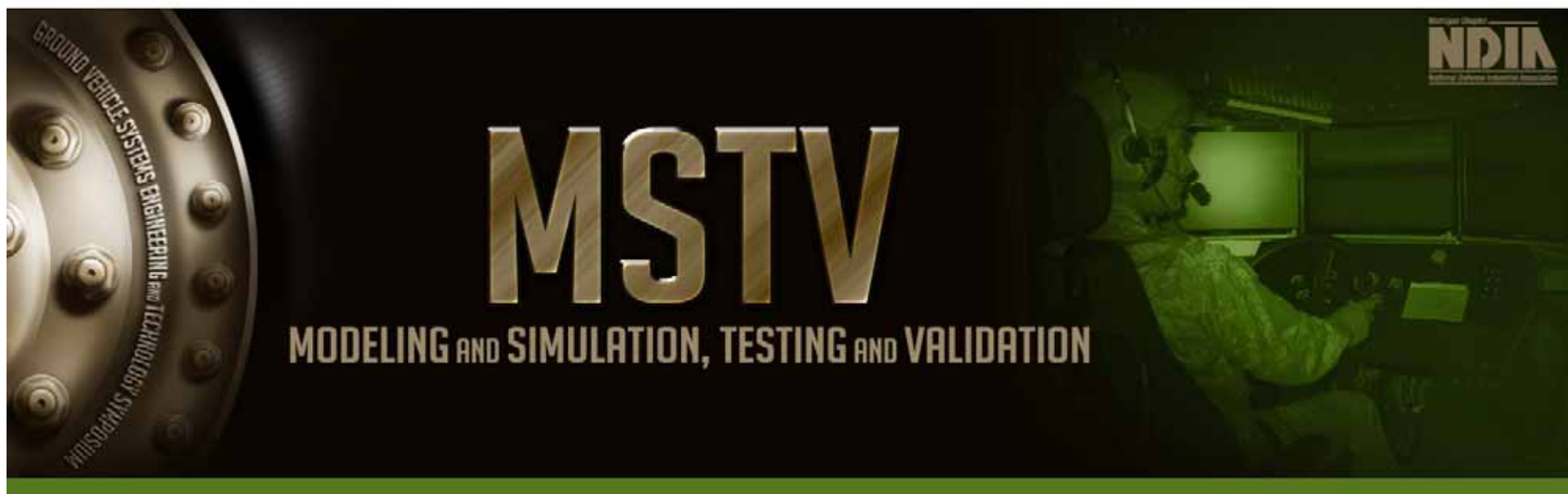


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FUNCTIONALLY-GRADED NPR (NEGATIVE POISSON'S RATIO) MATERIAL FOR A BLAST-PROTECTIVE DEFLECTOR

Zheng-Dong Ma, Gregory M. Hulbert, University of Michigan
Hongxin Bian, Ce Sun, MKP Structural Design Associates, Inc.
Krishan Bishnoi, Farzad Rostam-Abadi, US Army TARDEC

August 19, 2010

GVSETS

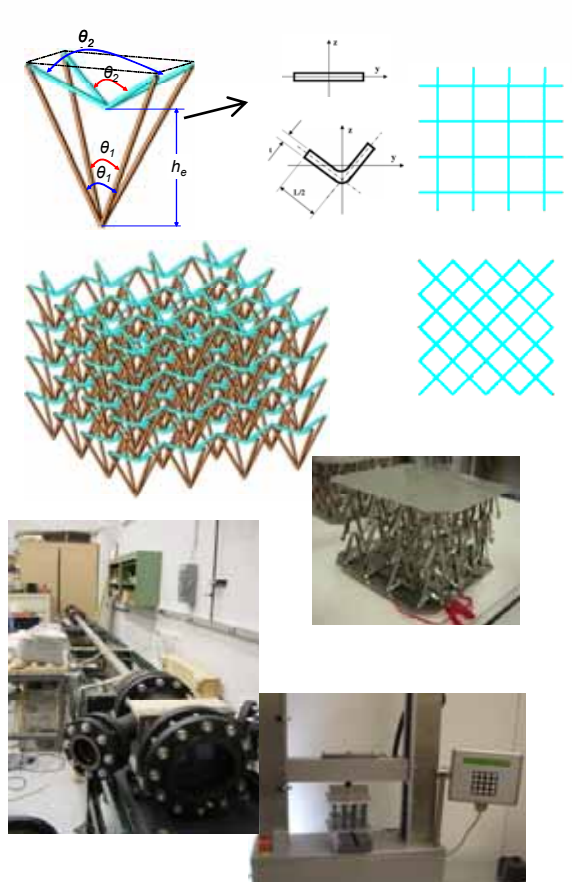
Report Documentation Page

Form Approved
OMB No. 0704-0188

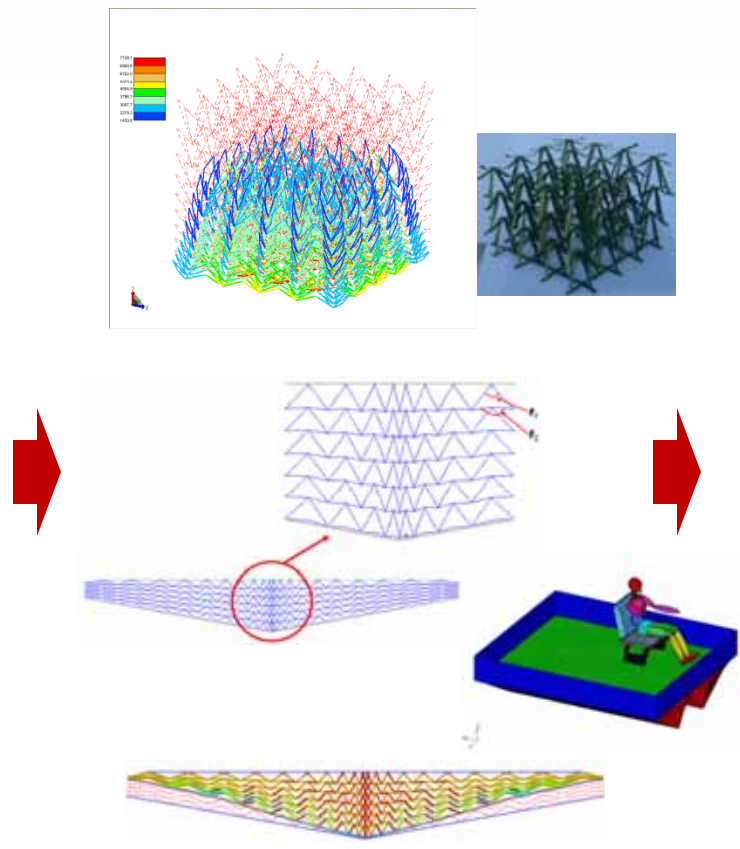
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Presentation Outline



NPR



Functional and
Functionally-graded
NPR

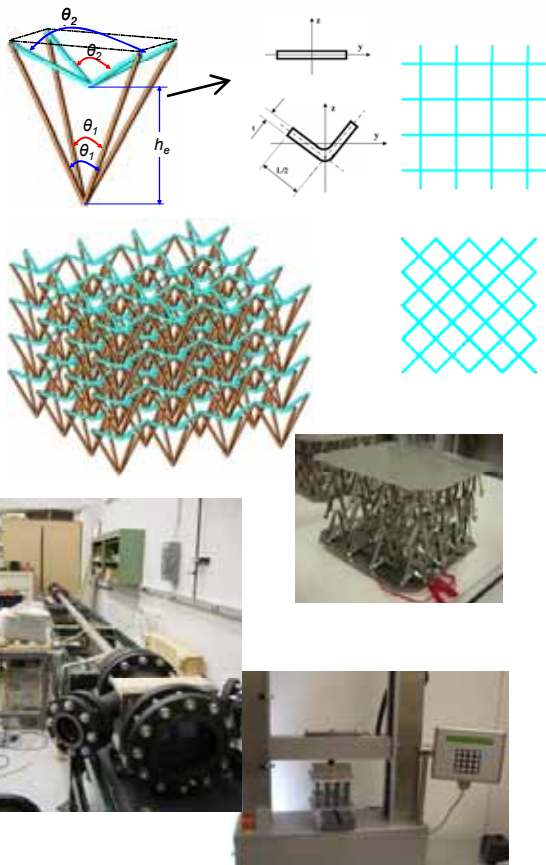


Application to blast
protection

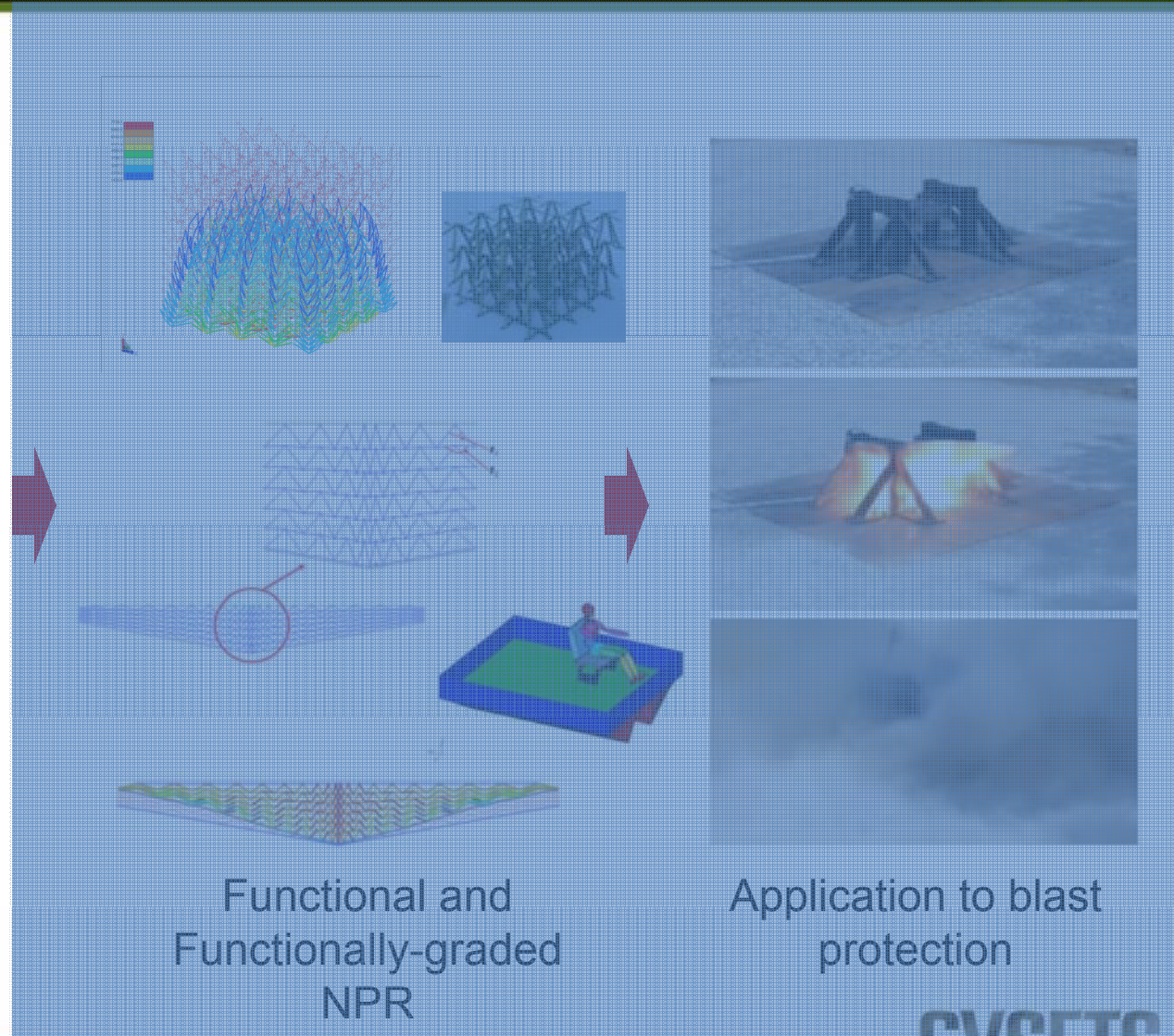
Presentation Outline

MSTV

MODELING AND SIMULATION, TESTING AND VALIDATION



NPR

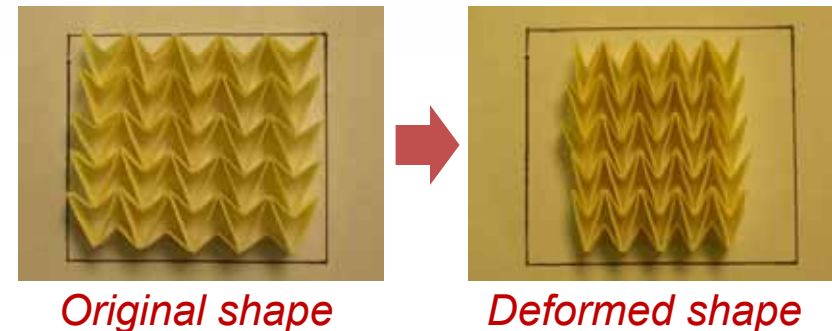


Functional and Functionally-graded NPR

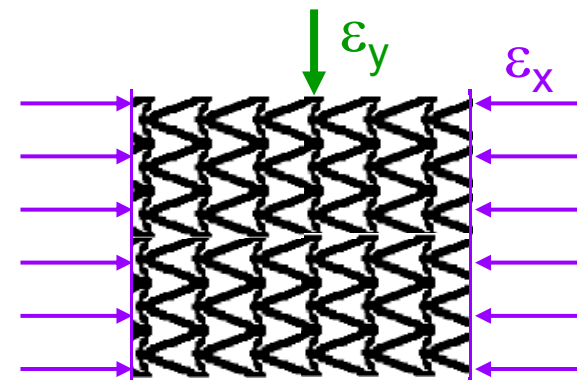
Application to blast protection

Negative Poisson's Ratio (NPR) Material

- *NPR materials* first introduced in 1987 (Lakes, *Science*)
- Unlike conventional materials, NPR materials may shrink when compressed along a perpendicular direction.
- Engineered NPR material concept obtained from a topology optimization process (Larsen, 1997)
- Extended to three-dimensional NPR design (patent pending)



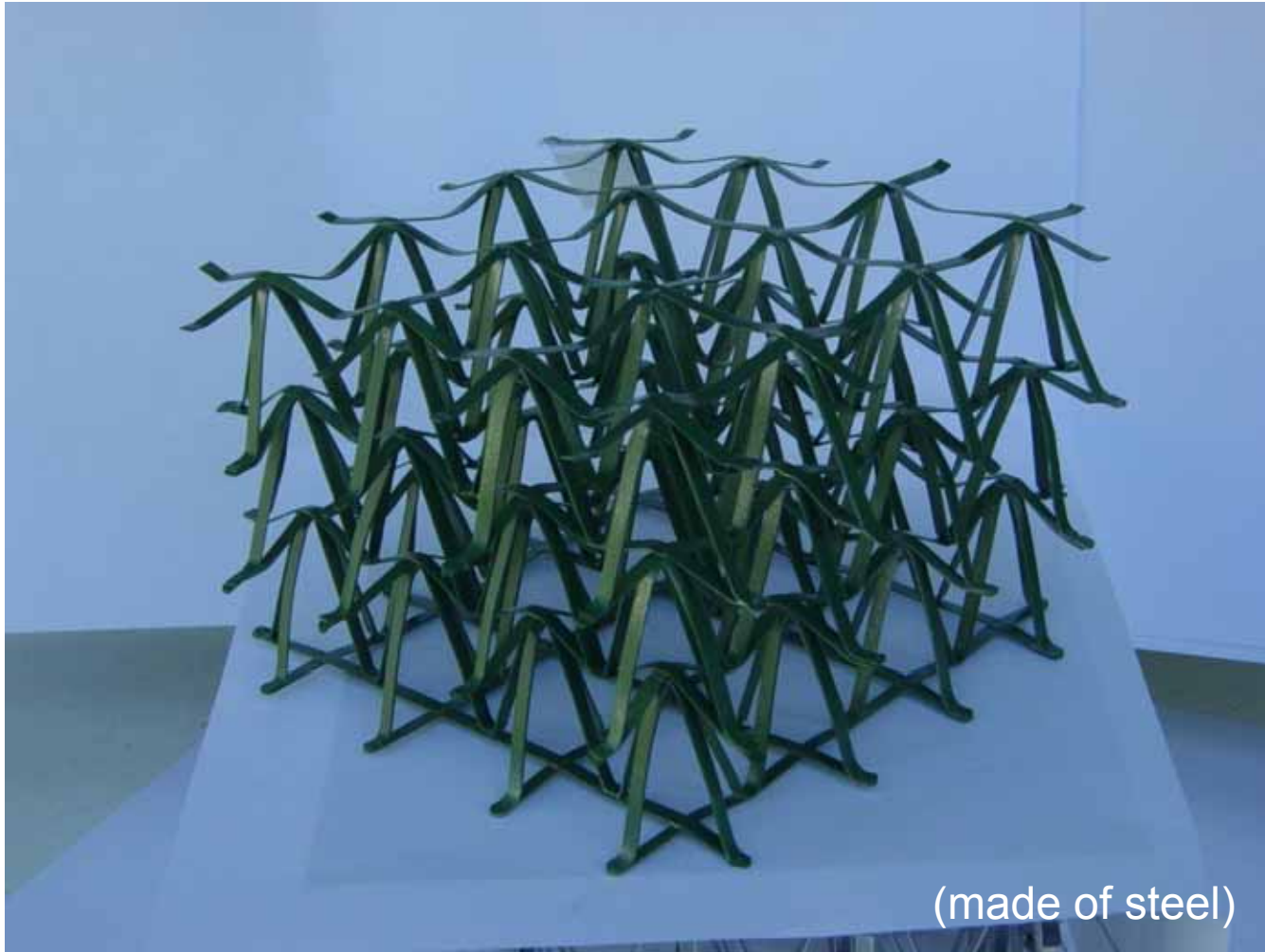
a) NPR effect



b) NPR design from a topology optimization process (Larsen 1997)

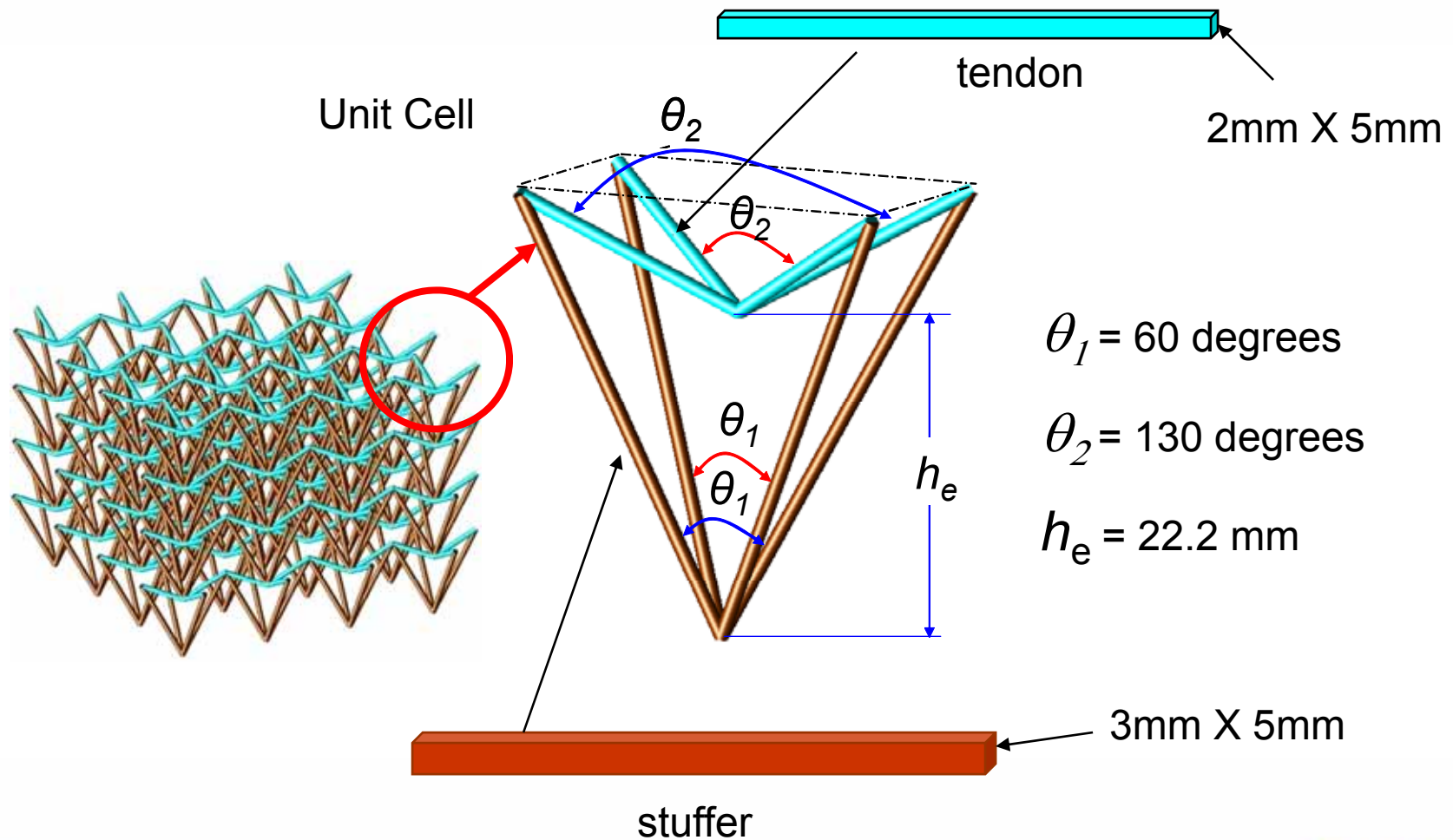
Three-Dimensional NPR Material (MKP Patent Pending)

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MODELING AND SIMULATION, TESTING AND VALIDATION



(made of steel)

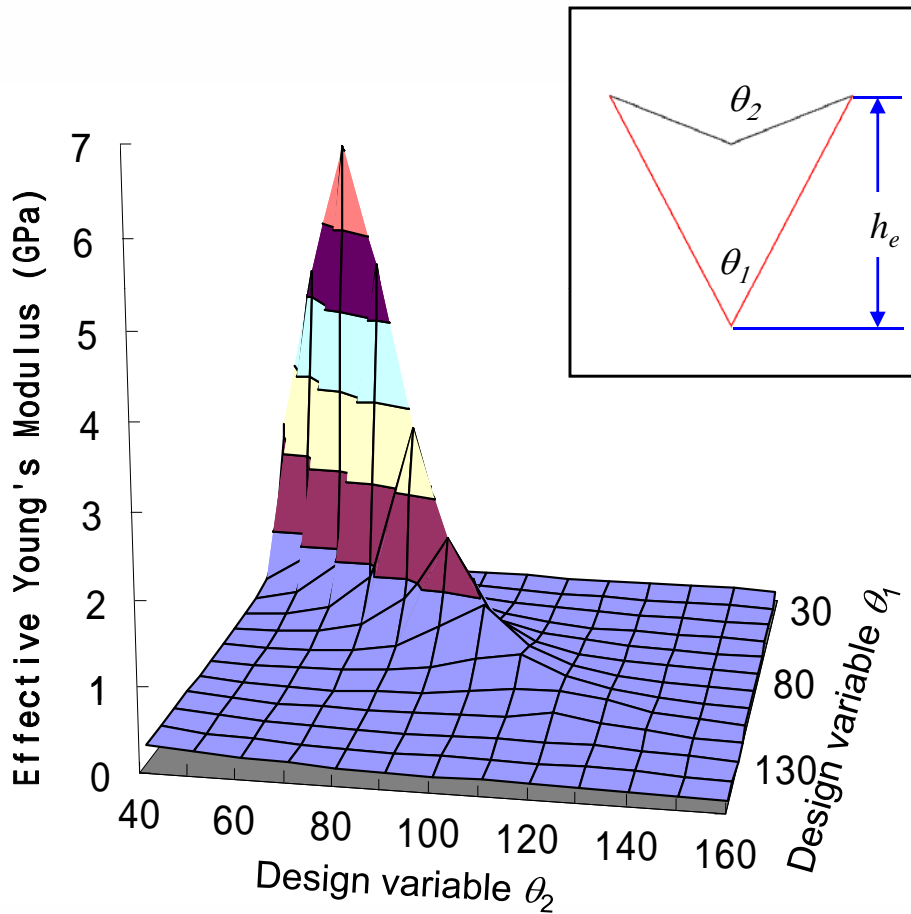
Design Variables



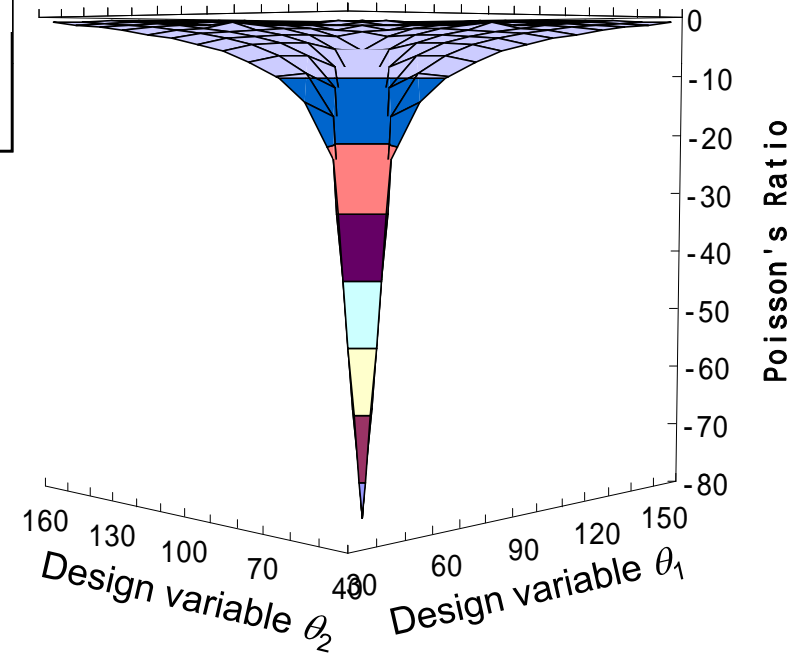
Effective Material Properties

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Effective Young's Modulus

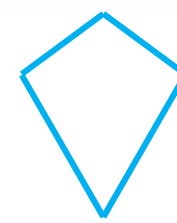
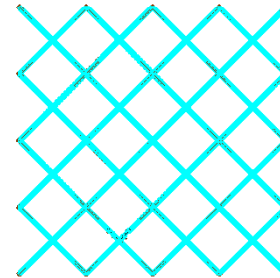
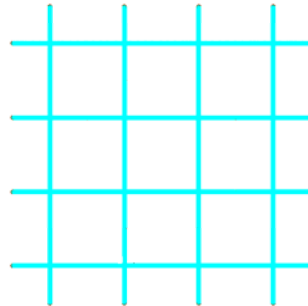
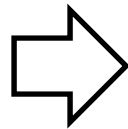
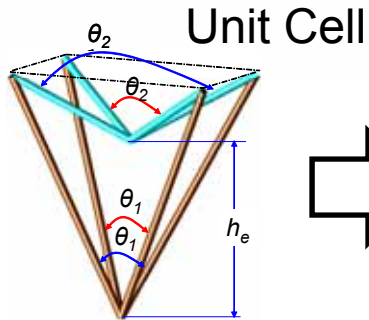


Effective Poisson's Ratio

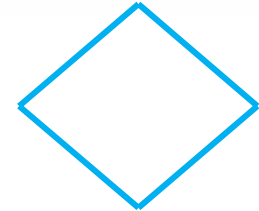
Variations of Arrangement

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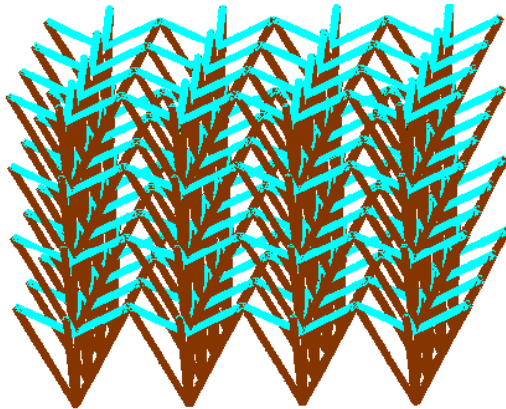
MODELING AND SIMULATION, TESTING AND VALIDATION



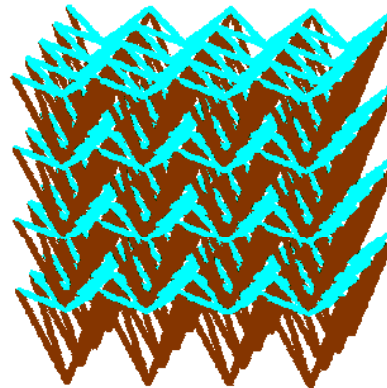
PPR-1



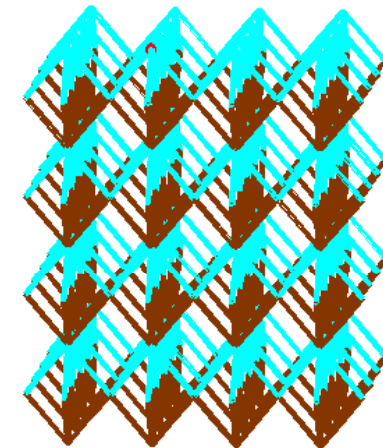
PPR-2



Parallel Configuration
(NPR-p)

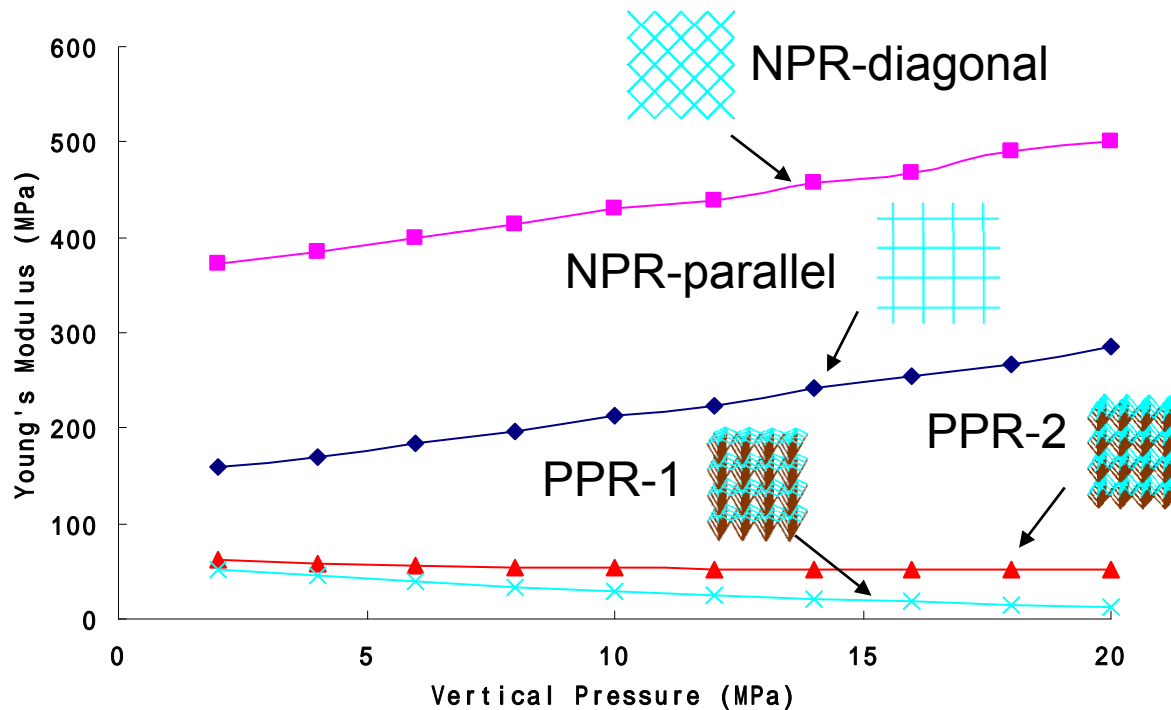


Diagonal configuration
(NPR-d)



PPR configuration
(PPR-1/PPR-2)

Stiffness Comparison of NPR & PPR Materials



- NPR materials are much stiffer and stronger than PPR materials
- When normal pressure increases
 - Stiffness of NPR material increases
 - Stiffness of PPR material decreases
- NPR diagonal material
 - Is the strongest
- NPR parallel material
 - Is the second strongest

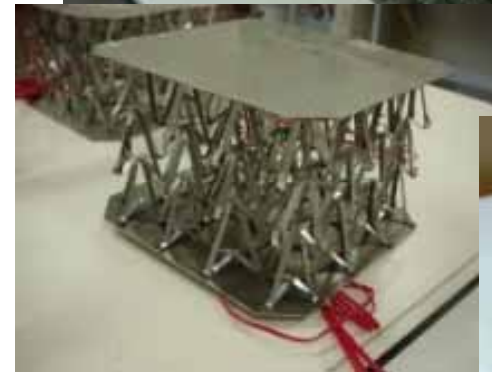
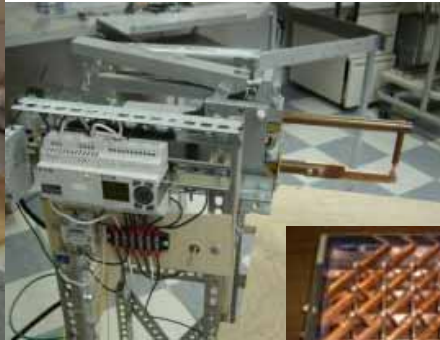
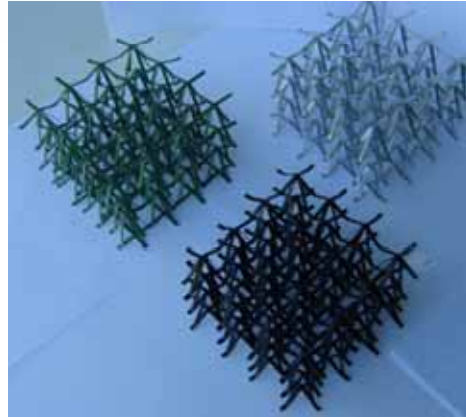
- Young's Modulus with respect to normal pressure
- Same weight and same area density (area density of the NPR-diagonal is 2X)

Manufacturing Process for Coupons Development

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MODELING AND SIMULATION, TESTING AND VALIDATION



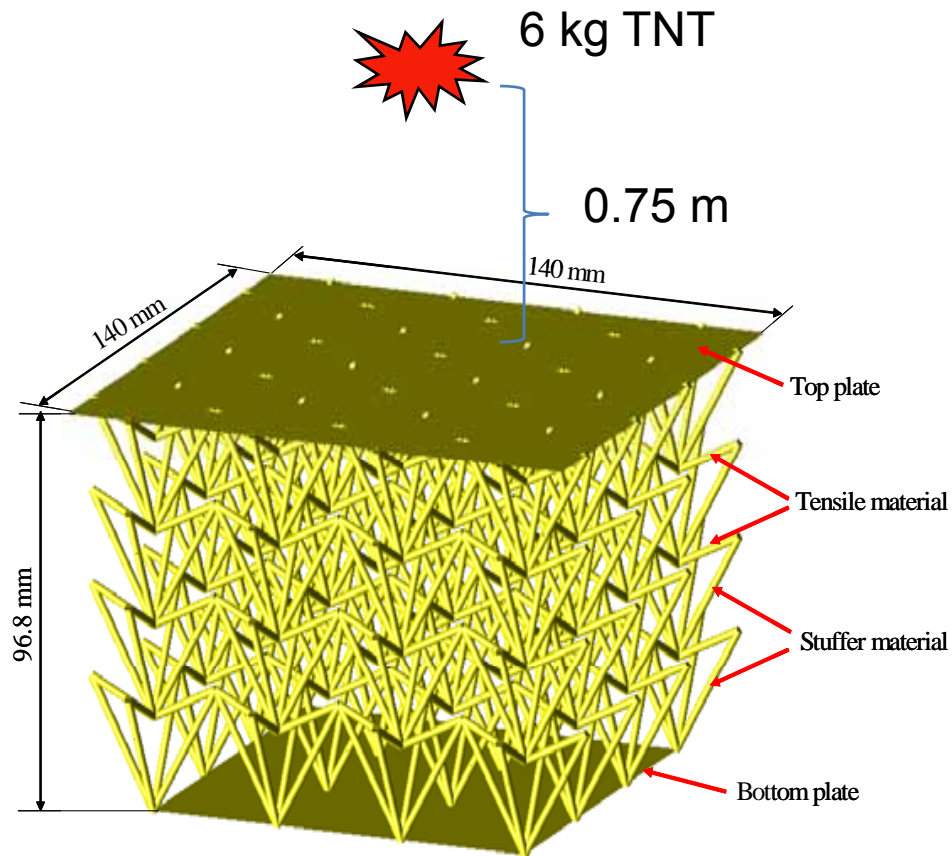
Manufacturing process



- Prove manufacturability and fabrication method
- Develop testing specimens

Virtual Blast Testing

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MODELING AND SIMULATION, TESTING AND VALIDATION



Parameters:

TNT: 6kg with offset 75cm

Material: Steel

Tensile: 2.0 mm x 2.0 mm

Stuffer: 2.0 mm x 4.0 mm

Plate thickness: 3.0 mm

Theta 1: 60 deg

Theta 2: 130 deg

Cell unit periodicity in x: 4

Cell unit periodicity in y: 4

Cell unit periodicity in z: 4

Damping: 0.1%

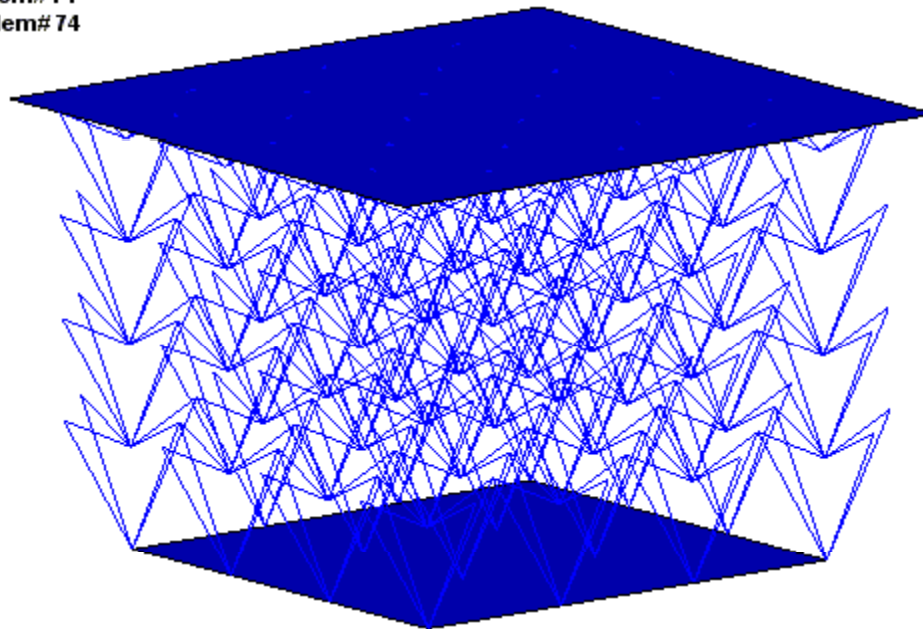
BCs: nodes on bottom plate no displacement in vertical direction

Simulation Result

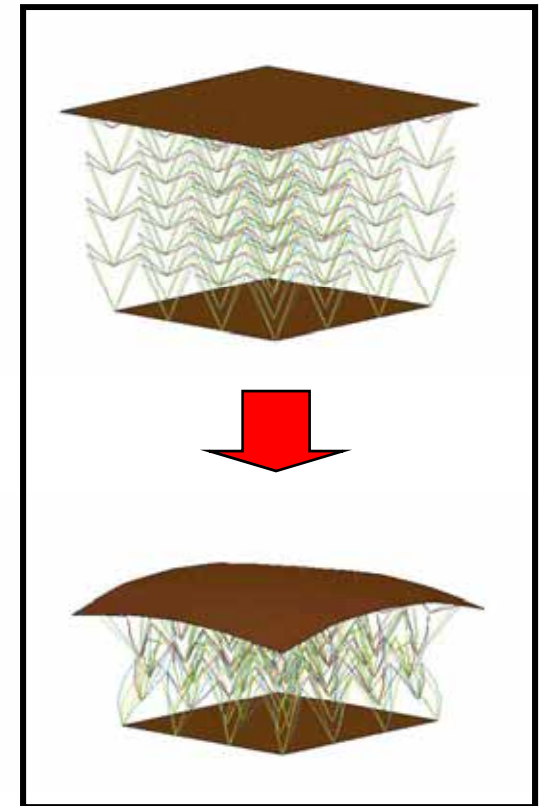
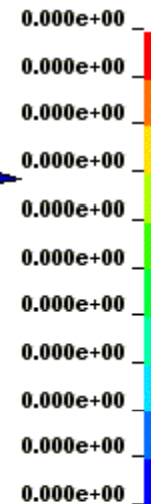
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BLAST_CASE1
Time = 199.92
Contours of Effective Stress (v-m)
max ipt. value
min=0, at elem# 74
max=0, at elem# 74



Fringe Levels

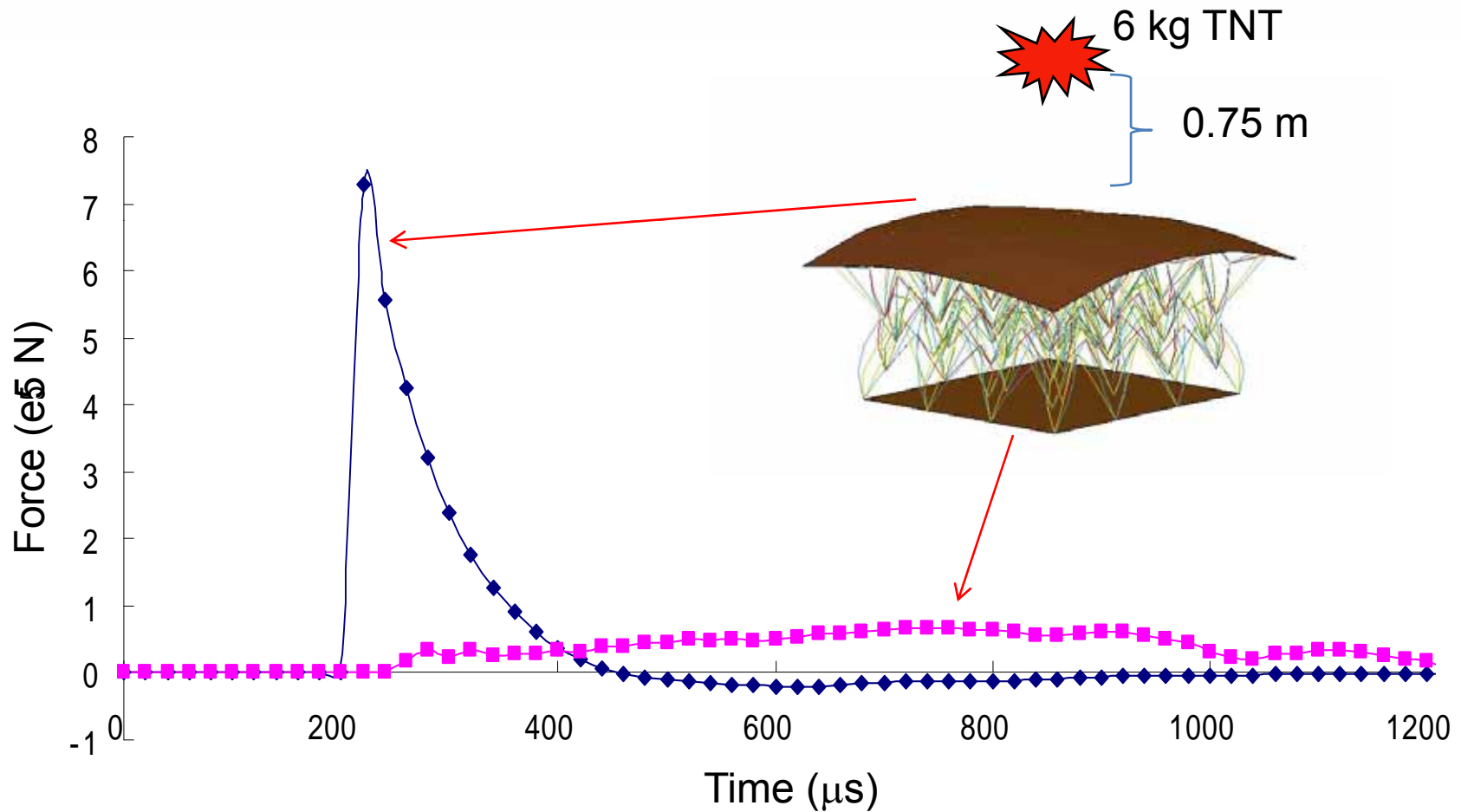


Deformation and effective Von Mises stress
on the top plat (in Mbar)

Blast Force Mitigation

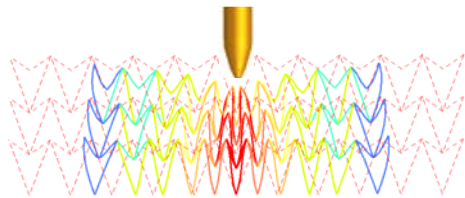
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MODELING AND SIMULATION, TESTING AND VALIDATION

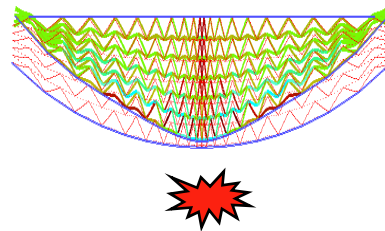


Unique Features of the NPR Material

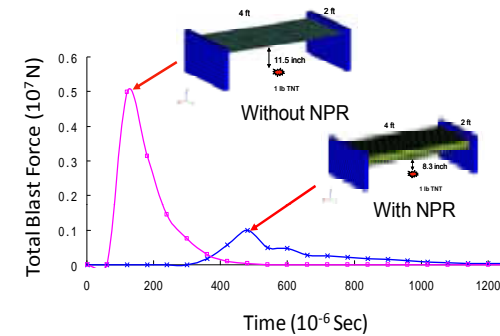
➤ Basic Features of the *NPR* (Negative Poisson's Ratio) Material:



Material concentration

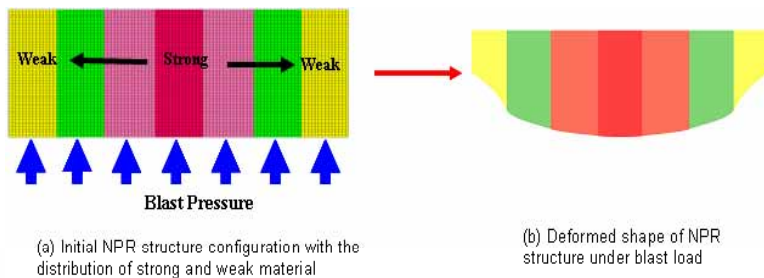


Bulging effect

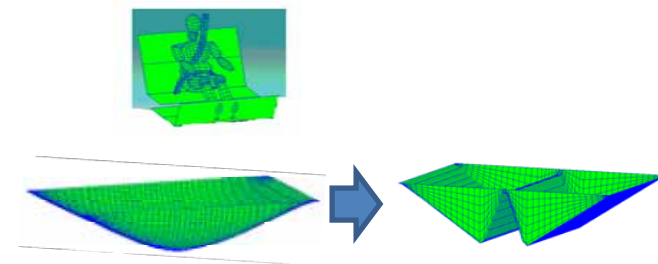


Impact force mitigation

➤ Functional and Functionally-Graded Design



Adaptive Shape Change

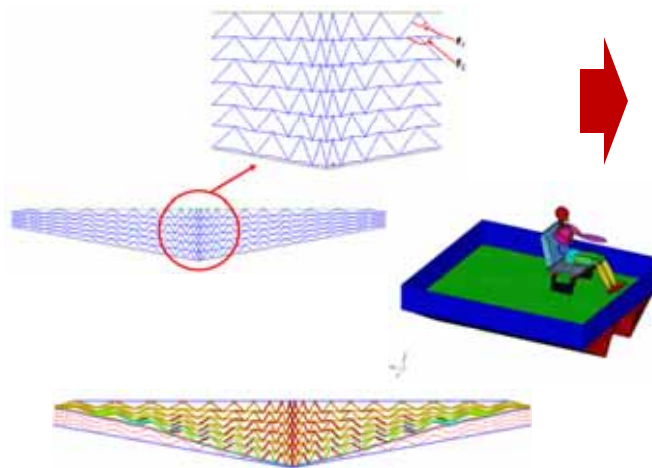
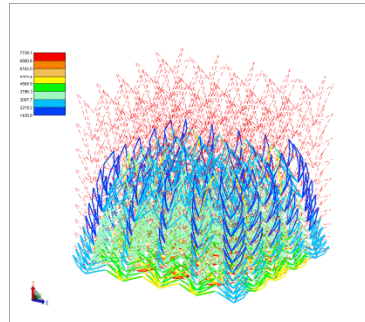
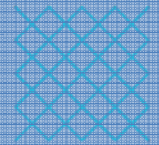
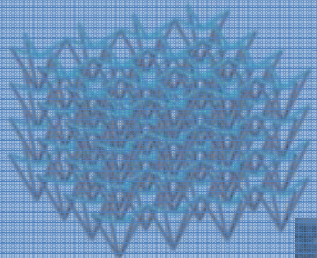
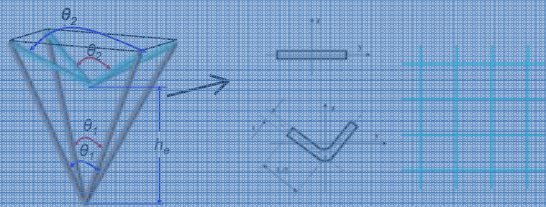


Optimal Shape Design

Presentation Outline

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MODELING AND SIMULATION, TESTING AND VALIDATION



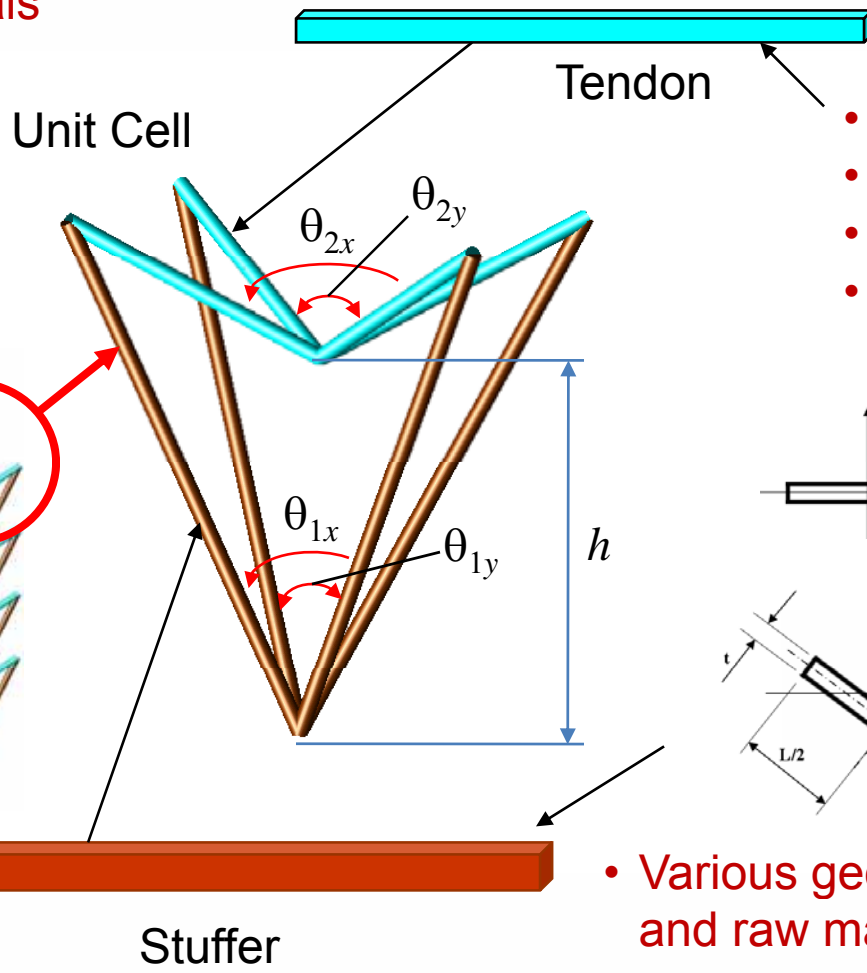
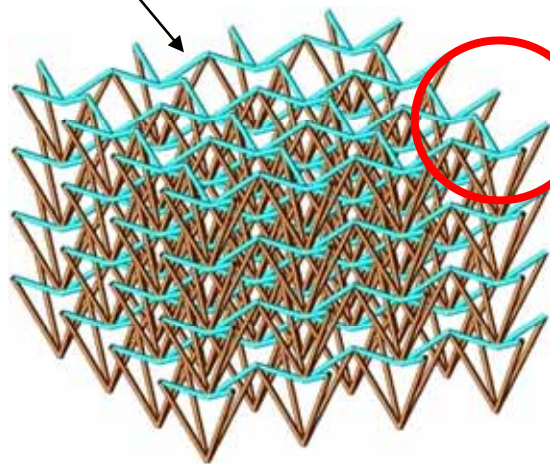
Functional and
Functionally-graded
NPR



Application to blast
protection

Generalized Design Variables

- Various filling materials
- Or no filling



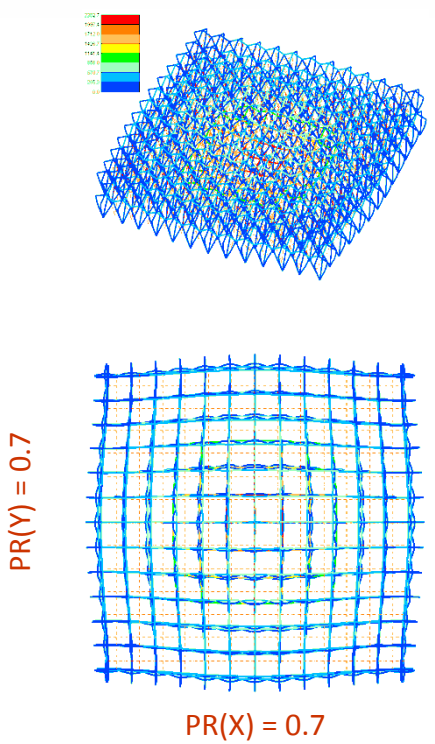
- Metallic strip
- Cable
- Organic fiber
- ...

- Various geometry shapes and raw material selections

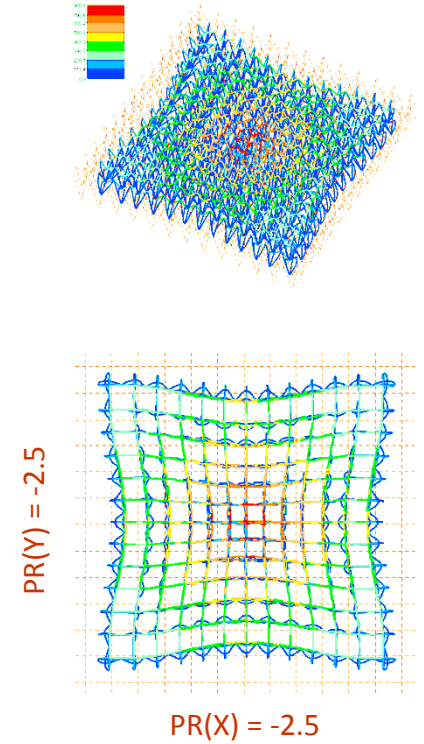
NPR by Design

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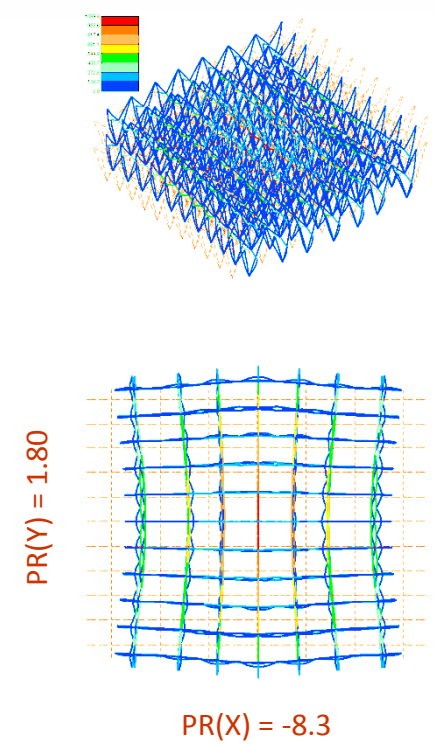
MODELING AND SIMULATION, TESTING AND VALIDATION



$$\theta_{2x} = -110^\circ$$
$$\theta_{2y} = -110^\circ$$



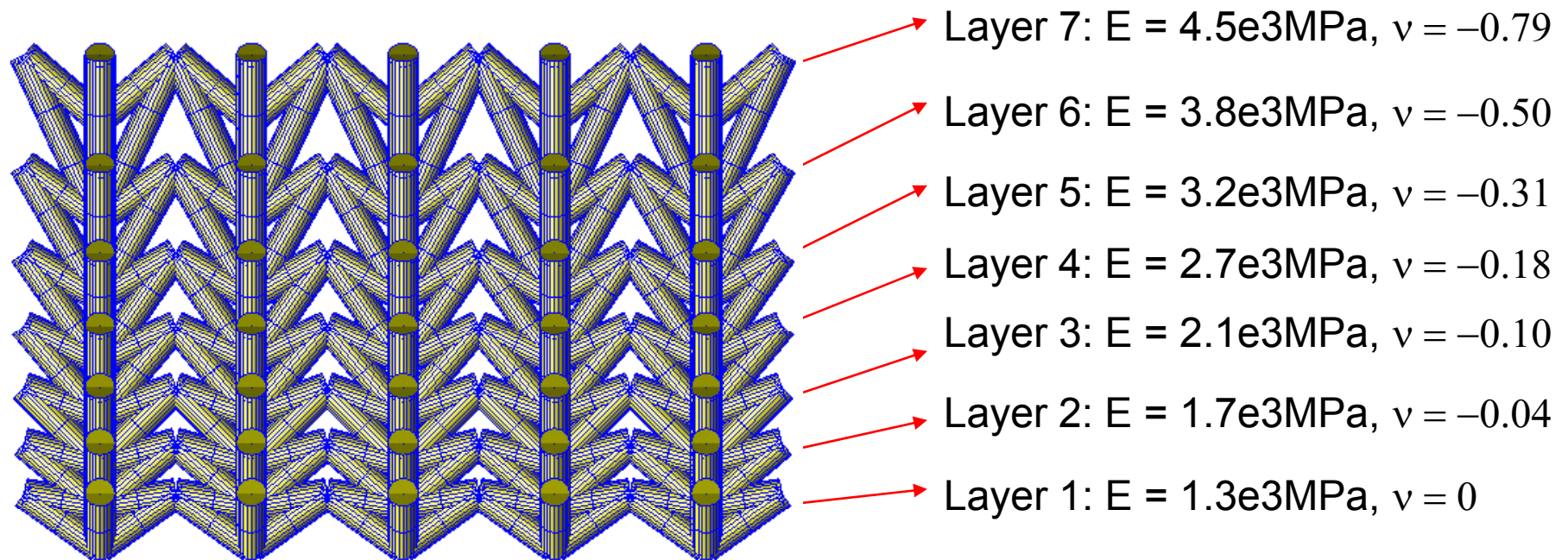
$$\theta_{2x} = 110^\circ$$
$$\theta_{2y} = 110^\circ$$



$$\theta_{2x} = 90^\circ$$
$$\theta_{2y} = -110^\circ$$

Functionally-Graded NPR

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MODELING AND SIMULATION, TESTING AND VALIDATION

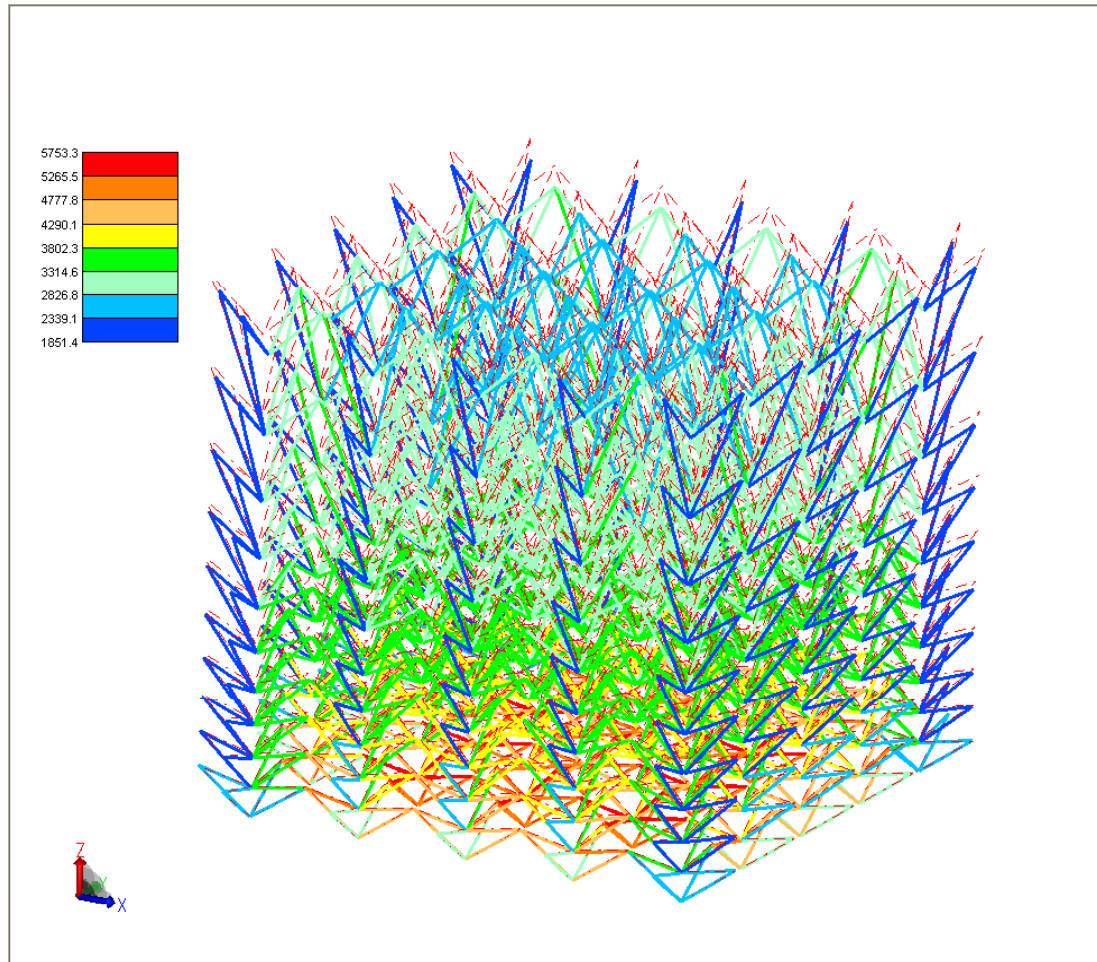


The integrated structure's properties are: $E = 2.8e3\text{MPa}$, $\nu = -0.24$

Simulation Result

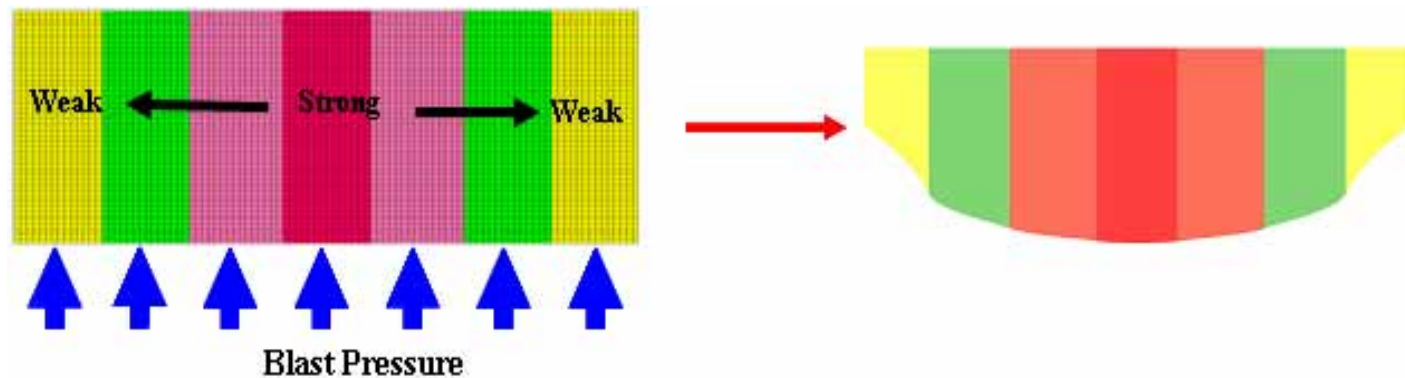
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MODELING AND SIMULATION, TESTING AND VALIDATION



The “Reactive” Deflector Concept

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MODELING AND SIMULATION, TESTING AND VALIDATION



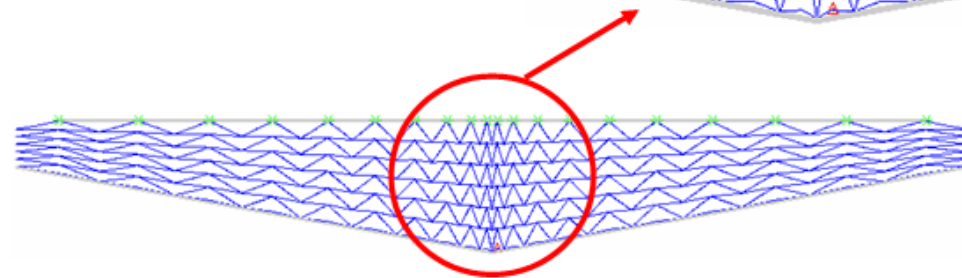
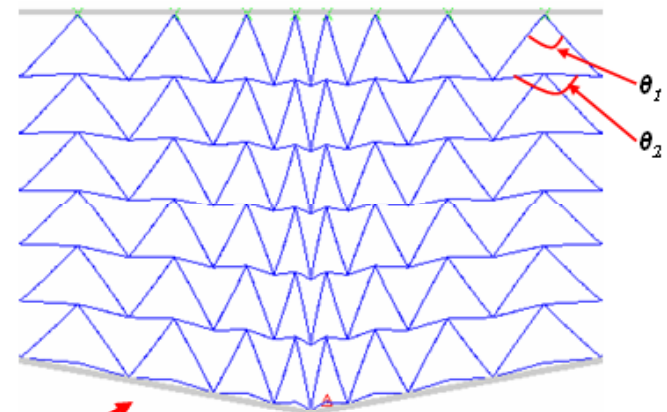
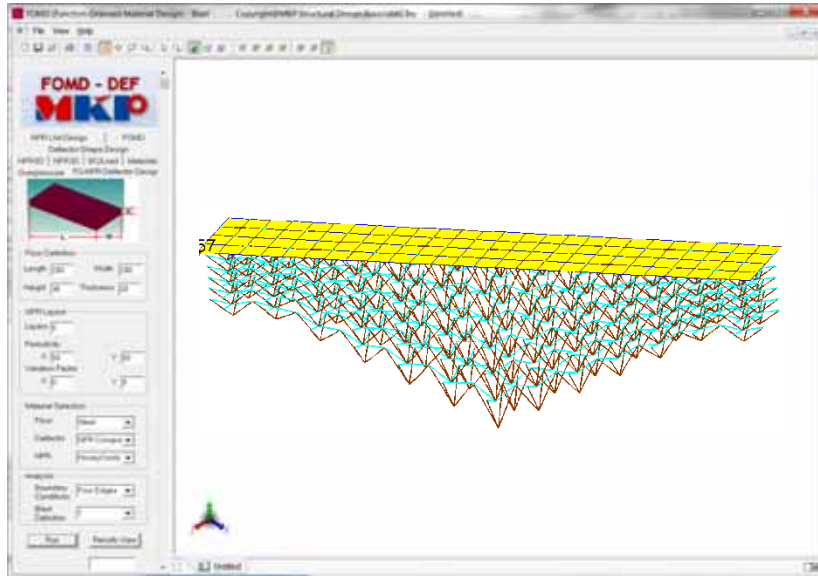
(a) Initial NPR structure configuration with the distribution of strong and weak material

(b) Deformed shape of NPR structure under blast load

- Based on the bulging effect of NPR material
- Is enhanced by a functionally-graded NPR concept with varied stiffness along the lateral direction

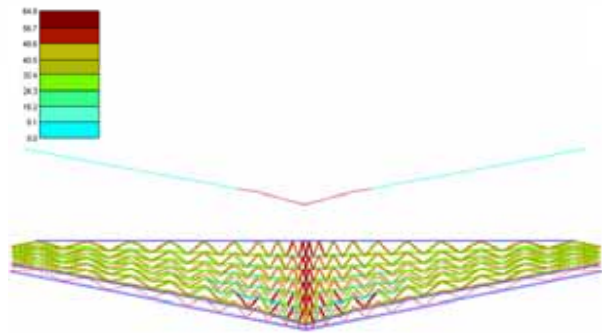
Varied Stiffness Distribution

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MODELING AND SIMULATION, TESTING AND VALIDATION

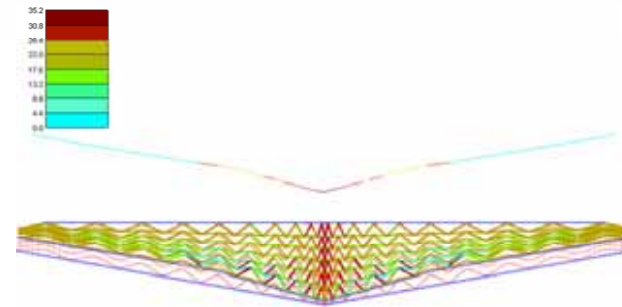


Adaptive Structure for Blast Protection

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MODELING AND SIMULATION, TESTING AND VALIDATION



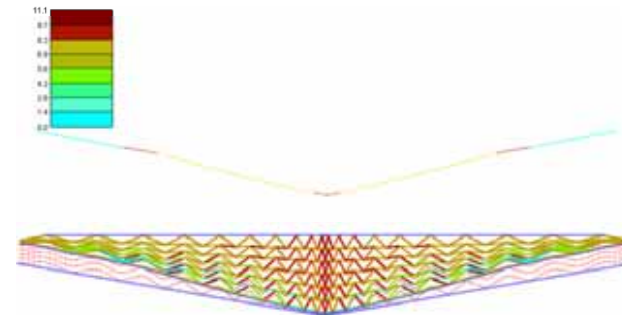
a) T1=150 μ s



b) T2=210 μ s



c) T3=270 μ s

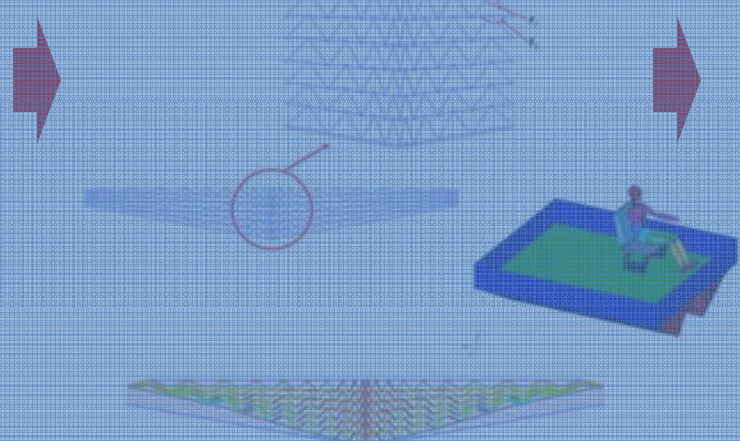
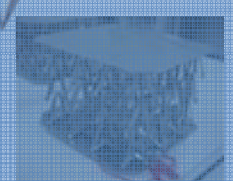
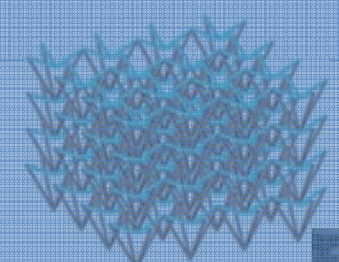
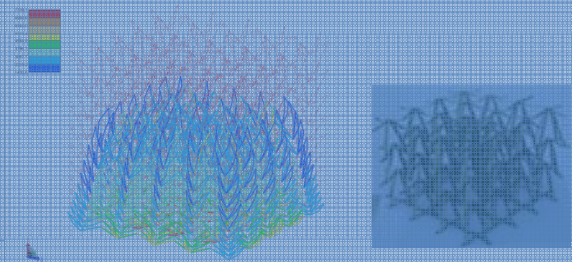
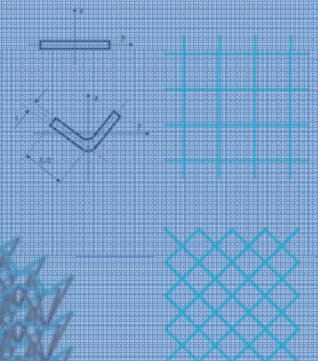
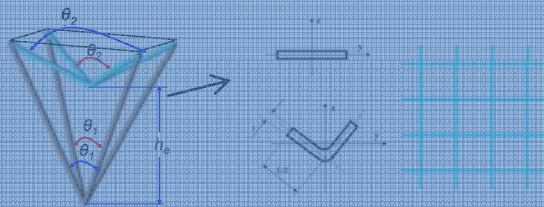


d) T4=330 μ s

Presentation Outline

MSTV

MODELING AND SIMULATION, TESTING AND VALIDATION



NPR

Functional and
Functionally-graded
NPR



Application to blast
protection

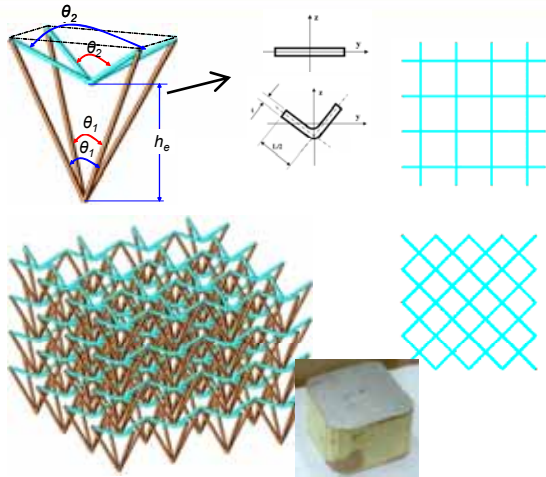


Objective

- Develop an innovative structural-material concept for a novel deflector that can significantly improve crew protection under explosives with minimum vehicle weight and C.G. height
 - New structural-material configuration, which can react to the blast of explosives and improve protection by adaptively changing material configuration
 - Maximize blast protection
 - Minimize vehicle weight
 - Minimize vehicle C.G. height
 - Can be functionally designed

Accomplishments

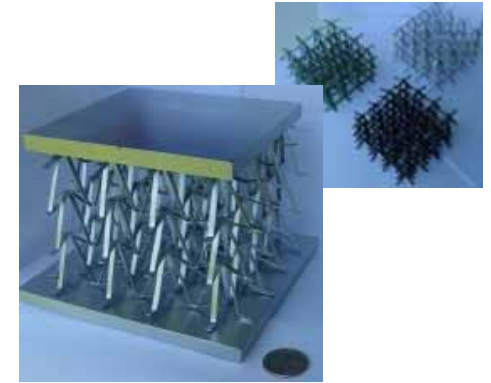
MSTV
MODELING AND SIMULATION, TESTING AND VALIDATION



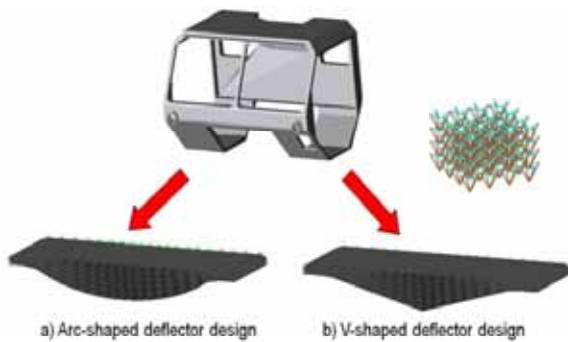
Concept development



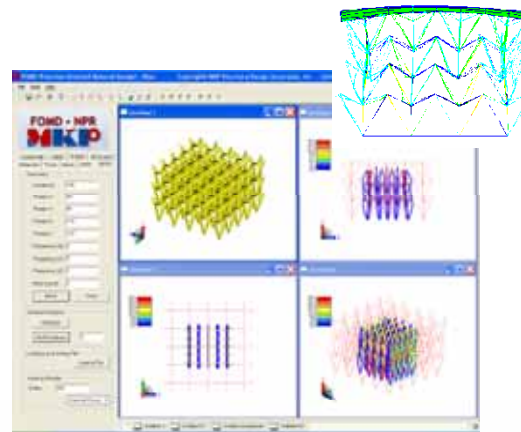
Manufacturing process



Prototyping



Design optimization



New design capabilities

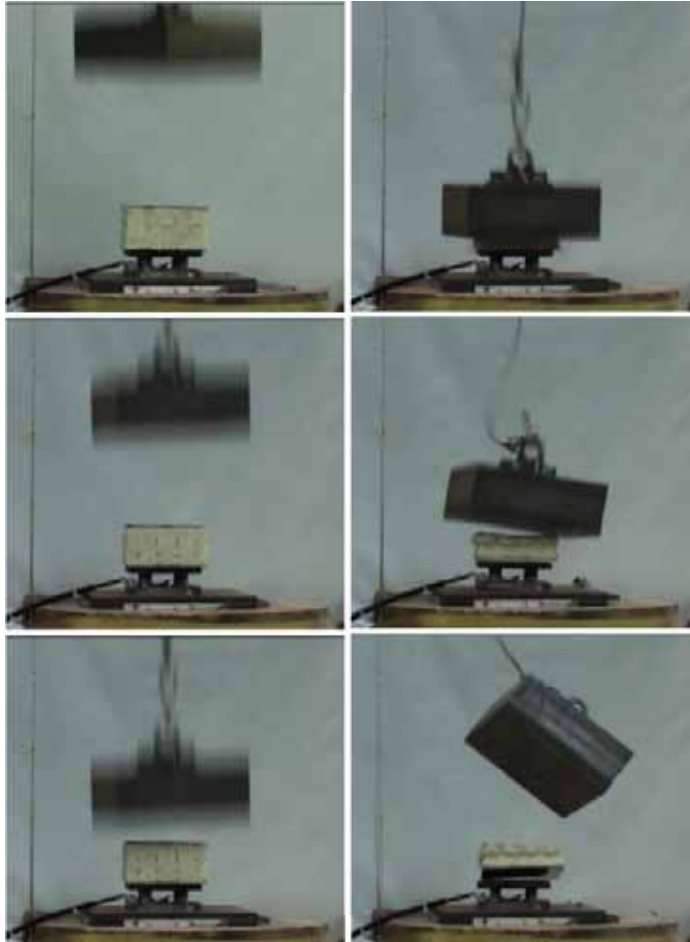


Mechanical & blast tests

Drop Tower Tests

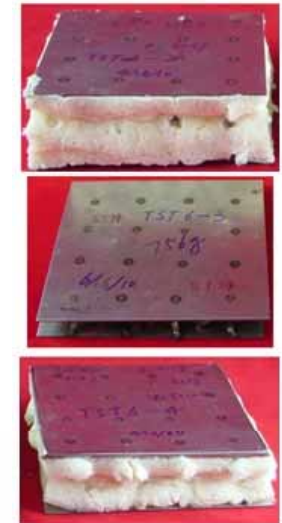
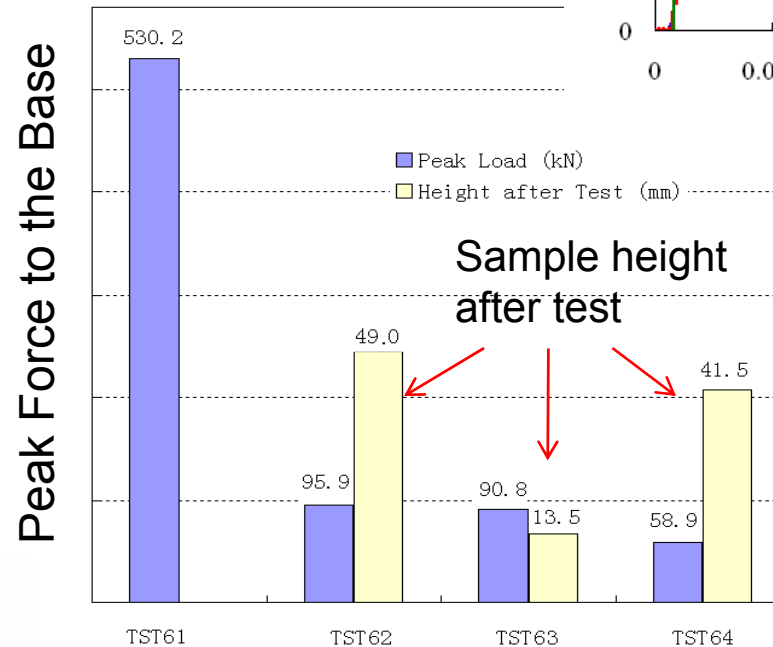
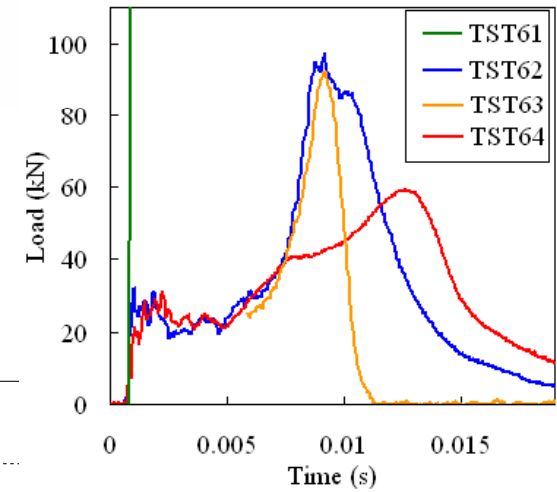
MSTV

MODELING AND SIMULATION, TESTING AND VALIDATION



A 50 kg mass from 12 feet height

- TST61: without NPR
- TST62: FG-NPR (1.0/1.2/1.8 mm with foam)
- TST63: NPR (1.0 mm) without foam
- TST64: NPR (1.0 mm) with foam

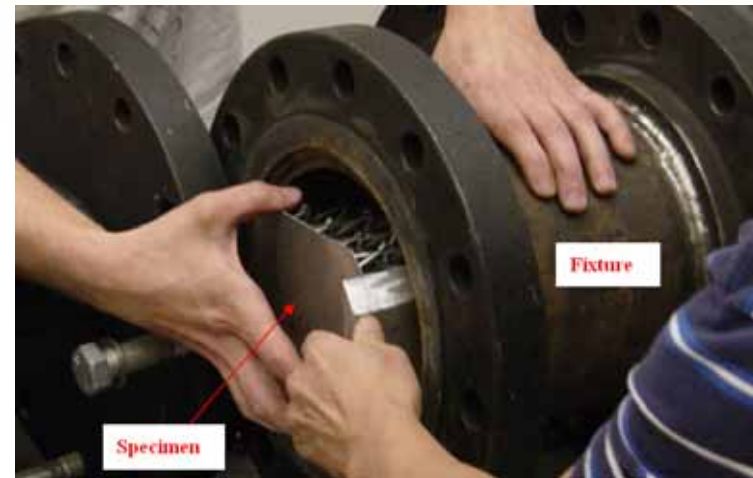
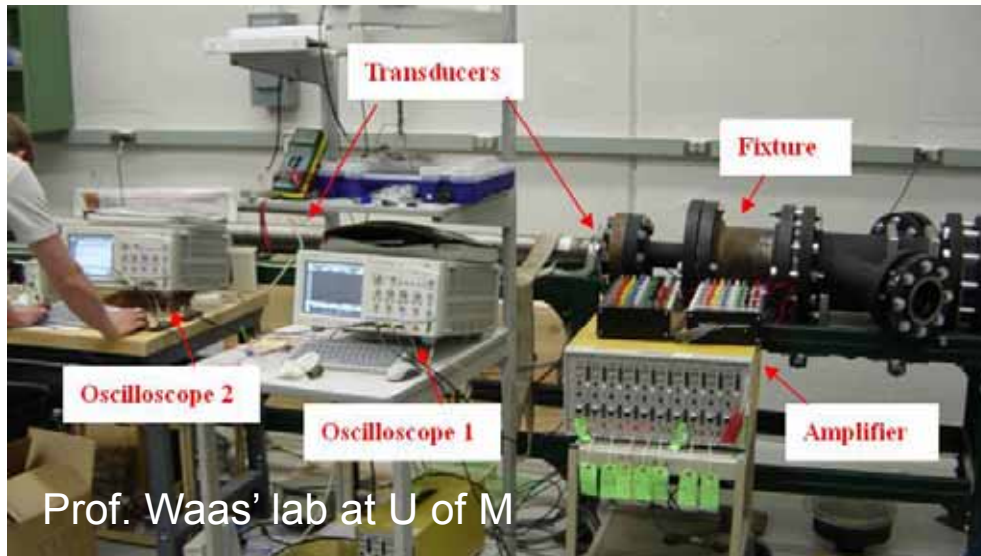


Sample #

Blast Tube Tests: BTR Composite vs. Honeycomb

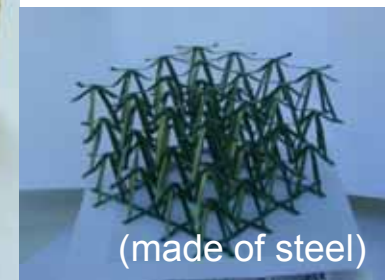
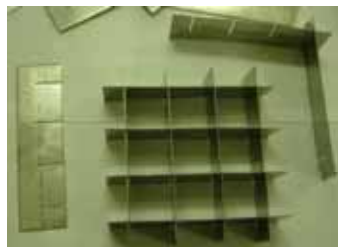
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Prof. Waas' lab at U of M

Square honeycomb core panel (HC-1, HC-2):
5.5" X 5.5" X 1.6".
Weight: 506 g.



Geometry of NPR: 5.5" X 5.5" X 3.5",
Weight: without foam: 398g, with foam: 540g

Comparison of NPR with Honeycomb

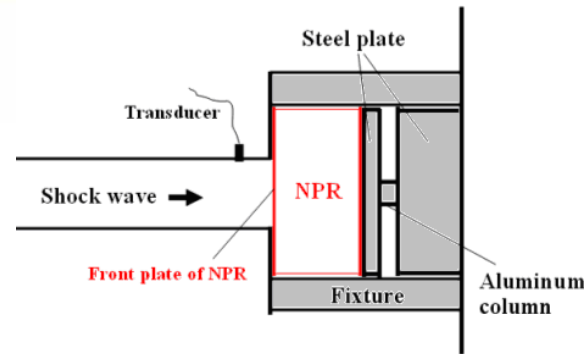
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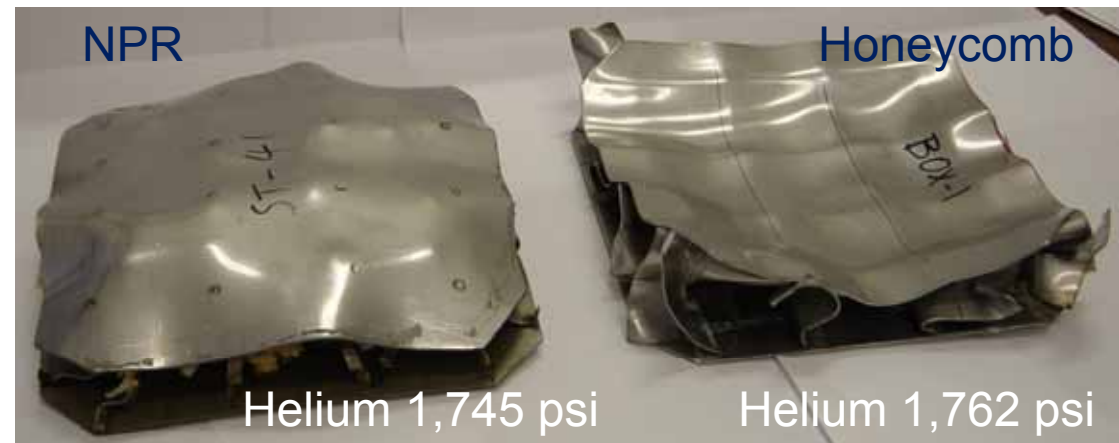
Geometry of the square honeycomb core: 5.5" X 5.5" X 1.6",
Weight: 506g.



Geometry of NPR: 5.5" X 5.5" X 3.5",
Weight: without foam: 398g, with foam: 540g



Boundary & loading conditions



- Profiles of specimens after testing
- NPR presents a convex surface, while square honeycomb presents a concave surface

Field Blast Test Plan

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TNT Air Blast Parameter:

Standard test: **6 kg** = 13.23 lb

0.5 m = 1.64 ft

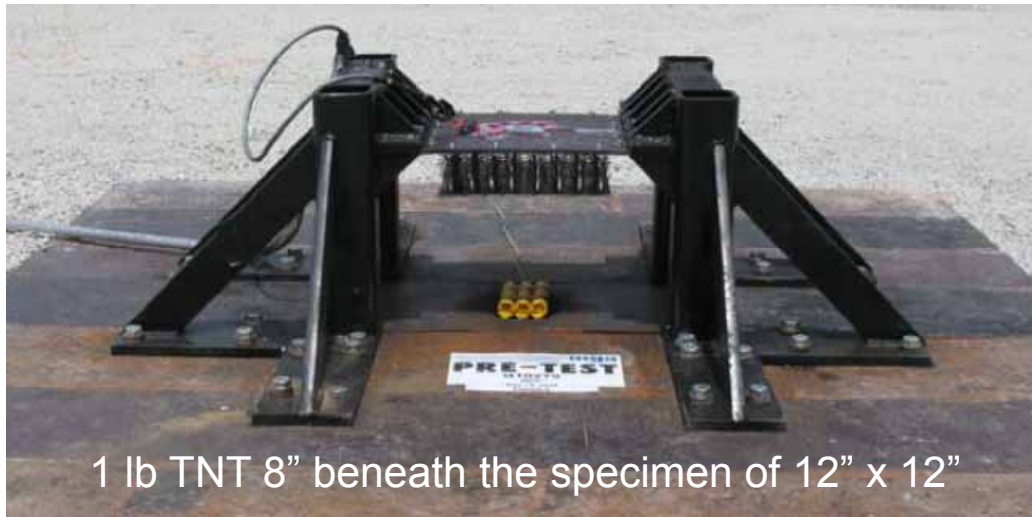
Scaled Distance = $0.69 \text{ ft/lb}^{1/3}$



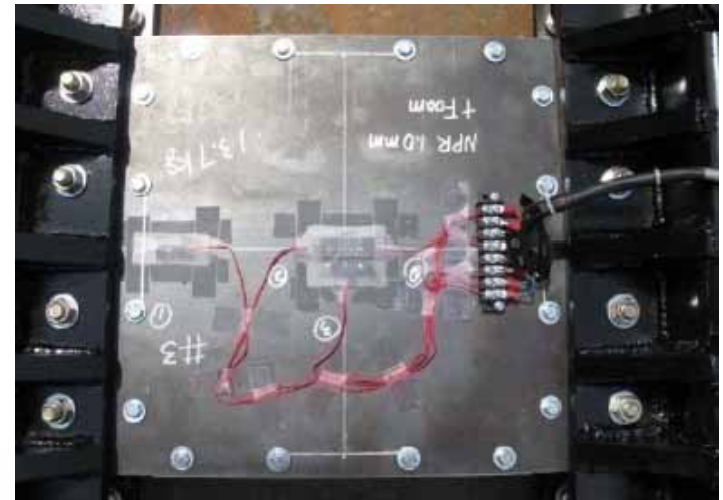
Equivalent Air Blast Parameter:

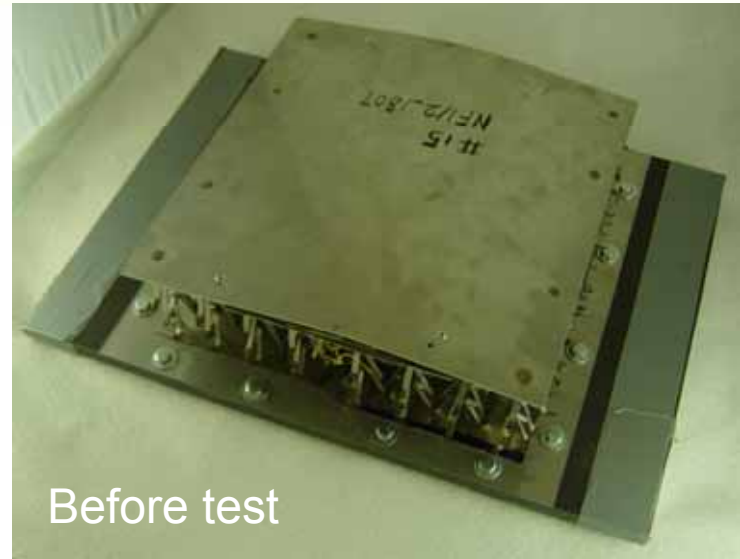
Standard test: **1 lb** and

0.69 ft = 21 cm



1 lb TNT 8" beneath the specimen of 12" x 12"





Concluding Remarks

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- Three unique features of the NPR material concept-validated by both virtual prototyping and physical tests
 - Material concentration under the load
 - Bulging effect for blast wave deflection
 - Blast force mitigation
- NPR materials many perform much better than regular materials
 - Better stiffness and strength characteristics
 - Better shear resistance – more stable
- Functionally-graded NPR design may provide
 - Shape morphing and material redistribution, and hence better protection performance
 - Less deflector height required for the same level of protection

Lightweight, Shape Adaptive Blast Deflector Concept

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