Blast Response Limits for Load-Bearing Prestressed Concrete Panels

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Presentation Overview

- Research Significance
- Shock Tube Testing
- Panel Modeling
- Response Criteria for Analysis and Design
- Conclusions

Research Significance

- Structural response limits for load-bearing prestressed concrete wall panels have not previously been studied
- PCI funded a research project to fill data gaps
  - Perform full-scale shock tube tests
  - Develop SDOF methodology
  - Develop response limits

Non-Load-Bearing Response Limits

Prestressed limits: PDC TR-06-08

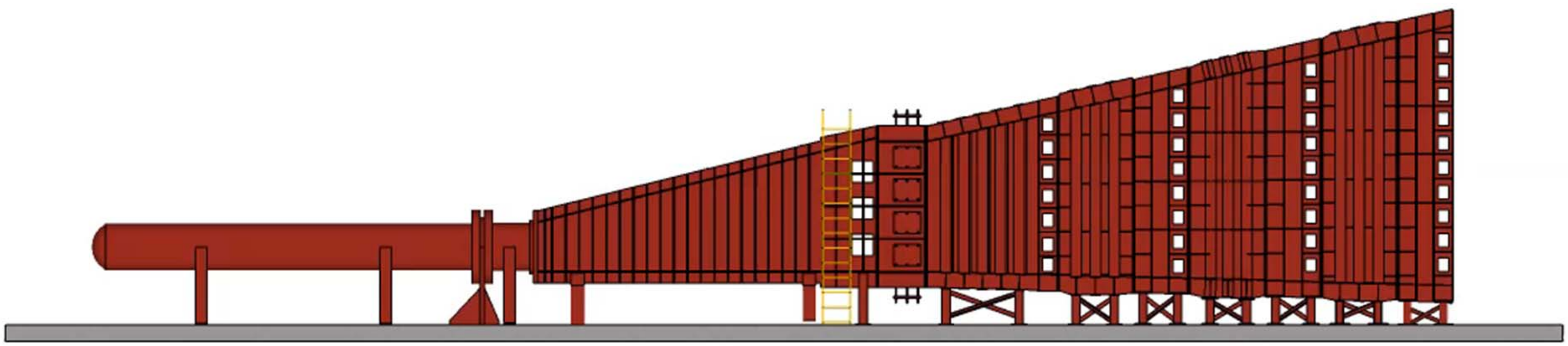
$\omega_p = \frac{A_{ps}}{bd_{ps}}\frac{f_{ps}}{f'_c}$	Superficial Damage		Moderate Damage		Heavy Damage		Hazardous Failure	
	μ	θ	μ	θ	μ	θ	μ	θ
$\omega_p > 0.30$	0.7	-	0.8	-	0.9	-	1	-
$0.15 \le \omega_p \le 0.30$ or $0.15 \le \omega_p$ and no shear reinforcing	0.8	-	$\frac{0.25}{\omega_p}$	1°	$\frac{0.29}{\omega_p}$	1.5°	$\frac{0.33}{\omega_p}$	2°
$0.15 \le \omega_p$ with shear reinforcing	1	-	-	1°	-	2°	-	3°

Reinforced Concrete limits: PDC TR-06-08

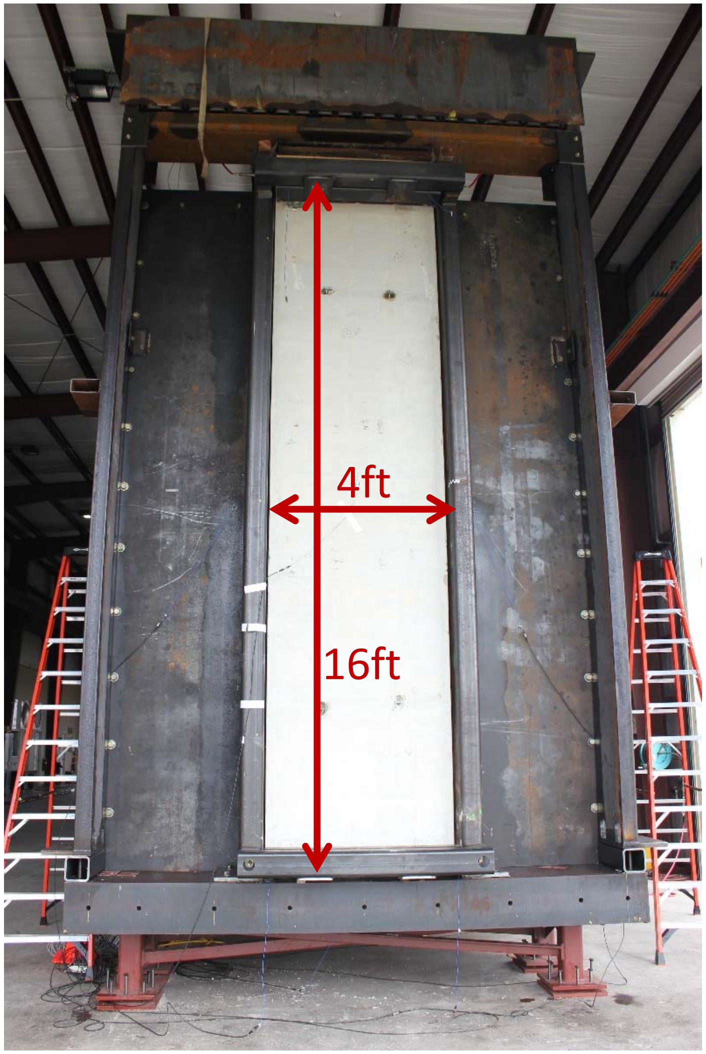
Single reinforced slab or beam	Superficial Damage		Moderate Damage		Heavy Damage		Hazardous Failure	
	μ	θ	μ	θ	μ	θ	μ	θ
Flexure	1	-		2°		5°		10°
Flexure-compression	1	-	-	2°	-	2°	-	2°

Shock Tube Testing

Shock Tube Testing



Precast Wall



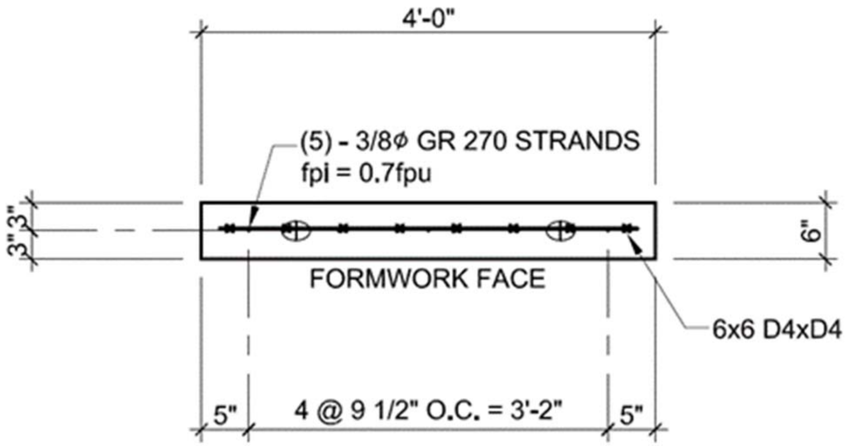
Axial Load Magnitude

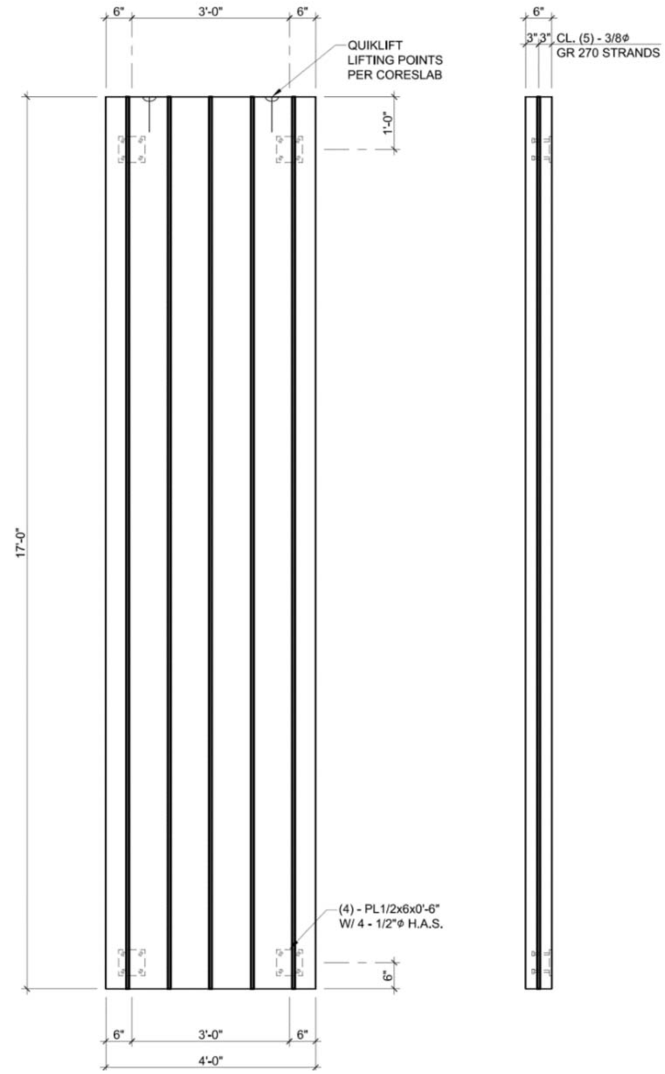
- PDC TR-06-08 does not require axial loads to be considered for concrete members until they exceed $0.2f'_{dc}A_g$
  – Unconservative threshold

- Axial load magnitude of $0.05f'_cA_g$ and $0.10f'_cA_g$ using a nominal compression strength of 5000 psi
  – Capture majority of load-bearing wall cases

Solid Prestressed Panel

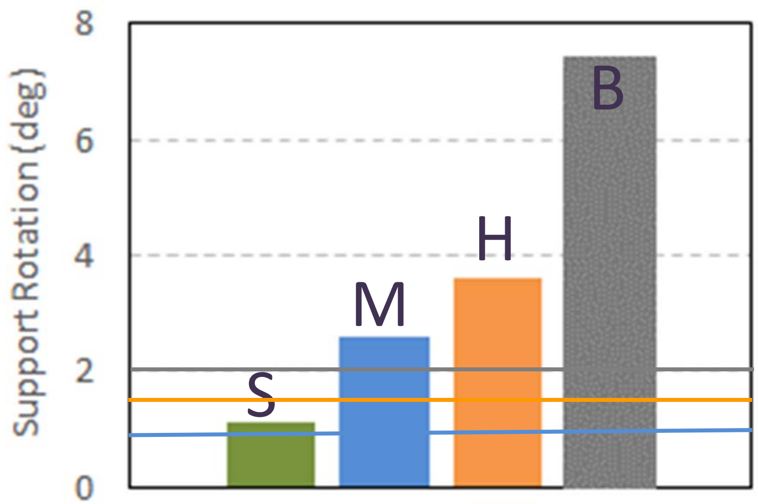
- 6-inch thick solid concrete
- Prestressed to 250 psi
- 6x6 D4xD4 WWF at mid-depth
- f'_c = 7200 psi at first test date





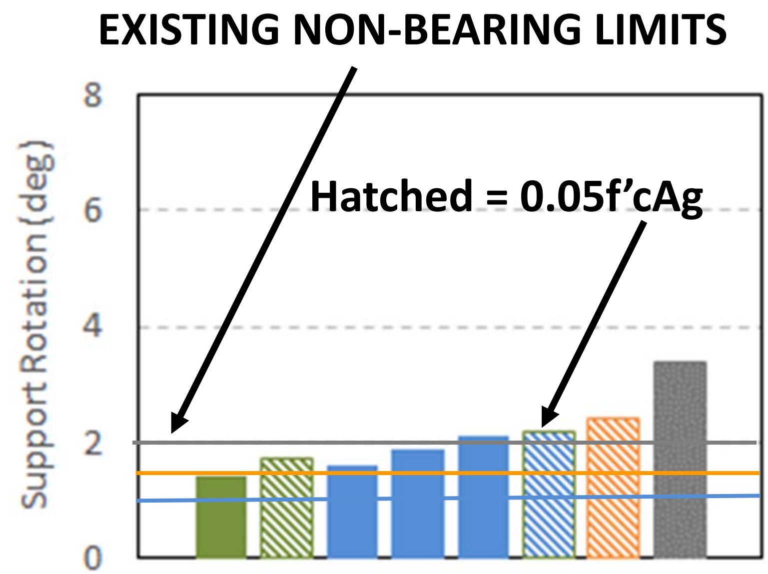
Solid Prestressed Panel

- Panels performed beyond current limits for non-load-bearing panels



Non-Load-Bearing

Test loads ranging from:
4.4 psi, 78 psi-ms to
7.2 psi, 146 psi-ms



Load-Bearing

Test loads ranging from:
5.9 psi, 105 psi-ms to
7.3 psi, 135 psi-ms

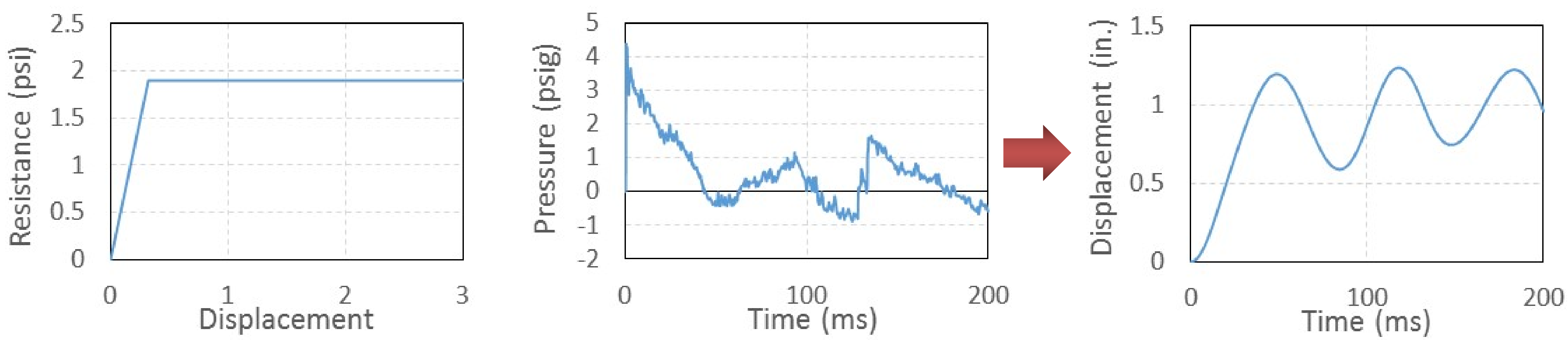
Analytical Modeling

State-of-Practice

- Blast analysis of structures are commonly done on a component basis using SDOF methods

$$K_{LM}m\ddot{x} + c\dot{x} + kx = p(t)$$

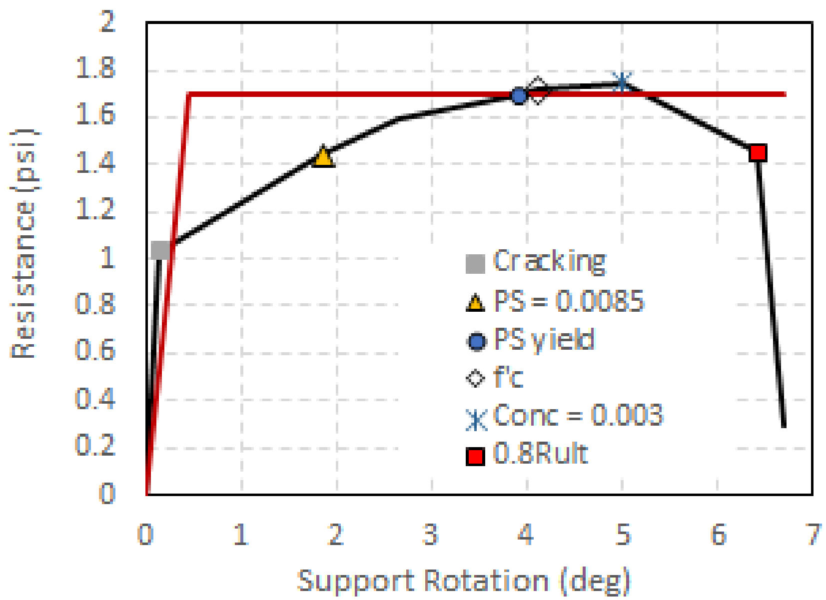
- Simplified elastic-plastic resistance functions are assumed



- Peak dynamic deflection from SDOF model is compared to published response limits to determine damage level

Analysis Approach

- Simplified elastic-plastic resistance functions provides no indication of damage from yielding or crushing throughout the response
- Moment-curvature model is used to quantify damage and correlate to qualitative criteria

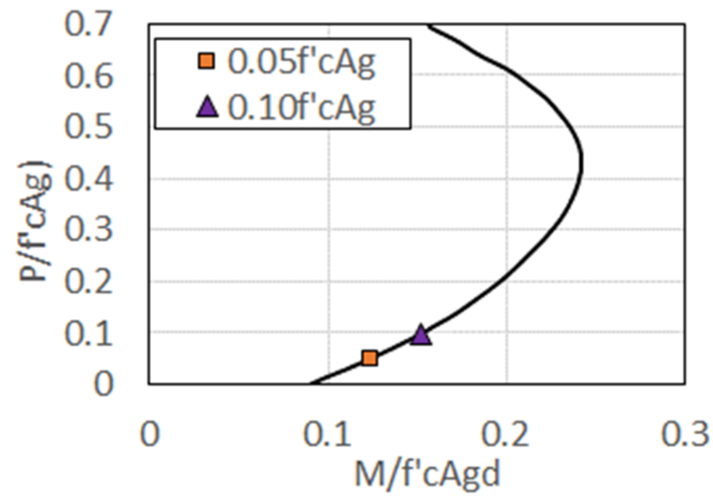


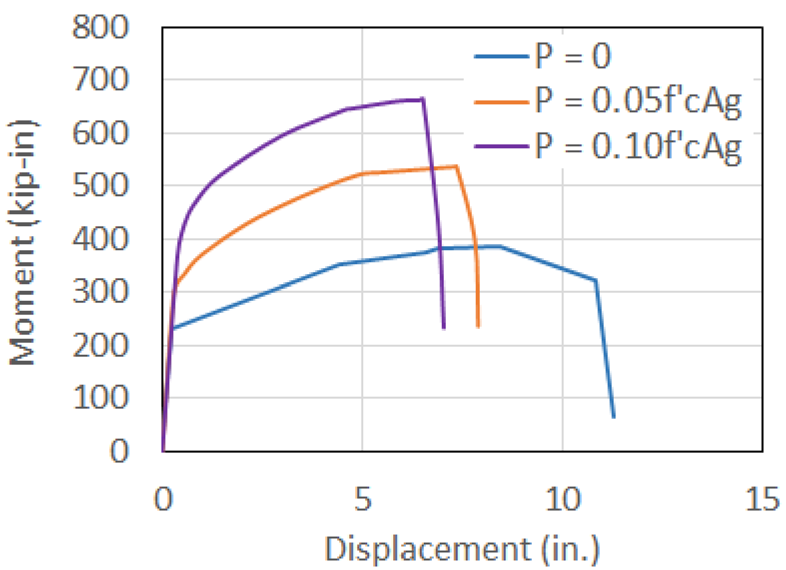
Effect of Axial Load

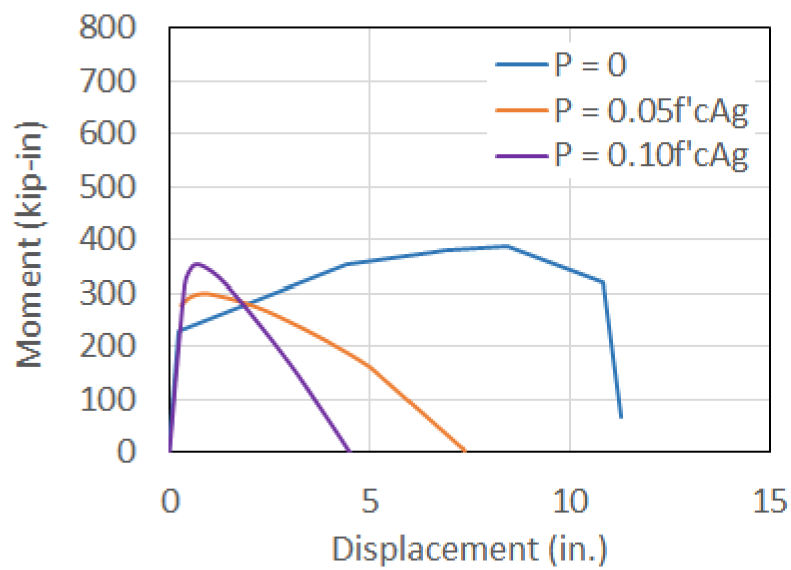
$$M_{du} = A_{ps} f_{ps}\left(d_p - \frac{a}{2}\right) + A_s f_{dy}\left(d - \frac{a}{2}\right) + \frac{P}{2}(t - a)$$

$$M_{P\Delta} = P\Delta$$

$$M_{effective} = M_{du} - M_{P\Delta}$$

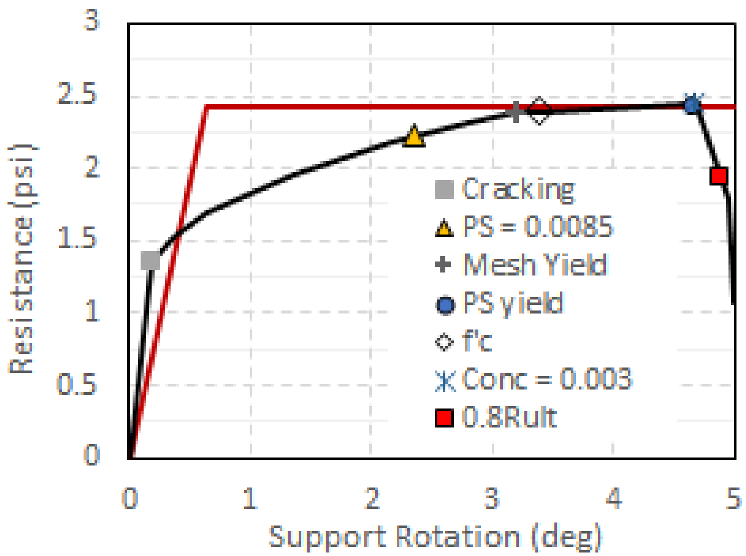




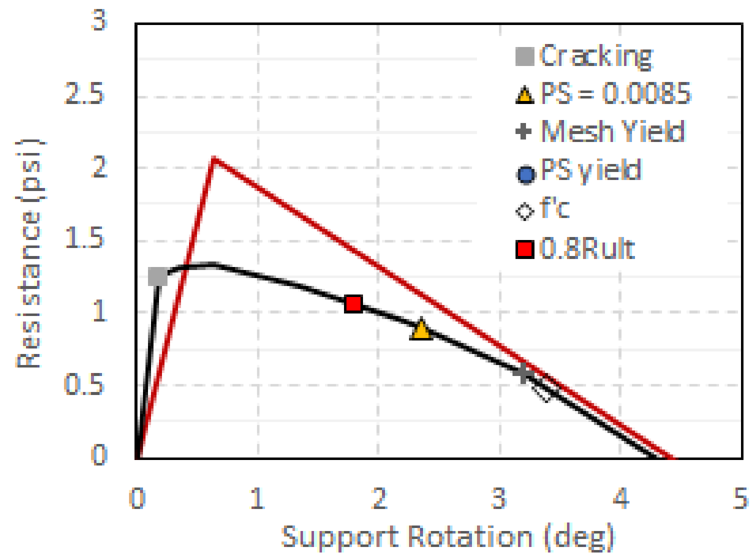


Solid Prestressed Panel: $0.05f'_cA_g$

- Axial load causes PS yielding (set as 0.011 using 2% offset strain) to occur simultaneously with concrete crushing



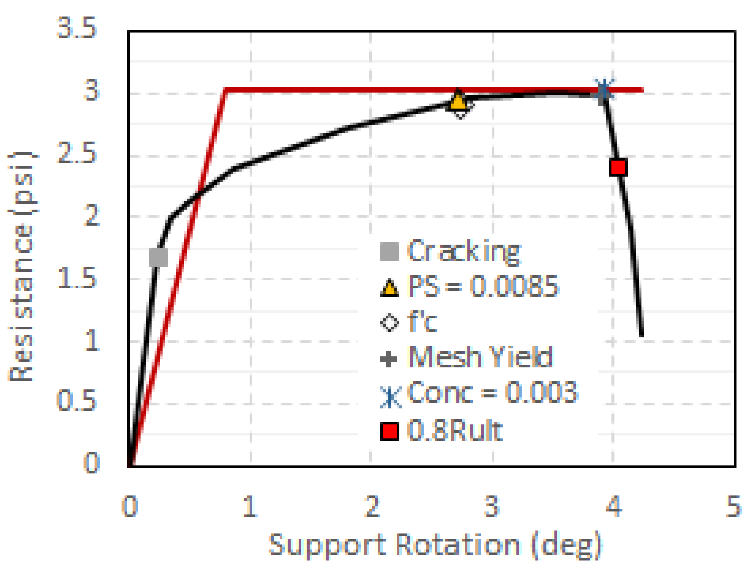
Including Axial Load Without PΔ



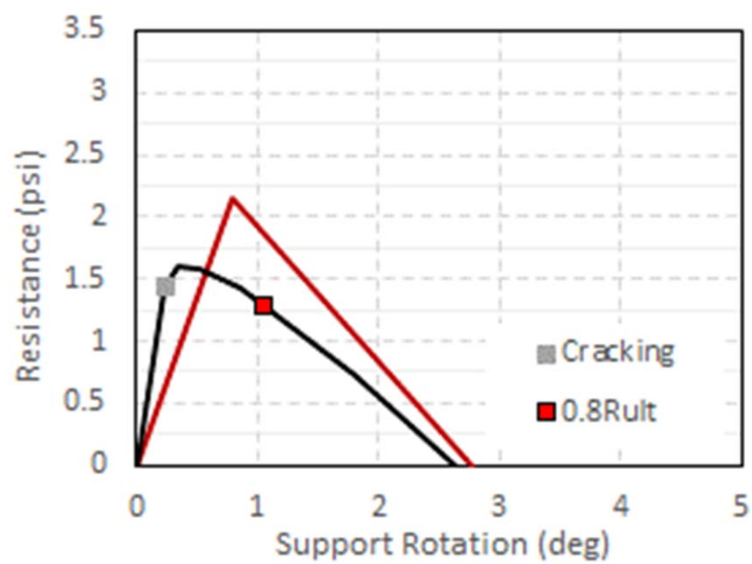
With PΔ

Solid Prestressed Panel: $0.10f'_cA_g$

- Axial load causes PS proportional limit (0.0085) to occur simultaneously with concrete at peak stress

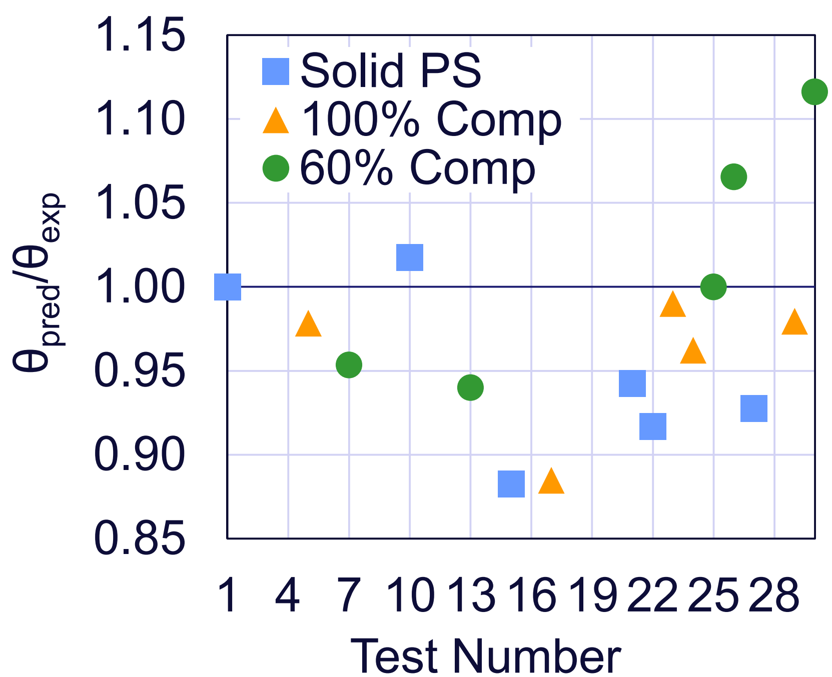


Including Axial Load Without PΔ

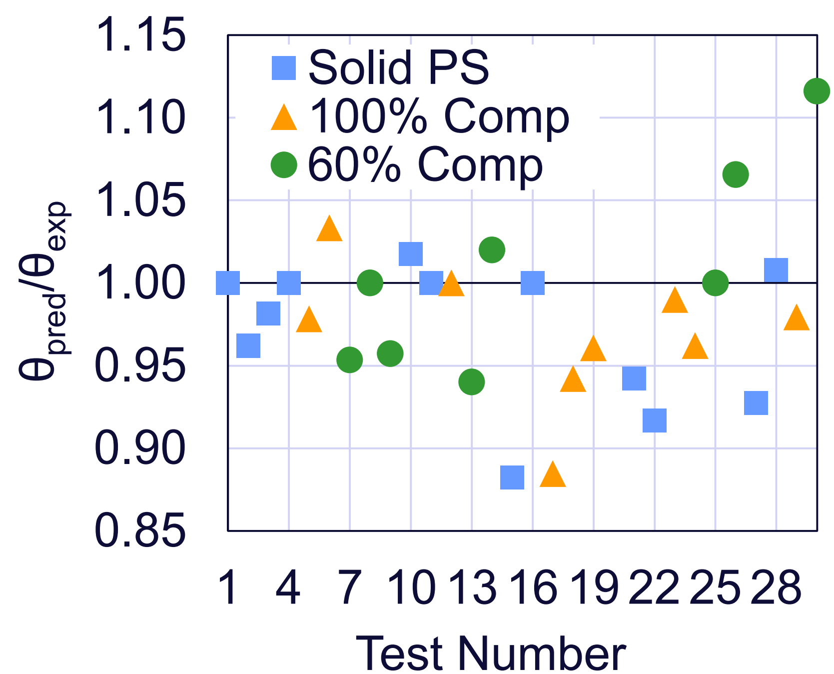


With PΔ

SDOF Predictions vs. Measured



UNDAMAGED SPECIMENS



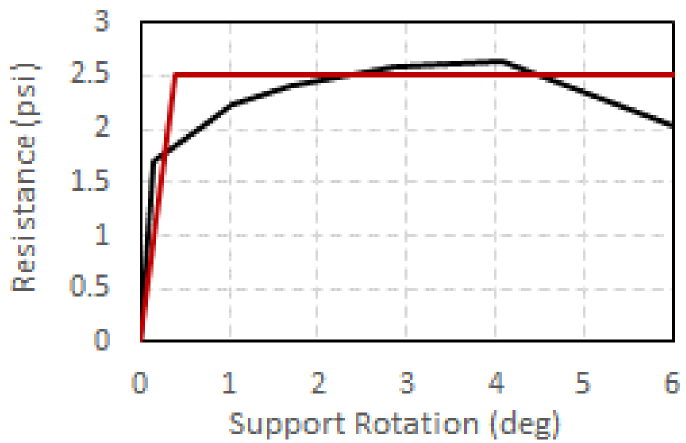
ALL TESTS (INCLUDING RE-TESTS)

Response Criteria for SDOF Analysis and Design

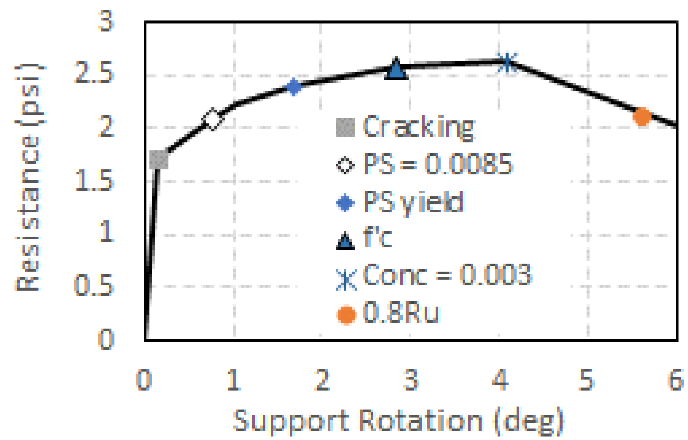
Parametric Study

- Moment-curvature model provided good agreement with test results
- Analyze different sections to determine damage thresholds for blast design
  - ω_{ps} = 0.15 to 0.25 (225 psi to 400 psi)
  - Span-to-depth (L/d) = 48 to 64

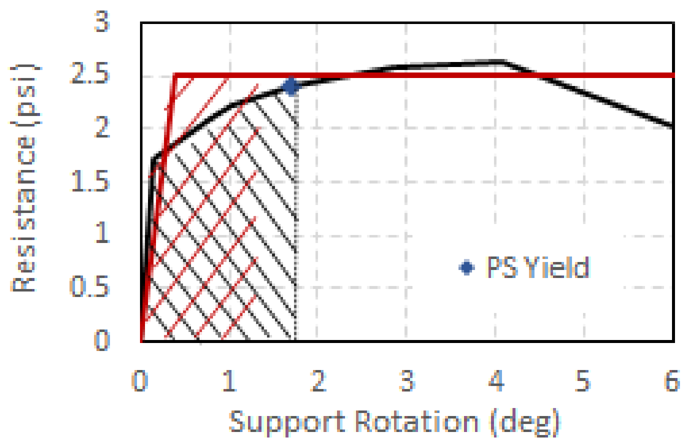
Parametric Study



(a) Compare M-Ø and EP Resistance Functions



(b) Determine M-Ø Damage Thresholds



(c) Calculate Equivalent Strain Energy

$$U_{M-\emptyset} = \int_{0}^{\theta_{limit}} R(\theta)\,d\theta$$

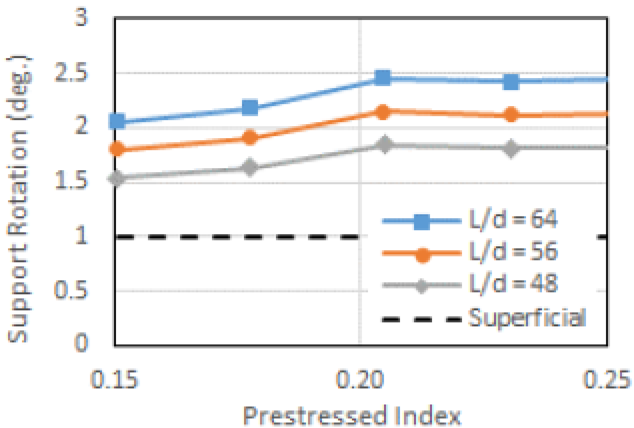
$$\theta_{equiv} = \frac{U_{M-\emptyset}}{R_u} + \frac{\theta_y}{2}$$

(d) Convert Calculated Support Rotation to EP

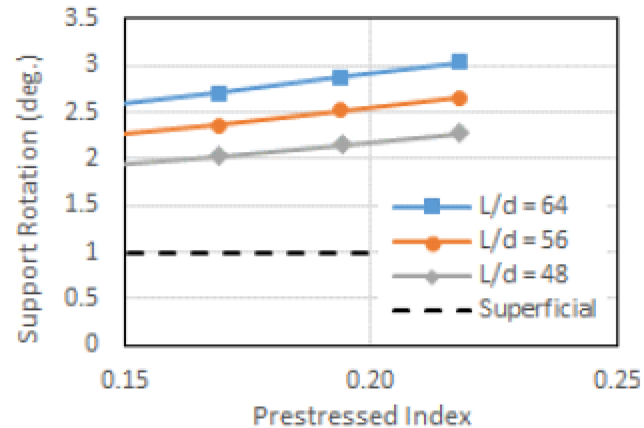
Damage Limit States

Component Damage	PDC TR-06-08 Component Consequence	BakerRisk Selected Threshold
Superficial	Component has no visible damage	Prestressing below proportional limit of 0.0085. Strains below this level will cause near elastic response, with cracks closing after event. Permanent displacement not visible.
Moderate	Component has some permanent deflection. It is generally repairable, if necessary, although replacement may be more economical and aesthetic	The smaller of prestressing at yield threshold of 0.011, which will cause permanent displacement, or concrete reaching its peak stress, f'_c. Load-bearing panels with permanent displacement less than $L/360$.
Heavy	Component has not failed, but it has significant permanent deflections, causing it to be irreparable.	Concrete reaching a strain of 0.003, associated with concrete crushing. Load-bearing panels resistance dropping to $0.8R_u$.
Hazardous	Component has failed, and debris velocities range from insignificant to very significant.	Resistance dropping to $0.8R_u$, classified as failure point

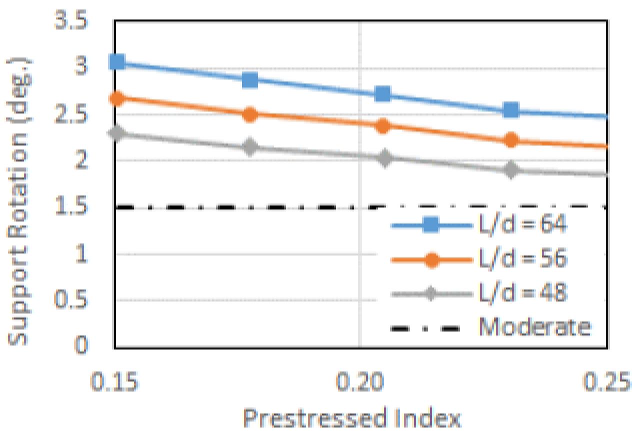
Prestressed LB Panels



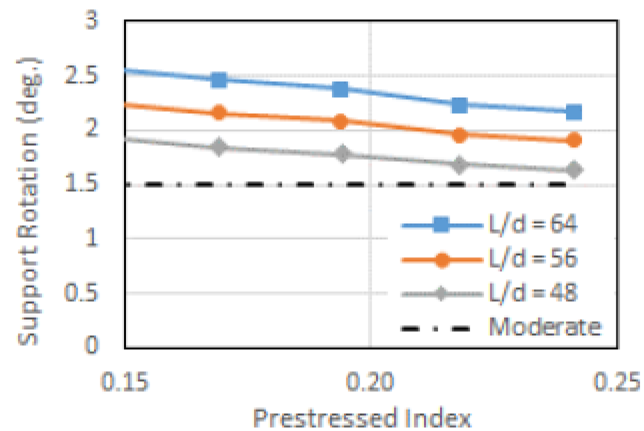
Prestressing Prop. Limit (Axial Load 0.05f'$_c$A$_g$)



Prestressing Prop. Limit (Axial Load 0.10f'$_c$A$_g$)

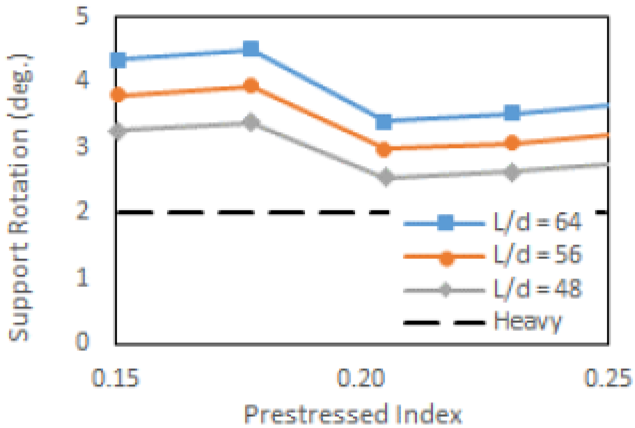


Peak Concrete Stress (Axial Load 0.05f'$_c$A$_g$)

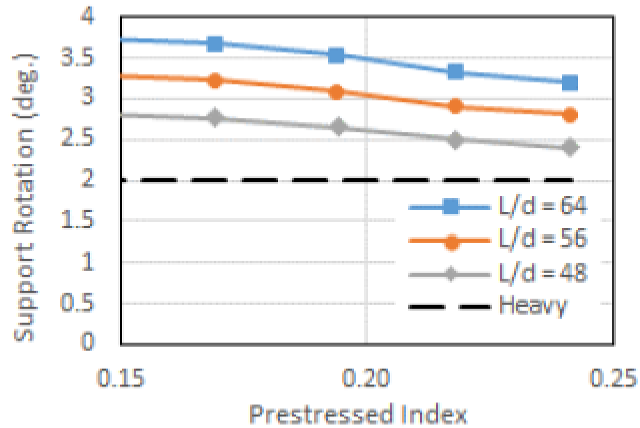


Peak Concrete Stress (Axial Load 0.10f'$_c$A$_g$)

Prestressed LB Panels



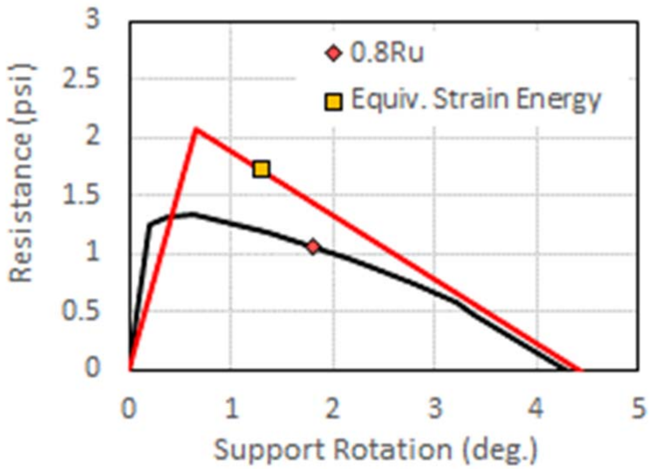
Concrete at 0.003 Strain (Axial Load 0.05f'$_c$A$_g$)



Concrete at 0.003 Strain (Axial Load 0.10f'$_c$A$_g$)

Ductility Limit

- Ductility limit imposed to handle P-delta effects
- Based on resistance function dropping to 80% of ultimate resistance, and calculating equivalent elastic-plastic strain



$$\mu = \frac{\Delta_{max}}{\Delta_y}$$

$$\mu_H = \frac{0.3\boldsymbol{M_{du}}}{\boldsymbol{P_{max}}\Delta_y} + \frac{20}{(\boldsymbol{L}/\boldsymbol{d})}$$

Solid Prestressed Panel Criteria

PROPOSED CRITERIA

Wall Type	Superficial		Moderate		Heavy		Hazardous	
	μ	θ	μ	θ	μ	θ	μ	θ
Load-Bearing	1	1°	μ_H	1.5°	μ_H	2°	μ_H	2°

EXISTING PDC TR-06-08 NLB CRITERIA

	Superficial		Moderate		Heavy		Hazardous	
	μ	θ	μ	θ	μ	θ	μ	θ
$0.15 \le \omega_p \le 0.30$ or $0.15 \le \omega_p$ and no shear reinforcing	0.8	-	$\frac{0.25}{\omega_p}$	1°	$\frac{0.29}{\omega_p}$	1.5°	$\frac{0.33}{\omega_p}$	2°

Conclusions

- Panels tested achieved peak support rotations in excess of published limits for NLB panels
- A moment-curvature model effectively predicted the panels response and was used for deducing panel damage limits with varying prestressing and span-to-depth ratios
- Response limits for design were developed, which can be used with elastic-plastic resistance functions

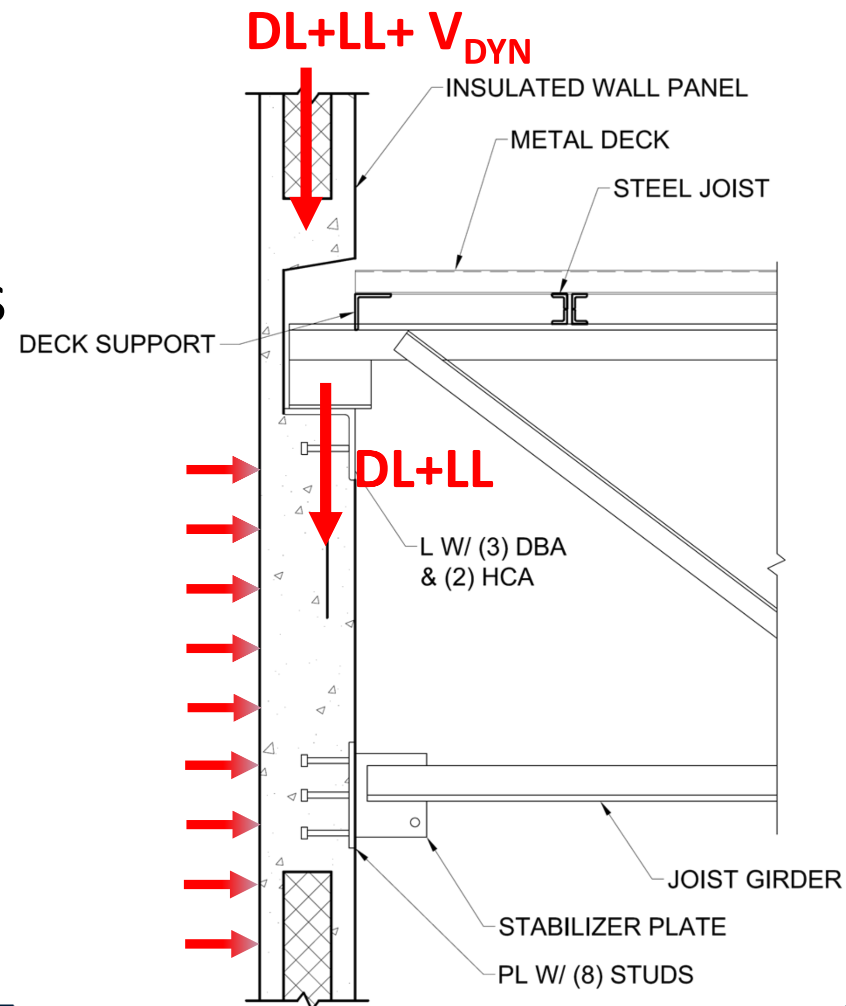
Acknowledgements

- PCI advisory committee: Roger Becker, Greg Force, Suzanne Aultman, Phil Benshoof, Steven Brock, James Davidson, John Geringer, John Hoemann, Clay Naito and Pat O'Brien

- Coreslab Structures (Texas) Inc. and Tindall Corporation (Texas) for fabricating and supplying the prestressed wall specimens

Axial Load Application

- Static axial load applied concentrically on panels
  - Conservatively represents dead and live loads and dynamic roof reactions
  - Interior eccentricity counteracts direction of blast load – benefits response



Axial Load Measurements

- Example axial force measurement (Test 13) on wall that did not fail