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

**Authors:** Zheng-Dong Ma; Gregory Hulbert; Hongxin Bian; Krishan Bishnoi; Farzad Rostam-Abadi

**Performing Organization:** University of Michigan, 4260 Plymouth Road, Ann Arbor, MI, 48109

**Sponsoring Agency:** U.S. Army TARDEC, 6501 East Eleven Mile Rd, Warren, MI, 48397-5000

**Distribution Statement:** Approved for public release; distribution unlimited

**Abstract:**

For 2010 GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM (GVSETS) AUGUST 17-19

**Subject Terms:**

briefing charts
Presentation Outline

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)
Three-Dimensional NPR Material (MKP Patent Pending)

(made of steel)
Design Variables

Unit Cell

\[ \theta_1 = 60 \text{ degrees} \]
\[ \theta_2 = 130 \text{ degrees} \]
\[ h_e = 22.2 \text{ mm} \]

3mm X 5mm stuffer

2mm X 5mm tendon
Effective Material Properties

Effective Young’s Modulus

Effective Poisson’s Ratio
Variations of Arrangement

Unit Cell

Parallel Configuration (NPR-p)

Diagonal configuration (NPR-d)

PPR configuration (PPR-1/PPR-2)
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

Manufacturing process

- Prove manufacturability and fabrication method
- Develop testing specimens
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

**BLAST_CASE1**

- **Time = 199.92**
- **Contours of effective stress (V-M)**
- **max ipt. value**
  - min=0, at elem# 74
  - max=0, at elem# 74

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

6 kg TNT
0.75 m

<table>
<thead>
<tr>
<th>Time (μs)</th>
<th>Force (e5 N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>200</td>
<td>8</td>
</tr>
<tr>
<td>400</td>
<td>6</td>
</tr>
<tr>
<td>600</td>
<td>4</td>
</tr>
<tr>
<td>800</td>
<td>2</td>
</tr>
<tr>
<td>1000</td>
<td>1</td>
</tr>
<tr>
<td>1200</td>
<td>0</td>
</tr>
</tbody>
</table>
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
Application to blast protection

Functional and Functionally-graded NPR

NPR
Generalized Design Variables

- Various filling materials
- Or no filling

• Metallic strip
• Cable
• Organic fiber
• ...

• Various geometry shapes and raw material selections

[Diagram of Unit Cell with Tendon and Stuffer]
NPR by Design

\[ \text{PR}(Y) = 1.80 \]

\[ \text{PR}(Y) = -2.5 \]

\[ \text{PR}(Y) = 0.7 \]

\[ \text{PR}(X) = -8.3 \]

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

\[ \theta_{2x} = 110^\circ \]
\[ \theta_{2y} = 110^\circ \]

\[ \theta_{2x} = 90^\circ \]
\[ \theta_{2y} = -110^\circ \]
Functionally-Graded NPR

Layer 7: $E = 4.5\times 10^3\,\text{MPa}$, $\nu = -0.79$
Layer 6: $E = 3.8\times 10^3\,\text{MPa}$, $\nu = -0.50$
Layer 5: $E = 3.2\times 10^3\,\text{MPa}$, $\nu = -0.31$
Layer 4: $E = 2.7\times 10^3\,\text{MPa}$, $\nu = -0.18$
Layer 3: $E = 2.1\times 10^3\,\text{MPa}$, $\nu = -0.10$
Layer 2: $E = 1.7\times 10^3\,\text{MPa}$, $\nu = -0.04$
Layer 1: $E = 1.3\times 10^3\,\text{MPa}$, $\nu = 0$

The integrated structure’s properties are: $E = 2.8\times 10^3\,\text{MPa}$, $\nu = -0.24$
The “Reactive” Deflector Concept

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

(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
Adaptive Structure for Blast Protection

a) $T_1 = 150 \mu s$

b) $T_2 = 210 \mu s$

c) $T_3 = 270 \mu s$

d) $T_4 = 330 \mu s$
Presentation Outline

Application to blast protection

UNCLASSIFIED: Dist A. Approved for public release
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

Concept development

Manufacturing process

Prototyping

Design optimization

New design capabilities

Mechanical & blast tests
Drop Tower Tests

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

A 50 kg mass from 12 feet height
Blast Tube Tests:
BTR Composite vs. Honeycomb

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

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

NPR Helium 1,745 psi

Honeycomb Helium 1,762 psi

Profiles of specimens after testing

- NPR presents a convex surface, while square honeycomb presents a concave surface
Field Blast Test Plan

TNT Air Blast Parameter:
Standard test: 6 kg = 13.23 lb
0.5 m = 1.64 ft
Scaled Distance = 0.69 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”
Before test

Convex surface

After test
Concluding Remarks

• 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

W-shape deflector

V-shape adaptive deflector

BTR deck/floor plate
(Patent No.: US 7,563,497 B2)

NPR adaptive deflector core

Nanoclay-reinforced composite front plate
(Fiber-reinforced woven composite with nanoclay-reinforced matrix)