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Design of FRP Catcher Systems for Blast Loads

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Focus of Presentation

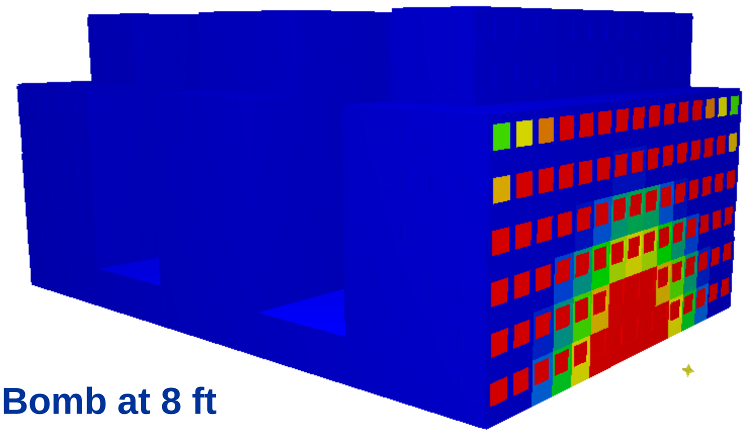
- **Background**
  - ***Masonry walls are widely used in building construction***
  - ***They afford little in the way of protection from a terrorist bombing or accidental explosion***
  - ***However, their blast resistance is easily enhanced with FRP***

- **Topics covered**
  - ***Response of conventionally designed masonry walls to blast loads***
  - ***Description of one way (i.e., FRP catcher system) to enhance blast resistance of masonry walls***
    - **Discuss issues related to such designs**
    - **Discuss analysis methods for selection of design parameters**
  - ***Blast test results demonstrating validity of the FRP enhancements***

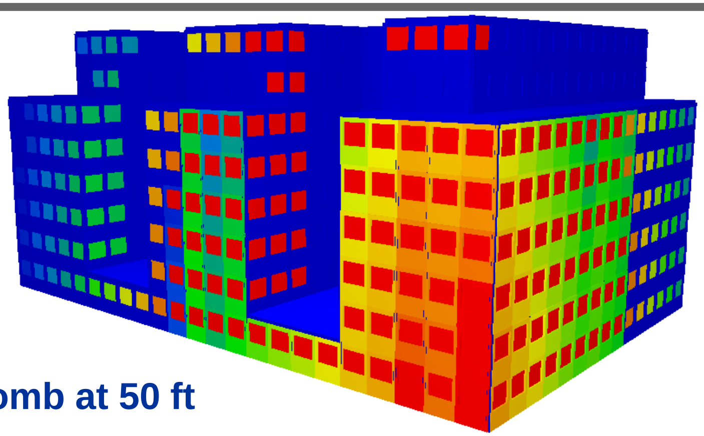
Part 1A: Buildings w/ Masonry Wall Façades Often Manifest a High Level Vulnerability to Terrorist Bomb Threats

- That is, the structural system will remain intact, but lethal debris is plentiful

Assessment of damage to brick wall



Bomb at 8 ft



Bomb at 50 ft

Terrorist Bombing at the Pakistan Marriott (20 September 2008)

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Part 1B: Blast Tests of Masonry Walls Provided Data to Quantitatively Study the Behavior of these Types of Façades when Subjected to Blast

- Example of a blast test, where a whole building is involved
- Full-scale test articles are important here because of the need to characterize the responses accurately along with the debris these walls produce
- The setup shown is for a blast test of a framing system and in-fill masonry walls

Posttest View (Video); CMU Debris Spread Through All Floors

- **What is the key lesson learned?**
- **What protection is most import here?**

Part 2: Observations as to the Threat Posed by Unreinforced (or Lightly Reinforced) Masonry Walls Exposed to Blast Loads

- Masonry walls exhibit several potential failure modes
  - *Catastrophic failure, where the wall is severely damaged resulting in highly lethal debris being propelled into occupied spaces*
  - *Localized failure resulting in debris being propelled into the occupied spaces, even if the wall as a whole stays relatively intact*
  - *Failures in flexure; diagonal and direct shear*
- Masonry walls suffer greatly in blast environments because they often lack ductility, internal continuity, and robust attachment to the framing system
  - *Generally composed of materials that may become highly fractured in a blast environment and produce the type of high velocity/mass debris likely to be highly dangerous to a building's equipment and injurious to its occupants*
  - *These walls are usually poorly anchored to the structural system*
- Masonry walls represent a major source of blunt trauma lethality in a blast environment

Blast Tests Have Shown These Walls Largely Act as Rigid Bodies

- **This has several implications**
  - ***The velocity of their debris is easily computed: $v = I/m$ given the impulse of the blast and the mass of the wall***
  - ***These walls have little in the way of bending resistance***
  - ***Their shear capacity is nearly nonexistent***
- **Also of key import is that these walls are usually not major components of the structural system**
  - ***This means their damage is important only in so far as the resulting debris is prevented from entering the occupied spaces***
- **These forms of response define the key aspects to be addressed in developing an effective design for enhancing the blast protection afforded by masonry walls**

Part 3: Early on (Mid 90s), K&C Began Exploring the Use of FRP for Enhancing the Blast Resistance for Masonry Walls

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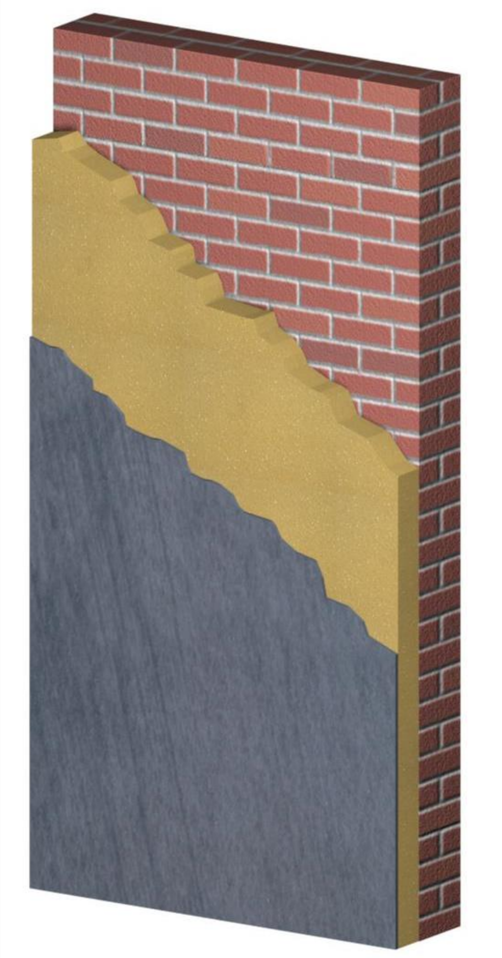
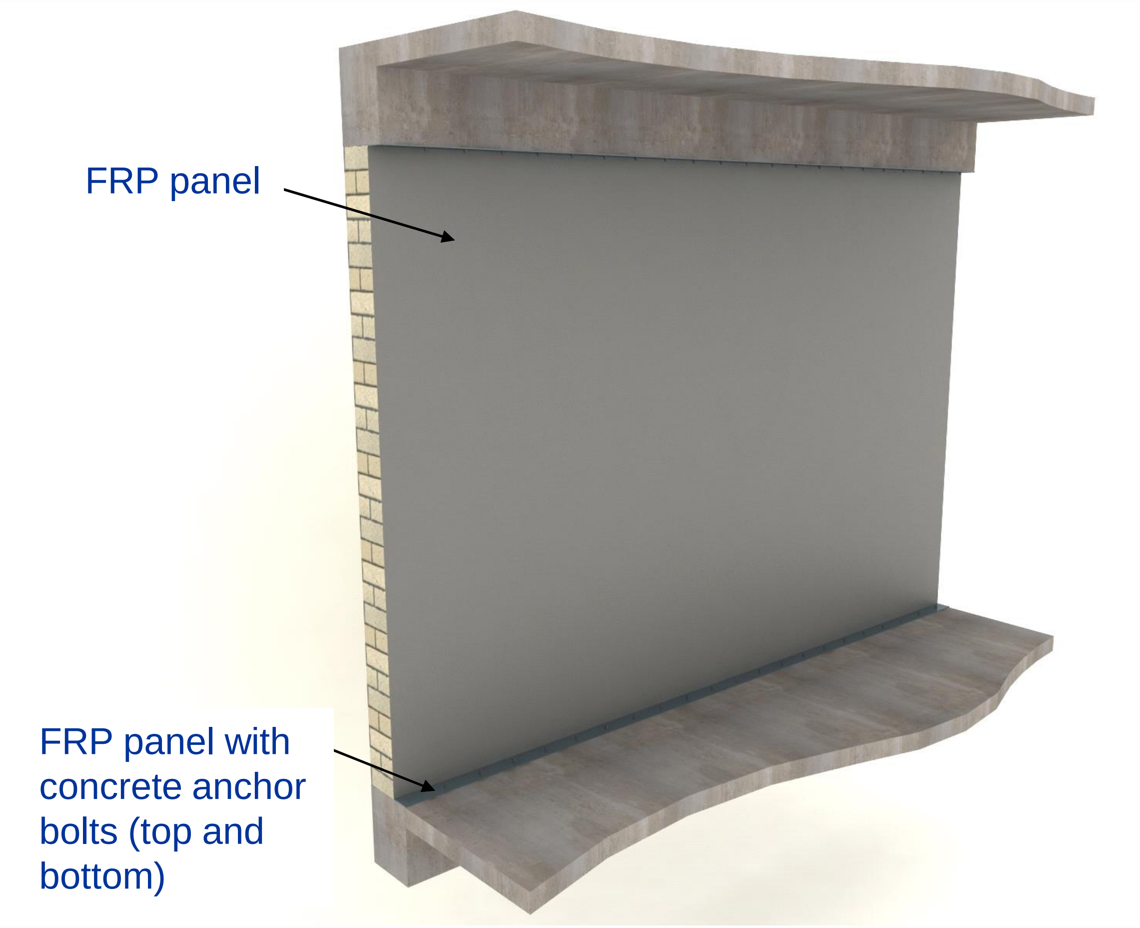
- **FRP offered a number of advantages in this over more conventional materials**
- **Especially for unreinforced or lightly reinforced walls**
  - ***Composed of CMU, brick, tile, and adobe***
  - ***Likely different for new and existing construction***
  - ***Herein focus on retrofit techniques***
- **Two classes of strengthening**
  - ***For bearing walls, strengthening***
  - ***For non-bearing walls, to prevent debris entry***
  - ***For the most part, herein focused on debris risk (i.e., assume walls are not load bearing)***
- **There are a variety of retrofit techniques and design approaches**
  - ***CFRP, GFRP, or AFRP (bonded, unbonded)***
  - ***Polyurea coatings (bonded, unbonded)***
  - ***Composite panels (bonded, unbonded)***

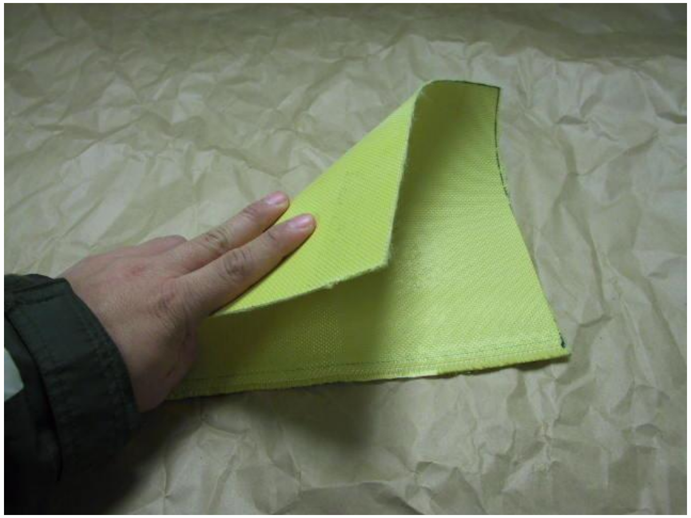
FRP Thin Panel Catcher Systems Can Offer Very High Levels of Protection > 1,000 psi-ms

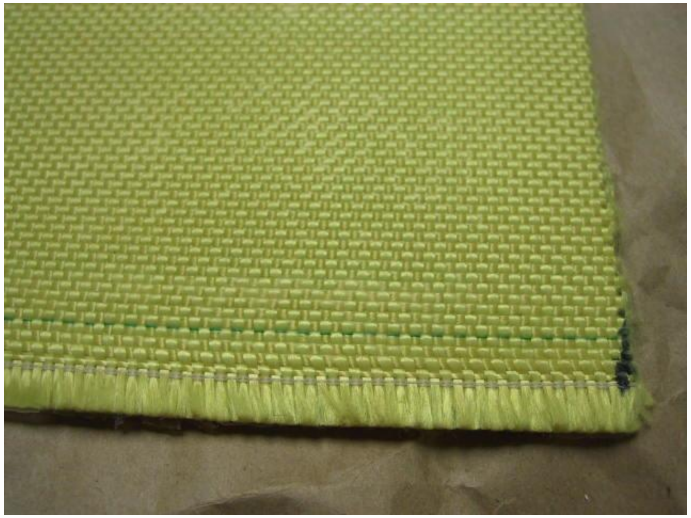
Masonry retrofit





Fabric Catcher System: Kevlar Laminate Attached to Floor





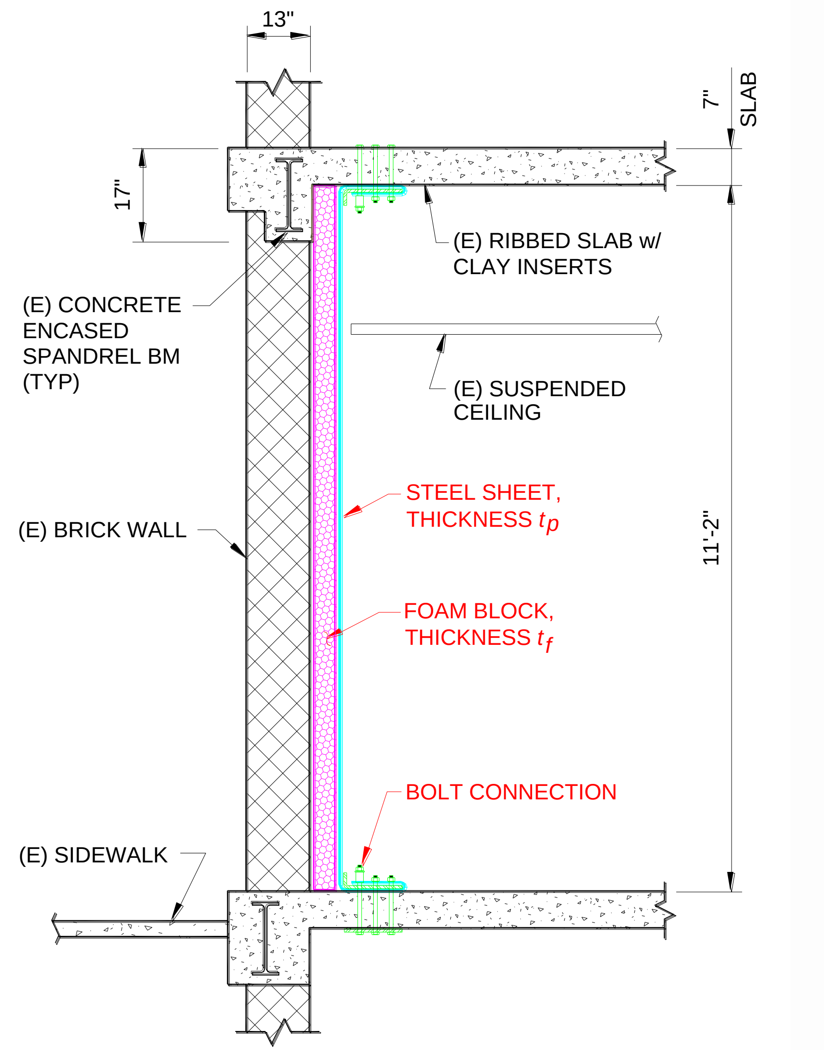
The Key Features of these Walls Include:

- Provide very high-blast resistance
- Forces in thin panel catcher (TPC) system are easily calculated
- Forces exhibited in TPC are relatively low since its resistance is realized in an optimal fashion
- Anchorage forces are easily calculated and controlled by the selection of the TPC components and strengths

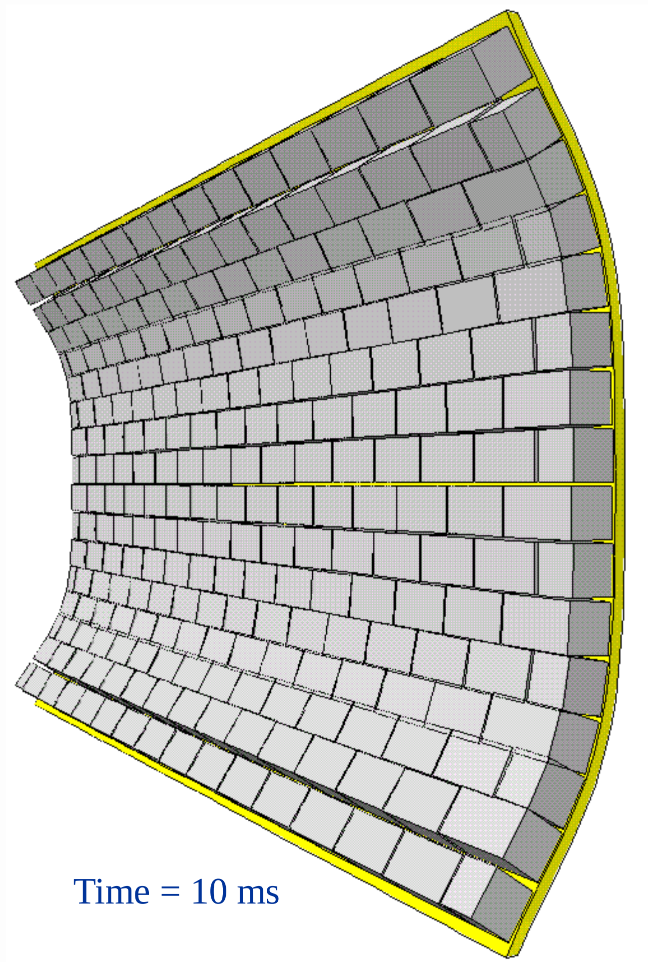
Part 4: Use Physics-Based Analytical Models to Study System Behaviors when FRP and Composite Panels are Employed to Enhance Blast Resistance of Walls

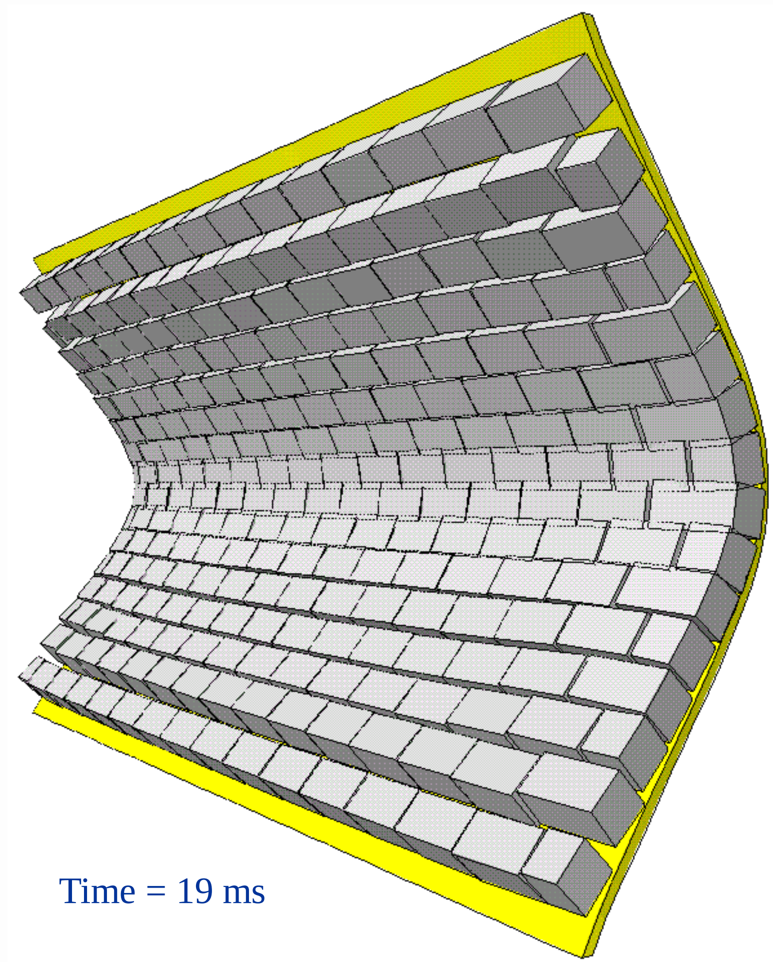
- Define basic properties / behaviors of catcher system
- Here, a foam core with only one skin (on its interior face) is used, as depicted
- Two hundred cases run
- Use ductile anchorage to obtain an elastic-plastic response of FRP panel

Section Modeled



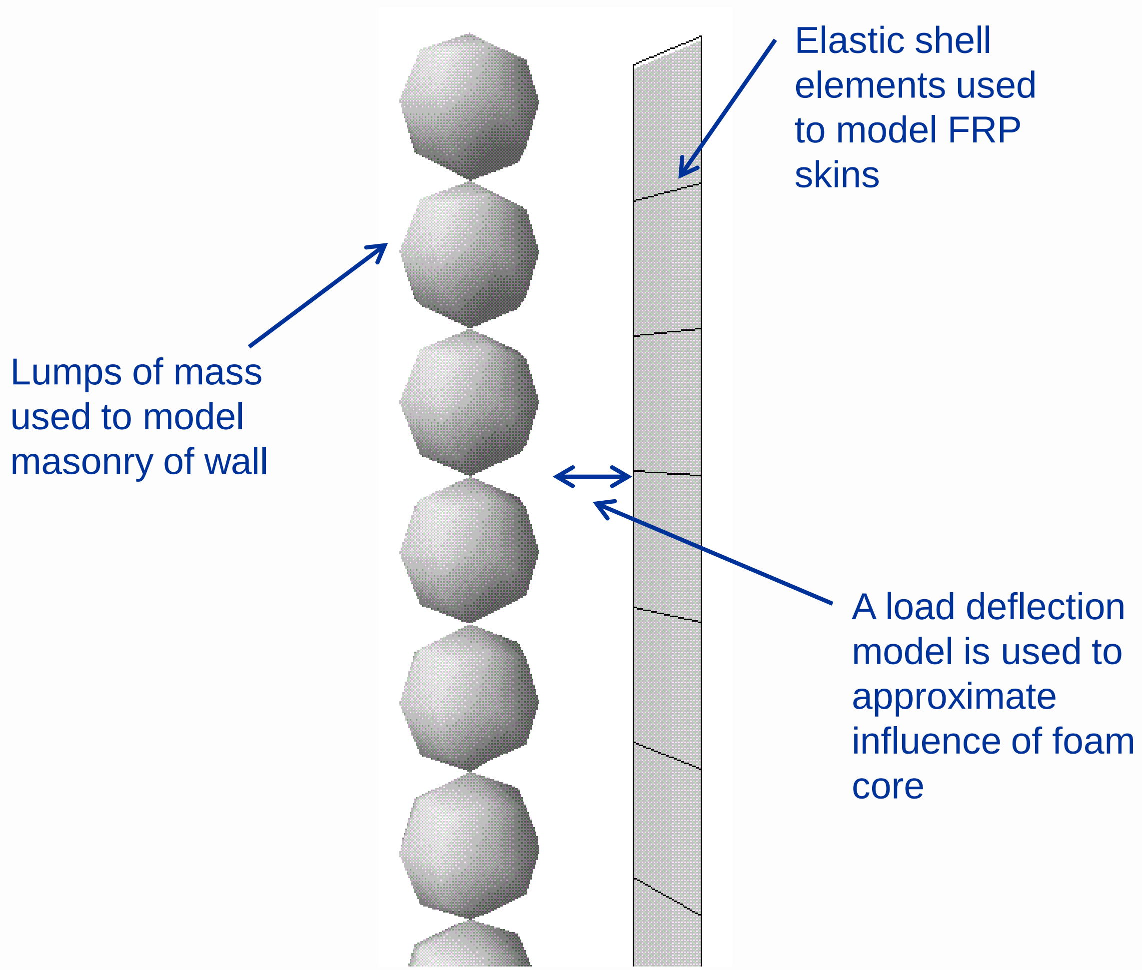
Analytic Studies of Response: Response Predicted by HFPB Finite Element Model; Depicts Basic Nature of TPC Systems



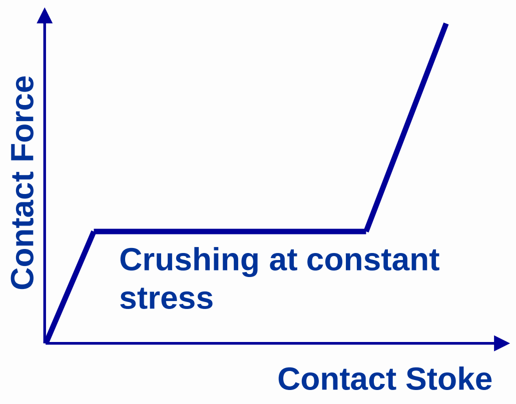


Responses Predicted by Simplified HFPB Model: Use to Study Behaviors

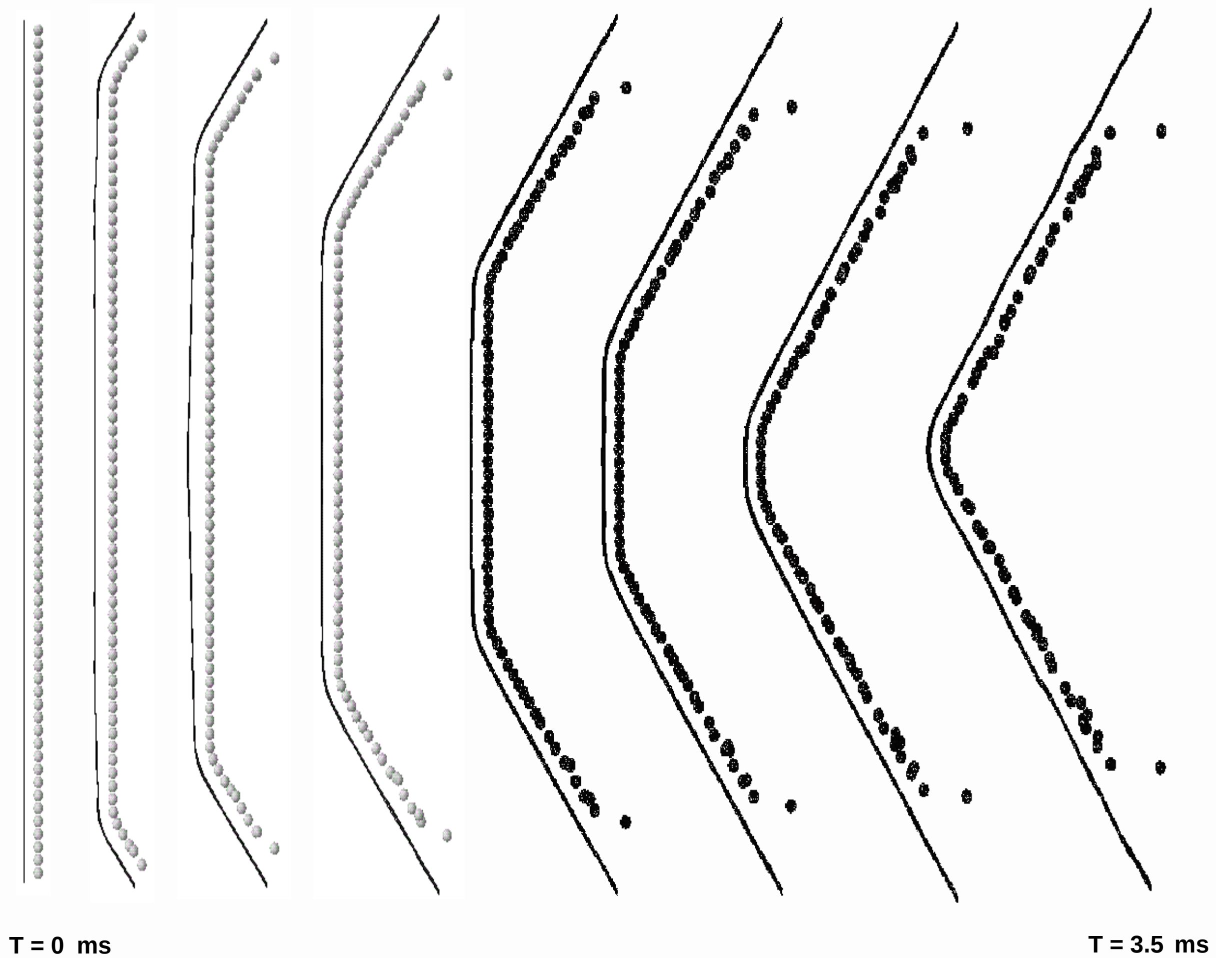
Simplified Model



Foam Model

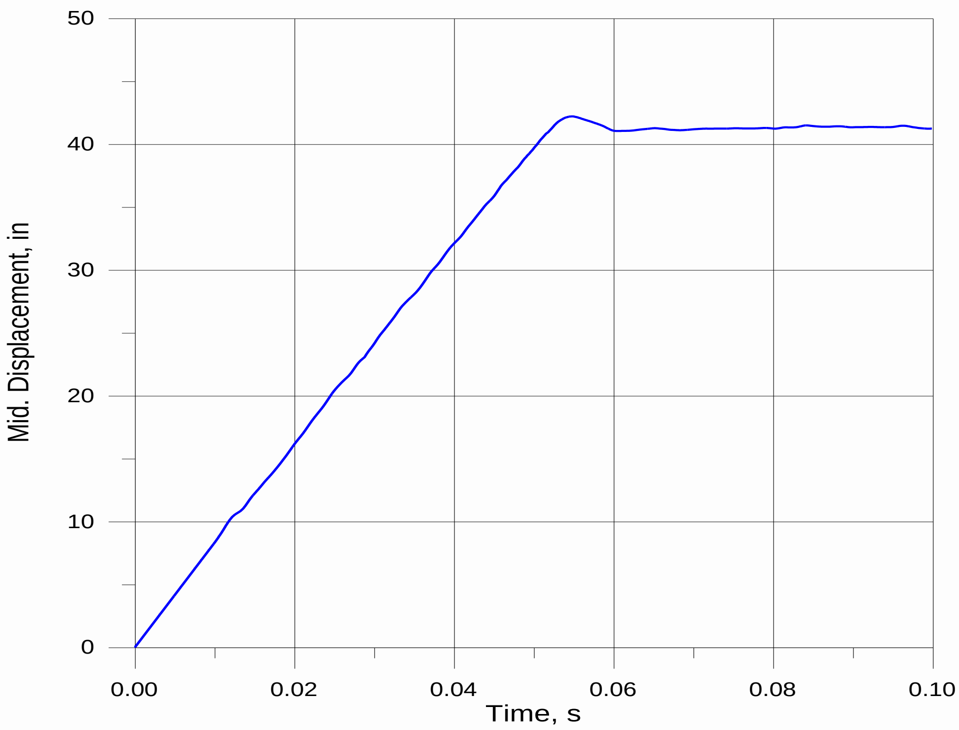


Deformation Plots Show Characteristic Kink Wave

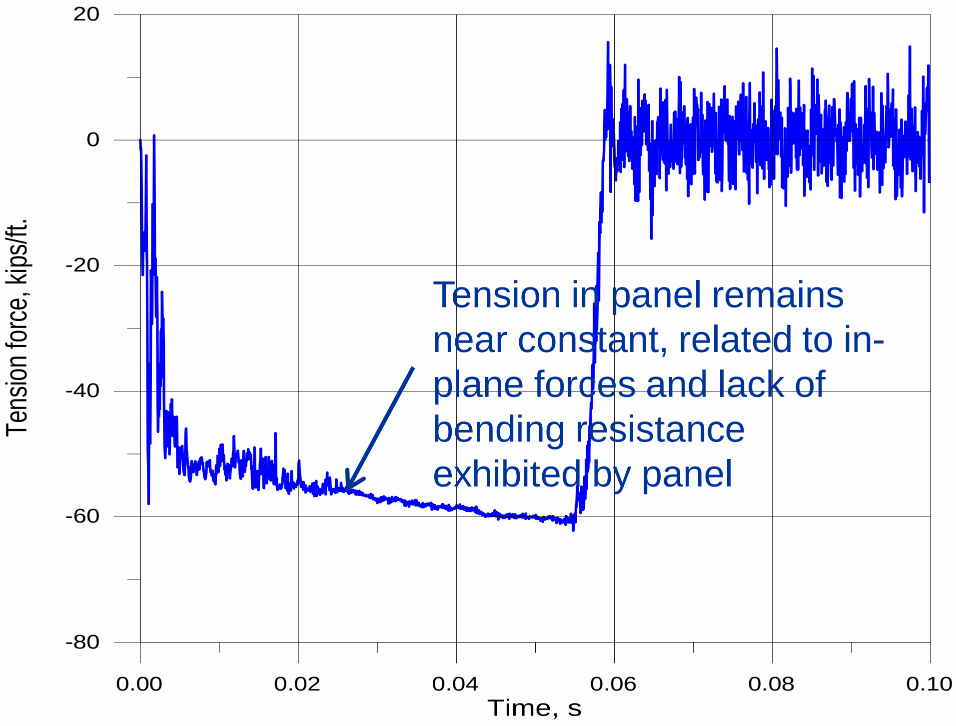


Results for Case 57: Depicts Tensile Force at Support Compared to Mid-Span Deflection

Displacement at Midspan

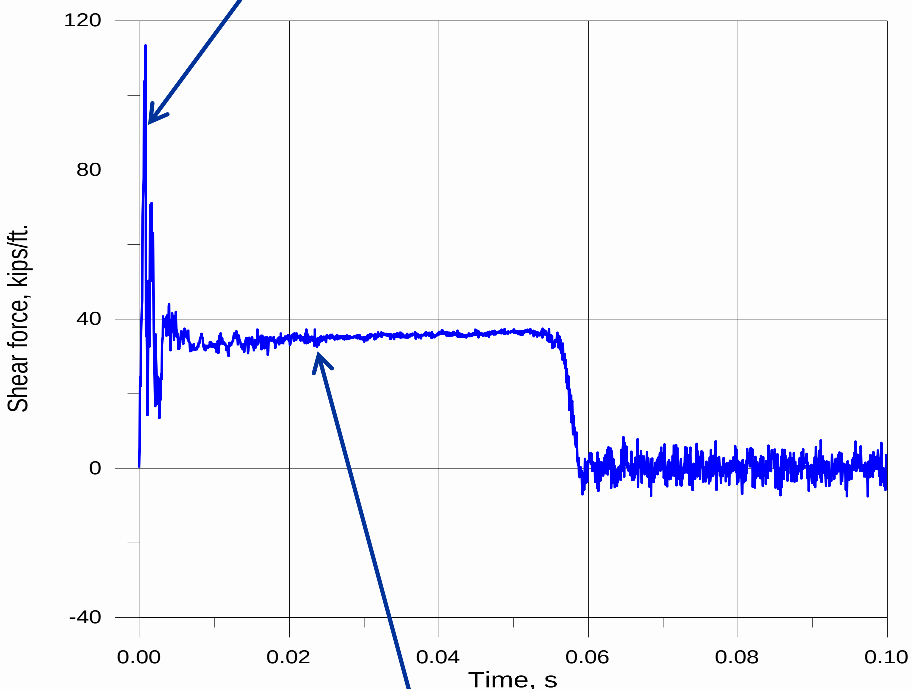


In-plane Panel Force at Support



Shear at Support: Critical Aspect of Design: Spike in Shear Force can Range from ~20 to 300 kips/ft Depending Closeness of Charge, and Anchorage and Panel Design

Shear demand can be 3-5 times conventional demand; main benefit of thin panel is to minimize shear spike



Conventional form of shear demand at anchorage (i.e., related to membrane force in FRP) , which is quite easily characterized and handled

Results from some of cases run relate to variations in standoff R, panel thickness t_p, and foam strength F and thickness t_f

	Variable Parameters				Results			
Case	*R*, ft	t_p, in	F_c, psi	t_f, in	Middle Displacement, in	Max. Strain, in/in	Bolt Shear, kips/ft	Bolt Tension, kips/ft
52	8	1/16	1000	1	28.9	0.046	42.2	-30.5
53	4	1/8	100	4	41.8	0.116	77.1	-61.7
54	8	1/8	100	4	20.0	0.024	38.5	-61.4
5	4	1/8	250	4	41.9	0.109	100.2	-61.8
4	8	1/8	250	4	20.1	0.021	37.5	-61.0
55	4	1/8	500	4	42.1	0.104	110.6	-61.7
56	8	1/8	500	4	20.1	0.019	41.0	-60.8
57	4	1/8	1000	4	42.2	0.106	113.3	-62.4
58	8	1/8	1000	4	20.2	0.02	47.3	-61.1
59	4	1/8	100	2	42.0	0.105	276.8	-61.9
60	8	1/8	100	2	20.1	0.023	269	-61.3
61	4	1/8	250	2	42.2	0.115	81.9	-61.5
62	8	1/8	250	2	20.1	0.02	28.7	-61.0
63	4	1/8	500	2	42.3	0.11	82.8	-61.6
64	8	1/8	500	2	20.1	0.02	56.4	-61.3
65	4	1/8	1000	2	42.4	0.103	109.2	-61.7
66	8	1/8	1000	2	20.2	0.02	59.0	-61.1
67	4	1/8	100	1	42.0	0.105	233.5	-61.9
68	8	1/8	100	1	20.1	0.02	23.5	-61.2

Part 5: How Can These TPC Systems be Analyzed for Purpose of Design?

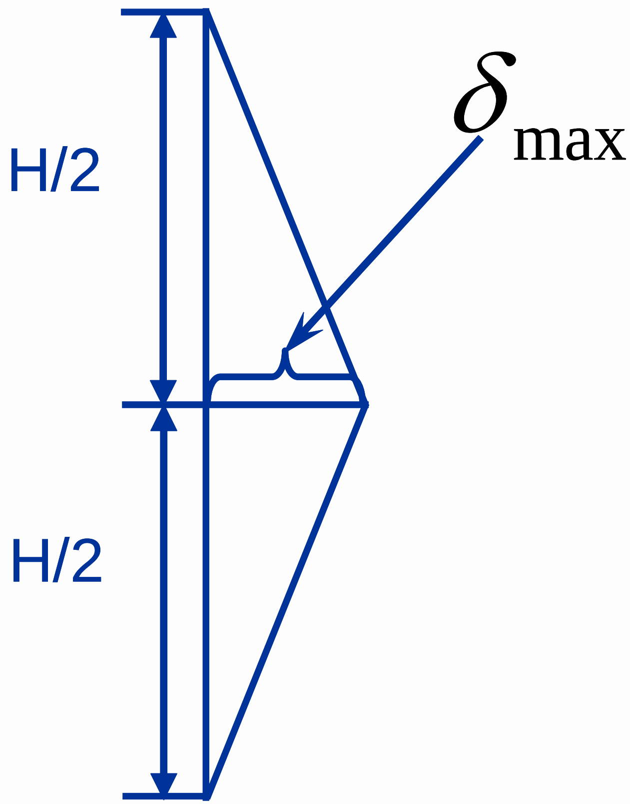
- To determine their performance
  - *Develop an understanding of the basic TPC phenomenology*
  - *Conducting R&D studies to determine optional design configurations and concepts*
  - *Provide a basis for the selection of design parameters*
- At K&C, our philosophy is generally to develop high-fidelity physics-based (HFPB) models in the study of the concepts attributes
  - *These are validated with test data*
- After this R&D phase, we develop design tools for use in the parameter selection required in the deployment of these designs and two forms of design tools are considered here: one based on conservation of energy, the other on SDOF modeling

For the Energy Based Model, the Design of a TPC System is Predicated on Five Basic Assumptions

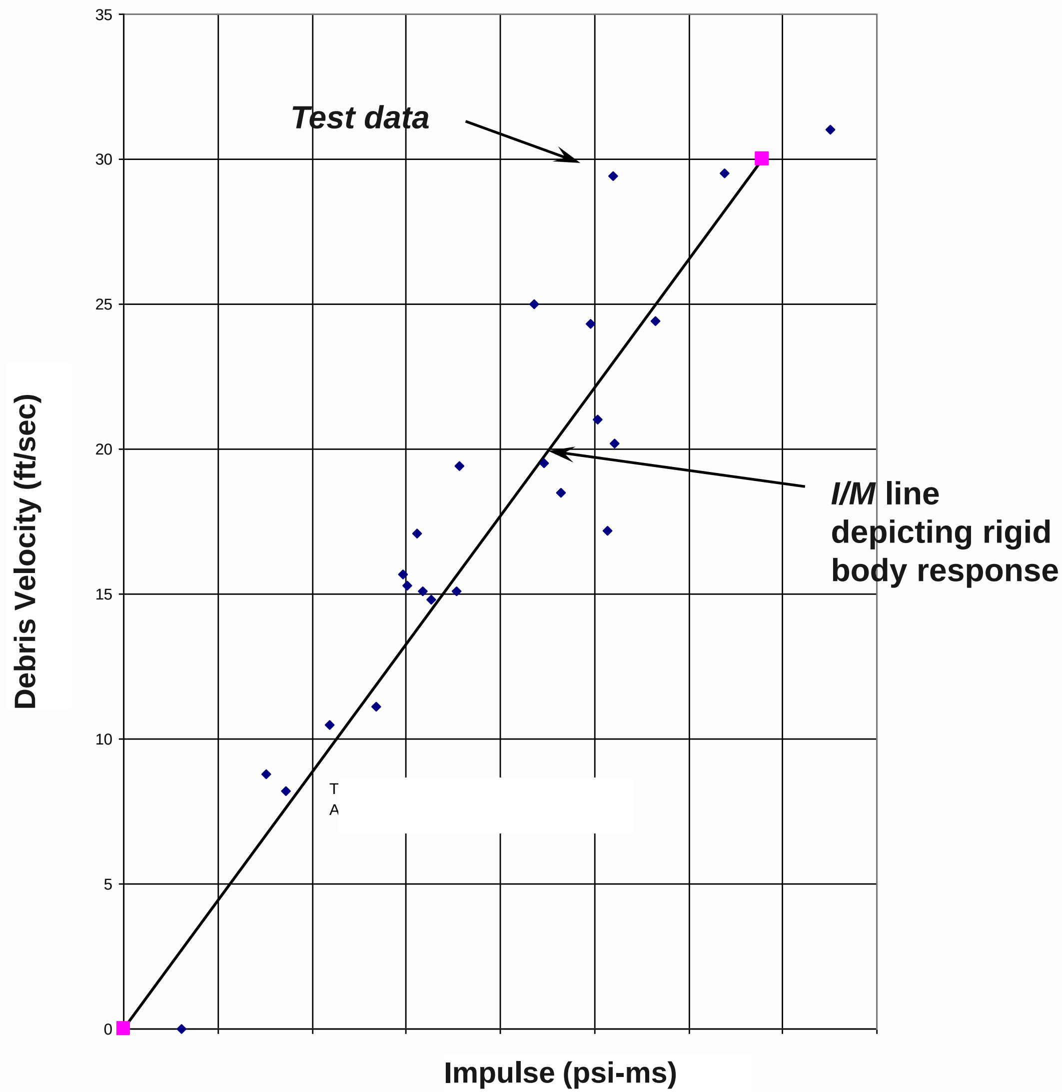
- Assumptions
  - *Assumption 1. The sheet is composed of a bilinear material*
  - *Assumption 2. The final deformed shape may be represented by a triangular form*
  - *Assumption 3. The debris generated from the breakup of a masonry wall or window may be computed from rigid body mechanics— $v_{\text{debris}} = I/m_w$*
  - *Assumption 4. The energy involved in the wall's response and breakup is negligible as compared to the kinetic energy of the debris*
    - Not so critical since the method provides an upper bound estimate of the response.
  - *Assumption 5. The strains in the panel are fairly uniform over its area and through its thickness at the time of the peak deflection*
- Blast tests and HFPB analyses have shown these assumptions to be reasonable simplifications for this class of problem

Measured and Calculated Response Showing These Assumptions Are Valid

Deformed shape at peak deflection

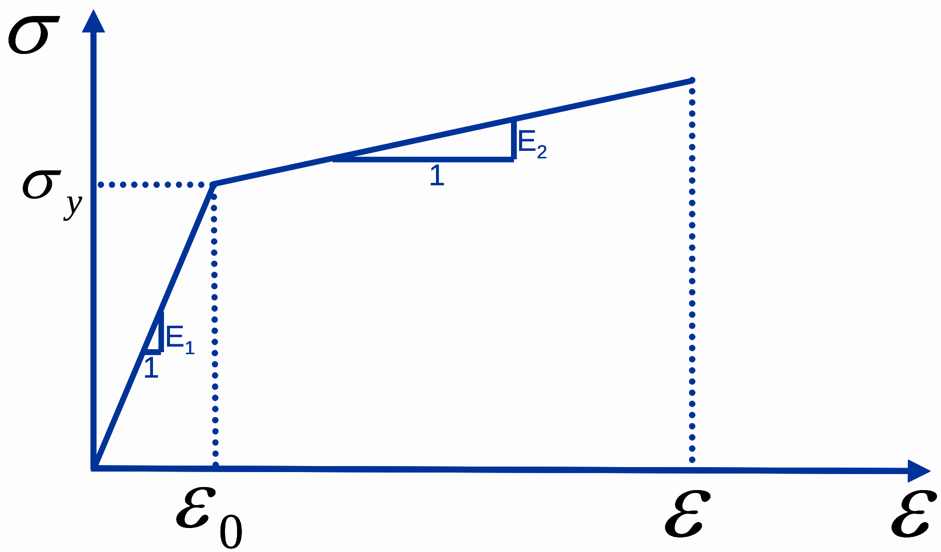


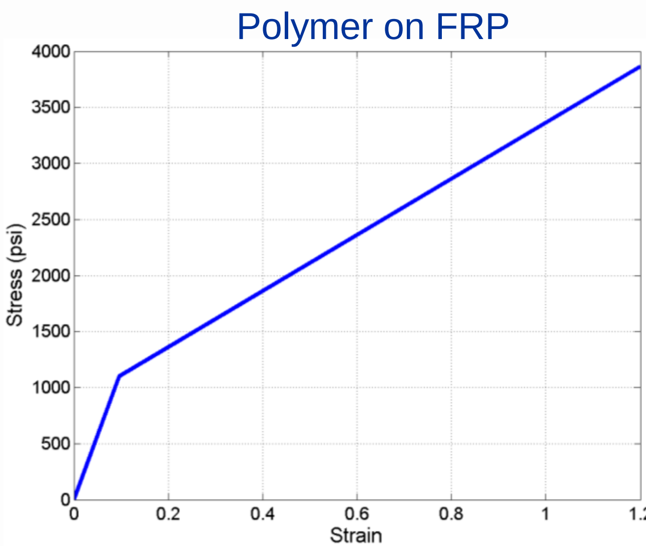
Debris velocity

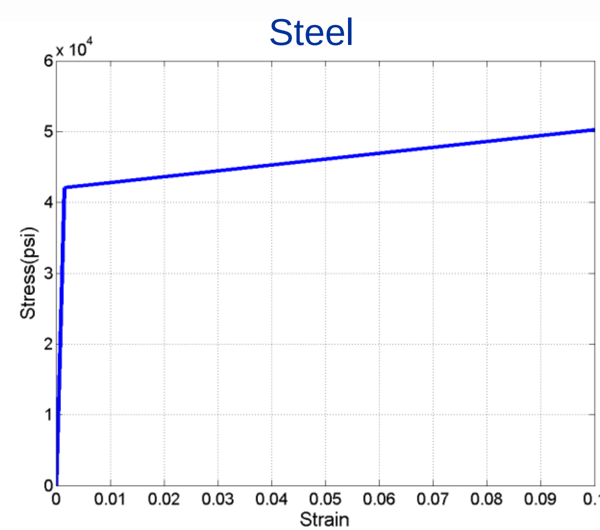


Panel Composed of Bilinear Material

Bilinear elastic-plastic behavior assumed for sheet







Design of Method Based on Equating the Internal Energy of the Panel at the End of the Event to the Kinetic Energy of the Window/Wall Debris

- The total internal strain energy in the catcher panel is

$$\int \eta dV = \frac{1}{2} t_p WH \left[E_2 \varepsilon^2 + 2\left(E_1 - E_2\right)\varepsilon_0 \varepsilon - \left(E_1 - E_2\right)\varepsilon_0^2 \right]$$

- The kinetic energy of the wall debris is

$$k.e._{debris} = \frac{1}{2} M_w v_{debris}^2 = \frac{1}{2} M_w \left(\frac{I}{m_w} \right)^2$$

- Equating energies results in an expression for the panel's displacement

$$\delta_{\max} = \frac{H}{2} \sqrt{\varepsilon_{\max}\left(\varepsilon_{\max} + 2\right)}$$

where

$$\varepsilon_{\max} = \left(1 - \frac{E_1}{E_2}\right)\varepsilon_0 + \sqrt{\left(\frac{E_1}{E_2} - 1\right)\frac{E_1}{E_2}\varepsilon_0^2 + \frac{\rho_w t_w v_{debris}^2}{E_2 t_p}}$$

For Design of the Anchorage, the Forces are Calculated from ε_{max}

- **Panel peak stress**

  $\sigma_p = E_1\varepsilon_0 + E_2\left(\varepsilon_{max} - \varepsilon_0\right)$ for $\varepsilon_{max} > \varepsilon_0$

  otherwise

  $\sigma_p = E_1\varepsilon_{max};\ F_p = t_p\sigma_p$

- **Anchorage forces**

  $F_2 = F_p \sin\beta$

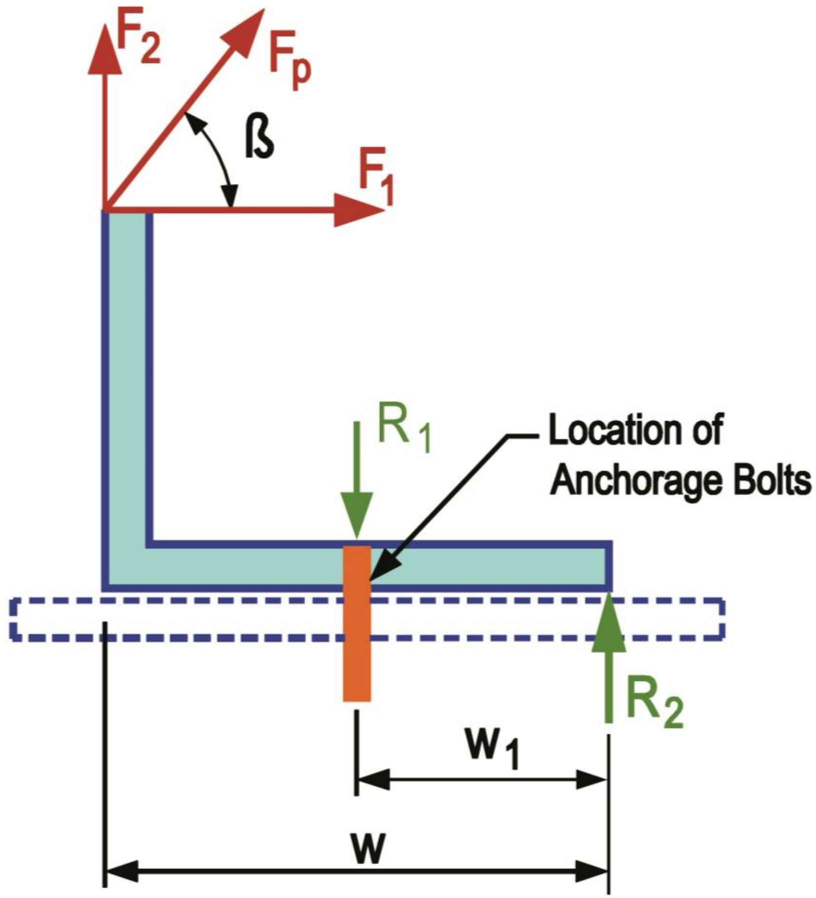
  $F_1 = F_p \cos\beta$

  $\mathrm{Tan}\beta = 1/2 \times H / \delta_{max}$

- **Bolt forces**

  $R_1 = F_2 w / w_1 + F_1 h / w_1$ in tension

  F_1 in shear



Part 6: Validation of Design/Analysis Concepts

- **In developing and validating concepts for these TPC systems and the design tools to use for them, we conducted a variety of blast tests**
  - ***Using HE, shock tubes, and THUMPER (impact loader) tests***
  - ***All tests conducted at full-scale***

- **These tests also provided the data needed to validate our HFPB models of these systems**
  - ***Given these validated HFPB models, we could explore and illuminate the phenomena involved, as shown earlier***
  - ***These tools also allowed us to use HFPB models to develop simplified design tools for use in design of TPC systems (i.e., as shown above with equations and later with SDOF models)***

The Design Equations Shown Here were Validated Against HFPB Model Results

- Basic design equation for a TPC system
- Expression for the panel's displacement

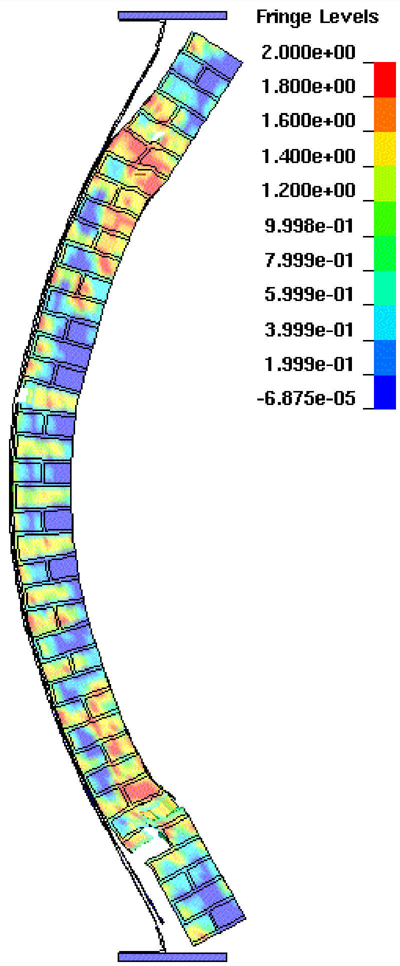
$$\delta_{\max} = \frac{H}{2}\sqrt{\varepsilon_{\max}\left(\varepsilon_{\max} + 2\right)}$$

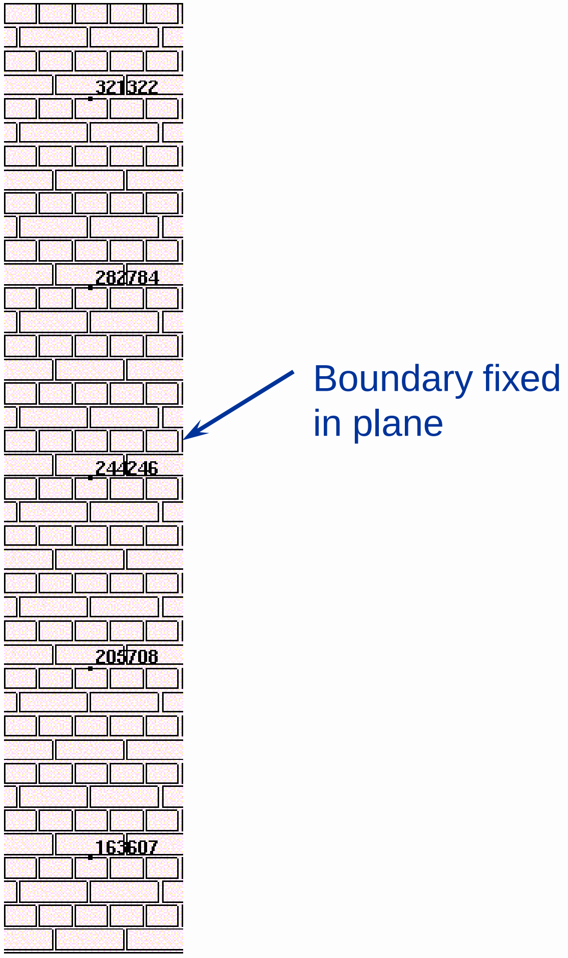
where

$$\varepsilon_{\max} = \left(1 - \frac{E_1}{E_2}\right)\varepsilon_0 + \sqrt{\left(\frac{E_1}{E_2} - 1\right)\frac{E_1}{E_2}\varepsilon_0^2 + \frac{\rho_w t_w v_{debris}^2}{E_2 t_p}}$$

- Solving this equation for the peak displaced of the TP allows all the rest of the response parameters for a TPC system to be computed (as shown earlier)

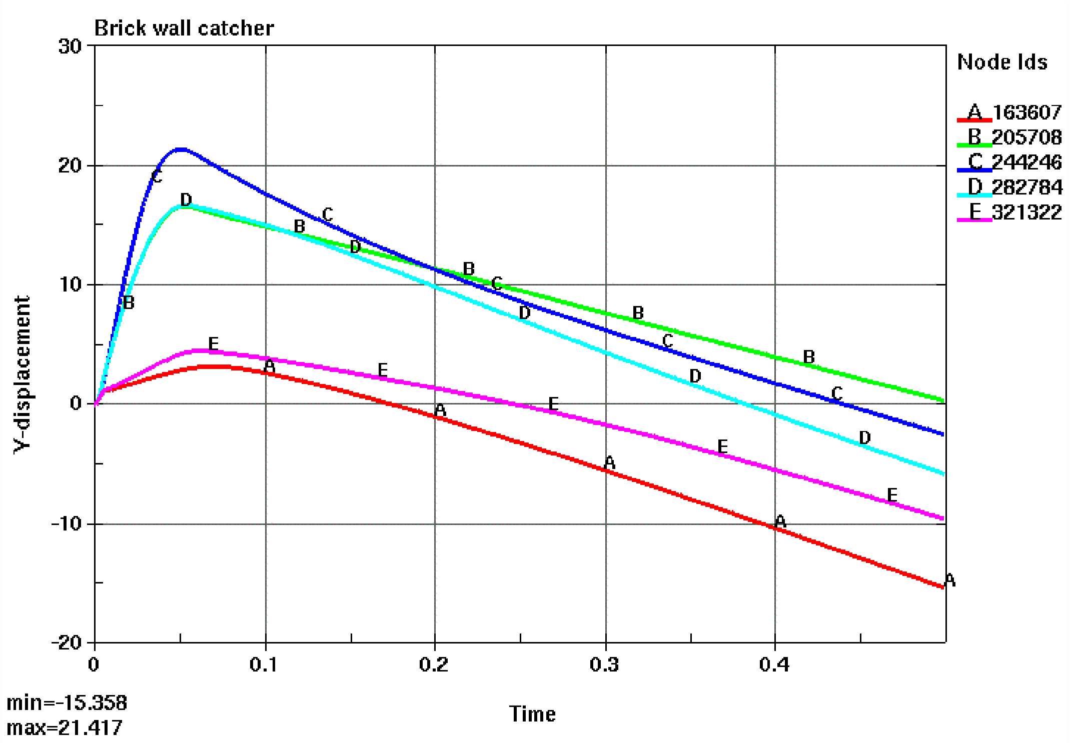
Validation Problem: Model of Brick Wall





Comparison of LS-DYNA Results with those Computed using δ_{max} Equation

- δ_{max} = 21.4 inches (LS-DYNA)
- δ_{max} = 26.1 inches (equation)

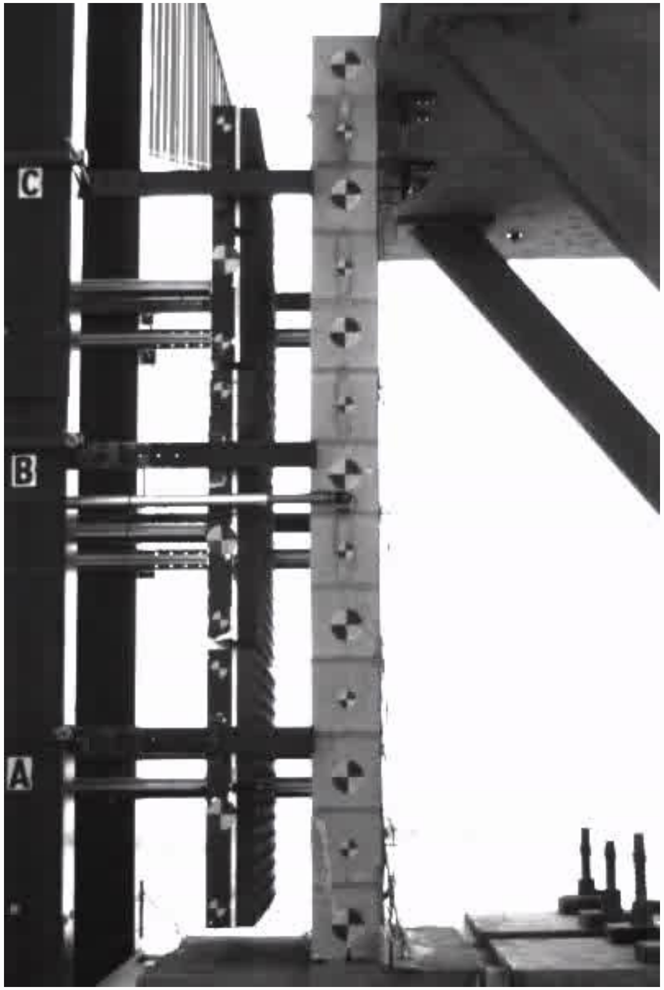


Part 7: For Development of an SDOF Model for Use in Design of TPC Systems, Considerable More Work is Needed

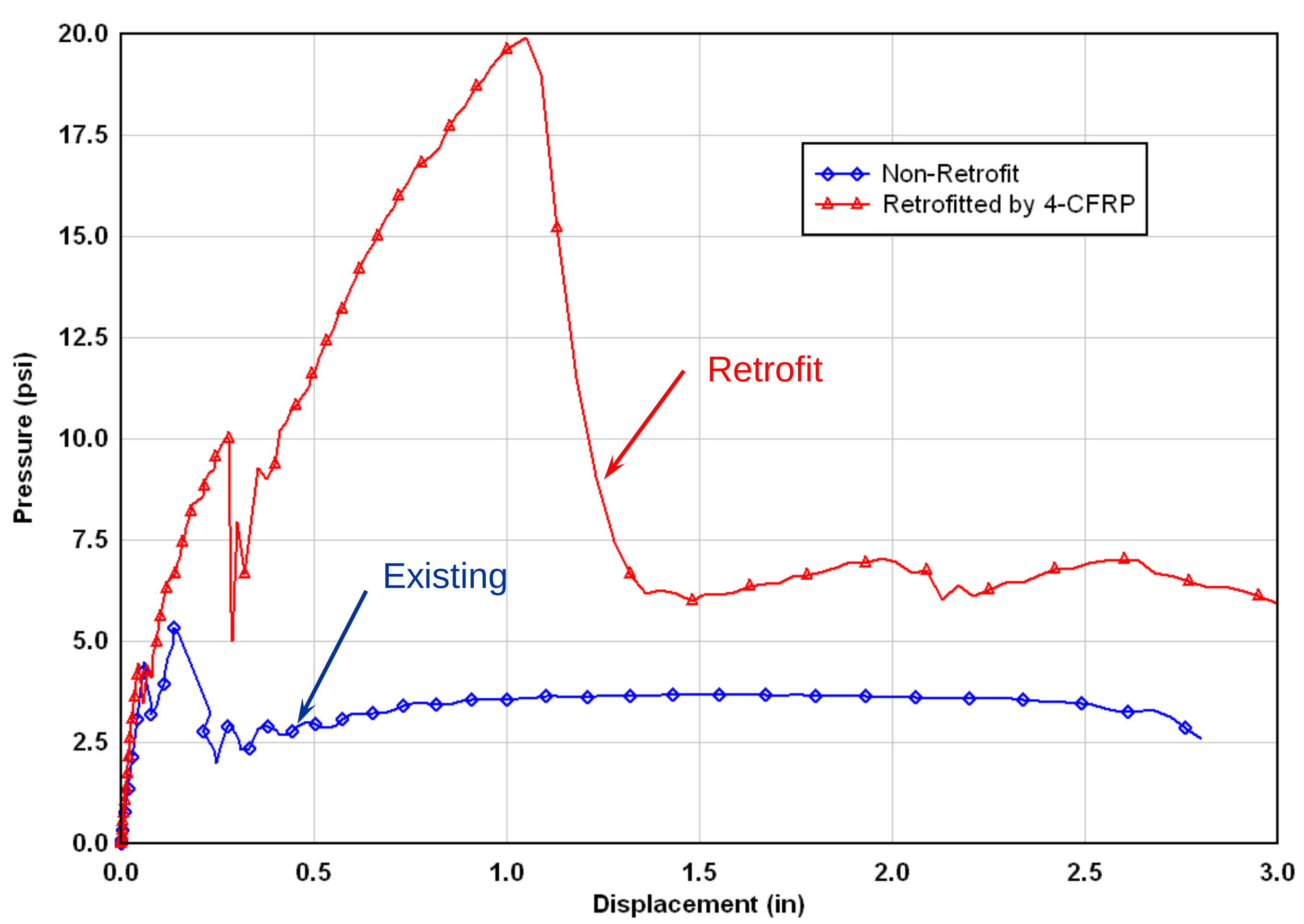
- The major difficulty here is development of appropriate resistance functions and shape factors that can represent a broad range of design problems and cover the many types of masonry walls in play and the variability in their construction quality and boundary conditions
  - *Also will need blast effects testing and quasi-static tests to verify SDOF-kinds of data*
- Moreover, there is a major issue here in that for many levels of blast load, walls just do not act like the sort of conventional structure that might be addressed with an SDOF model making little sense to address them as some sort of bending-centric structure
- It is important to note: these details and test data are largely unneeded for the energy methods just discussed
  - *A major advantage to their use*

Same Specimen After Second Repair at 300 psi-ms (Video)

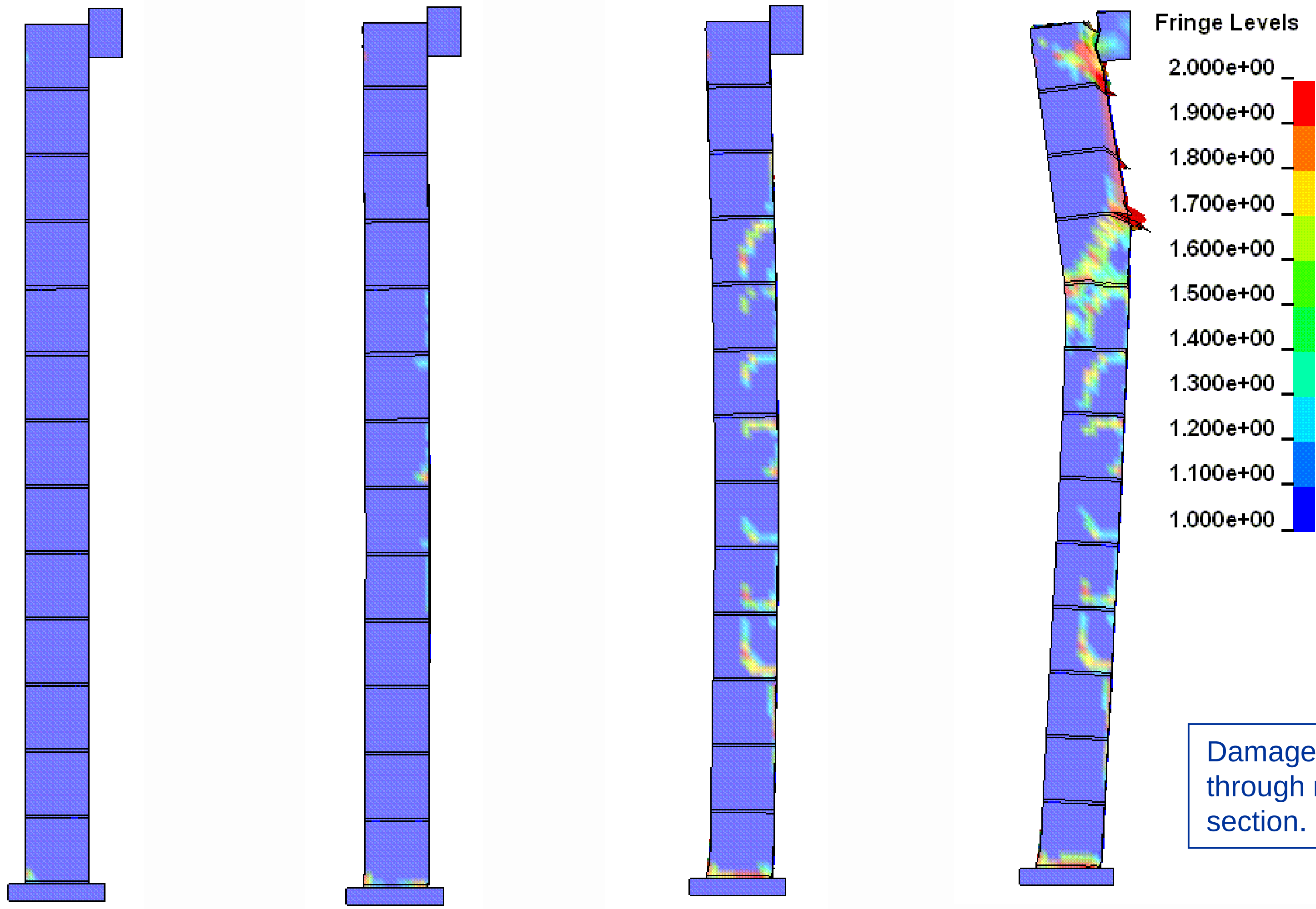
- Note even though wall fails, CFRP holds it together
- This kind of response is not very conducive to using an SDOF model to capture



Comparison of Resistance Functions



Deformed Shape and Material Damage Fringes Shown as a Function of the Pressure Load (Applied p in psi = time t/100);Wall Retrofit with 4-layers CFRP



t = 600 ms. t = 1,000 ms. t = 1,500 ms. t = 2,000 ms.

Damage fringes through mid-width section.

Summary

- **Masonry walls are generally weak in blast resistance**
- **Enhancing masonry wall blast resistance is simple and straightforward if TPC systems are employed with these walls**
- **Design of TPC systems is straightforward if energy methods are used**
  - ***In contrast, employing an SDOF model to provide the basis to design is problematic at best***
- **Caution is needed in blast load testing to ensure that the responses measured in the test reflect realistic results**
  - ***i.e., those that would occur if the DBT were to occur***
  - ***In this regard, shock tubes often provide too low a peak stress and too long a duration to well simulate a blast***
  - ***Of a similar concern is that the test specimen for a wall should be tested in a configuration consistent with its situation as part of an actual structural system (e.g., whether the wall exhibits arching or not)***