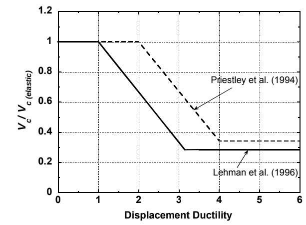
- For $3\sqrt{f_c'} \le v_u \le 6\sqrt{f_c'}$, use intermediate longitudinal reinforcement (also enhances joint behavior)
- If $v_u > 6\sqrt{f_c'}$, say **NO**

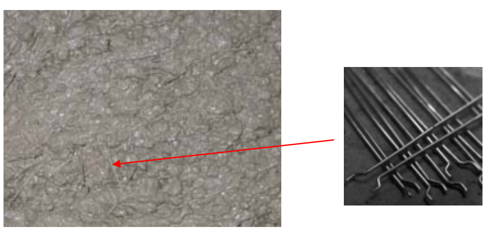
## 1990s – Early 2000s

- 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

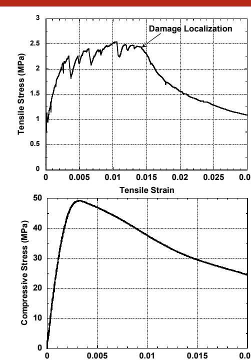


## ADDRESING SHEAR STRENGTH DECAY AT THE MATERIAL LEVEL

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

RC

HPFRC




## HPFRC FLEXURAL MEMBERS UNDER DISPLACEMENT REVERSALS

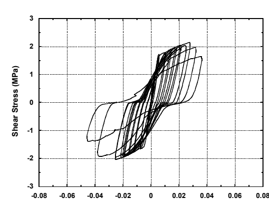
- RC member with closed hoops at $d/4$; $V_c = 0$
- HPFRC member **DID NOT** contain transverse reinforcement

RC Member (4.0% drift)

HPFRC Member (4.0% drift)

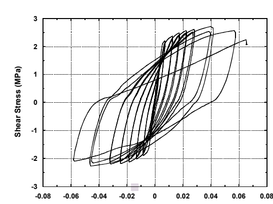
*(Chompreda and Parra, 2005)*

## HPFRC FLEXURAL MEMBERS UNDER DISPLACEMENT REVERSALS




**RC Member**

$$v_u = 4.2\sqrt{f_c'}$$




**HPFRC Member**

$$v_u = 4.9\sqrt{f_c'}$$

*(Chompreda and Parra, 2005)*

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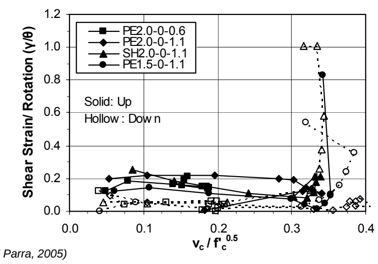


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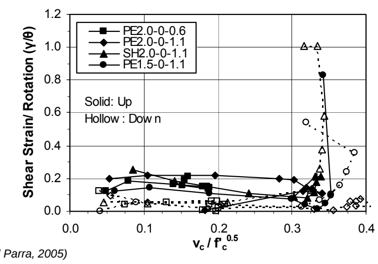


(Chompreda and Parra, 2005)

$$v_C = 3.5\sqrt{f_c{}'}$$

## SUMMARY & RECOMMENDATIONS

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- For moderate shear stress levels (between 3 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 ($> 6\sqrt{f_c'}$)

## METE SOZEN'S ASSISTANT GRADER OF EARTHQUAKE ENGINEERING HOMEWORKS