

AFRL-ML-TY-TP-2005-4508



Full Scale Testing of Polymer Reinforced Blast Resistant Windows

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Interim Report, December 2004

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14. ABSTRACT Summary of the state of the art in research and design of protective glazing and recent full-scale testing efforts of the Air Force Research Laboratory (AFRL) on blast resistant windows that use advanced materials. Failure mechanisms observed from recent explosive tests are presented, along with analytical models that are being developed to predict the resistance provided by the polymer reinforcement. Challenges include optimizing mechanical properties of reinforcement, design thickness and lay-up of the polymer and glass layers, and designing optimum mechanisms for transferring load to host structure. The needs and direction of future blast resistant window research are discussed.					
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Full Scale Testing of Polymer Reinforced Blast Resistant Windows

December 2004

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Airbase Technologies Division
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Tyndall AFB, Florida





Topics of Discussion

- Current design of blast resistant windows
- Development of AFRL blast resistant windows
- Design approach
- Full-scale experiments
- Material testing
- Modeling
- Future goals



Current Design of Blast Resistant Windows



- High profile targets
 - Airports / highly populated areas
 - Embassies
 - Government facilities



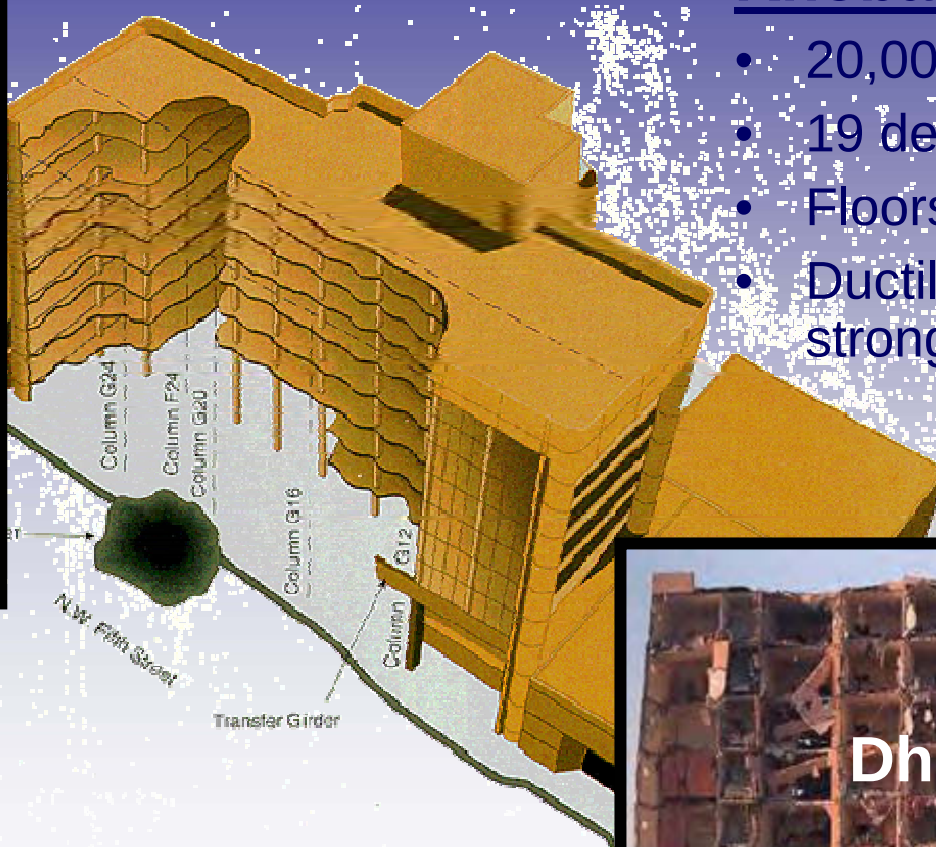
High Profile Targets



Oklahoma City

Murrah Building

- 4,000-lb bomb
- 168 deaths
- Floors progressively collapsed
- Beam and column discontinuity



Khobar Towers

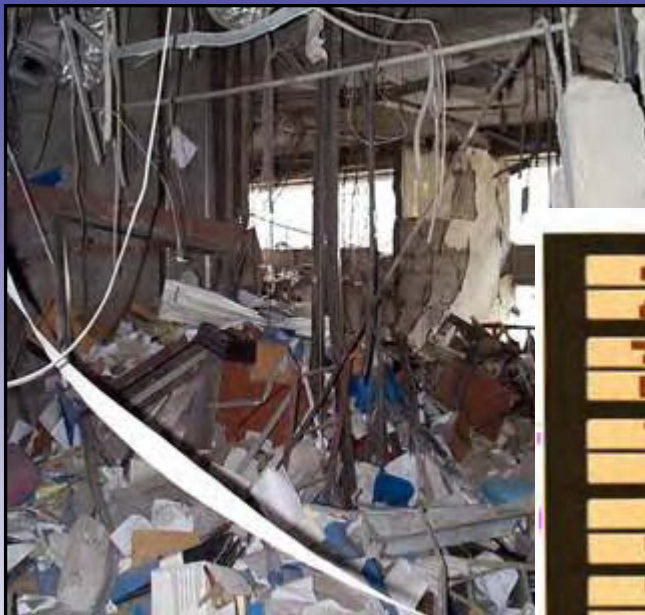
- 20,000-lb bomb
- 19 deaths
- Floors did not collapse
- Ductile structure with strong joints



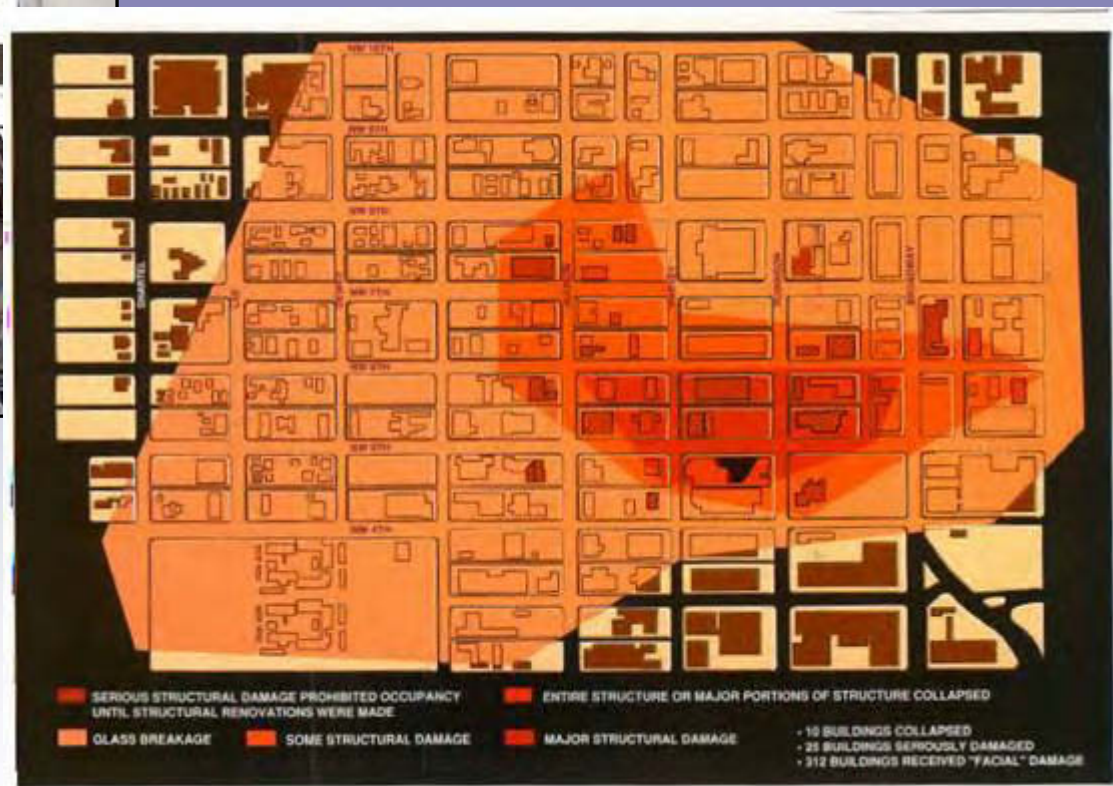
Dhahran



High Profile Targets



Glass Hazards
> 80% Human
Casualties



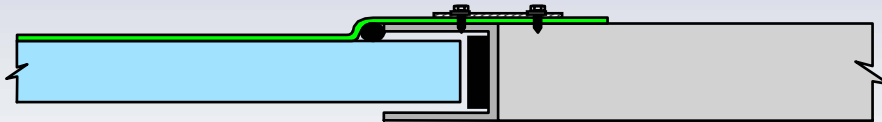
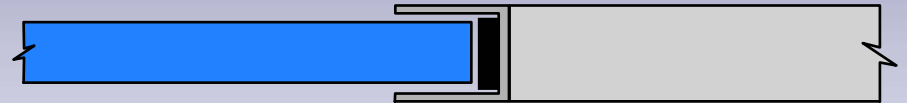


Current Design of Blast Resistant Windows

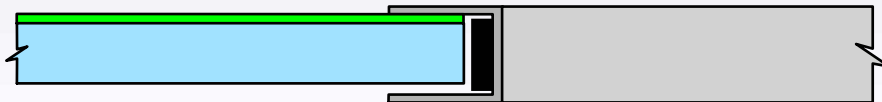


- High profile targets
 - Airports / highly populated areas
 - Embassies
 - Government facilities

- Design methods
 - Large bites with thick glass
 - High strength anchored films



Film captured externally

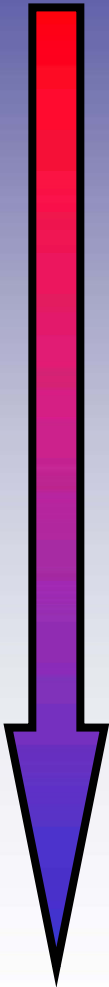


Film captured in the bite



Design Methods - Glazing Options



- 
- **Annealed Glass** Fails at ~0.2 psi into shards
 - **Chemically Treated Glass** Reacts like annealed glass
 - **Wire-Reinforced Glass** Reacts similar to annealed glass
 - **Acrylic (Plexiglass)** Fails similar to annealed glass
 - **Heat Strengthened Glass** Fails at ~0.4 psi into shards
 - **Fragment Retention Film** Film (4 mil+) holds fragments; blunt trauma hazard unless film retained by frame/catcher system
 - **Thermally Tempered Glass** 4-5X stronger than annealed glass; fractures into small cubes
 - **Laminated** Use interlayer bonding materials with plies of glass, polycarbonate or both; frame can be weak point
 - **Polycarbonate** Suitable for blast resistance up to ~5 psi; can abrade and degrade from UV unless coated



Design Methods - Glazing Options (Videos)



Annealed/Heat Strengthened



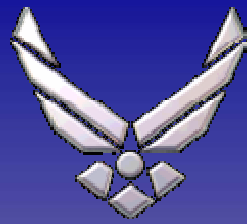
Film Glazing



Anchored Film Glazing



Current Design of Blast Resistant Windows



- High profile targets
 - Airports / highly populated areas
 - Embassies
 - Government facilities

- Design methods
 - Large bites with thick glass
 - High strength anchored films

- Design examples...



Design Examples - Fragment Retention Film



- Broken, annealed glass turns into shards
- Fragment retention film (e.g., "Mylar") holds shards together
 - Minimum 4 mils thick
 - Glass/film bond important
 - Estimated life of ~10 years
- Film with catcher bar provides good level of protection at low cost (Army TL 1110-3-501, 14 Jul 99)





Design Examples – Stainless Steel Net Blast Curtain





Design Examples – Arpal Windows



- Window size: 5'2"x7'1"
- Thin glass laminates
- Cables used to absorb energy

- Aluminum shear devices absorb energy
- Complex system
- Very practical windows



Design Examples - Structural Muntin Windows



Exterior View



Interior View



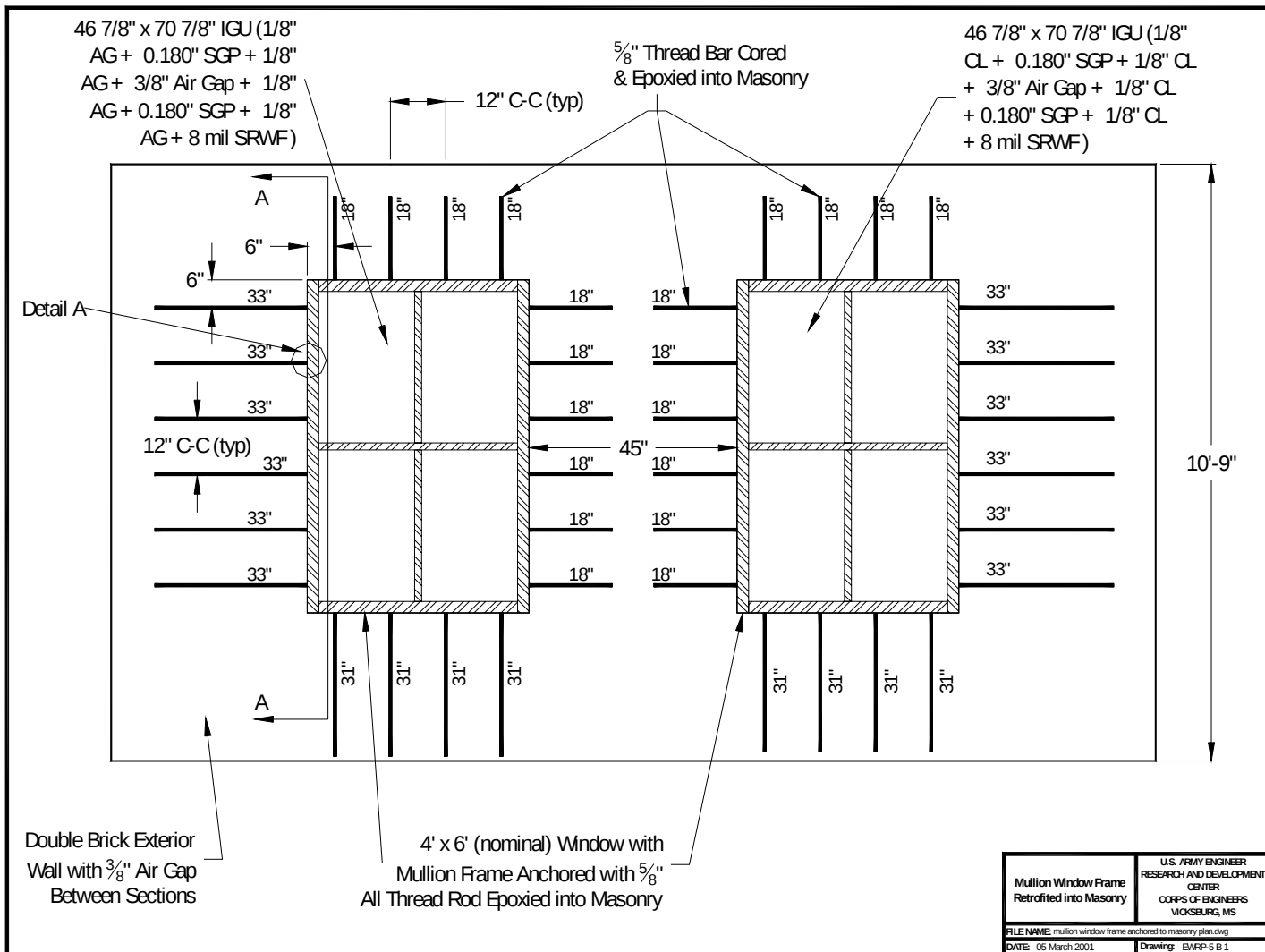
Vertical Non-continuous
Muntin Steel Tubing Member

Horizontal Continuous
Muntin Steel Tubing Member

Steel Tubing Muntin
Window Frame
Anchored Into
Masonry Wall Using
Threaded, Epoxied
Rods

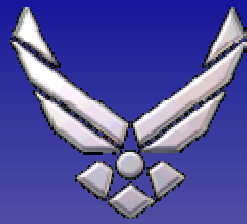
Two sandwiched interlayers of
1/8" AG (Annealed Glass) +
0.180" SGP (Sentry Glass Plus)
+1/8" AG with 3/8" Air Gap
between + 8 mil Shatter
Resistant Window Film

Coreguard Consisting of
20 Gage Sheet Metal
Glued to 1/4" Gypsum
Board





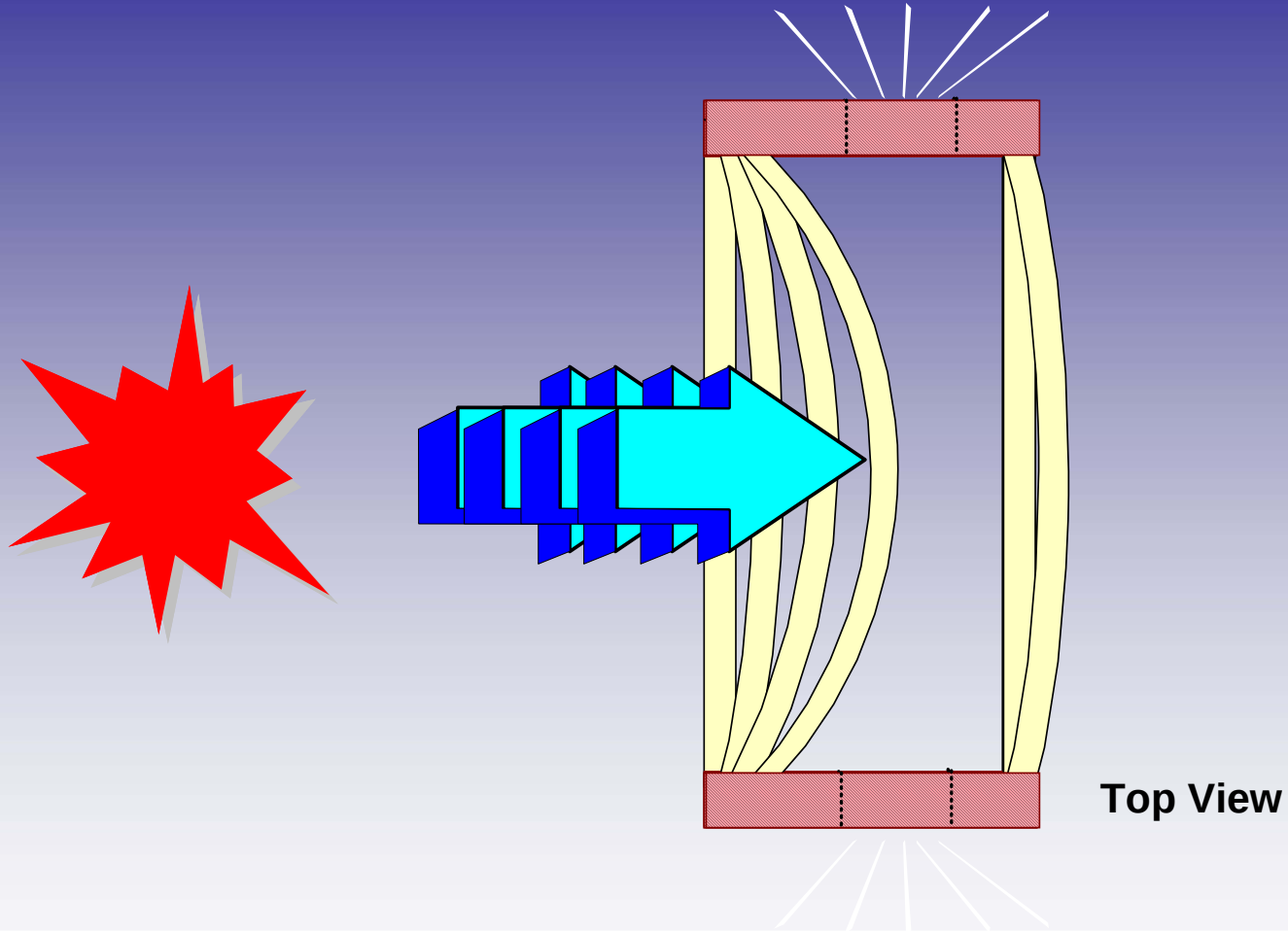
AFRL Blast Resistant Windows New Concepts



- Damping chamber windows
- Perimeter anchored laminate (PAL) glazings
- Engineered thermoplastics with abrasion resistant coatings



Damping Chamber Windows



Conceptual Performance of Damping Chamber Window

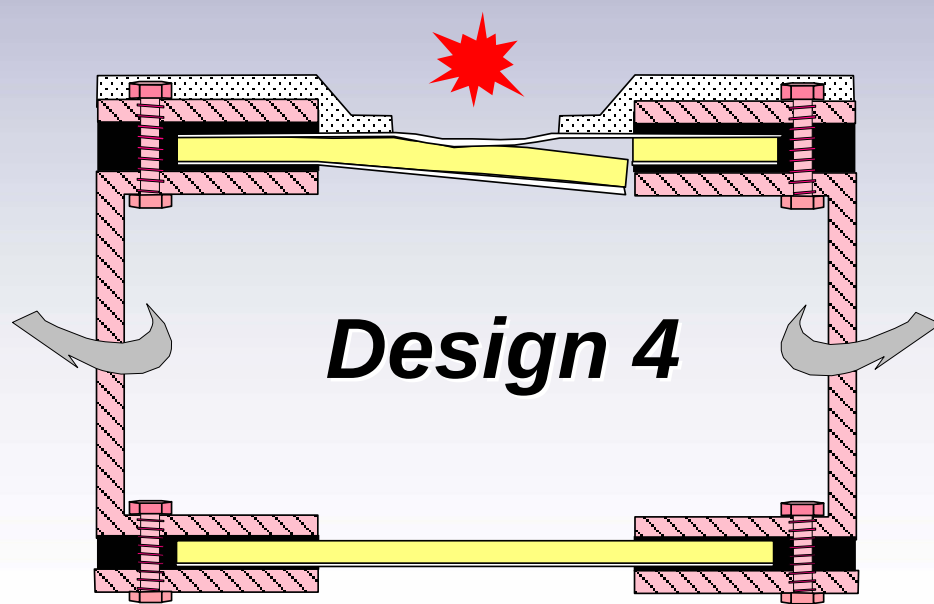
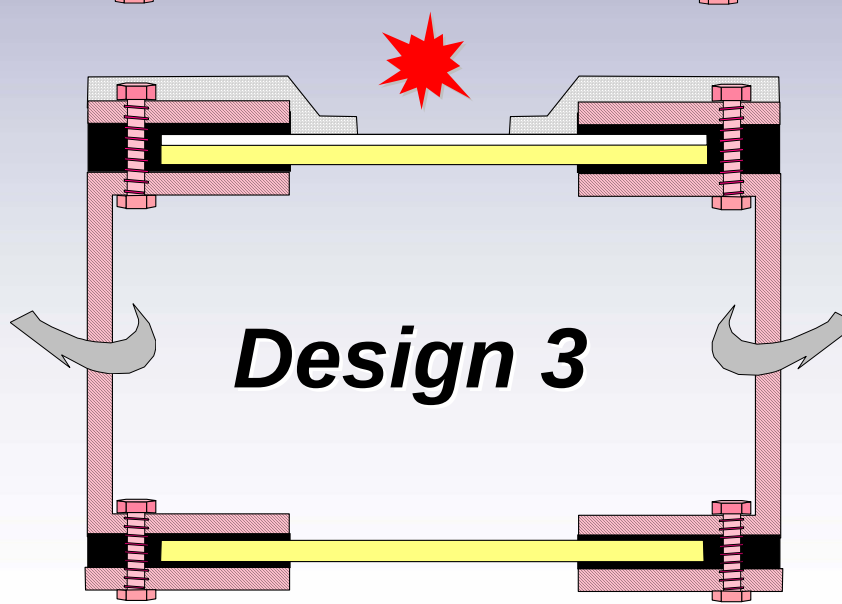
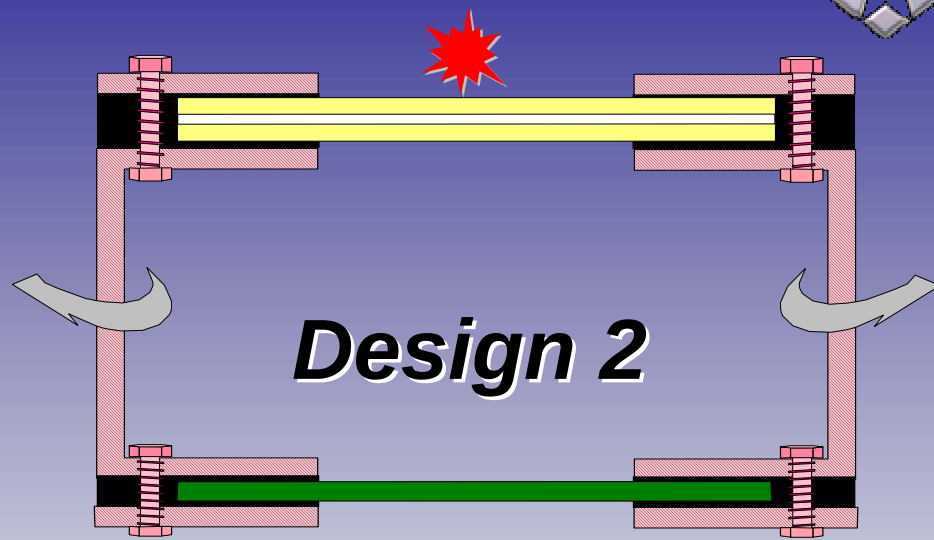
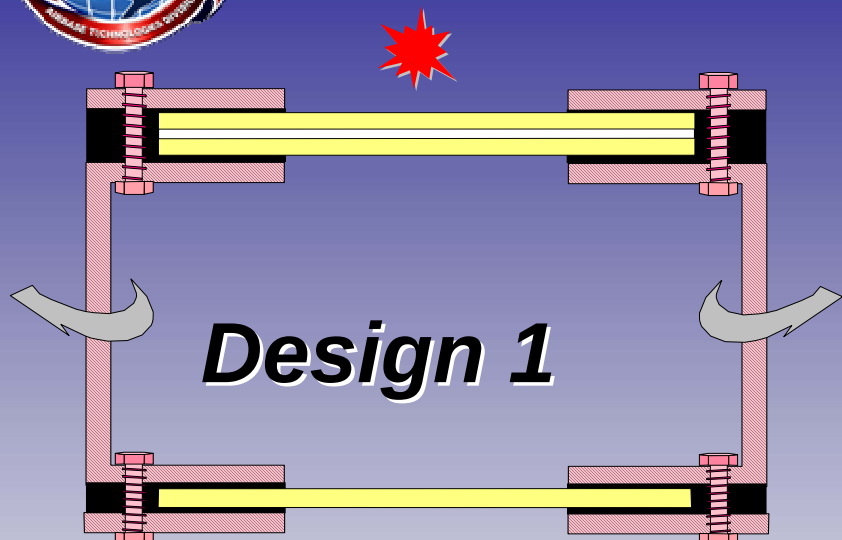


Damping Chamber Window Window Frame



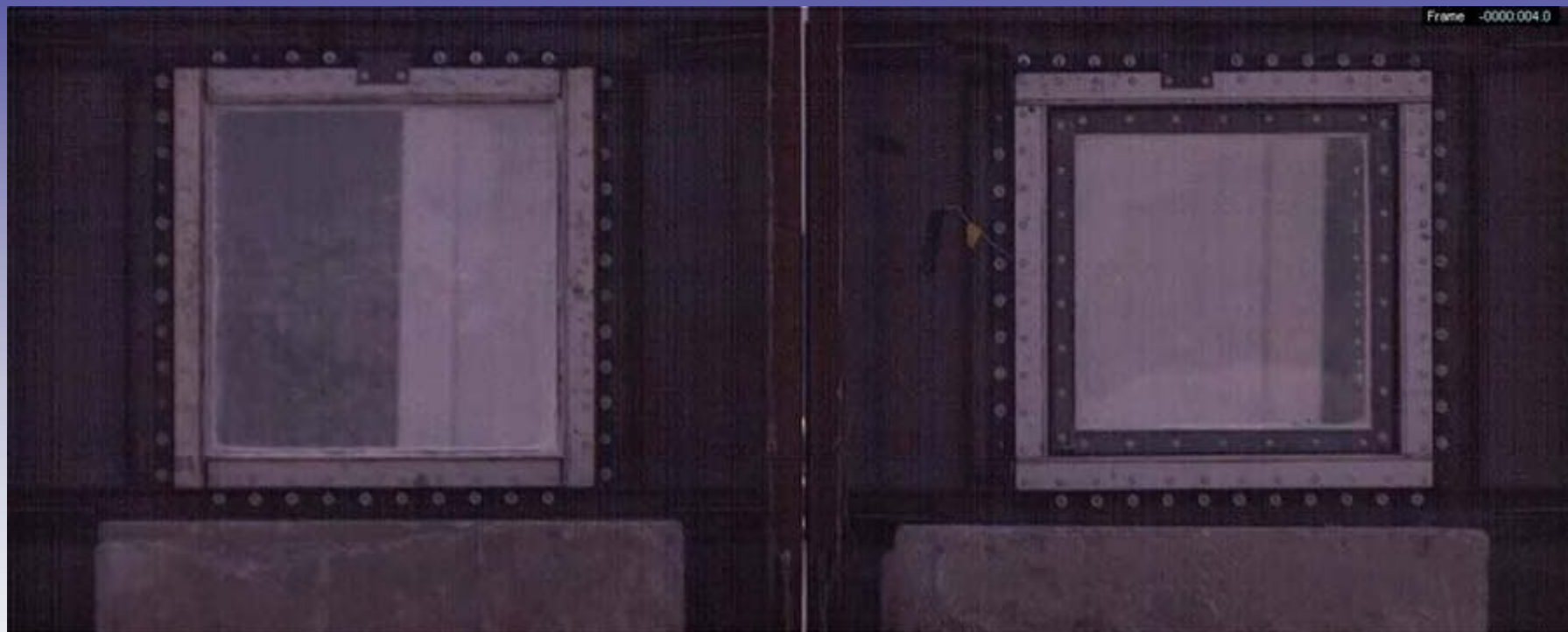


1st Generation Windows





2nd Generation Designs 3 and 4



High Speed Video of 2nd Generation Damping Chamber
Window Designs 3 and 4 During Testing



2nd Generation Design 3



Pretest Photo of Blast Side



Posttest Photo of Blast Side



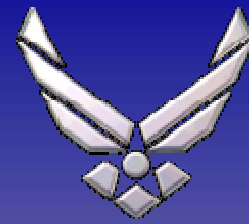
2nd Generation Design 4



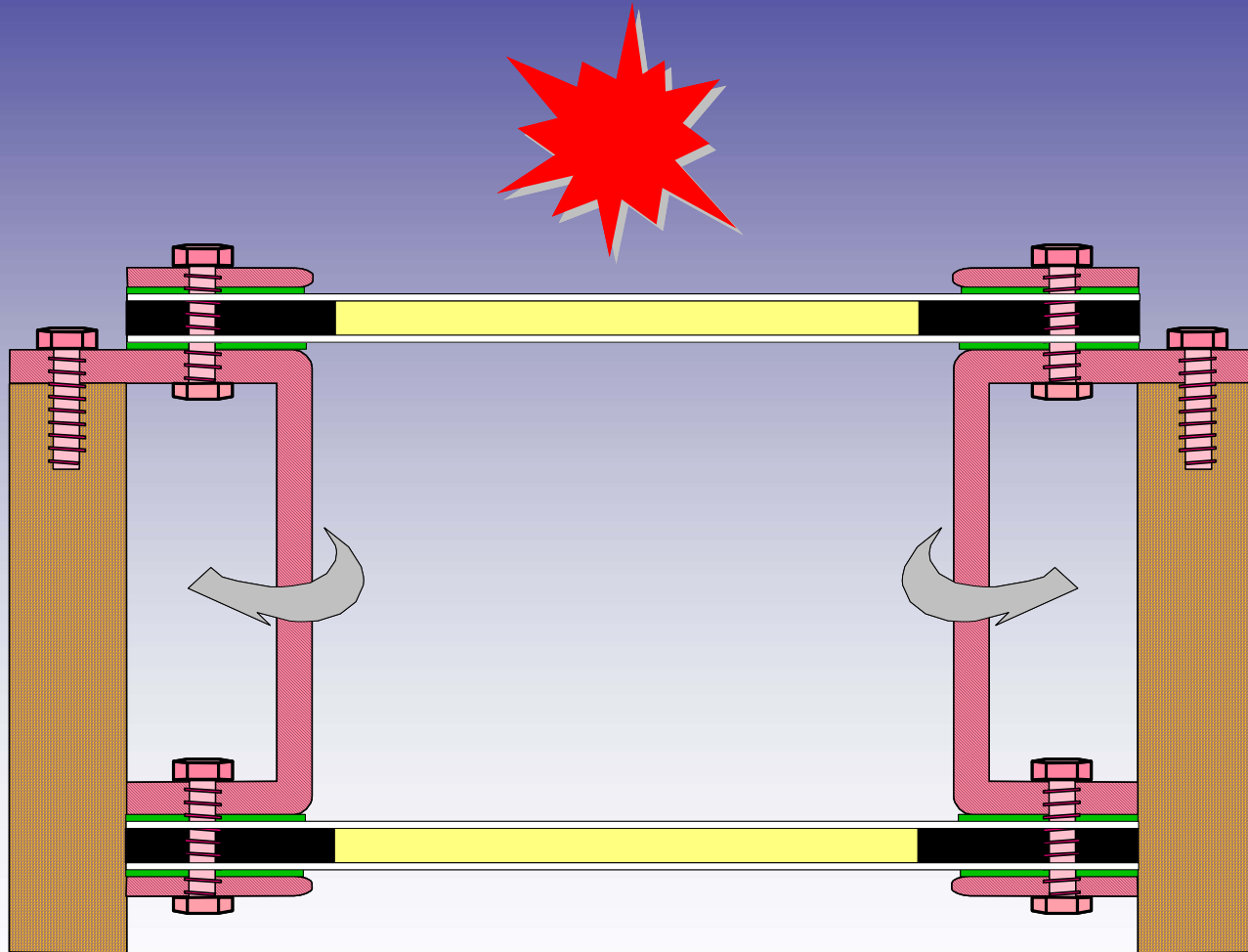
Pretest Photo of Blast Side



Posttest Photo of Blast Side



2nd Generation Accepted Design





Perimeter Anchored Laminates Design Approach



- Laminate to exhibit tension membrane: extend and attach interlayer(s) into the frame rather than the glass
- Anchor system stronger than laminate
- Laminate to withstand blast overpressure



PAL

Laminate Types

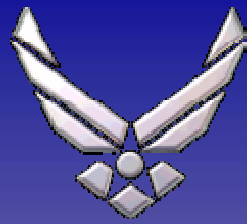


- Polycarbonate
- PolyVinylButyral (PVB)
- SentryGlas® Plus (SGP)
 - Developed by DuPont
 - Provides greater tear strength and rigidity than PVB



PAL

Anchoring Methods

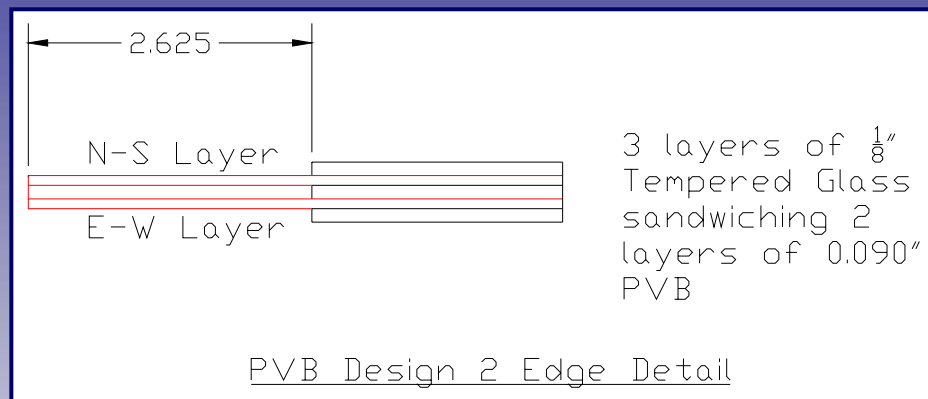


- Clamping
- Mechanical anchoring (i.e. LAMLOK system)
- Bolting
- Modified designs
- Adhesive (not examined)

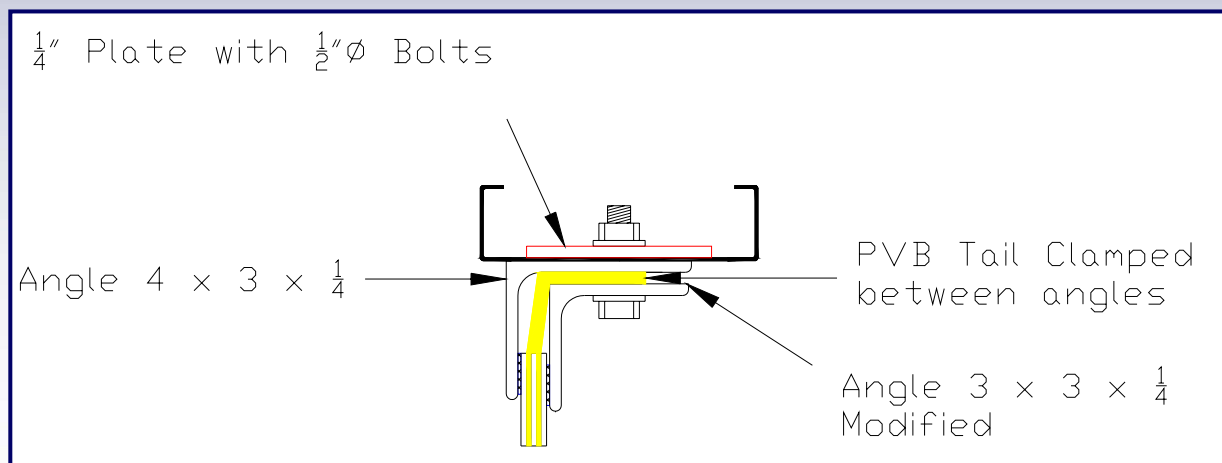


PAL Anchoring Methods

Clamping



PVB Laminate "Tails" Clamped in Frame





PAL Anchoring Methods

Clamping



Corked Outer Frame



Glazing Before Inner Frame

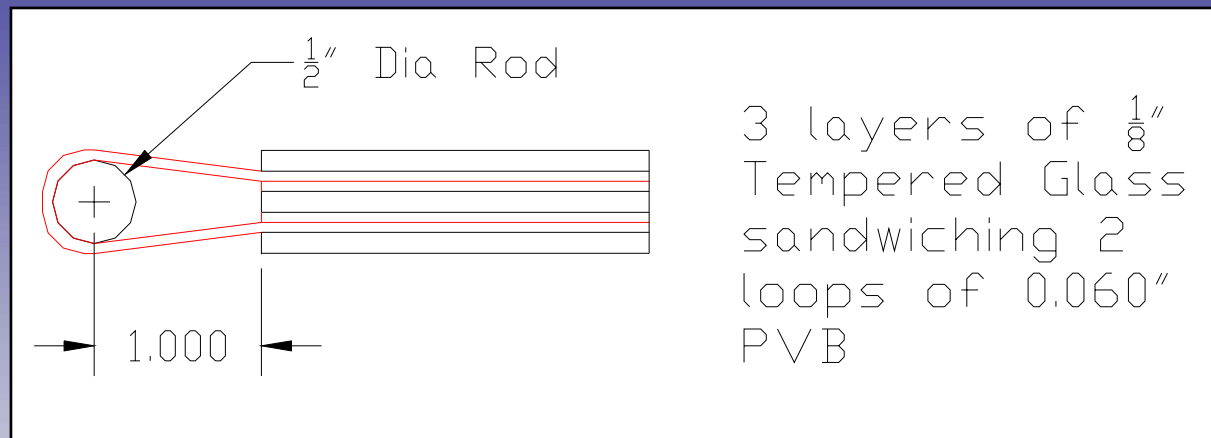


PVB Tails

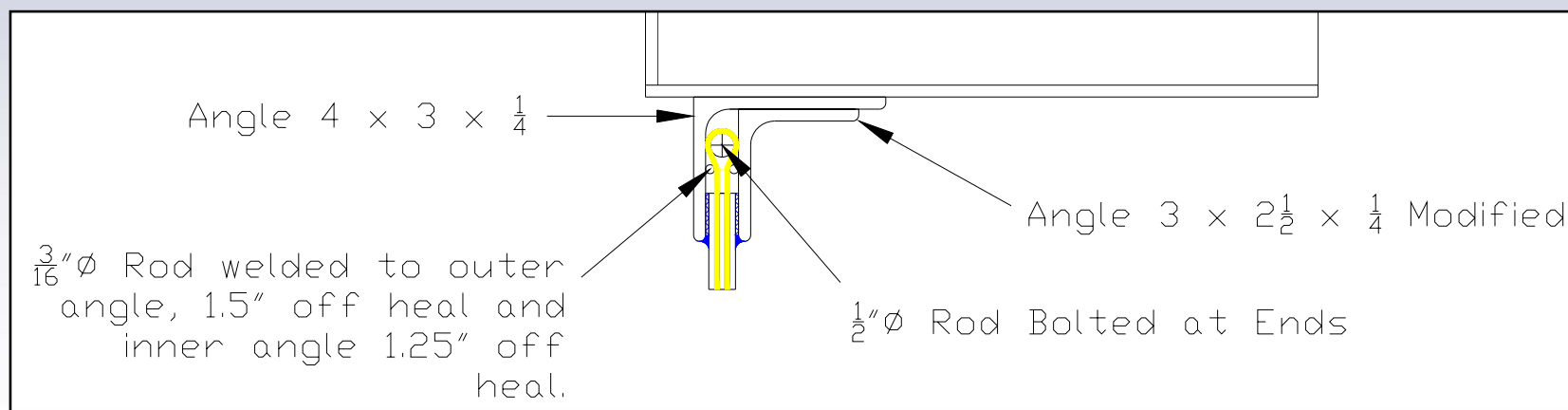


PAL Anchoring Methods

Mechanical Anchoring



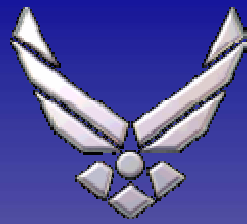
PVB Laminate Wrapped Around Steel Rod and Clamped in Frame





PAL Anchoring Methods

Mechanical Anchoring



Laminated 1/2" Rods



Rods Welded on Frame



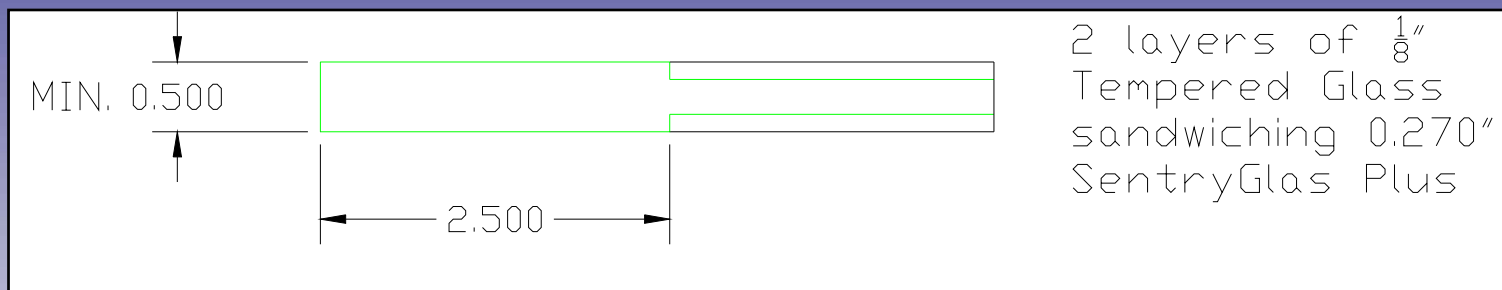
Rod Placement Close-up



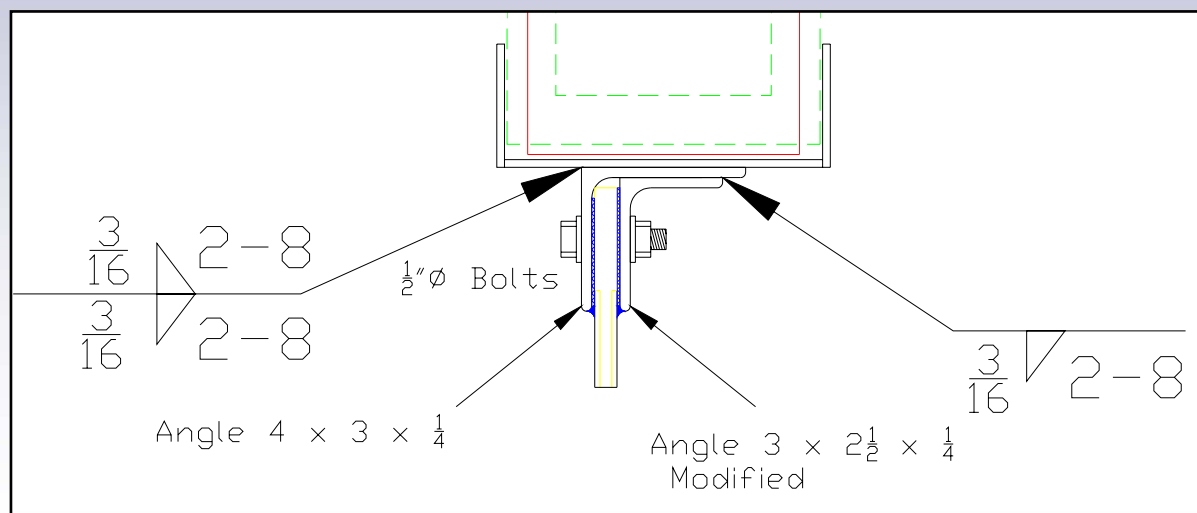
Finished Inner Corner



PAL Anchoring Methods Bolting



SentryGlas® Plus Laminate "Tails" Bolted in Frame





PAL Anchoring Methods Bolting



Outer Frame Detail



Detail Before Inner Frame

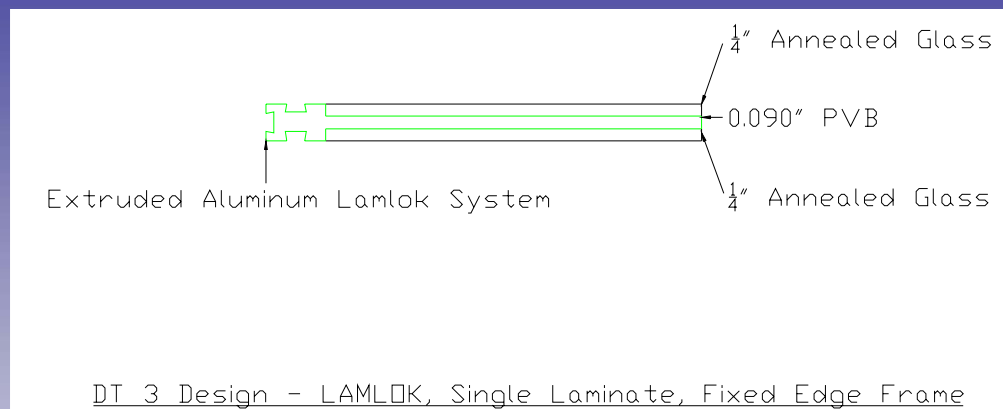


Completed Window

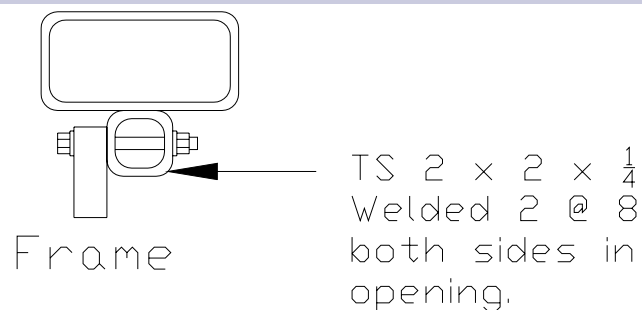


PAL Anchoring Methods

LAMLOK



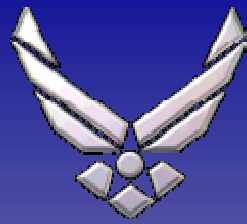
"Lock" and "Key" Mechanism Holds Laminate in Frame



Steel Frame Section A-A (Typ)



PAL Full-Scale Testing



Objectives

- Establish proof-of-concept data points for perimeter anchored laminate designs
- Evaluate performance of perimeter anchored laminate designs framed within blast retrofitted walls
- Establish blast resistance data points for various types of laminate windows including bent glass designs
- Validate improved perimeter anchorage methods



Full-Scale Testing Initial Validation



Blast Response of Exterior Walls Experiment 2 (BREW-2)





BREW 2

Window Descriptions



LAMLOK PVB (all 4 sides)

1/4" AG + 0.090"
PVB + 1/4" AG

Bolted Polycarbonate

1/8" TG + 0.050"
Polyurethane (PT)
+ 1/4" PC + 0.050"
PT + 1/8" TG +
0.008" Film

Clamped PVB

1/8" TG + 0.180"
PVB + 1/8" TG +
0.180" PVB + 1/8"
TG + 0.008" Film

Hinged LAMLOK PVB

1/4" AG + 0.270"
PVB + 1/4" AG



BREW 2

Window Descriptions



Standard Frame Bite PVB, Bent Glass

Two panes of 1/4"
AG + 0.270" PVB
+ 1/4" AG

Bolted SGP

1/8" TG + 0.270"
SGP + 1/8" TG +
0.008" Film

Mechanically Anchored PVB

1/8" Tempered
Glass (TG) +
0.180" PVB + 1/8"
TG + 0.180" PVB
+ 1/8" TG + 0.008"
Film

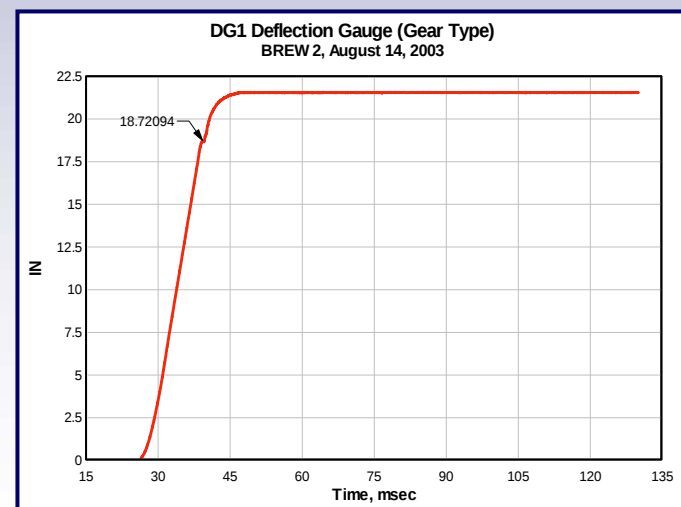
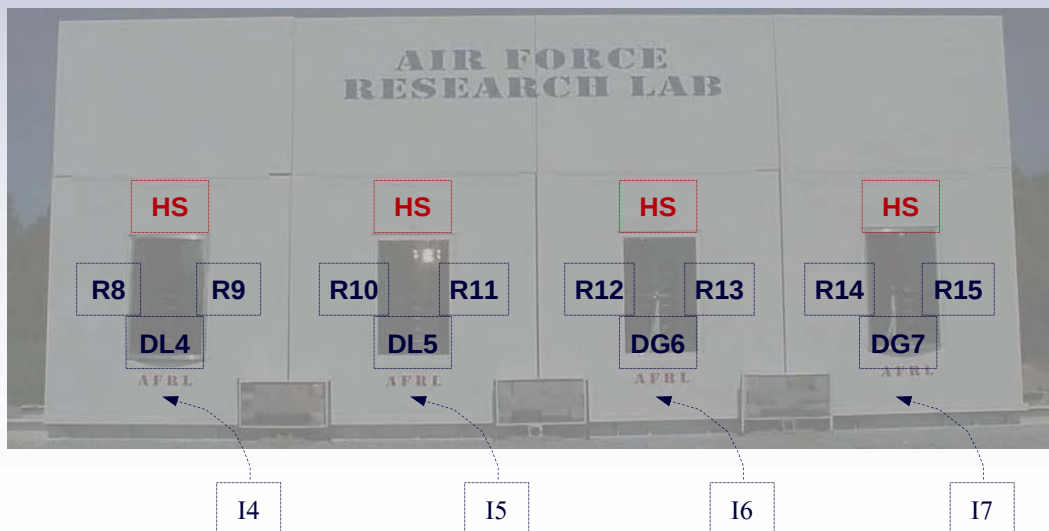
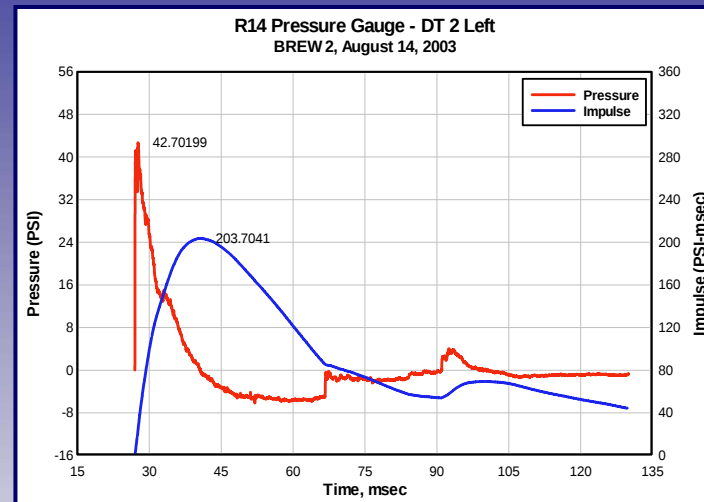
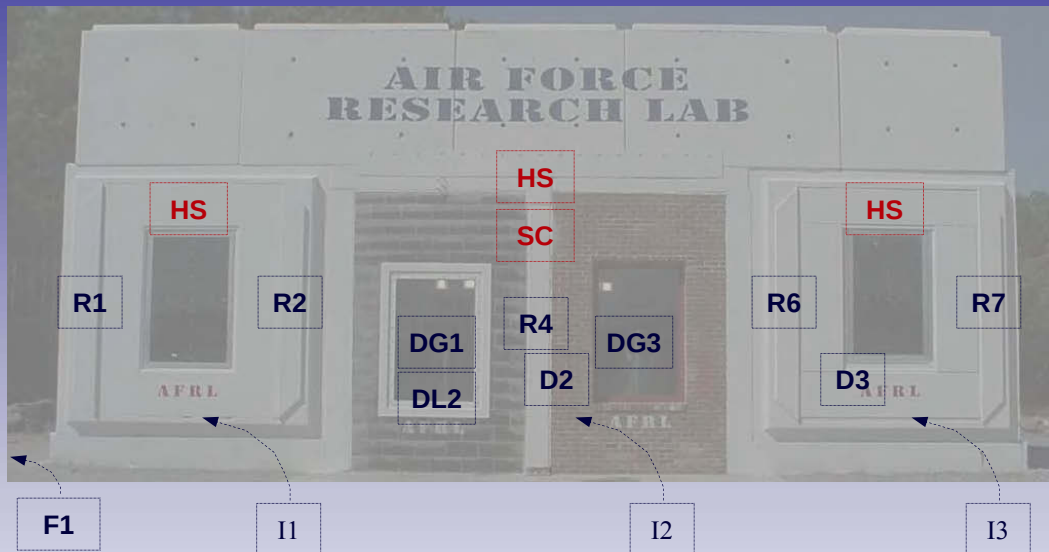
LAMLOK PVB, Bent Glass

1/4" AG + 0.270"
PVB + 1/4" AG



BREW 2

Data Collection





BREW 2 Test Results



SUCCESSFUL



Mechanically Anchored PVB



SUCCESSFUL



Clamped PVB



BREW 2 Test Results



★ **UNSUCCESSFUL**



Bolted SGP



SUCCESSFUL



Bolted Polycarbonate



BREW 2 Test Results



SUCCESSFUL



Standard Frame Bite PVB, Bent Glass



SUCCESSFUL



LAMLOK PVB, Bent Glass



BREW 2 Test Results



UNSUCCESSFUL



LAMLOK PVB (all 4 sides)



SUCCESSFUL



Hinged LAMLOK PVB



BREW 2

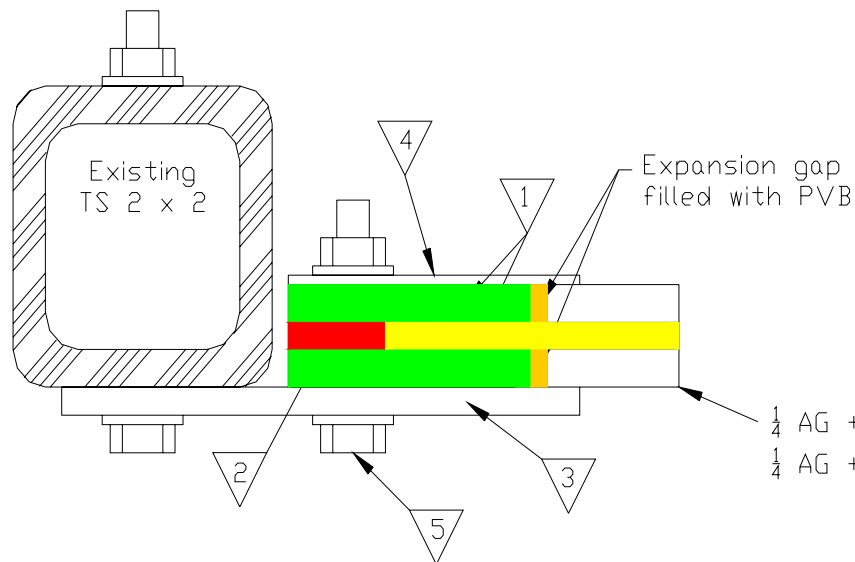
Conclusions



- Mechanical anchorage method effective in allowing laminate to reach maximum tension membrane
- Bent glazing provided higher resistance allowing greater dissipation of energy as indicated by glass shard size/pattern, reduced deflection, and lower glazing velocity
- Anchored, hinged edges demonstrated emergency egress capabilities
- Further research needed for bolting anchorage method



PAL Anchoring Methods Modified Designs



SGP Design 1

1	$\frac{1}{4}$ " $\times$ $1\frac{7}{8}$ " Aluminum flat stock
2	$\frac{1}{4}$ " $\times$ $\frac{3}{4}$ " Aluminum flat stock
3	$\frac{1}{4}$ " $\times$ 4" Aluminum flat stock
4	$\frac{1}{16}$ " $\times$ $2\frac{1}{4}$ " Aluminum
5	$\frac{1}{4}$ " $\varnothing$ Grade 5 bolts at 6" centers

$\frac{1}{4}$ AG + 0.270" SGP + $\frac{1}{4}$ AG + 0.008" film with 1.25" SGP tail
 $\frac{1}{4}$ AG + 0.180" SGP + $\frac{1}{4}$ AG + 0.008" film with 1.25" SGP tail

SGP Laminate Bonded to Aluminum and Bolted in Frame



PAL Anchoring Methods Modified Designs



Aluminum Edge Layup



Edge Anchorage Holes

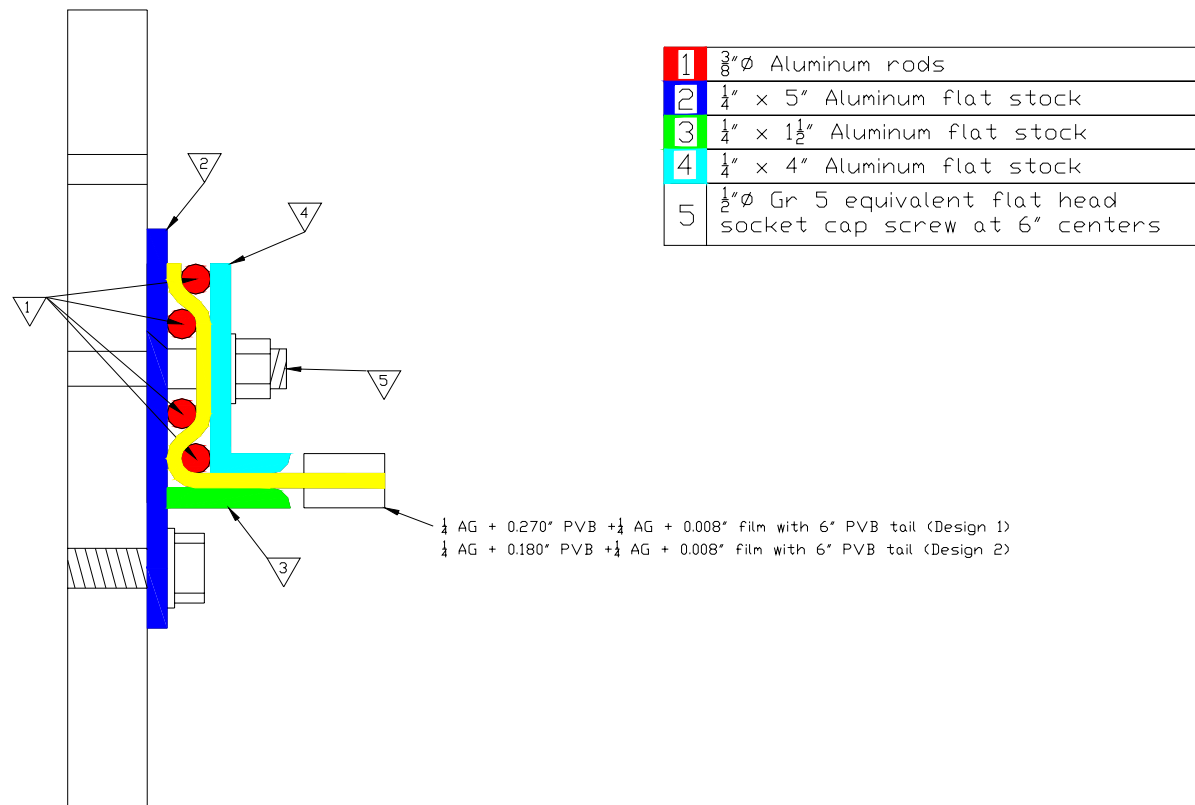


Ready For Vacuum Bag/Autoclave

SGP Laminate Bonded to Aluminum and Bolted in Frame



PAL Anchoring Methods Modified Designs



PVB Laminate "Tail" Turned 90 Degrees and Clamped in Frame
Between Aluminum Rods



PAL Anchoring Methods Modified Designs



Bagged Edges

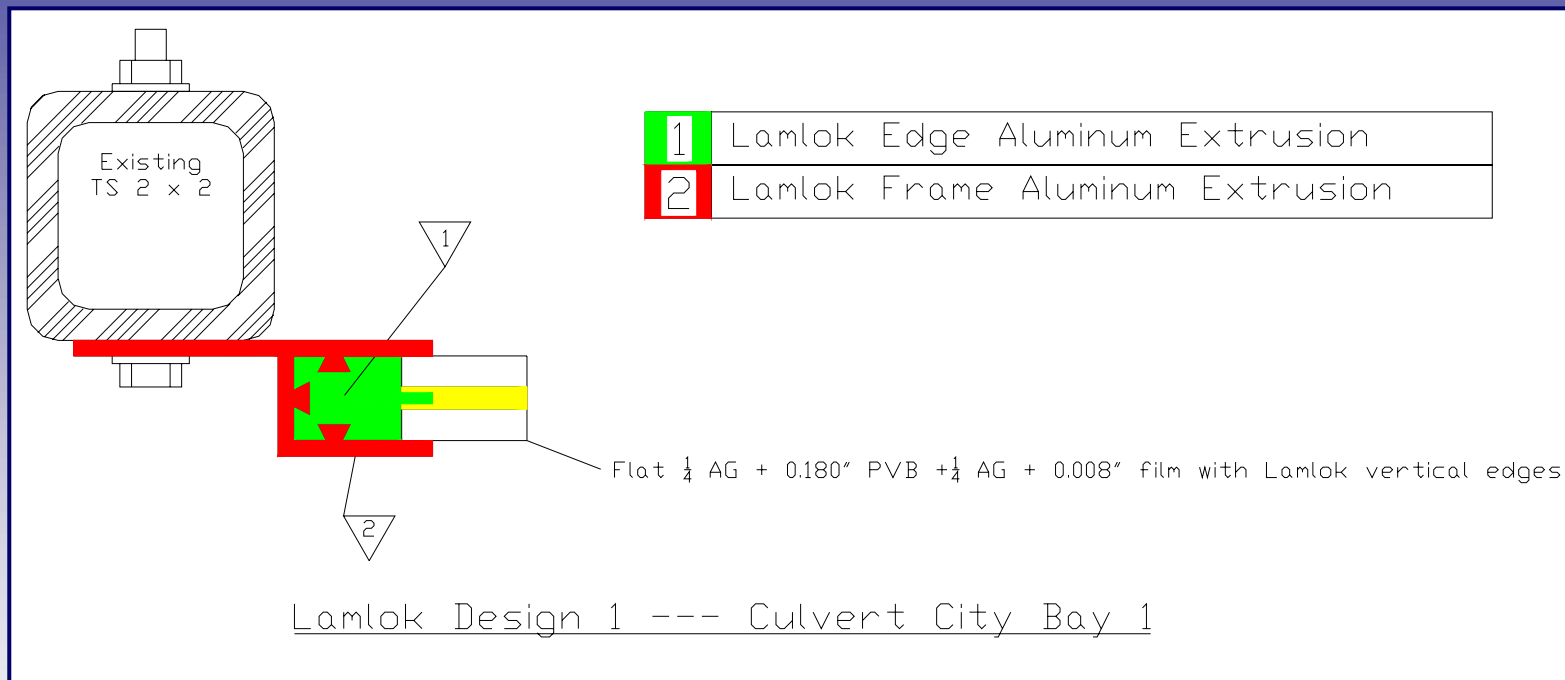
Clamped Corner



PVB Laminate “Tail” Turned 90 Degrees and Clamped in Frame
Between Aluminum Rods



PAL Anchoring Methods Modified Designs



LAMLOK System with Different Interlocking Mechanism



PAL Anchoring Methods Modified Designs



Edge Layup



Bent Frame Pieces

LAMLOK System with Different Interlocking Mechanism



Full-Scale Testing Second Iteration



Blast Response of Exterior Walls Experiment 3 (BREW 3)



BREW 3

Window Descriptions



**0.180" SGP
Bonded
Aluminum +
Bolts**

Flat ¼ AG + 0.180
SGP + ¼ AG +
0.008 Film

**0.270" SGP
Bonded
Aluminum +
Bolts**

Flat ¼ AG + 0.270
SGP + ¼ AG +
0.008 Film



BREW 3

Window Descriptions



LAMLOK PVB

Flat $\frac{1}{4}$ AG + 0.180
PVB + $\frac{1}{4}$ AG +
0.008 Film

0.180" PVB Clamped Tail

Flat $\frac{1}{4}$ AG + 0.180
PVB + $\frac{1}{4}$ AG +
0.008 Film

0.270" PVB Clamped Tail

Flat $\frac{1}{4}$ AG + 0.270
PVB + $\frac{1}{4}$ AG +
0.008 Film

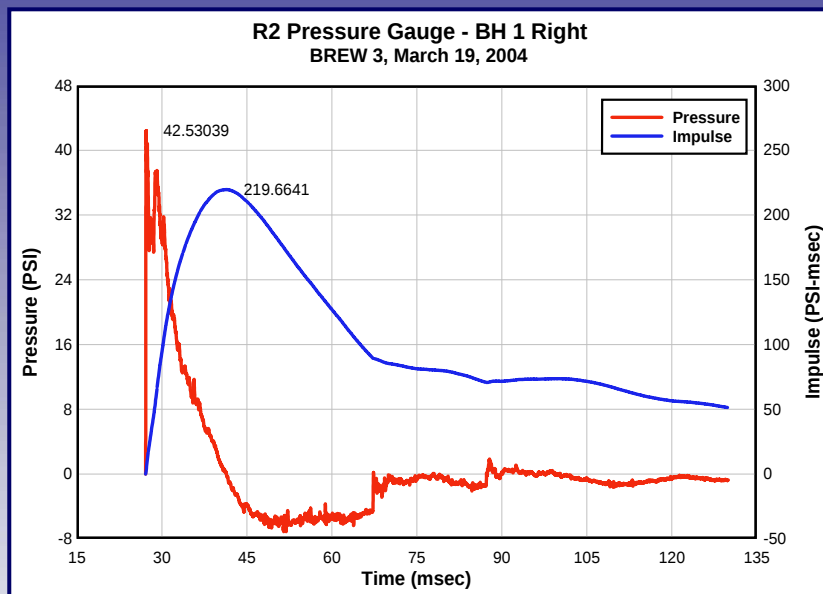
LAMLOK PVB, Bent Glass

60" rad. Bent $\frac{1}{4}$
AG + 0.180 PVB +
 $\frac{1}{4}$ AG + 0.008 Film

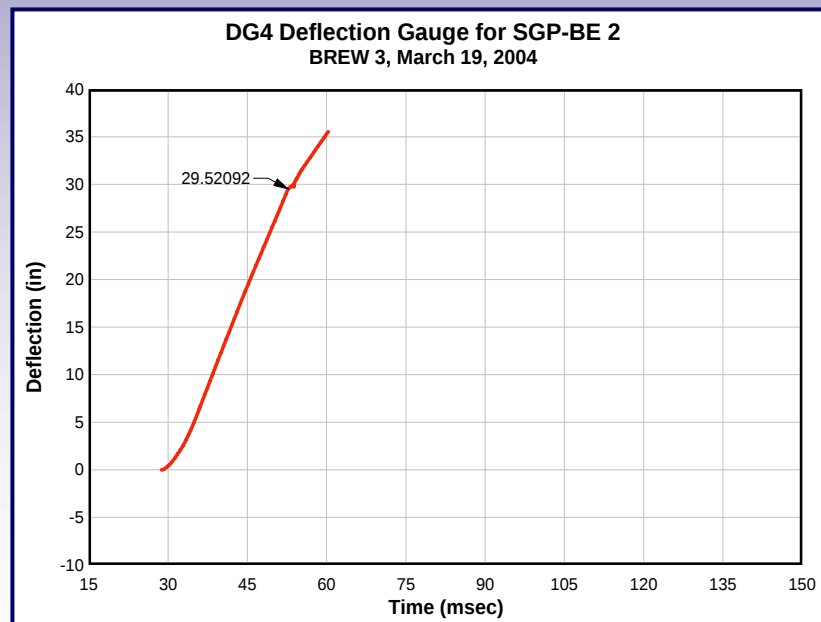


BREW 3

Data Collection



Deflection Readings Higher





BREW 3

Test Results



0.180" SGP Bonded Aluminum + Bolts
SUCCESSFUL



Prevented lethal fragments but portions of the edge
bond failed

0.270" SGP Bonded Aluminum + Bolts
SUCCESSFUL



Prevented lethal fragments with no tears or edge bond
failures





BREW 3

Test Results



**0.180" PVB Clamped Tail
SUCCESSFUL**



Prevented lethal fragments while tearing along a vertical edge

**0.270" PVB Clamped Tail
SUCCESSFUL**



Prevented lethal fragments without tearing



BREW 3 Test Results



**LAMLOK PVB
SUCCESSFUL**



Prevented lethal fragments while tearing along both vertical edges

**LAMLOK PVB, Bent Glass
SUCCESSFUL**



Prevented lethal fragments but an inadequate frame failed



BREW 3

Conclusions



- Anchoring PVB using 90 degree clamping method with bolts is an effective low cost option
- Key “tearing/stays in frame” data point established for 180 mil thick PVB
- Window deflection minimally affected by laminate type or thickness
- Additional investigation needed to eliminate bolt shear and edge bond failures

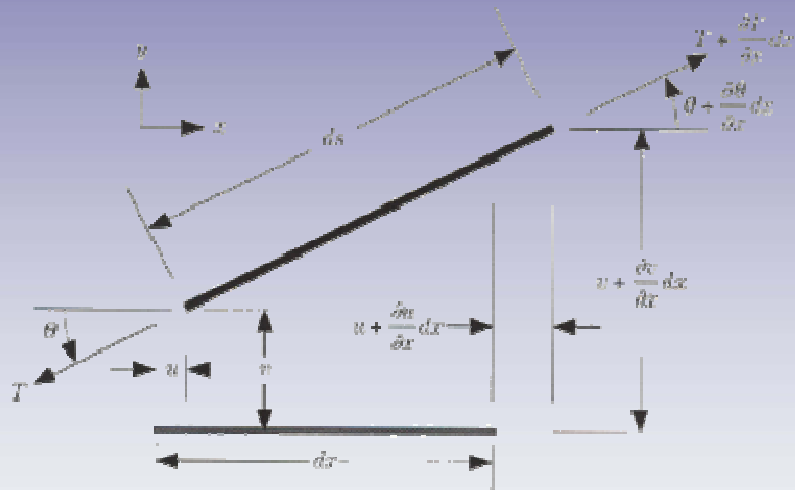


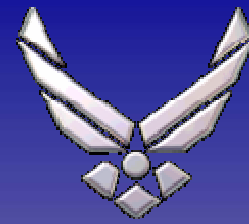
Modeling & Material Testing



ANALYTICAL APPROACH FOR LAMINATES

- Develop constitutive equations for the laminates at high strain rates
- Develop non-linear dynamic response model for PAL to airblast loads
- Validate models with experimental test data (loading functions on windows)
- Use models to predict/optimize material parameters for concept design



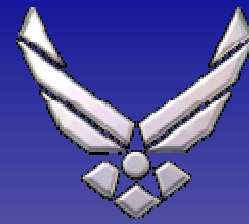


Material Testing

MTS-810 High Strain Rate Testing Machine



- One of few in the country
- Examine high strain rate of laminates (none available in literature)
- 15-400 in/s sample rate velocity
- Supporting polymer working group in testing high density, glass-filled composites for SAE (Society of Automotive Eng.)
- Supporting GERC (Graduate Eng. Research Center) testing PET films



Material Testing Samples



PVB/Annealed Glass Interlayer



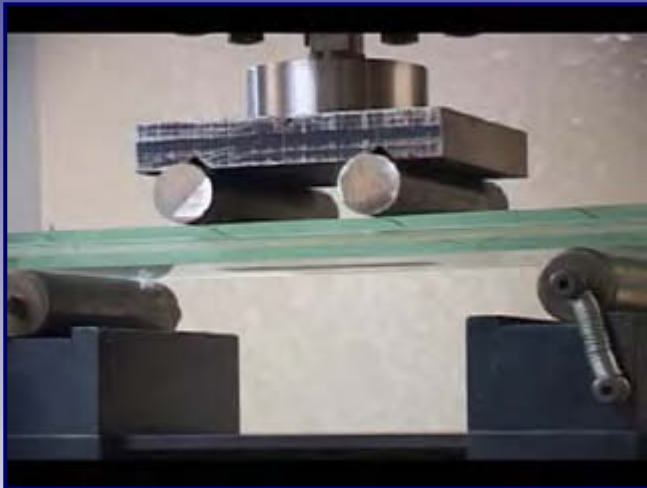
SGP Laminate Bonded to Aluminum



LAMLOK PVB Interlayer System



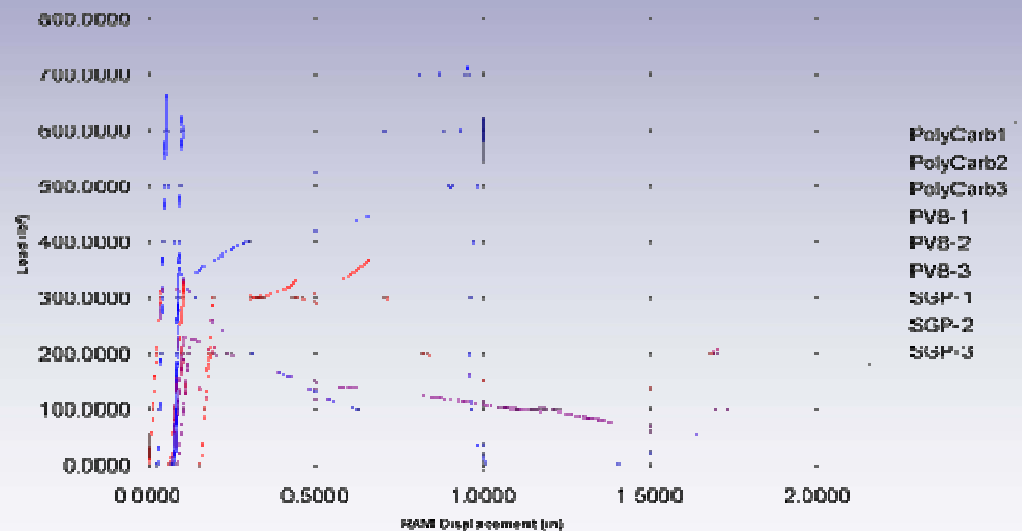
Material Testing



SGP Flexural Bend Test

Testing Results

Flexure Testing





Future Goals

- Improve the modeling of these systems by developing suitable constitutive models for the laminates to use in finite element codes
- Further characterize stress/strain and high strain rate behavior of window laminates to incorporate into finite element models and engineer level analytical tools
- Improve methods for inclusion of window concepts into wall/window blast protection systems
- Continue to adapt emerging materials for use in force protection



Summary



- Current design of blast resistant windows
- Development of AFRL blast resistant windows
- Design approach
- Full-scale experiments
- Material testing
- Modeling
- Future goals

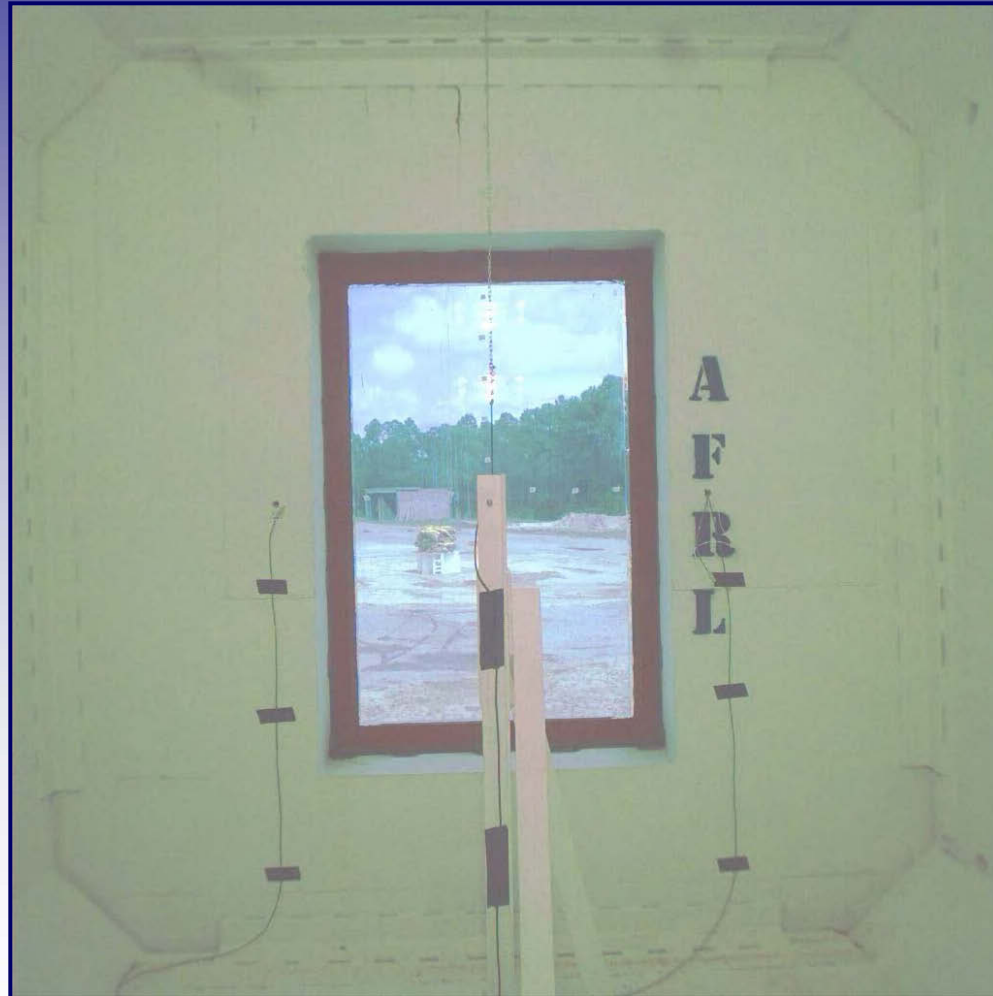


Questions?



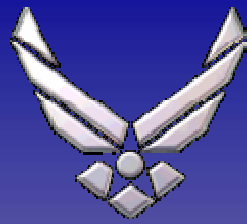


Bolted SGP High Speed Video





Hinged LAMLOK PVB High Speed Video





SGP Bonded Aluminum + Bolts

High Speed Video

