Unified Performance-Based Blast-Resistant Design Methodology for Precast Concrete Insulated Wall Panels

Matthew J. Gombeda
Clay J. Naito
Spencer E. Quiel

ATLSS Engineering Center
Lehigh University
Bethlehem, Pennsylvania

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Presentation **overview**

+ Background on approach for solid wall panels

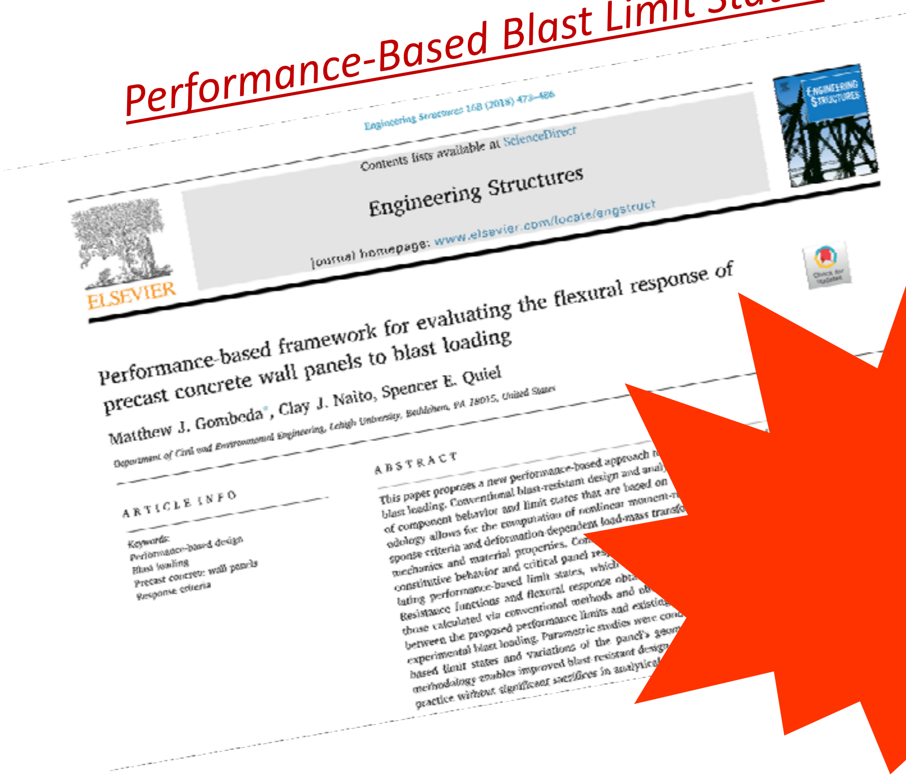
+ Background on IWP analysis method

+ Overview of proposed unified methodology
  → Synthesis of the two previous approaches

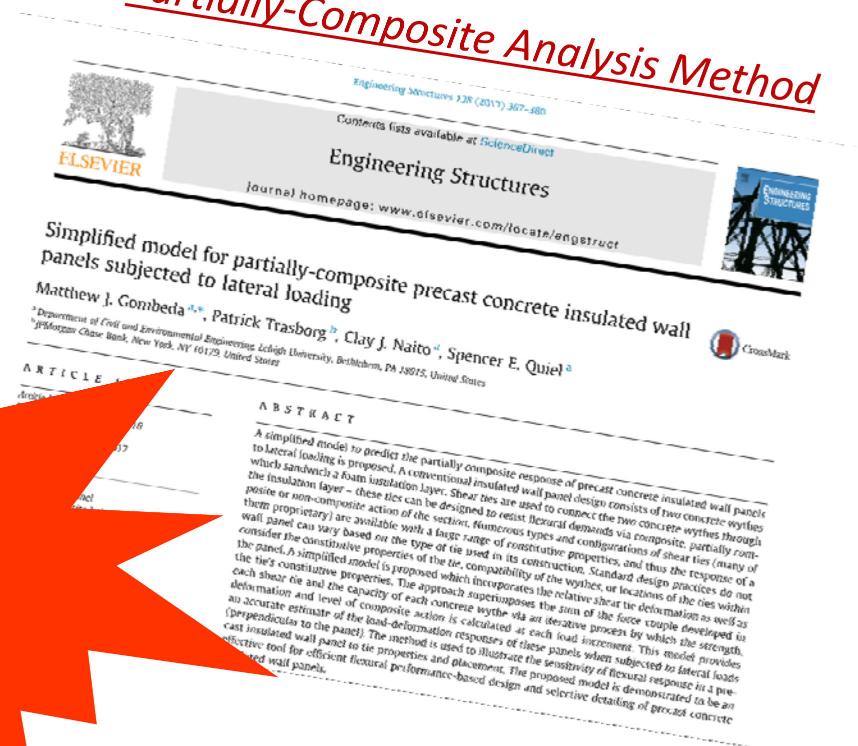
+ Comparison of results using proposed methodology with conventional blast design approach

+ Ongoing/upcoming work

Performance-Based Blast Limit States

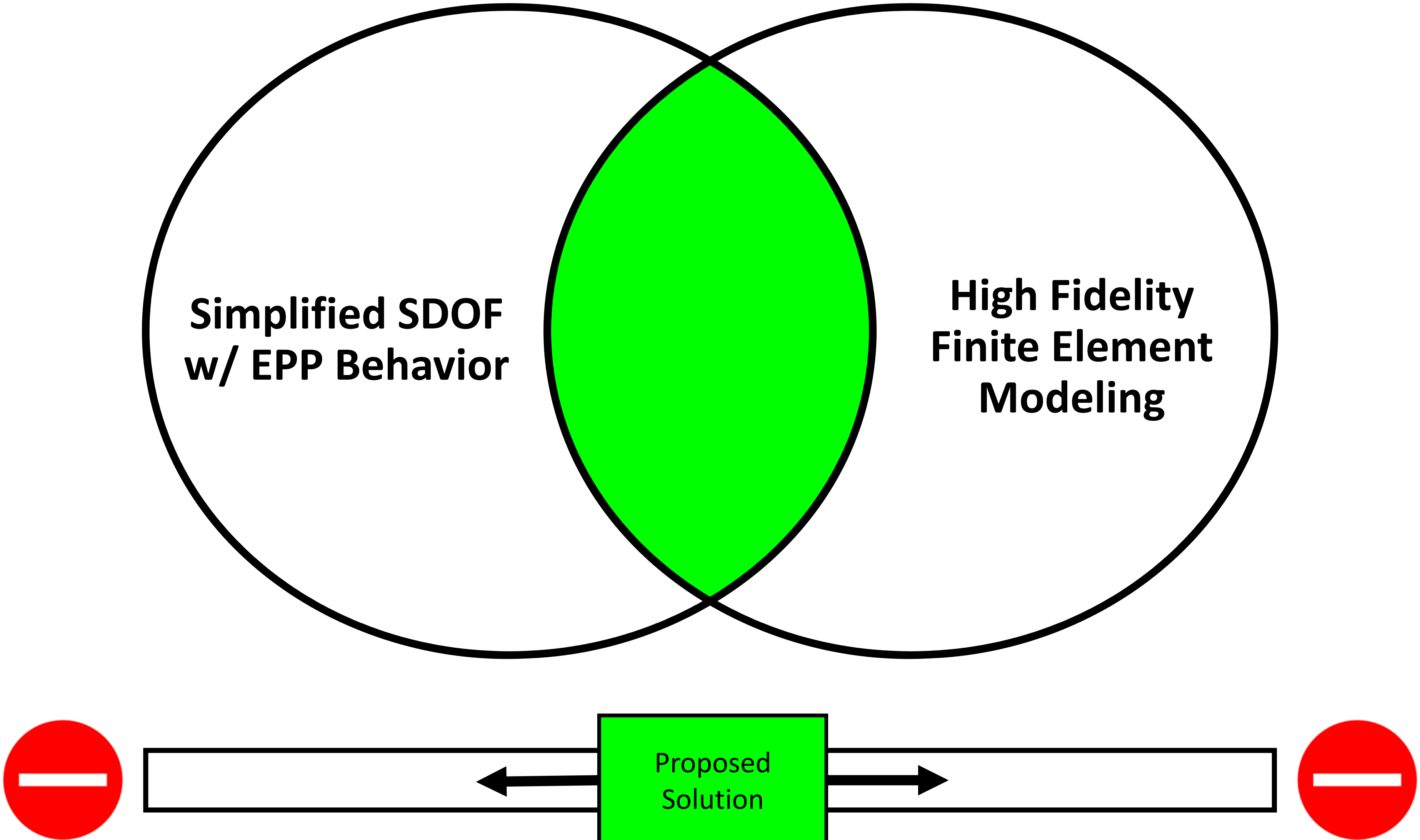


Partially-Composite Analysis Method



Background

Performance-Based Blast Design Methodology for Solid Wall Panels


Simplified SDOF w/ EPP Behavior
High Fidelity Finite Element Modeling
Proposed Solution

Current **antiterrorism** standards: (PDC TR-06-08)

Table 4-1 Response Limits for Reinforced Concrete

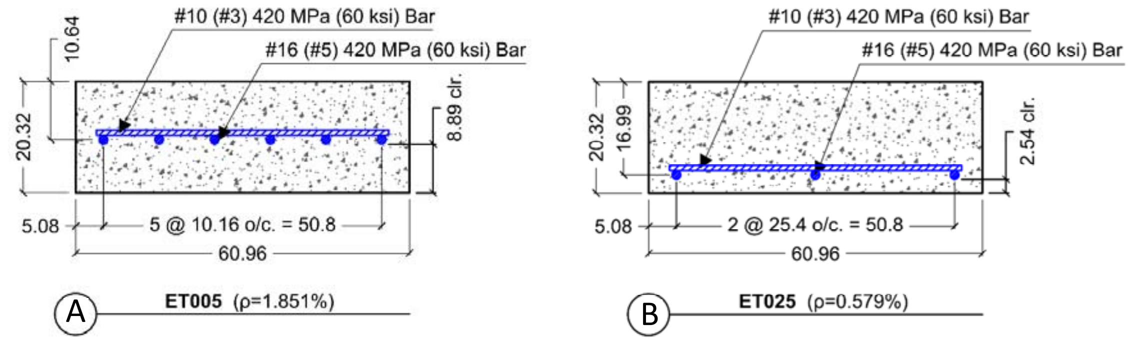
Member		B1		B2		B3		B4	
		μ	θ	μ	θ	μ	θ	μ	θ
Flexure	No shear reinforcing/ without tension membrane	1	-	-	2°	-	5°	-	10°
	With compression face steel reinforcement and shear reinforcing/without tension membrane [2]	1	-	-	4°	-	6°	-	10°
	With tension membrane (L/h>=5) [3, 4]	1	-	-	6°	-	12°	-	20°
Combined Flexure & Compression [5]	No shear reinforcing/ without tension membrane	1	-	-	2°	-	2°	-	2°
	With compression face steel reinforcement and shear reinforcing/without tension membrane [2]	1	-	-	4°	-	4°	-	4°
Compression [5, 6]	Walls & Seismic Columns	0.9	-	1	-	2	-	3	-
	Non-Seismic Columns	0.7	-	0.8	-	0.9	-	1	-
Tension or Combined Flexure & Tension		No response limits in this report, see SBEDS Methodology Manual							

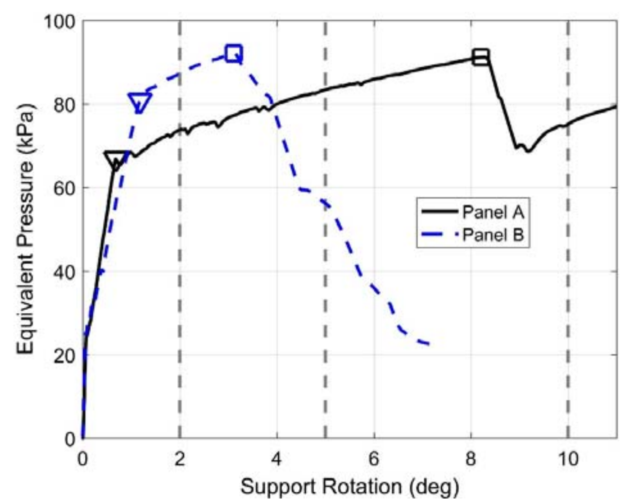
PDC-TR 06-08 Rev 1. Single Degree of Freedom Structural Response Limits for Antiterrorism Design

<u>The Issue</u>: Lack of **direct correlation** between material limit states and the response limits or damage states

+ Two reinforced concrete panels with **different reinforcement ratios** will reach yield and nominal strength at **different deformation levels**.

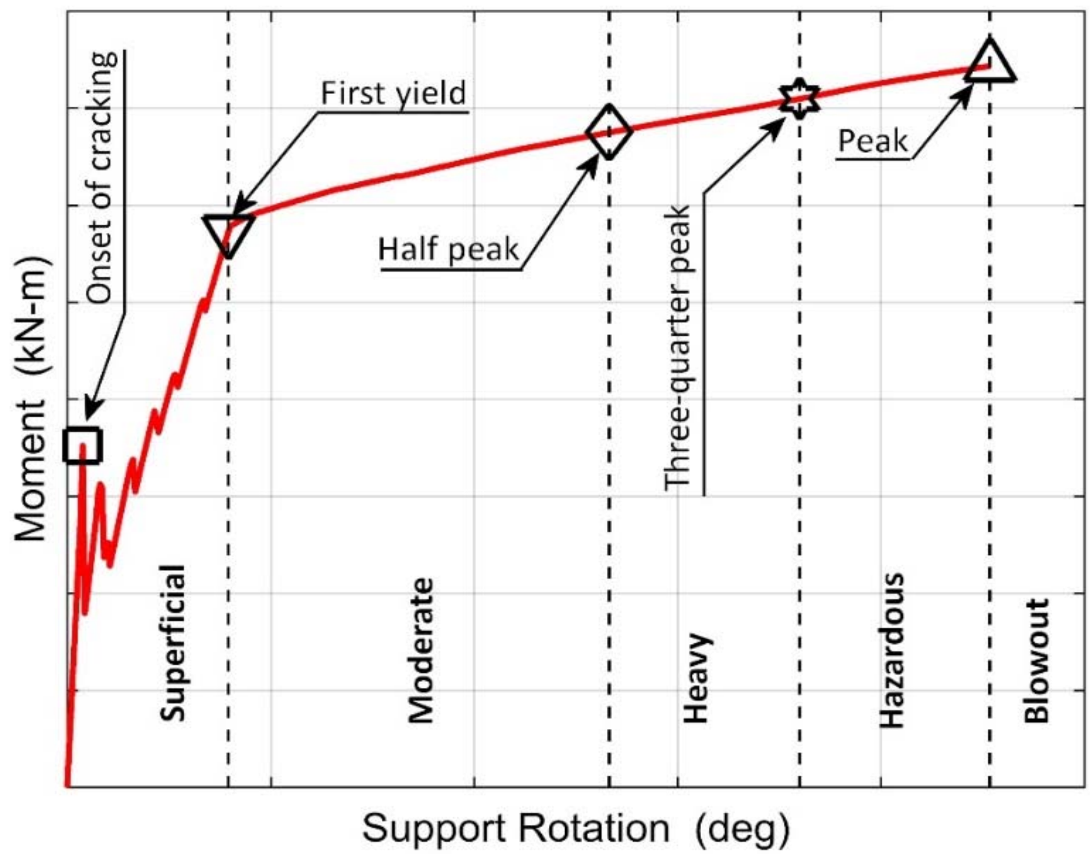
+ However, both panel designs would currently fall **within the same set of response criteria** in most of the current blast resistant design specifications.



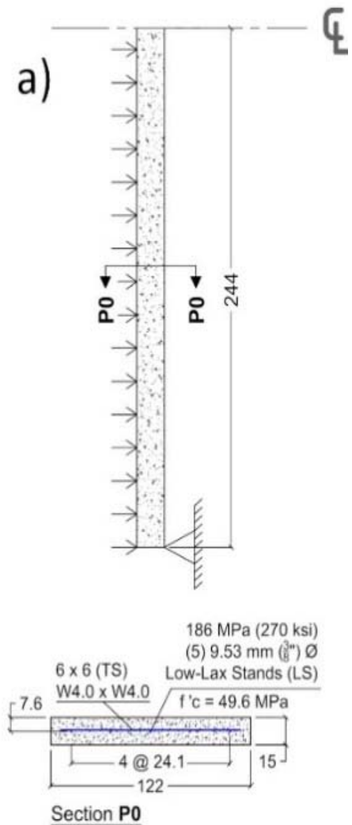


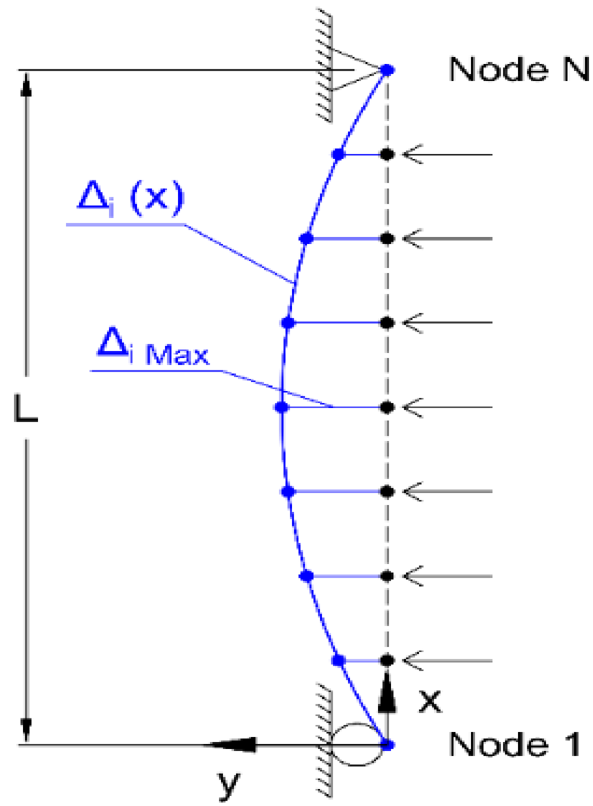
<u>Proposed Solution</u>: **Backbone response curve**
(generalized resistance function)

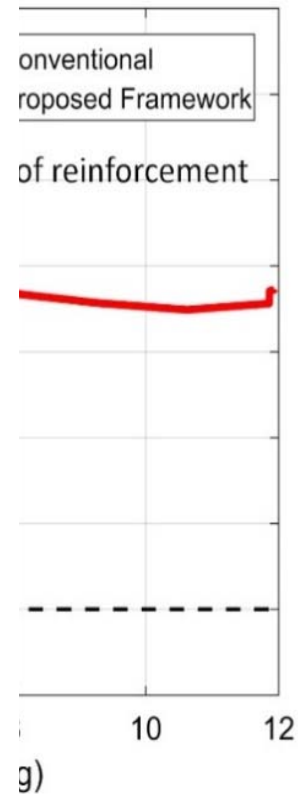
Updated **damage descriptions** & **limit states** were influenced by **current antiterrorism standards** and **ASCE 41**.



Deformation-dependent load-mass transformation factors (**KLM**)

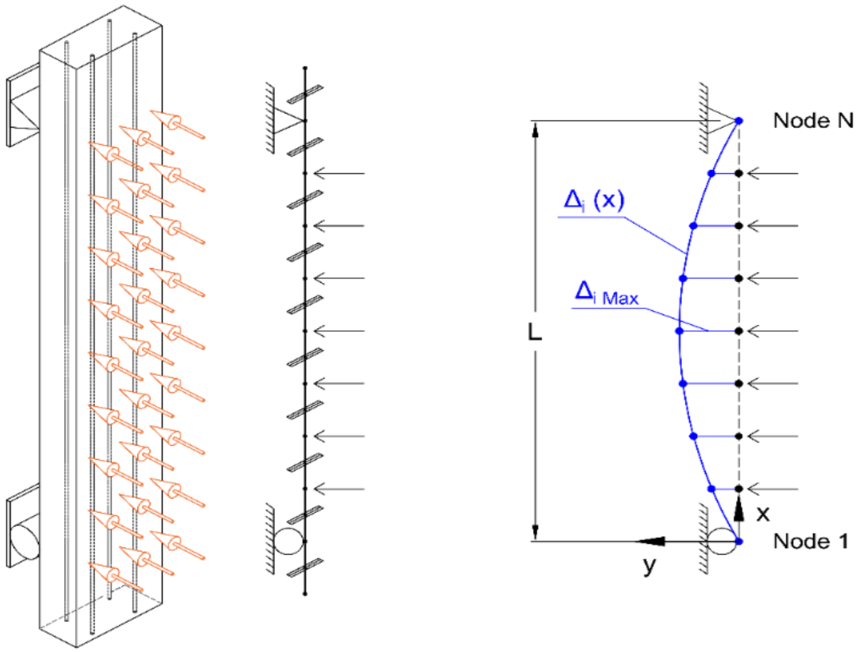




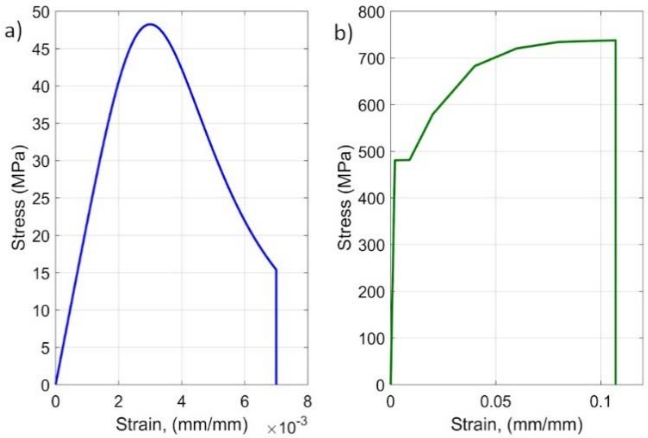


A **computational modeling framework** was used to calculate the response of the panel.

OpenSees

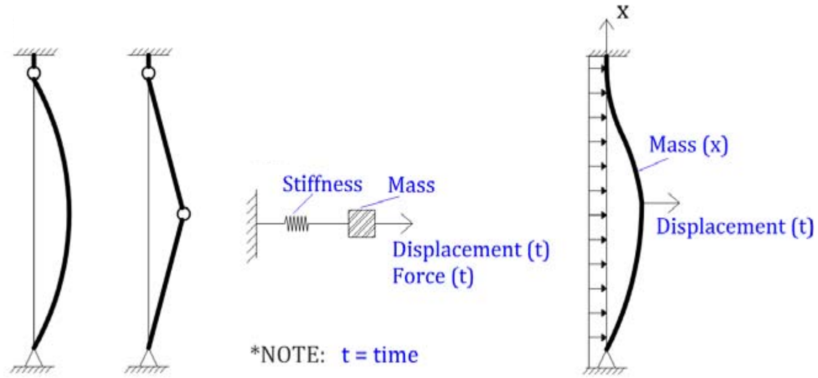


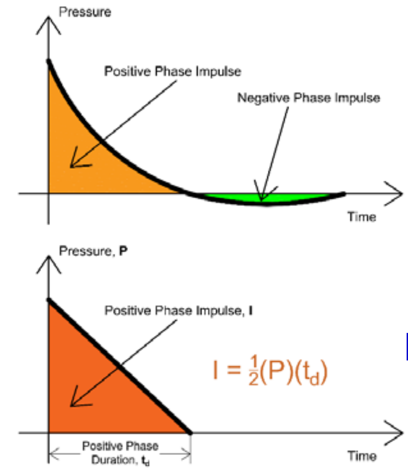
General model architecture



Example material properties

Updated generalized SDOF **equation of motion…**





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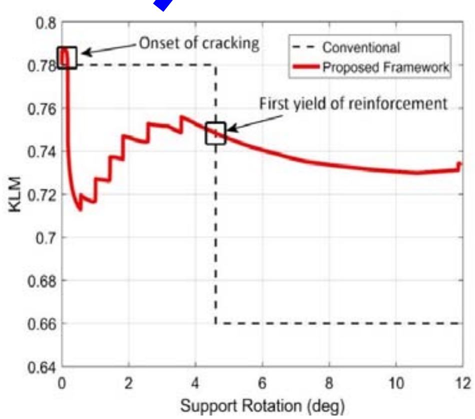
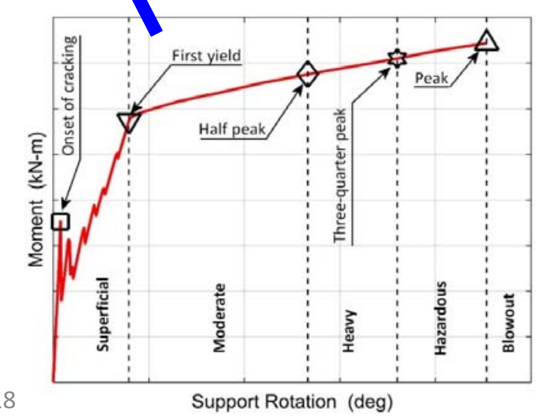
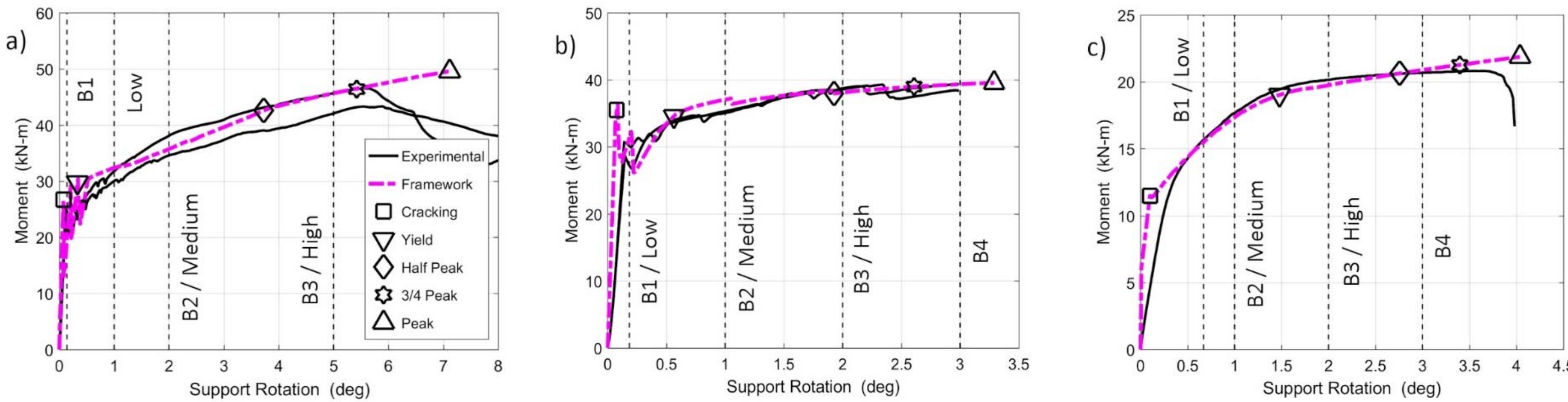
$$KLM\big(y(t)\big)m\ddot{y}(t) + c\dot{y}(t) + R\big(y(t)\big) = F(t)$$





Resistance functions vs. experimental semi-static test data



Comparison of results with experimental blast test data (and SDOF)

Specimen ID	R (m)	Eq. Mass TNT (kg)	Z (m/kg^1/3)	P_r (kPa)	I_r (kPa-ms)	Δ_M (mm)	Visual Damage	Δ_F (mm)	% Error Framework	Framework Damage	Δ_{SDOF} (mm)	% Error SDOF	SDOF Damage
P0-1 [1]	N/A	N/A	N/A	23.4	506.8	45.7	Superficial	38.7	-15.32	Superficial	38.9	-14.88	Superficial
P4-1 [2]	8.8	53.0	5.66	450	830	45	Moderate	46.9	4.22	Moderate	70.3	56.22	Heavy
P4-2 [2]	5.4	55.0	3.43	1930	1544	116	Heavy	123.7	6.64	Heavy	238.1	105.26	Blowout
P5-1 [2]	3.0	48.1	0.82	8620	2623	98	Heavy	90.8	-7.35	Heavy	392.7	300.71	Blowout
P5-2 [2]	3.0	48.1	0.82	8620	2623	92	Heavy	90.8	-1.30	Heavy	392.7	326.85	Blowout
P5-3 [2]	3.0	48.1	0.82	8620	2623	96	Heavy	90.8	-5.42	Heavy	392.7	309.06	Blowout
P5-4 [2]	5.4	52.8	3.48	1865	1496	53	Moderate	44.0	-16.98	Moderate	130.7	146.60	Hazardous
P5-5 [2]	4.0	48.0	1.10	3802	1798	55	Moderate	55.0	0.00	Moderate	183.3	233.27	Hazardous
P5-6 [2]	3.0	48.2	0.82	8620	2625	79	Heavy	90.9	15.06	Heavy	392.7	397.09	Blowout
P5-7 [2]	3.0	48.3	0.82	8620	2627	77	Heavy	91.1	18.31	Heavy	394.2	411.95	Blowout
P5-8 [2]	3.0	48.1	0.82	8620	2623	78	Heavy	90.8	16.41	Heavy	392.7	403.46	Blowout
P5-9 [2]	3.0	48.2	0.82	8620	2625	95	Heavy	90.9	-4.32	Heavy	392.7	313.37	Blowout
P6-1 [3]	48.8	394.6	6.65	55.2	439.9	54.4	Superficial	49.2	-9.56	Superficial	144.0	164.71	Moderate

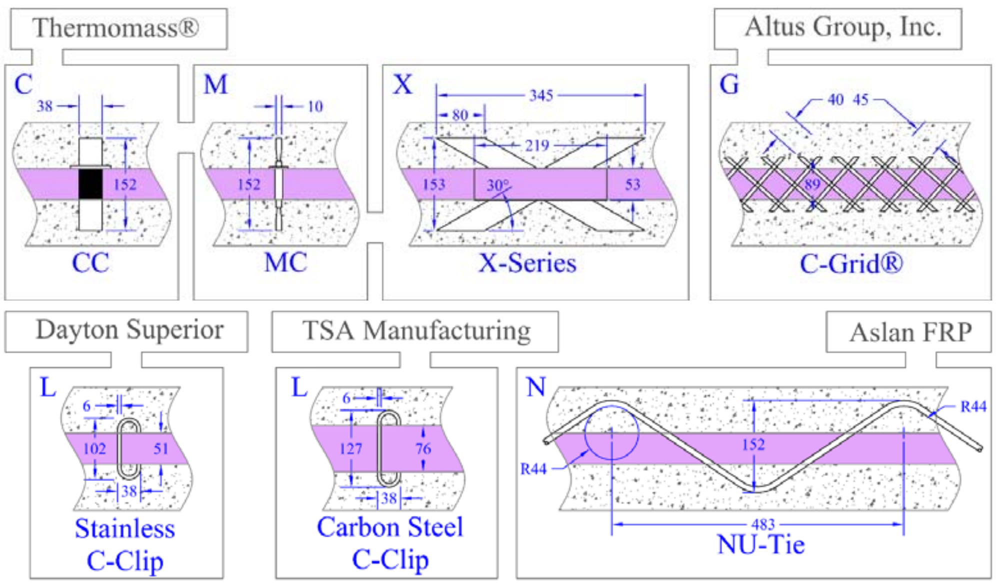
[1] Mander TJ, Bingham BL, Lowak MJ, Polcyn MA. Development of a Simplified Blast Design Procedure and Response Limits for Load-Bearing Precast Wall Panels Subject to Blast Loads. Precast/Prestressed Concrete Institute (PCI); 2016.
[2] Forsen R. Airblast Loading of Wall Panels FOA Report C 20586-06. Stockholm, Sweden: National Defense Research Institute; 1985.
[3] Cramsey N, Naito C. Analytical assessment of blast resistance of precast , prestressed concrete components. PCI J 2007:67–84.

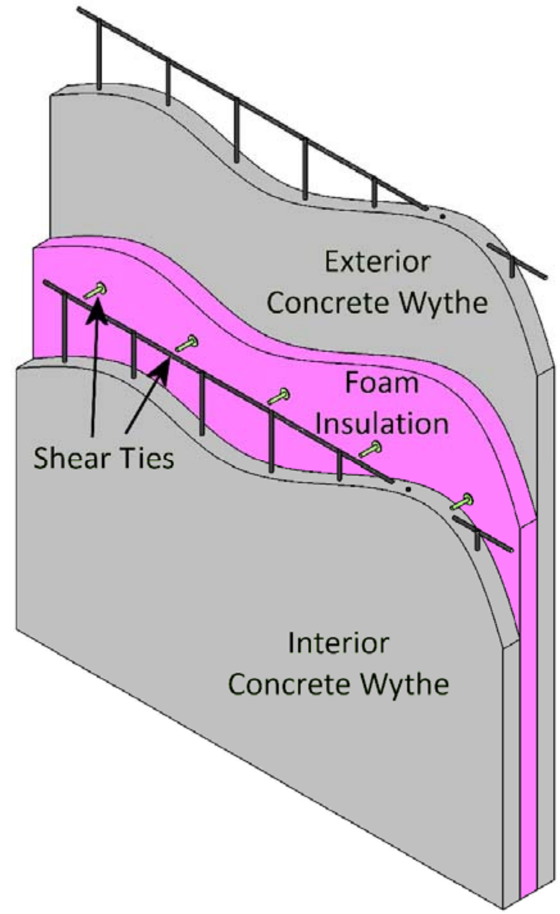
Background

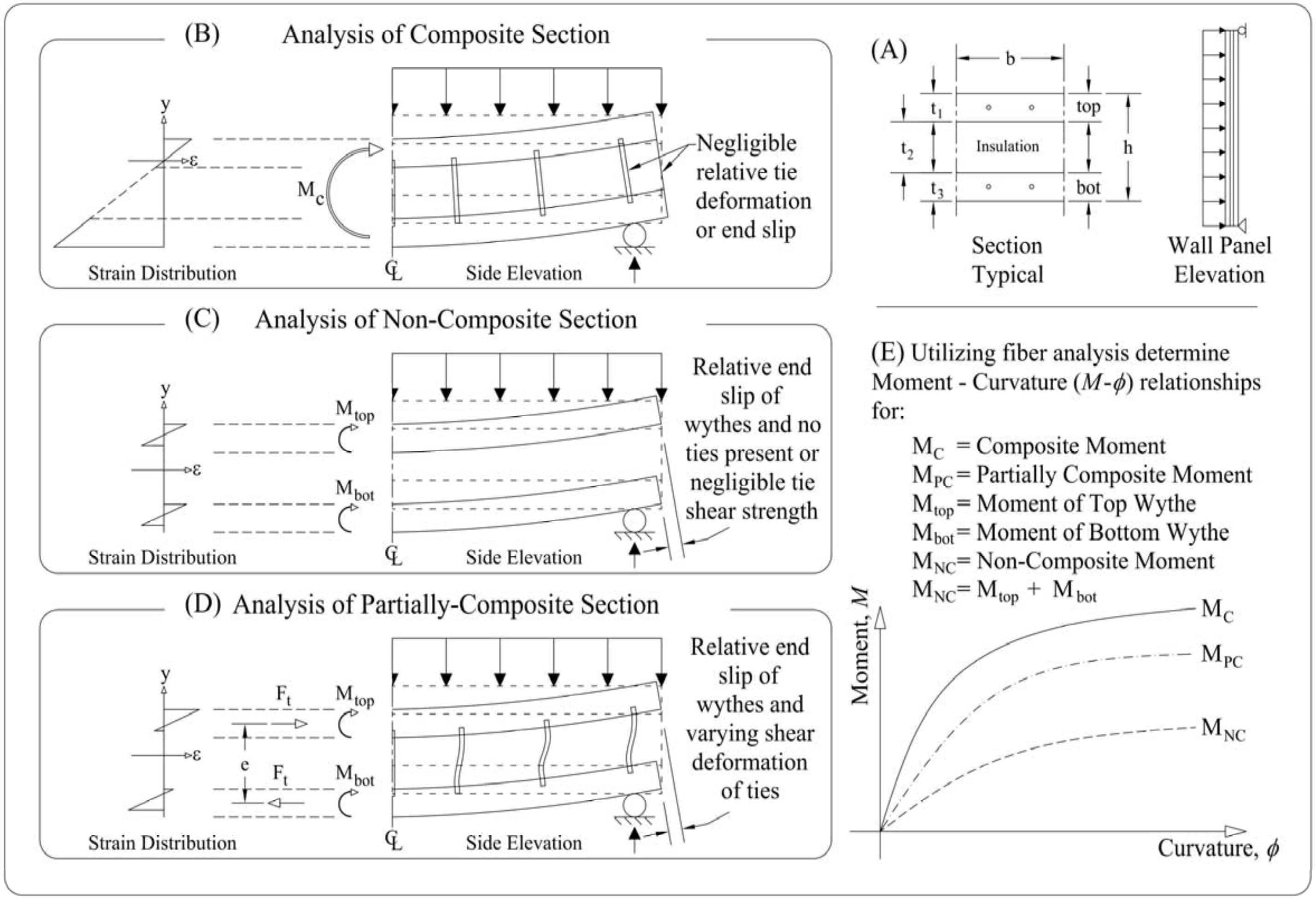
Partially-Composite Analysis of Insulated Wall Panels (IWP)

Precast concrete **insulated wall panels** (**IWP**) have grown in popularity due to **enhanced thermal properties**.

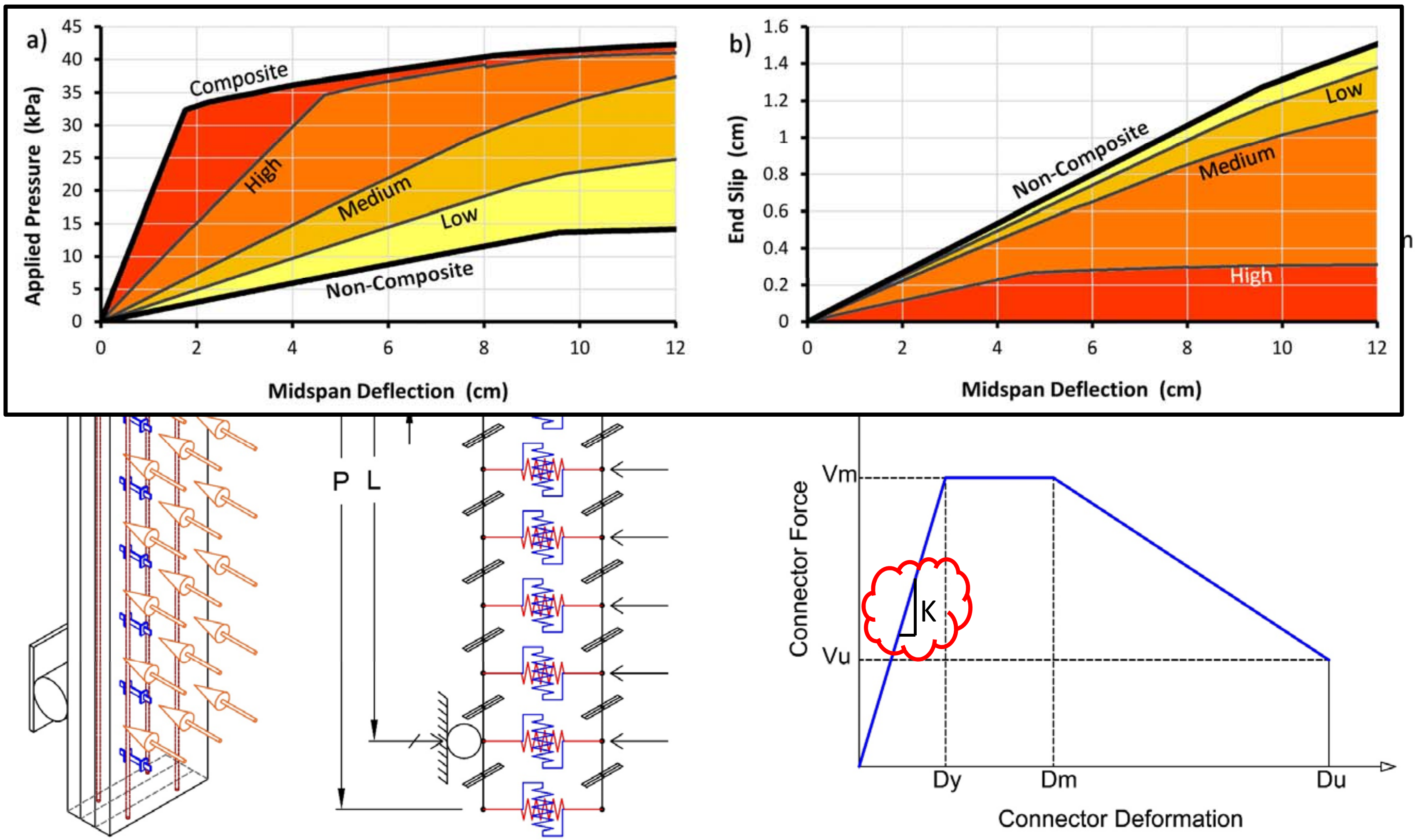
+ A large variety of shear ties are available
+ This causes variations of component response







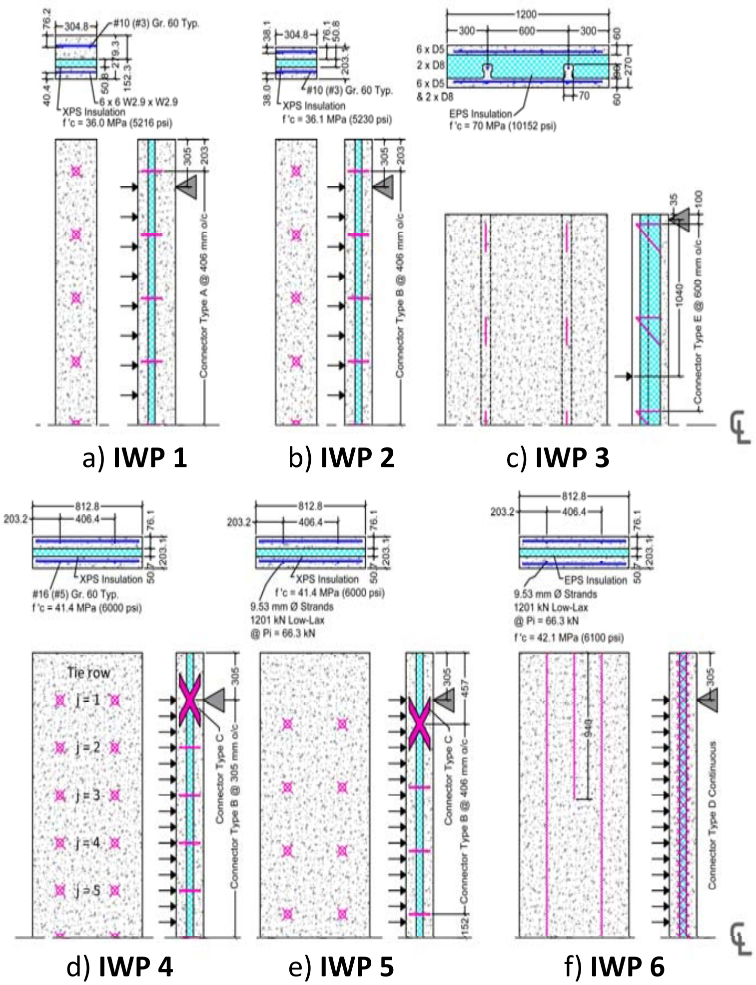
(B) Analysis of Composite Section
Strain Distribution
y
ε
Mc
Side Elevation
Negligible relative tie deformation or end slip
(C) Analysis of Non-Composite Section
Strain Distribution
Mtop
Mbot
Side Elevation
Relative end slip of wythes and no ties present or negligible tie shear strength
(D) Analysis of Partially-Composite Section
Strain Distribution
Ft
e
Mtop
Mbot
Side Elevation
Relative end slip of wythes and varying shear deformation of ties
(A)
b
t1
t2
t3
top
Insulation
bot
h
Section Typical
Wall Panel Elevation
(E) Utilizing fiber analysis determine Moment - Curvature (M-ϕ) relationships for:
MC = Composite Moment
MPC = Partially Composite Moment
Mtop = Moment of Top Wythe
Mbot = Moment of Bottom Wythe
MNC = Non-Composite Moment
MNC = Mtop + Mbot
Moment, M
Curvature, ϕ
MC
MPC
MNC

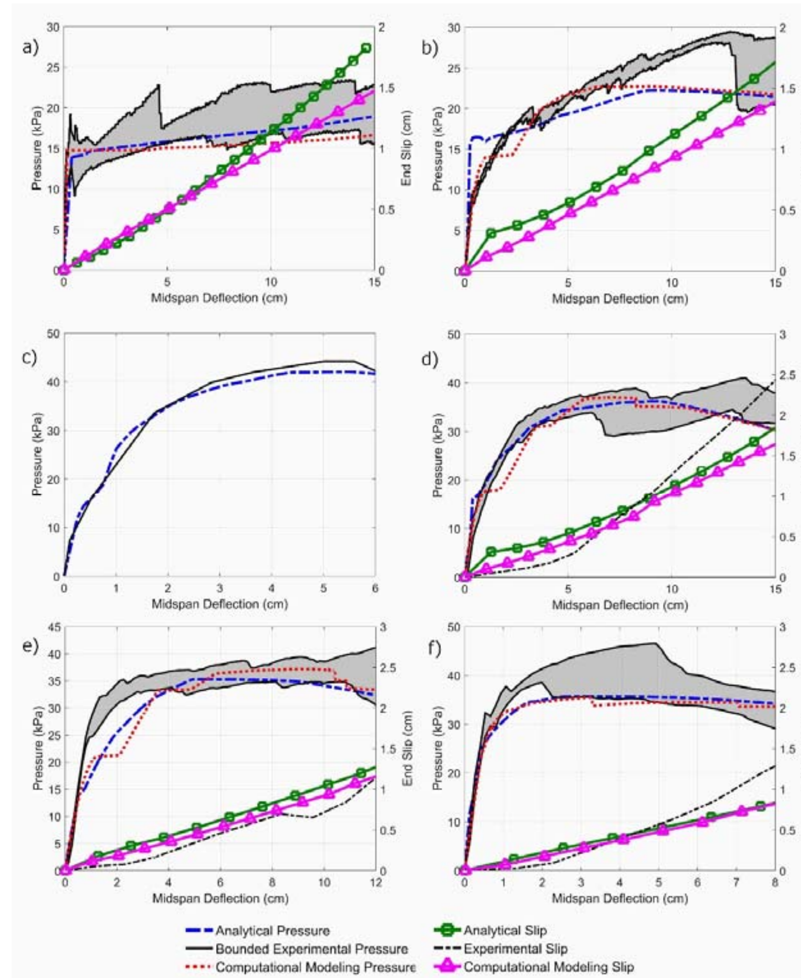


a) Loaded Panel

b) Numerical model

d) Shear element properties


a) IWP 1
b) IWP 2
c) IWP 3
d) IWP 4
e) IWP 5
f) IWP 6


Pressure (kPa)
End Slip (cm)
Midspan Deflection (cm)
Analytical Pressure
Bounded Experimental Pressure
Computational Modeling Pressure
Analytical Slip
Experimental Slip
Computational Modeling Slip

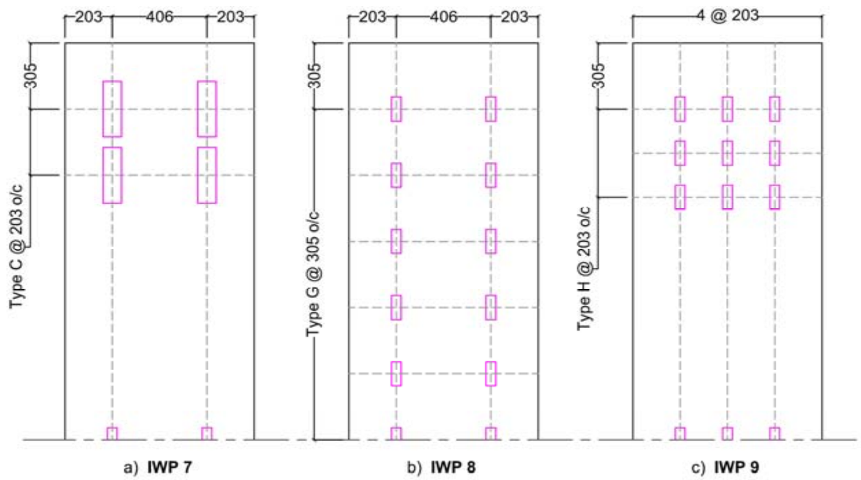
The Synthesis

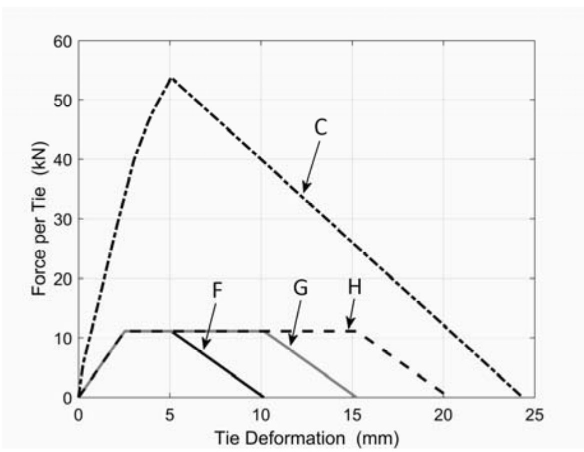
Performance-Based Blast Limit States

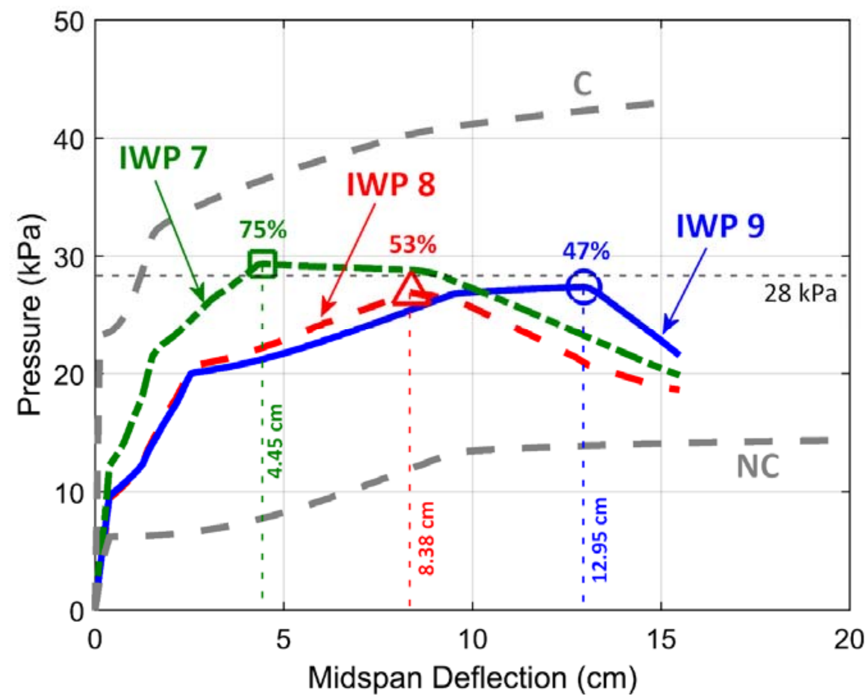
&

Partially-Composite IWP Analysis

IWPs with **different shear tie properties/layouts** may achieve **similar peak capacities** at **different deflections**







Unified methodology **flowchart**

A **Given:** Wall panel geometry, constitutive properties, loading type and boundary conditions

Conventional Approach	Unified Methodology
B Determine panel constitutive relationships	
Assume elastic-plastic resistance function and 100% composite action	Generate full non-linear partially-composite resistance function
Yield is calculated at nominal strength with appropriate stiffness based on average of gross and cracked moments of inertia	
C Determine applicable response limits	
Select appropriate response criteria (e.g., antiterrorism, petrochemical, etc.)	Select level of component damage (e.g., superficial, moderate, heavy, etc...)
Select level of component damage (e.g., superficial, moderate, heavy, etc...)	Determine corresponding performance-based limit state (e.g., yield, peak, etc...)
D Calculate KLM	
Assume elastic and plastic shape functions (ϕ)	Calculate shape function (ϕ_i) at each load step, *i*
$KM = \frac{1}{L}\int_0^L [\phi(x)]^2\,dx$	$KM_i = \frac{1}{L}\int_0^L [\phi_i(x)]^2\,dx$
$KL = \frac{1}{L}\int_0^L \phi(x)\,dx$	$KL_i = \frac{1}{L}\int_0^L \phi_i(x)\,dx$
$KLM = \frac{KM}{KL}$	$KLM_i = \frac{KM_i}{KL_i}$

E **Given:** Blast demands: reflected pressure and impulse

F Perform generalized SDOF analysis using panel properties and blast demands to calculate maximum deformation.

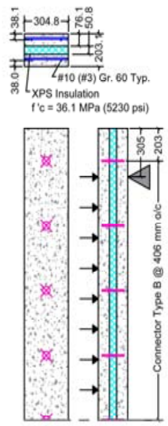
G Determine the level of component damage by comparing maximum deformation (step F) to response criteria (step C).

Case study

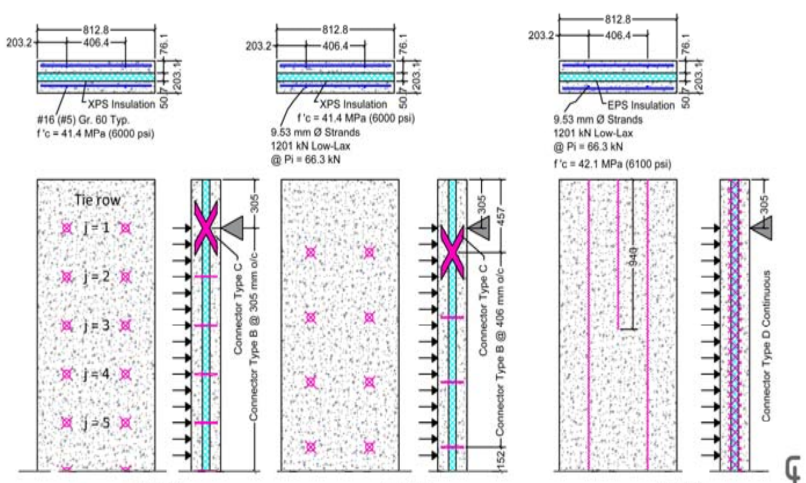
+ All IWPs would be designed for <u>100% composite</u> strength using <u>conventional approach</u>

+ Using design material properties (treating **PB approach** as an <u>enhanced design tool</u>)

+ UFC 3-340-02 <u>DIFs</u> included

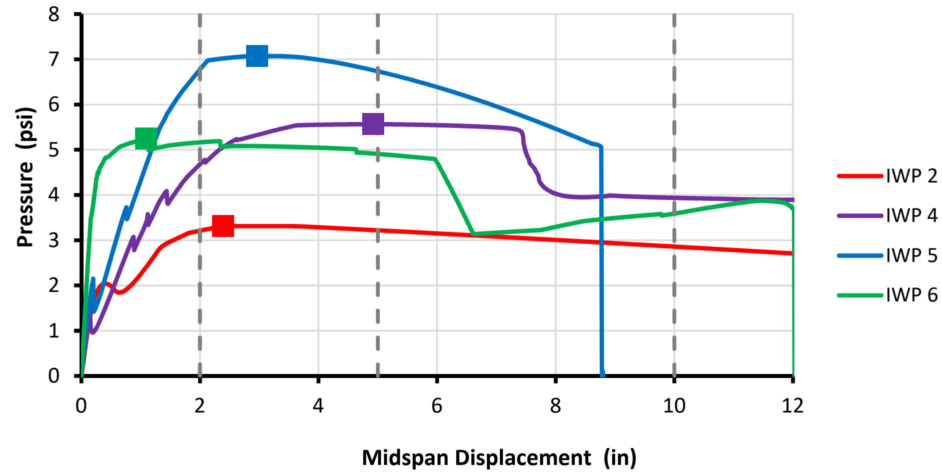


b) IWP 2

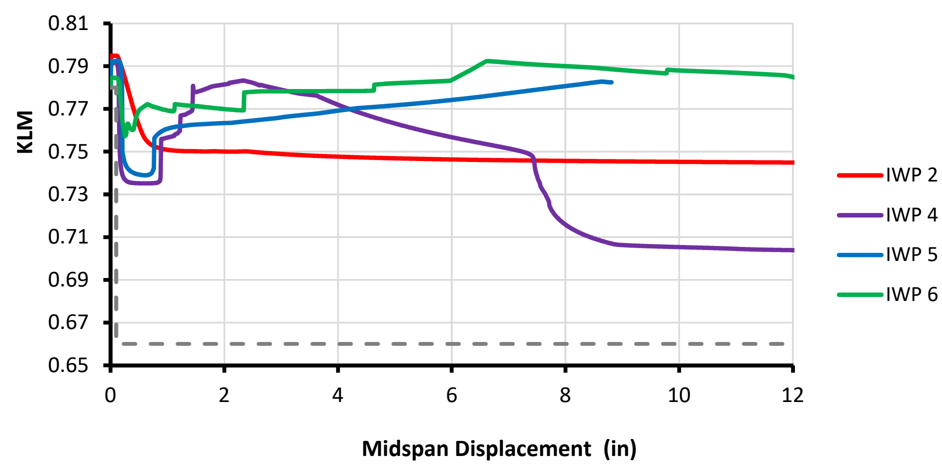


d) IWP 4 e) IWP 5 f) IWP 6

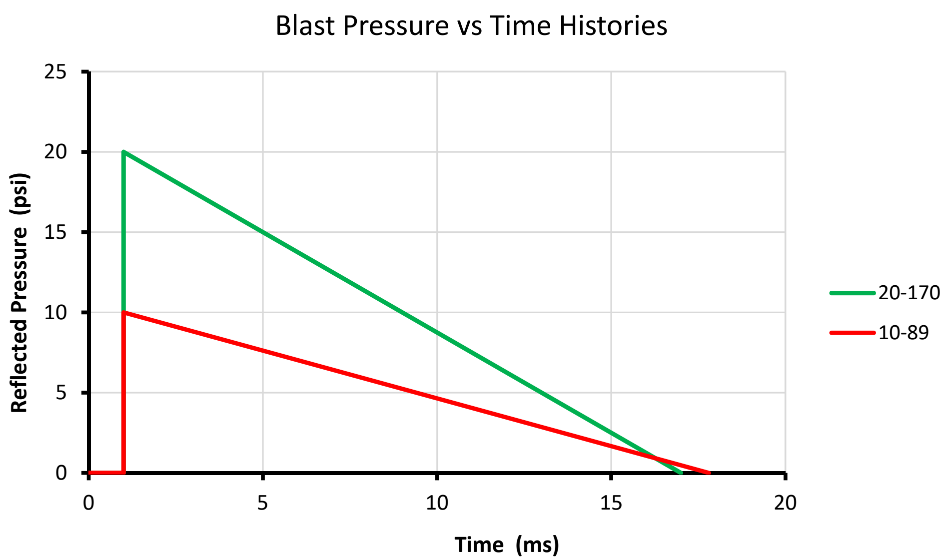
Performance-Based Partially-Composite Resistance Functions



Performance-Based Partially-Composite KLMs



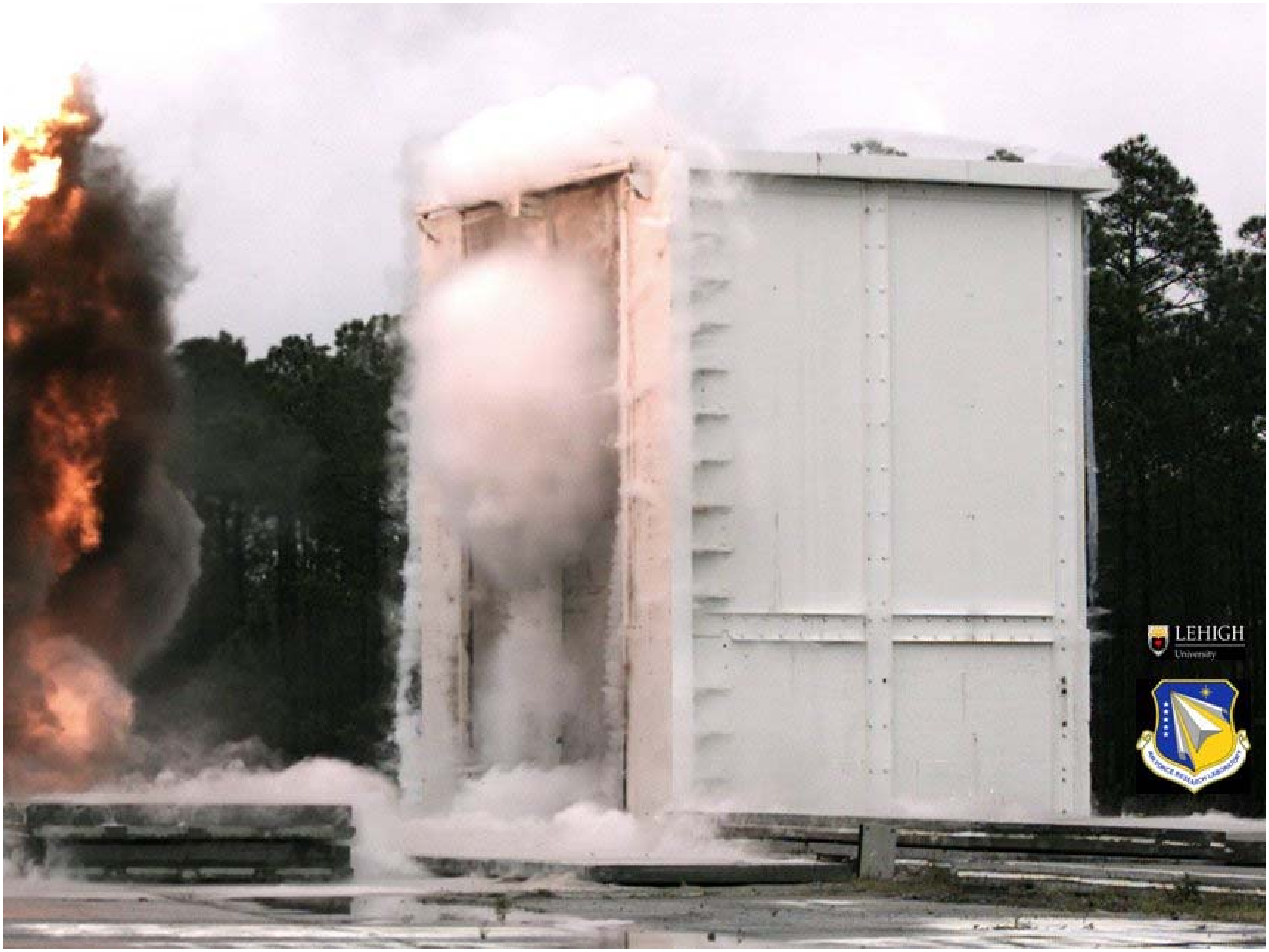
Comparisons of **SDOF analyses** using conventional UFC approach (fully-composite) and performance-based approach (partially-composite)



Peak Displacements (Δ) & Component Damage Levels (CDL)

	10-89				20-170			
Panel ID	Δ_{PB} (in)	CDL_{PB}	Δ_{UFC} (in)	CDL_{UFC}	Δ_{PB} (in)	CDL_{PB}	Δ_{UFC} (in)	CDL_{UFC}
IWP 2	1.54	SFC	0.84	MOD	4.30	BLO	3.56	HVY
IWP 4	1.41	SFC	0.55	MOD	3.40	MOD	2.36	HVY
IWP 5	1.14	SFC	0.49	MOD	2.58	HVY	2.10	HVY
IWP 6	0.69	MOD	0.49	MOD	2.35	BLO	2.10	HVY

LEGEND
SFC = Superficial
MOD = Moderate
HVY = Heavy
HZD = Hazardous
BLO = Blowout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Future work

+ Develop dynamic increase factors (DIFs) for shear ties and insulation types (in progress)

+ Experimental blast testing to verify new proposed DIFs

+ Extension of unified methodology to include other variations of insulated wall panels (e.g., multi-span, openings, etc…)

Summary & conclusions

+ Unified blast-resistant design methodology for insulated wall panels was proposed

+ Unified approach is a synthesis of two analysis frameworks:
  → Performance-based blast design of concrete panels
  → Partially-composite analysis of insulated wall panels

+ Critical response limit states vary depending upon panel geometry and constitutive properties

+ SDOF analysis results show conventional approach often underestimates peak displacements relative to PB methodology

Thank You!

Questions?