Identifying Optimal Concrete Strength For Varying Levels Of Blast Loading

TAREK H. KEWAISY
PhD, PE, PMP, BSCP
Principal Associate
tkewaisy@louisberger.com
202-557-3858
• **UMKC** Planned and Executed a Testing Program for **NSCNR** and **HSCVR** Specimens at the Blast Loading Simulator (**BLS**), ERDC, Vicksburg, MS

• On 2013, **NSF/ ACI 447** Organized **Blast Blind Simulation Contest** based on Available Test Measurements

• Response Prediction Using **Various Simulation Techniques** (**FEM** and **SDOF**)

• Objective was to Understand **Prediction Capabilities and Limitations** of Available Simulation Techniques
Compared to Test Measurements, **RCBlast** SDOF Estimates Were:

1. Within ±10.0% (on average) for **Maximum Displacement**
2. Within ±20% (on average) for **Residual Displacement**
OBJECTIVES OF CURRENT RESEARCH

- **Compute and Compare** Blast Responses of One-way RC Slabs Constructed of Different Material Strengths for Wide Range of Blast Load Intensities and Durations

- **Provide Recommendations** for Optimum Use of Different Strength Classes of Reinforced Concrete for Various Blast-Resistant Design Applications.
PRESENTATION OUTLINE

1 INTRODUCTION
2 STUDY PARAMETERS
3 DYNAMIC ANALYSIS
4 BLAST RESPONSE
5 CONCLUDING REMARKS
6 QUESTIONS
### MATERIAL PROPERTIES

#### Uniaxial Compressive Stress-Strain Curve (NSC, MSC, HSC)

<table>
<thead>
<tr>
<th></th>
<th>NSC</th>
<th>MSC</th>
<th>HSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_c'$</td>
<td>5,000</td>
<td>10,000</td>
<td>15,000</td>
</tr>
<tr>
<td>$f_t$</td>
<td>440</td>
<td>635</td>
<td>750</td>
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<tr>
<td>$E_c$</td>
<td>3,825,000</td>
<td>4,819,000</td>
<td>5,516,500</td>
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<tr>
<td>$\varepsilon_{c\text{-max}}$</td>
<td>0.0035</td>
<td>0.0032</td>
<td>0.0030</td>
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<tr>
<td>SIF$_c$</td>
<td>1.00</td>
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<tr>
<td>DIF$_c$</td>
<td>1.344</td>
<td>1.170</td>
<td>1.113</td>
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#### Reinforcement Tensile Engineering Stress-Strain Curve

<table>
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<tr>
<th></th>
<th>NSR A615 Gr-60</th>
<th>MSR A615 Gr-75</th>
<th>HSR A1035 Gr-100</th>
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<tr>
<td>$F_y$</td>
<td>60,000</td>
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<tr>
<td>$F_{sh}$</td>
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</tr>
<tr>
<td>$F_u$</td>
<td>92,000</td>
<td>105,000</td>
<td>165,000</td>
</tr>
<tr>
<td>$\varepsilon_{t\text{-max}}$</td>
<td>0.145</td>
<td>0.135</td>
<td>0.110</td>
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<tr>
<td>SIF$_s$</td>
<td>1.20</td>
<td>1.10</td>
<td>1.00</td>
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<tr>
<td>DIF$_s$</td>
<td>1.260</td>
<td>1.185</td>
<td>1.068</td>
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BLAST LOADS

- **LOW PRESSURE (LP)**: 30 psi
- **MEDIUM PRESSURE (MP)**: 45 psi
- **HIGH PRESSURE (HP)**: 60 psi

- **Short Duration (SD)**: 10 msec
- **Medium Duration (MD)**: 20 msec
- **Long Duration (LD)**: 40 msec
INVESTIGATED CASES

SIMPLE SUPPORTS

BL1 → BL2 → BL3 → BL4 → BL5 → BL6 → BL7 → BL8 → BL9

NS MS HS NS MS HS NS MS HS NS MS HS NS MS HS NS MS HS NS MS HS NS MS HS NS MS HS
C1 C2 C3 C4 C5 C6 C7 C8 C9 C10 C11 C12 C13 C14 C15 C16 C17 C18 C19 C20 C21 C22 C23 C24 C25 C26 C27

FIXED SUPPORTS

BL1 → BL2 → BL3 → BL4 → BL5 → BL6 → BL7 → BL8 → BL9

NS MS HS NS MS HS NS MS HS NS MS HS NS MS HS NS MS HS NS MS HS NS MS HS NS MS HS
C28 C29 C30 C31 C32 C33 C34 C35 C36 C37 C38 C39 C40 C41 C42 C43 C44 C45 C46 C47 C48 C49 C50 C51 C52 C53 C54

54 Cases 2 Boundary Conditions 9 Blast Loads 3 RC Classes 1 Slab Geometry/Structure
PRESENTATION OUTLINE

1. INTRODUCTION
2. STUDY PARAMETERS
3. DYNAMIC ANALYSIS
4. BLAST RESPONSE
5. CONCLUDING REMARKS
6. QUESTIONS
• **RCBlast** by Eric Jacque (M.A.Sc. University of Ottawa)
• SDOF Approach
• RC Components
• Hysteretic Response
• Plastic-Hinge Length
• Time History Loading
• P-I Option
• Experimentally Verified
**SDOF PARAMETERS**

### Simple Supports

<table>
<thead>
<tr>
<th>Symbol</th>
<th>NSC/NSR</th>
<th>MSC/MSR</th>
<th>HSC/HSR</th>
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<td>869</td>
<td>869</td>
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<td>0.78, 0.78, 0.66</td>
<td>0.78, 0.78, 0.66</td>
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<td>$K_E \text{ psi/in}$</td>
<td>49.58</td>
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<tr>
<td>$L_p \text{ in}$</td>
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<td>9.84</td>
</tr>
<tr>
<td>$r_u \text{ psi}$</td>
<td>29.05</td>
<td>30.64</td>
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<tr>
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### Fixed Supports

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<td>$M_{\text{psi.ms}^2\text{in}}$</td>
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<tr>
<td>$K_{LM}$</td>
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<td>$K_E \text{ psi/in}$</td>
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<td>9.84</td>
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<tr>
<td>$r_u \text{ psi}$</td>
<td>58.04</td>
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<td>$T_N \text{ msec}$</td>
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RESPONSE LIMITS/ DAMAGE LEVELS

End Rotations Limits

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<tr>
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<th>Damage Level</th>
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<tbody>
<tr>
<td>B1</td>
<td>B2</td>
<td>B3</td>
<td>B4</td>
<td>B5</td>
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<tr>
<td>Superficial Damage</td>
<td>Moderate Damage</td>
<td>Heavy Damage</td>
<td>Hazardous Failure</td>
<td>Blowout</td>
</tr>
<tr>
<td>( \mu )</td>
<td>( \theta )</td>
<td>( \mu )</td>
<td>( \theta )</td>
<td>( \mu )</td>
</tr>
<tr>
<td>1.0</td>
<td>-</td>
<td>2°</td>
<td>-</td>
<td>5°</td>
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USACE/PDC-TR 06-08 Single-Degree-of-Freedom Structural Response Limits for Anti-terrorism Design

Mid-Displacement Limits

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<td>B3</td>
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<tr>
<td>Superficial</td>
<td>Moderate</td>
<td>Heavy</td>
<td>Hazardous</td>
<td>Blowout</td>
</tr>
<tr>
<td>( X_{max}/L )</td>
<td>( X_{max}/L )</td>
<td>( X_{max}/L )</td>
<td>( X_{max}/L )</td>
<td>( X_{max}/L )</td>
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<tr>
<td>0.0175</td>
<td>0.070</td>
<td>0.175</td>
<td>0.353</td>
<td>&gt; 0.353</td>
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<td>( X_{max} ) (L=52in)</td>
<td>( X_{max} ) (L=52in)</td>
<td>( X_{max} ) (L=52in)</td>
<td>( X_{max} ) (L=52in)</td>
<td>( X_{max} ) (L=52in)</td>
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<tr>
<td>( \approx 0.907 )</td>
<td>0.907</td>
<td>2.275</td>
<td>4.585</td>
<td>&gt; 4.585</td>
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Simple Supports Low Pressure/Short Duration Blast $T/T_N \approx 0.50$, $P/r_u \approx 1.15$

B1/B2 (Low-Moderate) Damage for NSC, MSC, HSC

Approx. the Same Max Displ. For NSC, MSC, HSC

Response to LP/SD Blast (S-S)
Response to LP/MD Blast (S-S)

Simple Supports Low Pressure/ Medium Duration Blast  \( T/T_n \approx 1.06 \), \( P/r_u \approx 1.15 \)

B3 (Heavy) Damage for NSC, B2 (Moderate) Damage for MSC, HSC

Slight Variation in Max. Displ. Responses But With Comparable Level of Damage for NSC, MSC, HSC
Simple Supports Low Pressure/Long Duration Blast
$T/T_N \approx 2.04$, $P/r_u \approx 1.15$

B2/B3 (Moderate to Heavy) Damage for NSC, MSC, B2 (Moderate) Damage for HSC

Different Displ. Responses But Similar Damage Level for NSC, and MSC. No Advantage in Using MSC

Relatively Low Level of Damage for HSC. May indicate Overdesign in Some Cases
Response to MP/SD Blast (S-S)

Simple Supports Medium Pressure/ Short Duration Blast \( T/T_N \approx 0.50 \), \( P/r_u \approx 1.73 \)

B2/B3 (Moderate to Heavy) Damage for NSC, MSC, B2 (Moderate) Damage for HSC

Minor Variation in Max Displ. but Close Range of Damage Levels for NSC, MSC, HSC

Close Similarity of Max. and Resid. Response for NSC and MSC. No Advantage in Using MSC
Simple Supports Medium Pressure/Medium Duration Blast $T/T_N \approx 1.06$, $P/r_u \approx 1.73$

B3/B4 (Heavy to Severe) Damage for NSC, B3 (Heavy) Damage for MSC, HSC

Severe Damage for NSC Disqualifies its Use for Medium-High Blast Loads

Heavy But Acceptable Damage for MSC and HSC.
**Response to MP/LD Blast (S-S)**

- **Simple Supports Medium Pressure/Long Duration Blast**
  \[ \frac{T}{T_N} \approx 2.04, \frac{P}{r_u} \approx 1.73 \]

- **B5 (Blow-Out) Damage for NSC, B4 (Severe) for MSC, B3 (Heavy) Damage for HSC**

- Blow-out Failure for NSC and Severe Damage for MSC Dismisses Potential Use for Relatively High Blast Loads

- Acceptable Heavy Damage Indicates That HSC is the Best Viable Option for Relatively High Blast Loads
Slight Variation in Max. Displ. Responses But With Comparable Levels of Damage for NSC, MSC, HSC

Simple Supports High Pressure/Short Duration Blast $T/T_N \approx 0.50$, $P/r_u \approx 2.31$

B3 (Moderate to Heavy) Damage for NSC, MSC, HSC
Response to HP/MD Blast (S-S)

Blow-out Failure for NSC and Severe Damage for MSC Dismisses Potential Use for Relatively High Blast Loads

Acceptable Heavy Damage Indicates That HSC is the Best Viable Option for Relatively High Blast Loads

Simple Supports High Pressure/ Medium Duration Blast  $T/T_N \approx 1.06$, $P/r_u \approx 2.31$

B5 (Blow-Out) Damage for NSC, B4 (Severe) for MSC, B3/B4 (Heavy to Severe) Damage for HSC
Simple Supports

High Pressure/Long Duration Blast

\( T/T_N \approx 2.04 \), \( P/r_u \approx 2.31 \)

B5 (Blow-Out) Damage for NSC, MSC, B4 (Severe) Damage for HSC

Blow-out Failures for Both NSC and MSC Dismisses Potential Use for Severe Blast Conditions

Severe Damage w/o Blow-out Indicates That HSC is the Only Option for Severe Blast Conditions
SIMPLY SUPPORTED SLABS

- Use of **NSC/NSR** is adequate for **LP** blast with any **Duration**. For **MP** & **HP** blasts, proper use of **NSC/NSR** would be limited to **SD** only.

- Use of **MSC/MSR** proved to be practical primarily for **MP/MD** blast loading.

- Use of **HSC/HSR** is most effective for **HP** blast with **MD & LD** due to reduced **Damage Extents** and avoidance of **Blow-out Failure**.
The need to use MSC/MSR or HSC/HSR diminishes due to the inherent higher flexural resistance ($r_u$), higher stiffness ($K_E$), and lower fundamental period ($T_N$). The use of NSC/NSR is deemed adequate for most if not all Practical Blast-Resistant designs.
The use of **MSC/MSR** or **HSC/HSR** may be required to achieve Elastic Structural Response for Repeated Blast applications (e.g. blast containment).

The use of **MSC/MSR** is limited to **LP** blast with **SD**.

The use of **HSC/HSR** is more suited for **LP** blast with any **Duration**, or for **MP** blast with **SD & MD**, or for **HP** blast with **SD**.

<table>
<thead>
<tr>
<th>P/r₀</th>
<th>HSC/HSR</th>
<th>HSC/HSR</th>
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<tr>
<td>0.00</td>
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</tr>
<tr>
<td>0.40</td>
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<td></td>
</tr>
<tr>
<td>0.60</td>
<td></td>
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<td></td>
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<tr>
<td>0.80</td>
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</tbody>
</table>

- **SD**: Short Duration
- **MD**: Medium Duration
- **LD**: Long Duration

**NDIA**  
2018 International Explosives Safety Symposium & Exposition  
Arora G – 15, 2018 San Diego, CA  
Louis Berger
Favorable changes in the primary Dynamic Properties are not linearly proportional to the Material Strength. Therefore the emphasis of Efficient Blast-Resistant Reinforced Concrete Design should Not be on the use of Stronger materials. Rather the focus should be on the use of Tougher materials and Ductile detailing.
The Most Influential non-dimensional parameters affecting the structural response to shock loading are:
- Load Duration-to-Fund. Period Ratio ($\frac{T}{T_N}$)
- Load Intensity-to-Resistance Ratio ($\frac{P}{r_u}$)

SODF approaches that adequately capture response dependence on these parameters can be used successfully for Blast-Resistant Design
CONCLUDING REMARKS

When evaluating construction material alternatives for **Blast-Resistance**, it is not sufficient to consider the **Reduced Response/ Damage** as the only **Selection Criterion**. It is essential to conduct a **Cost-Benefit Analysis** to compare the **added value** (i.e. higher level of protection) obtained using **Stronger Materials** to the **increase in costs** (i.e. design & construction).
Questions