Metaconcrete: engineered aggregates for enhanced dynamic performance

Anna Pandolfi (Polimi, DICA), Deborah Briccola (Polimi, DICA), Stephanie Mitchell (Caltech, EAS), and Michael Ortiz (Caltech, EAS)

Milano - October 28, 2015
What is metaconcrete?

- Original in naming our *engineered material* ... but, searching the web one can find

A *song* by the sound abstractionist Rene Hell

A *korean design studio*: lights and illumination systems, signature shelves
Quick Outline

1. Metamaterials
2. Modeling Metaconcrete
3. Wave Transmission
4. Elastic Shock Mitigation
5. Brittle Fracture Shock Mitigation
6. Experimental Work
Metamaterials: composite materials engineered to show unconventional properties

Optical (for light) metamaterials: superlenses [Pendry, 2000], negative refractive index, invisibility [Urzhumov, 2011], photonic crystals

Acoustic (for sound) metamaterials: acoustic shelters, phononic crystals (for sound attenuation)

A photonic, or equivalently phononic, crystal is an artificially engineered material made of a regularly repeating arrangement of elements that allow impinging waves to undergo destructive interference (DI):

- DI: waves with frequencies falling within a range known as the bandgap are prevented from propagating in the material
- For DI to occur, the period of the structure must be of the order of the wavelength

Mechanical metamaterials: designed composite materials can have frequency dependent masses

- For now, it has been numerically proved and confirmed with dynamic experiments in a metaconcrete phantom [Kettenbeil & Ravichandran, 2015]
Sculpture ‘Organon’ by Eusebio Sempere

- Not only a piece of art, but a fortuitous example of a phononic crystal, a periodic arrangement of structures (in this case, metal tubes) that can block sound waves at specific frequencies [Thomas, Nature, 2009]

- The sculpture is a human scale acoustic metamaterial, i.e., it blocks sound for human hearing. This is because the periodicity of metal tubes is at the centimeter scale, and the overall structure is meter-sized
Acoustic Metamaterials

- Resonant layered inclusion structure arranged in a 3D lattice [Sheng et al, 2003]
- Resonance of the inclusions is activated by an applied acoustic wave
- Destructive Interference has been revealed by experiments through plots of amplitude transmission coefficient (received wave amplitude / transmitted wave amplitude)
- The band gaps structure observed at low frequency is NOT dictated by the dimension of the lattice spacing but by the structure of the inclusions [Liu et al, 2000]
Metaconcrete: A New Concept for an Engineered Concrete

Metaconcrete is a new concept for a modified concrete where traditional aggregates are replaced by “resonant” engineered inclusions

- Resonant inclusions consist of:
  - A heavy core (e.g. high density material such as lead)
  - A compliant outer layer (e.g. silicone, rubber, or nylon, a few millimeters in thickness)
- Changing the geometry and coating stiffness results in different aggregate resonant frequencies
  - Negative effective mass
  - Energy trapping
  - Shock mitigation

Attenuation and Filtering by Tuned Damping

• Multiple Mass Dampers: collection of mass dampers with distributed natural frequencies. MMDs modify the transfer function of a damper-building system by flattening the peaks [Kareem & Kline, JSE, 1995]

• Tuned Mass Dampers: viscoelastic materials used for rectifying floors in modern lightweight buildings characterized by annoying floor vibration [Nguyen et al, ASE, 2012]

• TMD are used in bridges for mitigating the buffeting dynamic vibrations induced by strong wind loading, whose variability calls for control strategies [Domaneschi et al, CS, 2015].

... metaconcrete attenuation is not based on viscous properties of the constituents, but on “mechanical energy sequestration”.

Kareem & Kline, 1995

Nguyen et al, 2012

Domaneschi et al, 2015
Applications for Metaconcrete: Blasts and Impacts

Blast Shielding and Impact Protection

- Blast shielding
- Protective slab for impact resistance
- Seismic isolation and earthquake protections
- Tuned damping protections
Applications for Metaconcrete: Vibrations

Foundations of Vibrating Machinery

- Paper production machine
- Rotary press machine

Fuel/Coal Extraction Support

- Support of coal screening machines
- Support of gas/oil drilling rig

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The difference between the static mass $M_S$ and the dynamic mass $M(\omega)$ is proved by 1D-2D examples in Milton and Willis (2007).

System oscillates harmonically with frequency $\omega$ under the action of external force $f(t)$

\[
M_S = m_0 \left(1 + n \frac{m}{m_0}\right)
\]

\[
M(\omega) = m_0 \left(1 + \alpha \frac{\omega^2}{\omega_\rho^2 - \omega^2}\right),
\]

\[
\alpha = \frac{nm}{m_0} \quad \text{and} \quad \omega_\rho = \sqrt{\frac{2k}{m}}
\]

Adapted from Sheng (2007)
Studied layered resonant aggregates

- Choose outer diameter of 24mm
- Mix into a cement paste that will form the mortar matrix
- Assume a number of configurations to investigate different resonant frequencies

<table>
<thead>
<tr>
<th>Configuration</th>
<th>( R_l ) (mm)</th>
<th>( t ) (mm)</th>
<th>( R_l \cdot t ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>11</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>B</td>
<td>10</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>C</td>
<td>9</td>
<td>3</td>
<td>27</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>( \rho ) (kg/m(^3))</th>
<th>( E ) (GPa)</th>
<th>( \nu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mortar</td>
<td>2,500</td>
<td>30</td>
<td>0.20</td>
</tr>
<tr>
<td>Lead</td>
<td>11,400</td>
<td>16</td>
<td>0.44</td>
</tr>
<tr>
<td>Silicone</td>
<td>1,100</td>
<td>0.001</td>
<td>0.47</td>
</tr>
<tr>
<td>Natural rubber</td>
<td>900</td>
<td>0.01</td>
<td>0.49</td>
</tr>
<tr>
<td>Low density polyethylene (LDPE)</td>
<td>1,100</td>
<td>0.1</td>
<td>0.45</td>
</tr>
<tr>
<td>Nylon</td>
<td>1,150</td>
<td>1.0</td>
<td>0.40</td>
</tr>
<tr>
<td>Urea formaldehyde (UF)</td>
<td>1,500</td>
<td>10</td>
<td>0.40</td>
</tr>
</tbody>
</table>
Spring-mass model

• Represent a single metaconcrete aggregate

• Aggregate resonant frequency:

\[
f = \frac{1}{2\pi} \sqrt{\frac{3}{2} \frac{E_c}{R_l t \rho_l}}
\]

• Resonant frequencies between 0.55 kHz and 55.04 kHz

• Simple relationships to tune geometry and compliant coating stiffness for specific resonant frequencies

Modal FE analysis

• Evaluate the first frequencies (Mode 1 to Mode 4) of the single aggregate within the mortar using a commercial code able to perform modal analysis.
3D model more accurately captures the resonant behavior

- Perform modal analysis using finite elements
- Compute eigenfrequencies and eigenmodes
- Consider four aggregate cases:
  - 1mm and 3mm rubber coated aggregates
  - 1mm and 3mm nylon coated aggregates

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Nodes</th>
<th>Elements</th>
<th>$V_{\text{mortar}}$ (%)</th>
<th>$V_{\text{coating}}$ (%)</th>
<th>$V_{\text{lead}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>40,307</td>
<td>25,047</td>
<td>73.2</td>
<td>6.2</td>
<td>20.6</td>
</tr>
<tr>
<td>C</td>
<td>41,074</td>
<td>26,260</td>
<td>73.2</td>
<td>15.5</td>
<td>11.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mm Rubber</td>
<td>1.74</td>
<td>1.99</td>
<td>25.00</td>
<td>27.70</td>
</tr>
<tr>
<td>3 mm Rubber</td>
<td>1.11</td>
<td>1.51</td>
<td>10.44</td>
<td>11.12</td>
</tr>
<tr>
<td>1 mm Nylon</td>
<td>17.41</td>
<td>18.84</td>
<td>32.14</td>
<td>36.42</td>
</tr>
<tr>
<td>3 mm Nylon</td>
<td>11.11</td>
<td>15.08</td>
<td>34.19</td>
<td>36.92</td>
</tr>
</tbody>
</table>

- Quadratic tetrahedral elements with 2.5mm maximum mesh size
- 1D model underestimates resonant frequency
Activate Mode 2 resonance in metaconcrete

Contour plot of maximum principal strain
- 1mm nylon coated aggregate
- Modes 1 & 2 display rigid body motion of the core
- Modes 3 & 4 display mixed bending and oscillation of the core and coating

3D analysis allows for more direct link between resonant frequency and changes in slab behavior
Section of an infinite planar slab

- \( L = 0.24 \) m and \( b = 0.03 \) m
- Periodic arrangement of aggregates
  - High-density 36 aggregate arrangement
  - Low-density 8 aggregate arrangement
- For all components use a Neo-Hookean material model extended to the compressible range

<table>
<thead>
<tr>
<th># Aggregates</th>
<th>Configuration</th>
<th>( R_i \times t ) (mm²)</th>
<th>( V_m ) (%)</th>
<th>( V_p ) (%)</th>
<th>( V_f ) (%)</th>
<th>( f_m ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>A</td>
<td>11</td>
<td>73.2</td>
<td>6.2</td>
<td>20.6</td>
<td>56.8-57.2</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>20</td>
<td>73.2</td>
<td>11.3</td>
<td>15.5</td>
<td>50.6-51.4</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>27</td>
<td>73.2</td>
<td>15.5</td>
<td>11.3</td>
<td>43.9-45.4</td>
</tr>
<tr>
<td>36</td>
<td>A</td>
<td>11</td>
<td>49.7</td>
<td>11.6</td>
<td>38.7</td>
<td>78.4-78.7</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>20</td>
<td>49.7</td>
<td>21.2</td>
<td>29.1</td>
<td>73.8-74.5</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>27</td>
<td>49.7</td>
<td>29.1</td>
<td>21.2</td>
<td>68.3-69.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mesh Size</th>
<th>Configuration</th>
<th>Nodes</th>
<th>Elements</th>
<th>( h_{\text{min}} ) (mm)</th>
<th>( h_{\text{avg}} ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>A</td>
<td>19228</td>
<td>96314</td>
<td>0.0026</td>
<td>0.503</td>
</tr>
<tr>
<td>( h = 2.5 ) mm</td>
<td>B</td>
<td>19645</td>
<td>95390</td>
<td>0.0271</td>
<td>0.502</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>20891</td>
<td>107562</td>
<td>0.1271</td>
<td>0.486</td>
</tr>
<tr>
<td>Fine</td>
<td>A</td>
<td>102,965</td>
<td>561,846</td>
<td>0.0762</td>
<td>0.279</td>
</tr>
<tr>
<td>( h = 1.5 ) mm</td>
<td>C</td>
<td>84,000</td>
<td>451,457</td>
<td>0.1031</td>
<td>0.287</td>
</tr>
</tbody>
</table>
Dynamic Loading Profiles

Harmonic Displacement
- Applied to end surface at prescribed frequencies
- Activates resonance (wave transmission)

Blast Wave
- Generated by an explosion in air, centered at 0.015 m from the end face
- Activates a large spectrum of frequencies
- Yield factor controlling parameter
  \[ \lambda = \frac{3 \sqrt{W}}{\sqrt{W_{\text{ref}}}} \]
- Force time history
  \[ F(t) = \int_{A_{\text{exposed}}} p(t) dA \]
Useful way of visualizing band gaps

- Experimental tests by Sheng et al. (2003) report change in wave amplitude across a locally resonant sonic crystal
- For metaconcrete consider the transmission of wave energy through a slab

\[ T = \frac{E^{RA}}{\sum_{j=1}^{N} E^j} \]

where \( E^j \) = total mechanical energy of the \( j \)-th aggregate, time-averaged

\( N \) = total number of aggregates

\( E^{RA} \) = Energy of the rightmost aggregate

- Decrease in \( T \): less energy has reached the rightmost aggregate, because of the activation of energy absorbing properties

[Sheng et al. (2003)]

[Energy Transmission Plots (Numerical only)]

[Mitchell et al., 2015b]
Considered different finite element slab models. Present here three representative models:

- Homogeneous mortar slab
- 1-3 mm nylon coated 36 aggregate arrangement
- 1-3 mm nylon coated 8 aggregate arrangement

Compute maximum allowable applied wave frequency using the mesh size $h$

$$f_{\text{max}} = \frac{c_L}{h}$$

For mortar: $c_L = \sqrt{\frac{E}{\rho}} = 3464 \text{ m/s}$

$$\Rightarrow f_{\text{max}} = 2309 \text{ kHz}$$

**Harmonic displacement forcing function**

- Assume the energy of the harmonic wave is proportional to $E \propto \omega^2 A^2$
- Maintain the same input energy by scaling the reference amplitude by $f_r/f$
Transmission Coefficients for 1 mm Nylon Coating

- Dips correspond to resonant frequencies
- Low frequency dip at 22 kHz correlates with 3D Mode 2 frequency of 21.12 kHz
- Second dip at higher frequencies corresponding to Mode 3 and 4 3D model frequencies
- Very high frequency decrease – possibly due to wave scattering or interference
- Improvement over homogeneous slab [Mitchell et al., 2015b]
Transmission Coefficients for 3 mm Nylon Coating

- Dips correspond to resonant frequencies
- Low frequency dip correlates with Mode 2 frequency of 15.94 kHz
- Second dip at higher frequencies corresponding to Mode 3 and 4 resonance
- Very high frequency decrease – possibly due to wave scattering or interference
- Improvement over homogeneous slab [Mitchell et al., 2015b]
Energy histories for each component

1 mm nylon coated aggregates

- Mechanical energy distributed among constituents: 60% carried by the lead cores, 30% by the mortar matrix, and 10% by the coating
- Trapping of the energy within the inclusions
- Elastic and kinetic energy transfer between the aggregate core and the coating material

[Mitchell et al., 2014]
Nylon and UF coatings provide improved performance, reducing the energy fraction absorbed by mortar.
Mechanical Energies and Aggregate Properties

[Mitchell et al., 2014]
Comparison of longitudinal stress wave propagation
Comparative view at time = 0.05 ms
Blast pressure acts for < 0.1 ms

blue = compression
red = tension

Homogeneous Material

1 mm Silicone Coated Aggregates

1 mm Nylon Coated Aggregates
Stress in the mortar matrix

- Maximum longitudinal tensile and compressive stress over the duration of the dynamical analysis

Considering only the stresses in the right half of the slab

[Mitchell et al., 2014]

- Higher coating stiffness indicates improved performance
- Nylon and urea formaldehyde coatings display the greatest reduction in stress transferred to the mortar matrix with 40-60% of the homogeneous mortar value
Modeling Fracture Using an Eigenerosion Scheme

• Incorporate the brittle behavior of the constituents through a Griffith criterion based eigenerosion algorithm combined to the finite element discretization of the slab.

• Eigenerosion, derived from a general eigenfracture approach, utilizes eigendeformations $\varepsilon^*$ to describe the fracture set

• According to its energetic level, an element can be either:
  • intact with elastic behavior
  • eroded with no load bearing capacity

• Requires the construction of an $\varepsilon$ – neighborhood around the crack set

• Requires the critical energy release rate $G_c$

[Pandolfi & Ortiz, 2012]
At each time \( t \) of the discrete dynamic analysis the elastic equilibrium is computed.

For each element \( K \) compute the net energy gain

\[
-\Delta F_K = -\Delta E_K - G_c \Delta A_K
\]

- \( \Delta E_K \): Elastic energy released upon erosion of element \( K \). Account also for failure in compression by considering only the deviatoric elastic energy.

- \( G_c \Delta A_K \): Fracture energy cost. Computed using the critical energy release rate \( G_c \) of the material multiplied by a measure of the crack extension.

The crack extension is based on the \( \epsilon \) – neighborhood construction

\[
\Delta A_K = \frac{|(C \cup K) \setminus C\epsilon|}{2\epsilon}
\]

[Pandolfi & Ortiz, 2012]
• Use a coarse discretization of the slab with dense (36) aggregate configuration
• Adopt Neo-Hookean material model for intact material
• $\epsilon$ - neighborhood construction:
  • Based on the minimum mesh size $h_{\text{min}}$
  • $\epsilon = C_1 h_{\text{min}}$, where $C_1 = 4$ or 6
• Considered critical energy release rates: $G_C = 60$, 70, or 80 N/m

• Blast load yield factor:
  • Low yield factor: $\lambda = 0.01 – 0.1$, erosion of the mortar matrix only and elastic metaconcrete constituents
  • High yield factor: $\lambda = 0.1 – 0.5$, erosion of all materials

Test various explosion yields applied to the slab exposed face
Comparison of longitudinal stress wave propagation

- $\lambda = 0.05$ and $G_c = 70$ N/m, comparative view at time $= 0.05$ ms

**Homogeneous Material**

**1 mm Silicone Coated Aggregates**

**1 mm Nylon Coated Aggregates**
Erosion of the Exposed Slab Surface

Compare the eroded surfaces attained for each slab case

- Erosion concentrated around the front of the slab
- $\lambda = 0.05$ and $G_c = 70$ N/m

Homogeneous Material

1 mm Silicone Coated Aggregates

1 mm Nylon Coated Aggregates

Eroded to expose first aggregate
Energy dissipated through fracturing of the mortar matrix

• Homogeneous mortar slab and metaconcrete slab with 1 mm nylon coated aggregates

[Fracture Energy Plot]

Small linear increase in fracture energy with $G_c$

Metaconcrete produces a smaller fracture energy for $\lambda > 0.065$

Similar fracture energy for $0.02 < \lambda < 0.065$

No erosion for $\lambda < 0.02$

[Mitchell et al., 2015a]
Fracture Energy Surfaces

\[ G_c = 60 \text{ N/m}, \lambda = 0.10 \]

\[ G_c = 80 \text{ N/m}, \lambda = 0.10 \]

\[ G_c = 60 \text{ N/m}, \lambda = 0.04 \]
Mechanical energy absorbed by the aggregates and maximum stress in the mortar matrix

- Investigate all the aggregate and geometry configurations and compare to a homogeneous mortar slab, $\lambda = 0.05$, $G_c = 70$ N/m

Nylon and UF coatings provide the most improved performance.
Analyze the behavior of metaconcrete under an extreme blast loading event, $\lambda \geq 0.1$

- Assume erosion of the aggregate core and coating materials:

$$G_{c}^{\text{core}} = 10,000 \text{ N/m}, \ G_{c}^{\text{coating}} = 1,000 \text{ N/m}, \ G_{c}^{\text{mortar}} = 80 \text{ N/m}$$
Analyze the behavior of metaconcrete under an extreme blast loading event, $\lambda \geq 0.1$

- Assume erosion of the aggregate core and coating materials:

$$G_{c_{\text{core}}} = 10,000 \text{ N/m}, \quad G_{c_{\text{coating}}} = 1,000 \text{ N/m}, \quad G_{c_{\text{mortar}}} = 80 \text{ N/m}$$

- Homogeneous Material

- Comparative view at time = 0.06 ms

- 1 mm Nylon Coated Aggregates

- blue = compression
- red = tension

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Seminari DICA 2015/2016 – A. Pandolfi
Analyze the behavior of metaconcrete under an extreme blast loading event, $\lambda \geq 0.1$

- Assume erosion of the aggregate core and coating materials:
  
  \[
  G_c^{\text{core}} = 10,000 \text{ N/m}, \quad G_c^{\text{coating}} = 1,000 \text{ N/m}, \quad G_c^{\text{mortar}} = 80 \text{ N/m}
  \]

\[
\begin{array}{cccc}
\lambda = 0.1 & \lambda = 0.2 & \lambda = 0.3 & \lambda = 0.4 & \lambda = 0.5 \\
\end{array}
\]

- Blue = compression
- Red = tension

Comparative view at time = 0.06 ms

1 mm Nylon Coated Aggregates

Homogeneous Material
Analyze the behavior of metaconcrete under an extreme blast loading event, $\lambda \geq 0.1$

- Assume erosion of the aggregate core and coating materials:

  $G_{c}^{\text{core}} = 10,000 \text{ N/m}$, $G_{c}^{\text{coating}} = 1,000 \text{ N/m}$, $G_{c}^{\text{mortar}} = 80 \text{ N/m}$

  $\lambda = 0.1$  $\lambda = 0.2$  $\lambda = 0.3$  $\lambda = 0.4$  $\lambda = 0.5$

**Homogeneous Material**

- **blue** = compression
- **red** = tension

Comparative view at time = 0.06 ms

**1 mm Nylon Coated Aggregates**
Analyze the behavior of metaconcrete under an extreme blast loading event, $\lambda \geq 0.1$

- Assume erosion of the aggregate core and coating materials:

$$G_{c}^{\text{core}} = 10,000 \text{ N/m}, \quad G_{c}^{\text{coating}} = 1,000 \text{ N/m}, \quad G_{c}^{\text{mortar}} = 80 \text{ N/m}$$

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>blue</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>red</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**Homogeneous Material**

Comparative view at time = 0.06 ms

**1 mm Nylon Coated Aggregates**
Analyze the behavior of metaconcrete under an extreme blast loading event, $\lambda \geq 0.1$

- Assume erosion of the aggregate core and coating materials:

\[
G_{c}^{\text{core}} = 10,000 \text{ N/m}, \quad G_{c}^{\text{coating}} = 1,000 \text{ N/m}, \quad G_{c}^{\text{mortar}} = 80 \text{ N/m}
\]

- For different values of $\lambda$:
  - $\lambda = 0.1$
  - $\lambda = 0.2$
  - $\lambda = 0.3$
  - $\lambda = 0.4$
  - $\lambda = 0.5$

Homogeneous Material

1 mm Nylon Coated Aggregates

Comparative view at time $= 0.06 \text{ ms}$
Concluding Remarks

• New type of concrete for enhanced performance in the presence of dynamic loading, consisting of spherical layered resonant aggregates suspended in a mortar matrix
• Resonance leads to negative effective mass, the formation of band gaps, and wave attenuation, with energy trapping and stress reduction (confirmed by FE analysis)
• Alternative to standard concrete in blast shielding and impact protection applications:
  • Composite wall panels, exterior walls, barriers, and shielding structures.
  • Seismic shielding, tuned damping foundations, or vibration attenuation.
• Future numerical work consider other slab configurations
  • Non-periodic aggregate arrangements, new geometries, materials and spacing
  • Other material behaviors, such as viscous effects
• Experimental work
  • Test the resonant properties of a single aggregate
  • Test a full scale sample for wave transmission characteristics
  • Refinement of design and fabrication method for large scale manufacture
Metaconcrete References


