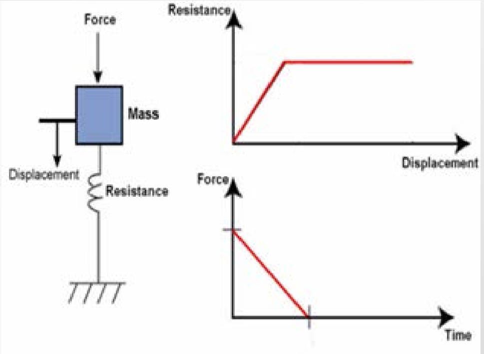
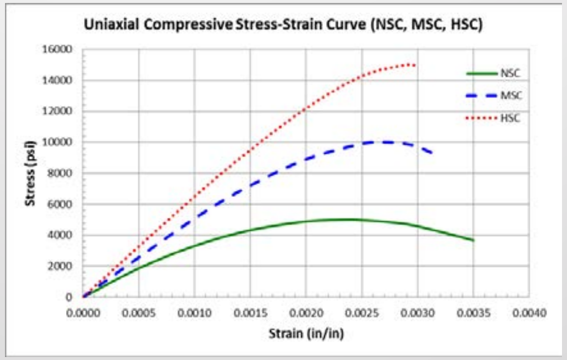
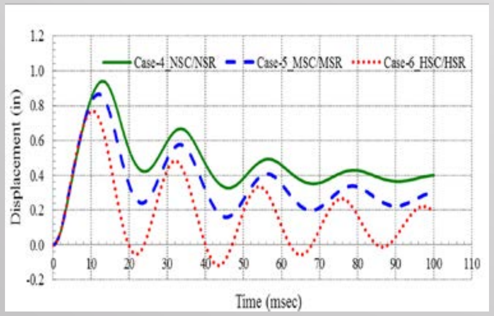
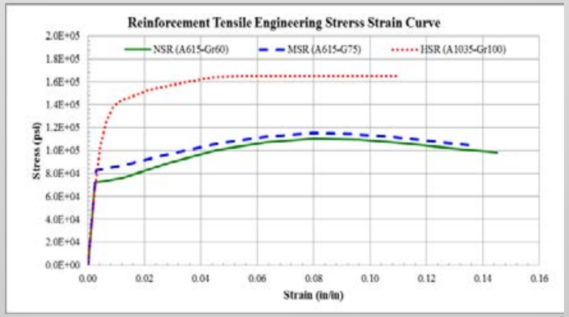
# Identifying Optimal Concrete Strength For Varying Levels Of Blast Loading

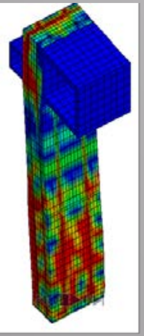
Louis Berger

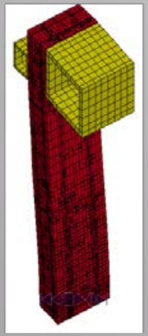


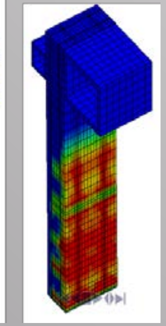



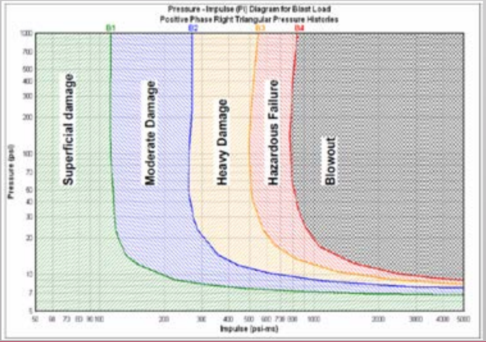



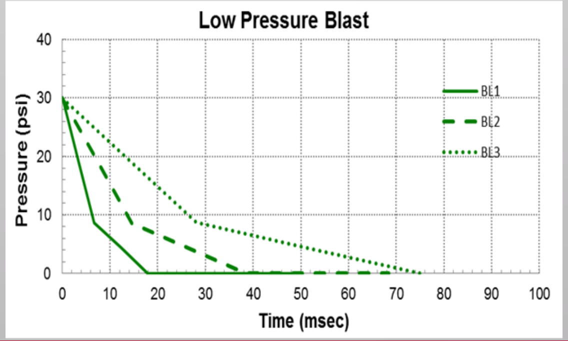







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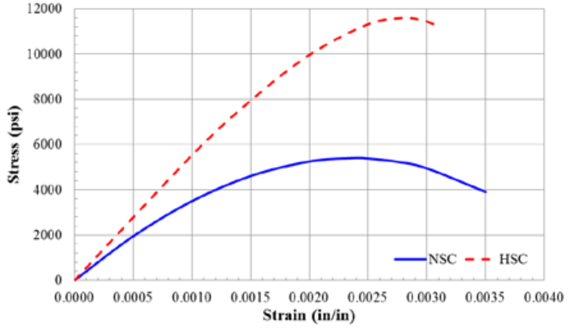
# PRESENTATION OUTLINE

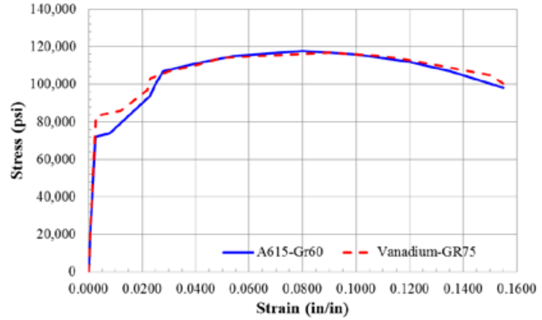




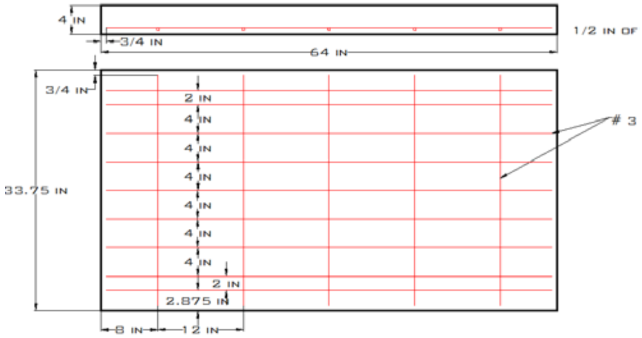
# PRIOR RESEARCH WORK

- **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

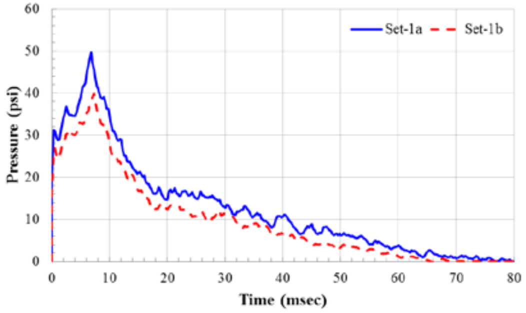



Materials Properties




Slab Details




Blast Loading

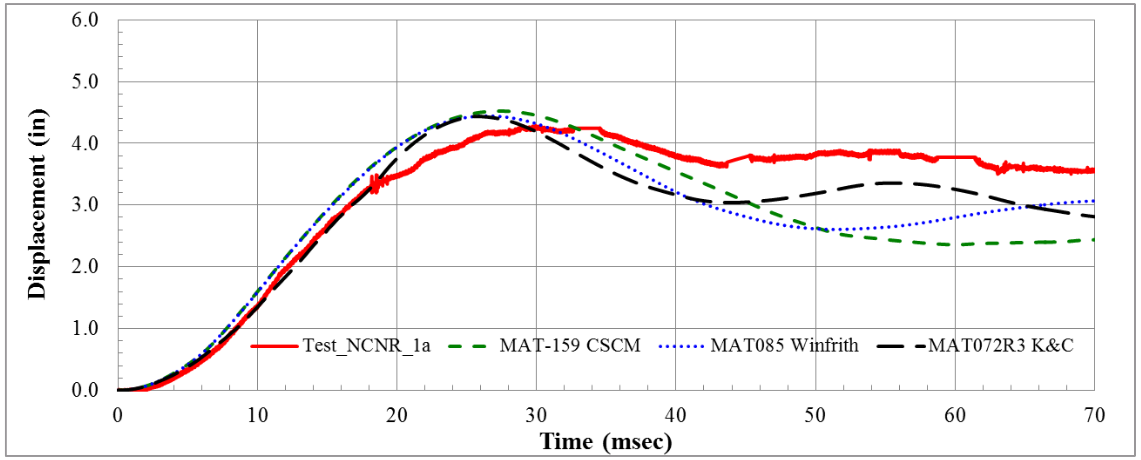


# PRIOR RESEARCH WORK

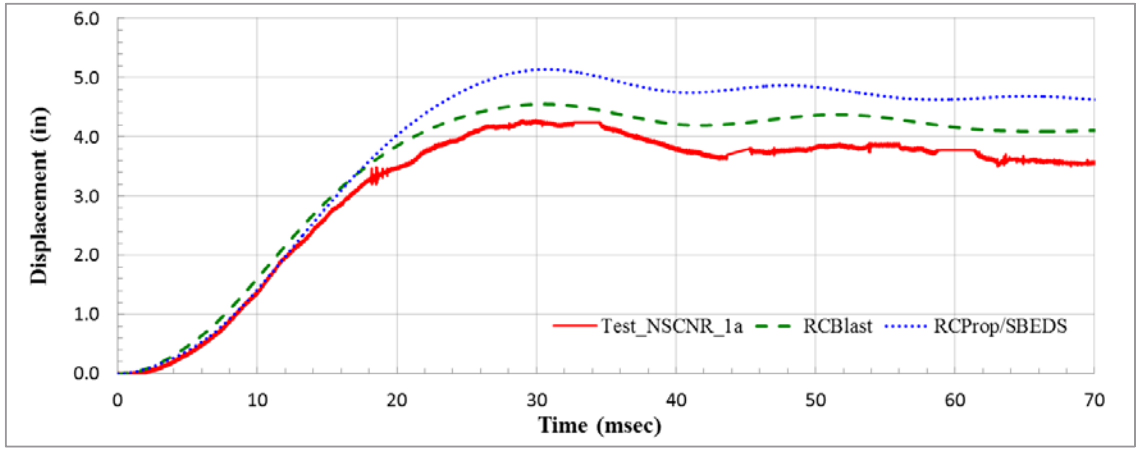
NSCNR Test

HSCVR Test

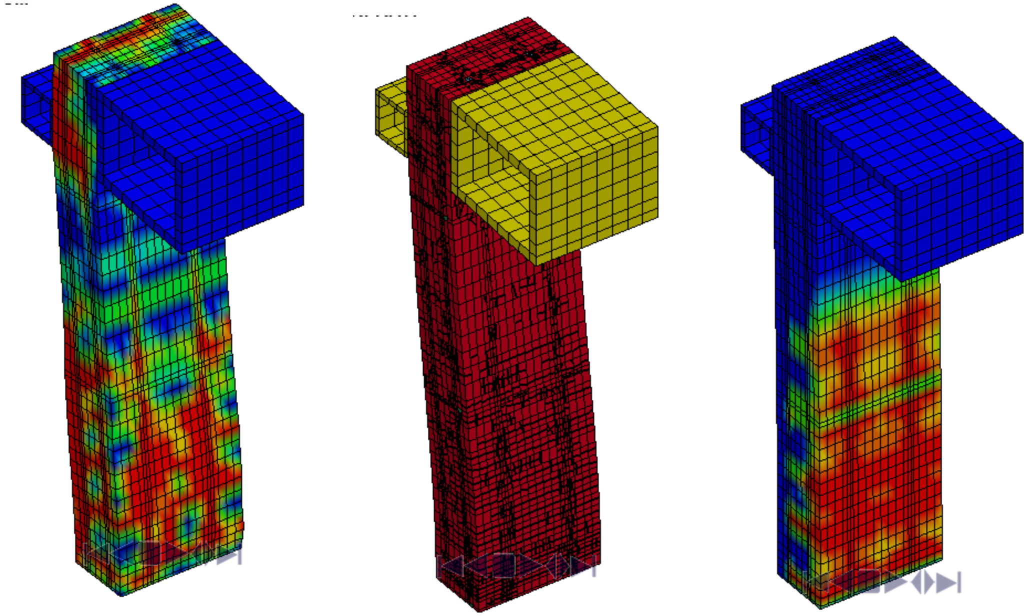
# PRIOR RESEARCH WORK




Finite Element (LS-DYNA) Simulation




SDOF (RCBlast, RCProp/SBEDS) Simulation



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

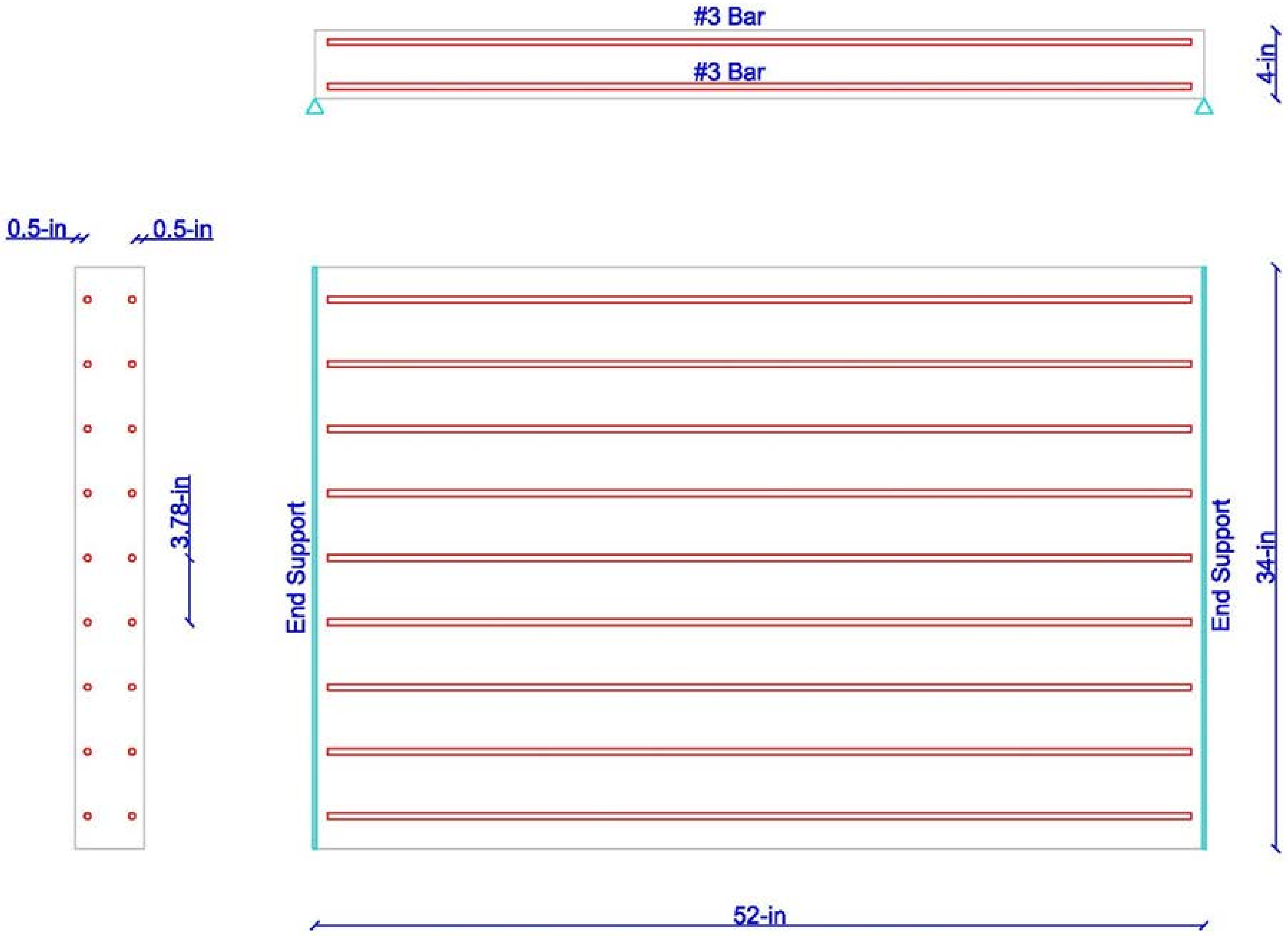
- **Provide Recommendations** for Optimum Use of Different Strength Classes of Reinforced Concrete for Various Blast-Resistant Design Applications.

# PRESENTATION OUTLINE

1. INTRODUCTION
2. **STUDY PARAMETERS**
3. DYNAMIC ANALYSIS
4. BLAST RESPONSE
5. CONCLUDING REMARKS
6. QUESTIONS



# RC SLAB GEOMETRY/ STRUCTURE





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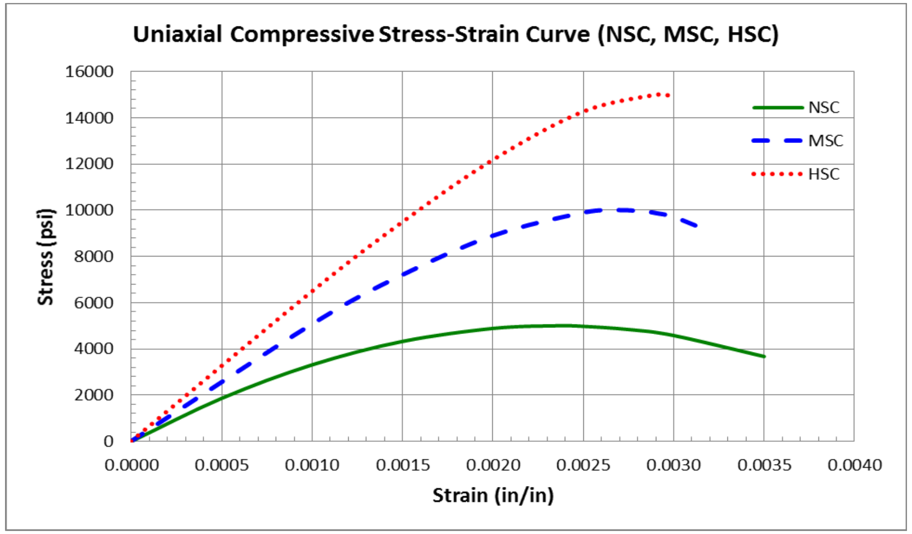
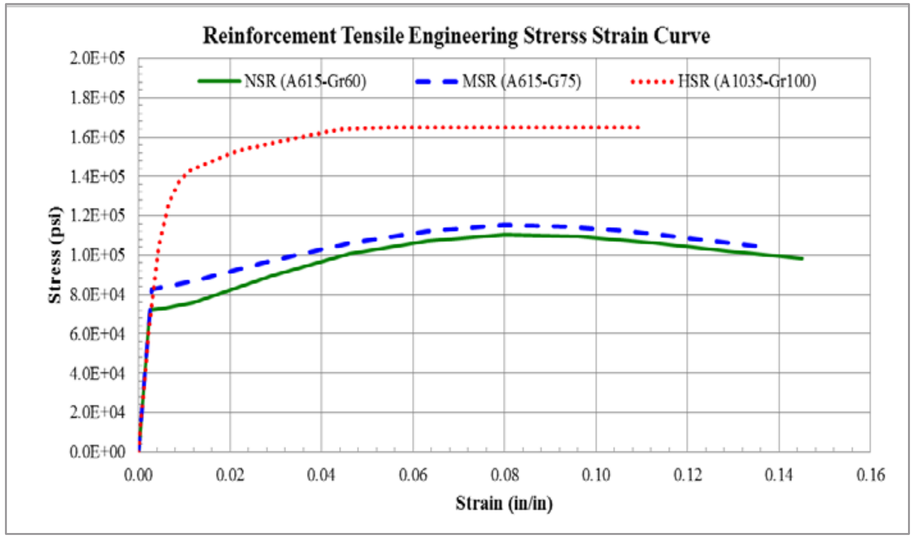
# MATERIAL PROPERTIES

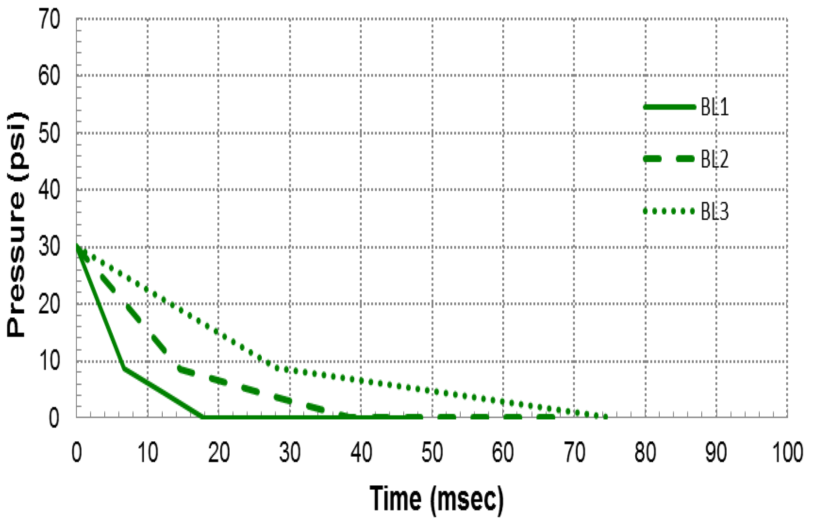


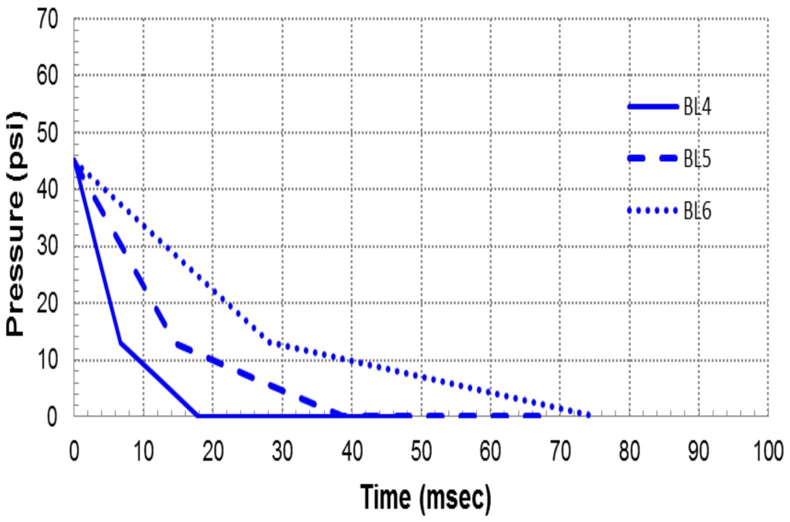

| | NSC | MSC | HSC |
|---|---|---|---|
| $f_{c'}$ | **5,000** | **10,000** | **15,000** |
| $f_t$ | 440 | 635 | 750 |
| $E_c$ | 3,825,000 | 4,819,000 | 5,516,500 |
| $\varepsilon_{c\text{-}max}$ | 0.0035 | 0.0032 | 0.0030 |
| $SIF_c$ | 1.00 | 1.00 | 1.00 |
| $DIF_c$ | **1.344** | **1.170** | **1.113** |

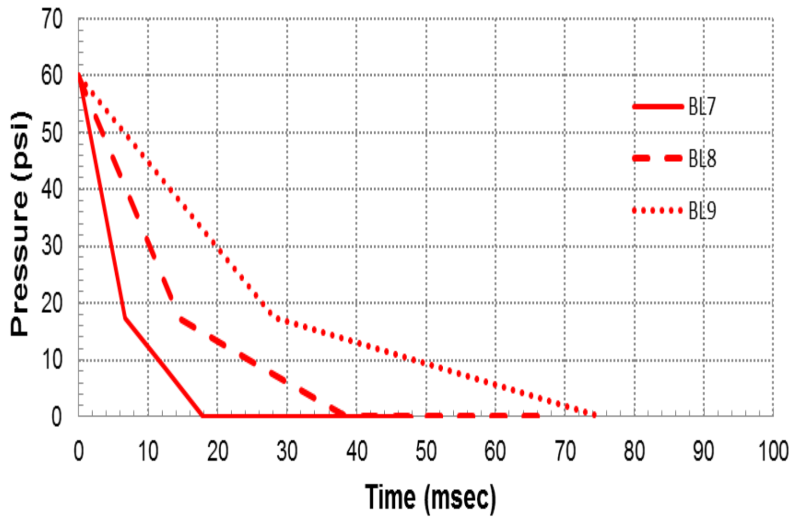



| | NSR A615 Gr-60 | MSR A615 Gr-75 | HSR A1035 Gr-100 |
|---|---|---|---|
| $F_y$ | **60,000** | **75,000** | **100,000** |
| $F_{sh}$ | 63,000 | 79,000 | 105,000 |
| $F_u$ | 92,000 | 105,000 | 165,000 |
| $\varepsilon_{t\text{-}max}$ | **0.145** | **0.135** | **0.110** |
| $SIF_s$ | **1.20** | **1.10** | **1.00** |
| $DIF_s$ | **1.260** | **1.185** | **1.068** |

# BLAST LOADS




LOW PRESSURE (**LP**)
**30** psi

MEDIUM PRESSURE (**MP**)
**45** psi

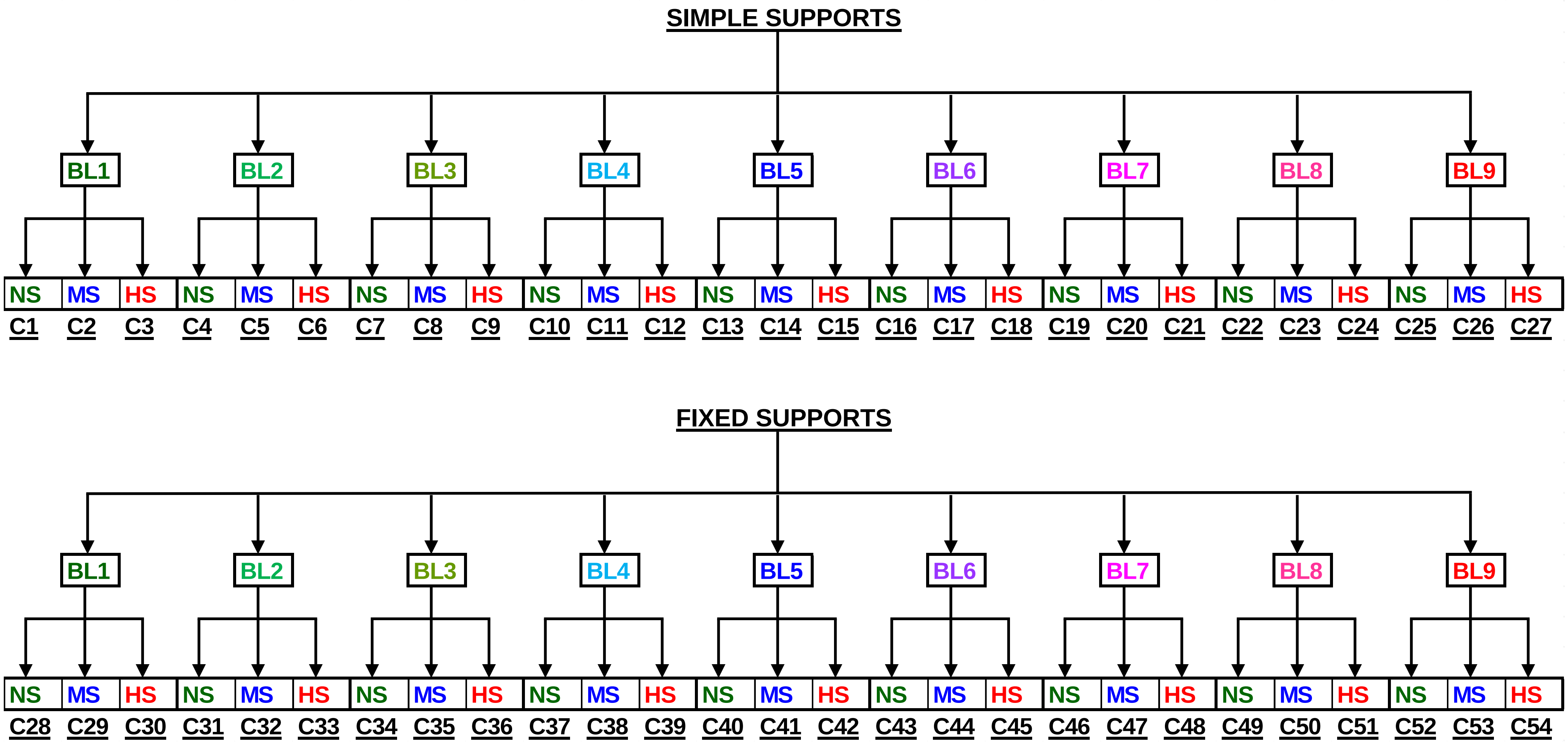
HIGH PRESSURE (**HP**)
**60** psi

Short Duration (**SD**)
**10** msec

Medium Duration (**MD**)
**20** msec

Long Duration (**LD**)
**40** msec

# INVESTIGATED CASES




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



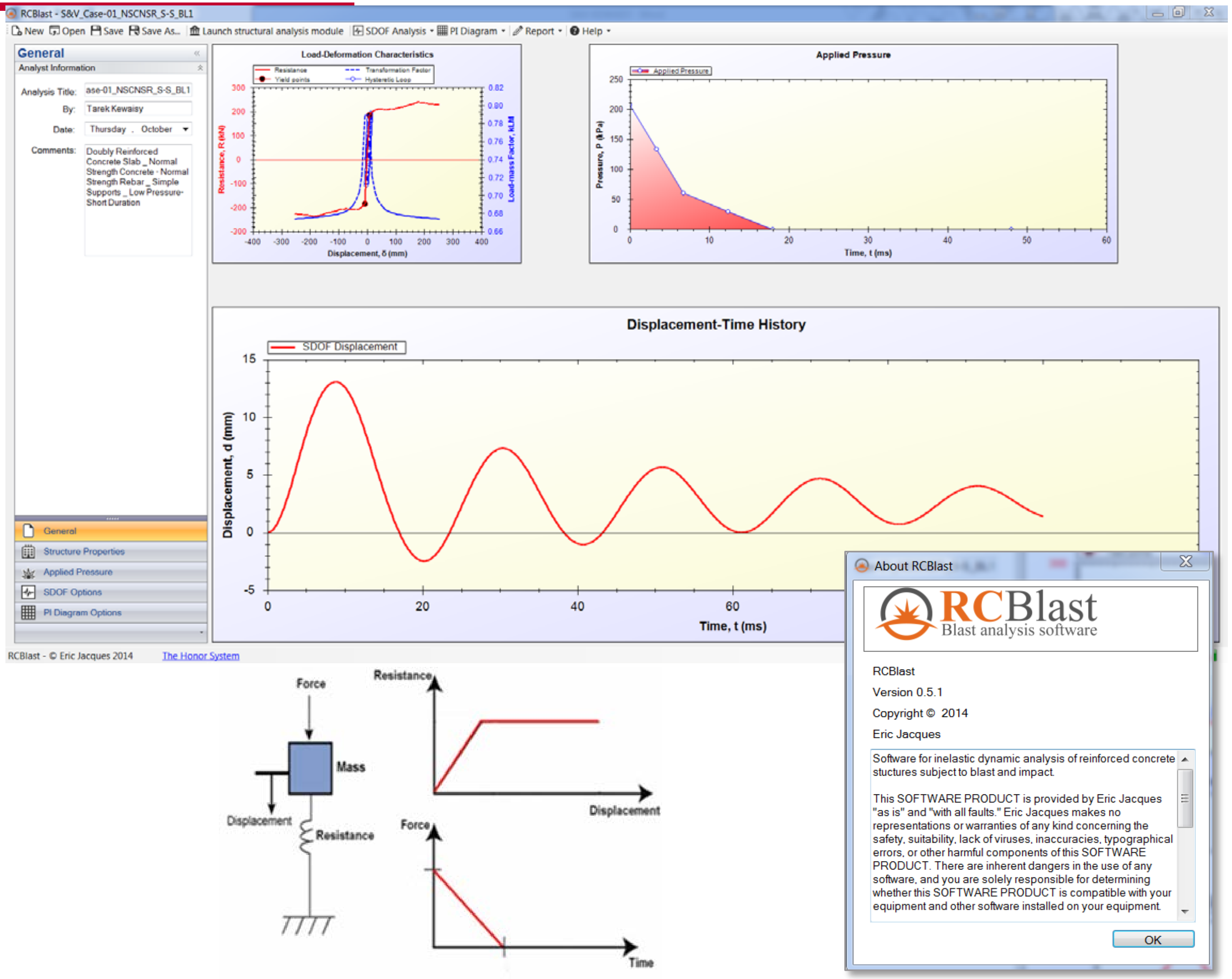
# PRESENTATION OUTLINE



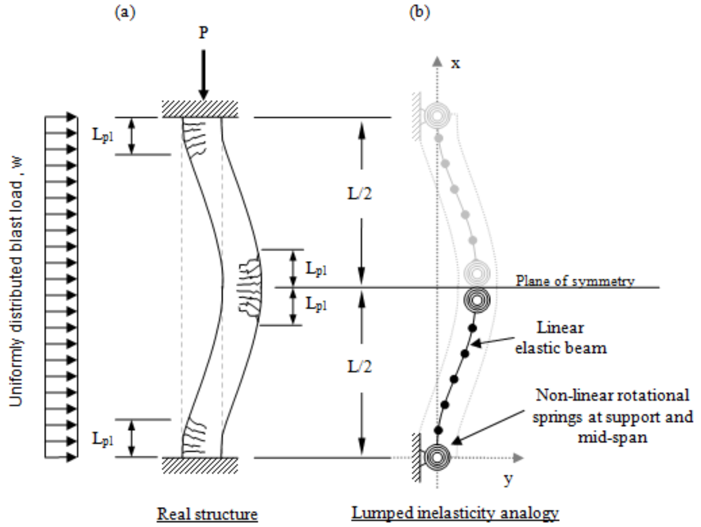


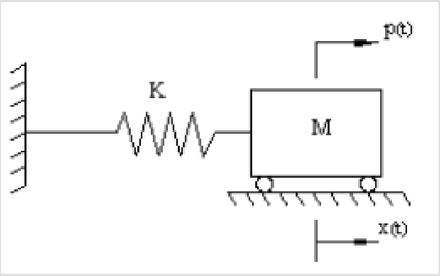
# SDOF TOOL

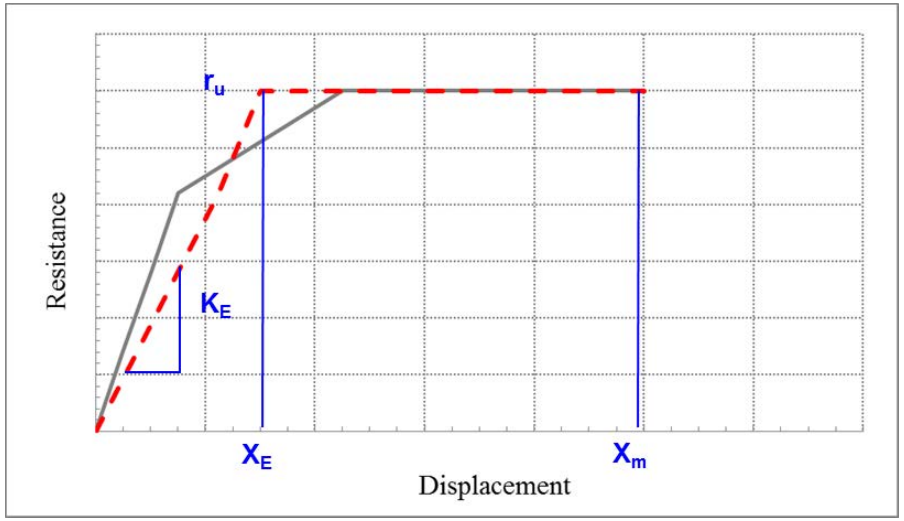
- **RCBlast** by **Eric Jacque** (M.A.Sc. University of Ottawa)
- **SDOF** Approach
- **RC** Components
- **Hysteretic** Response
- **Plastic-Hinge** Length
- **Time History** Loading
- **P-I** Option
- Experimentally **Verified**



# SDOF PARAMETERS



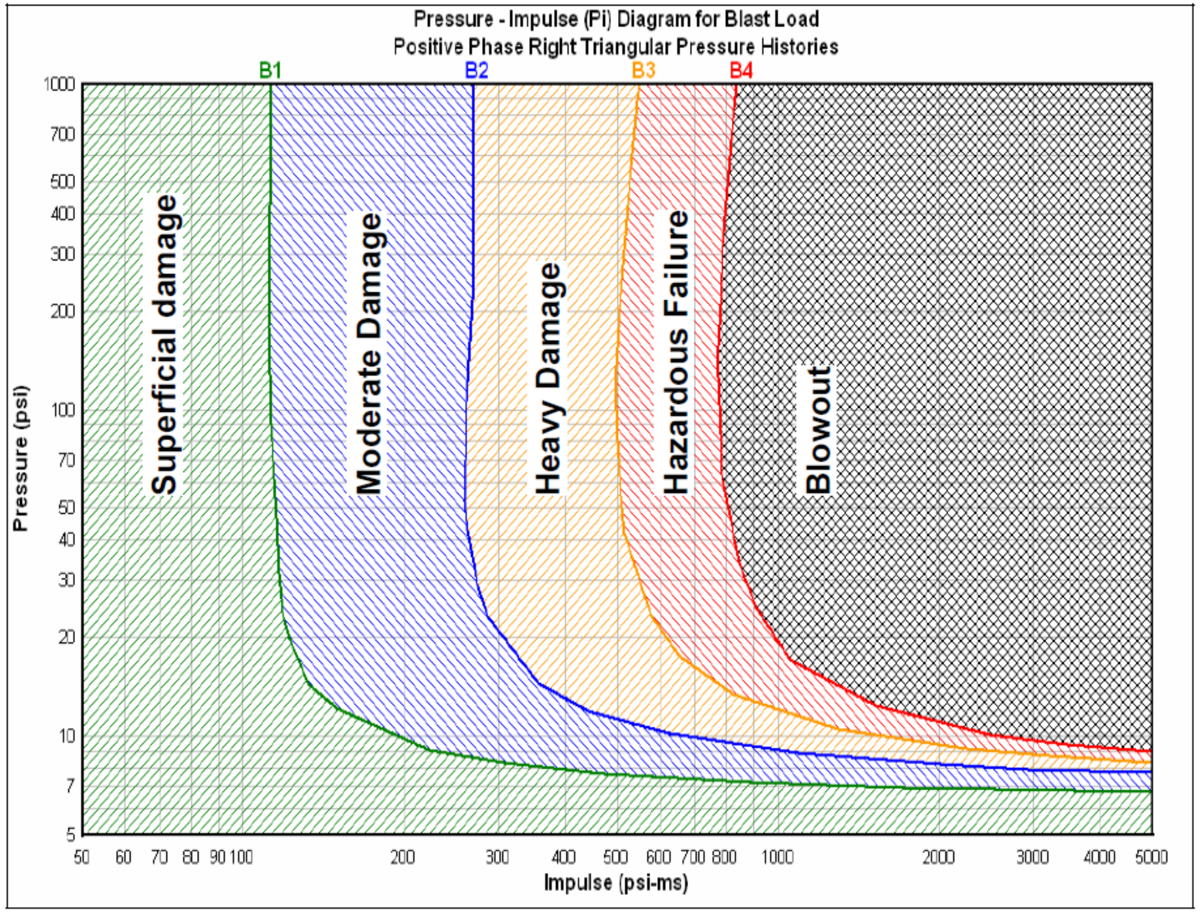

## Simple Supports

| Symbol | NSC/NSR | MSC/MSR | HSC/HSR |
|---|---|---|---|
| $M$ $_{psi.ms^2/in}$ | 869 | 869 | 869 |
| $K_{LM}$ | 0.78,0.78, 0.66 | 0.78,0.78, 0.66 | 0.78,0.78, 0.66 |
| $K_{E\ psi/in}$ | **49.58** | **45.83** | **43.12** |
| $L_{p\ in}$ | 7.48 | 8.46 | 9.84 |
| $r_{u\ psi}$ | **29.05** | **30.64** | **44.68** |
| $X_{E\ in}$ | 0.305 | 0.366 | 0.438 |
| $T_{N\ msec}$ | **18.66** | **19.41** | **20.02** |

## Fixed Supports

| Symbol | NSC/NSR | MSC/MSR | HSC/HSR |
|---|---|---|---|
| $M$ $_{psi.ms^2/in}$ | 869 | 869 | 869 |
| $K_{LM}$ | 0.77,0.78, 0.66 | 0.77,0.78, 0.66 | 0.77,0.78, 0.66 |
| $K_{E\ psi/in}$ | **112.53** | **116.08** | **129.2** |
| $L_{p\ in}$ | 7.48 | 8.46 | 9.84 |
| $r_{u\ psi}$ | **58.04** | **61.24** | **89.24** |
| $X_{E\ in}$ | 0.230 | 0.260 | 0.283 |
| $T_{N\ msec}$ | **12.31** | **12.12** | **11.49** |

# RESPONSE LIMITS/ DAMAGE LEVELS




## End Rotations Limits

| Damage Level B1 | | Damage Level B2 | | Damage Level B3 | | Damage Level B4 | | Damage Level B5 | |
|---|---|---|---|---|---|---|---|---|---|
| Superficial Damage | | Moderate Damage | | Heavy Damage | | Hazardous Failure | | Blowout | |
| μ | θ | μ | θ | μ | θ | μ | θ | μ | θ |
| 1.0 | - | - | 2 ° | - | 5 ° | - | 10 ° | - | > 10 ° |

**USACE/PDC-TR 06-08** Single-Degree-of-Freedom Structural Response Limits for Anti-terrorism Design

## Mid-Displacement Limits

| Damage Level B1 | Damage Level B2 | Damage Level B3 | Damage Level B4 | Damage Level B5 |
|---|---|---|---|---|
| Superficial | Moderate | Heavy | Hazardous | Blowout |
| $X_{max}/L$ | $X_{max}/L$ | $X_{max}/L$ | $X_{max}/L$ | $X_{max}/L$ |
| 0.0175 | 0.070 | 0.175 | 0.353 | > 0.353 |
| $X_{max}$ (L=52in) | $X_{max}$ (L=52in) | $X_{max}$ (L=52in) | $X_{max}$ (L=52in) | $X_{max}$ (L=52in) |
| ≈ 0.907 | 0.907 | 2.275 | 4.585 | > 4.585 |



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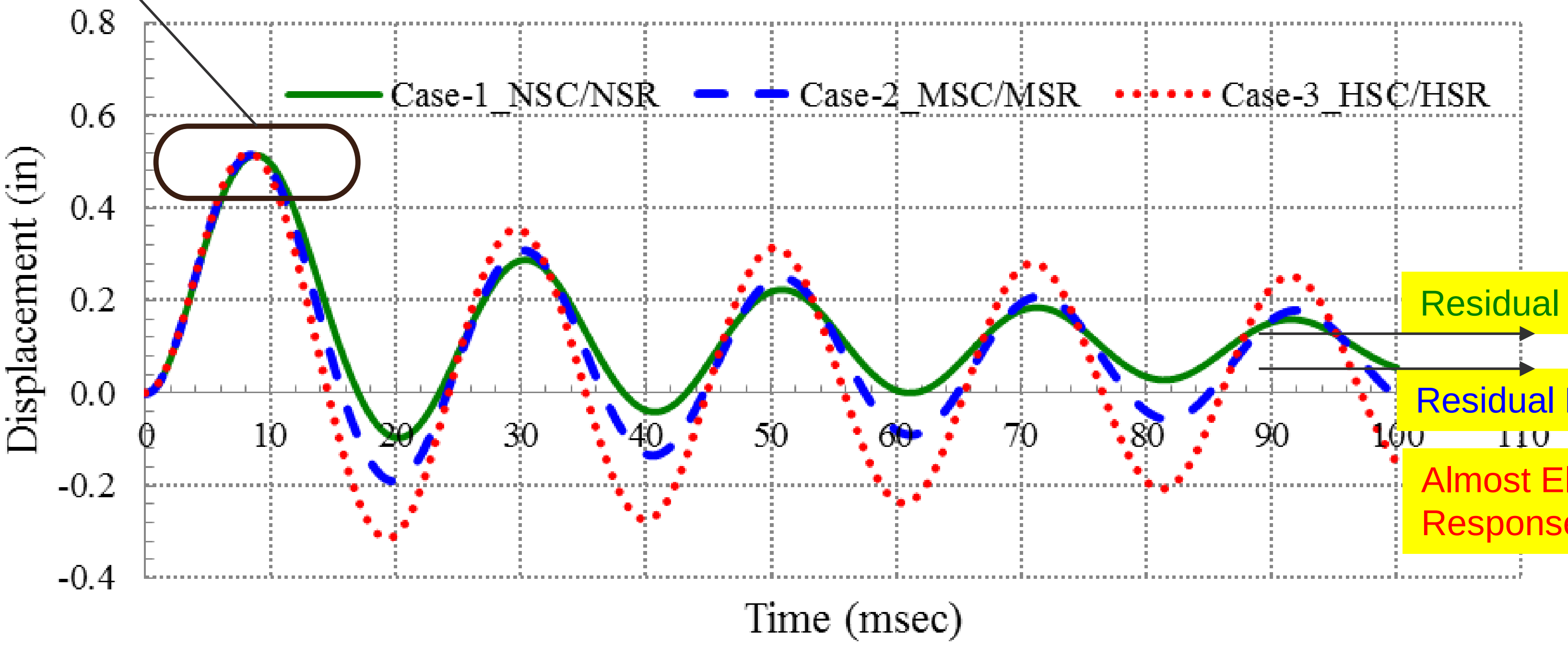
# Response to LP/SD Blast (S-S)

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




Residual Displ. NSC

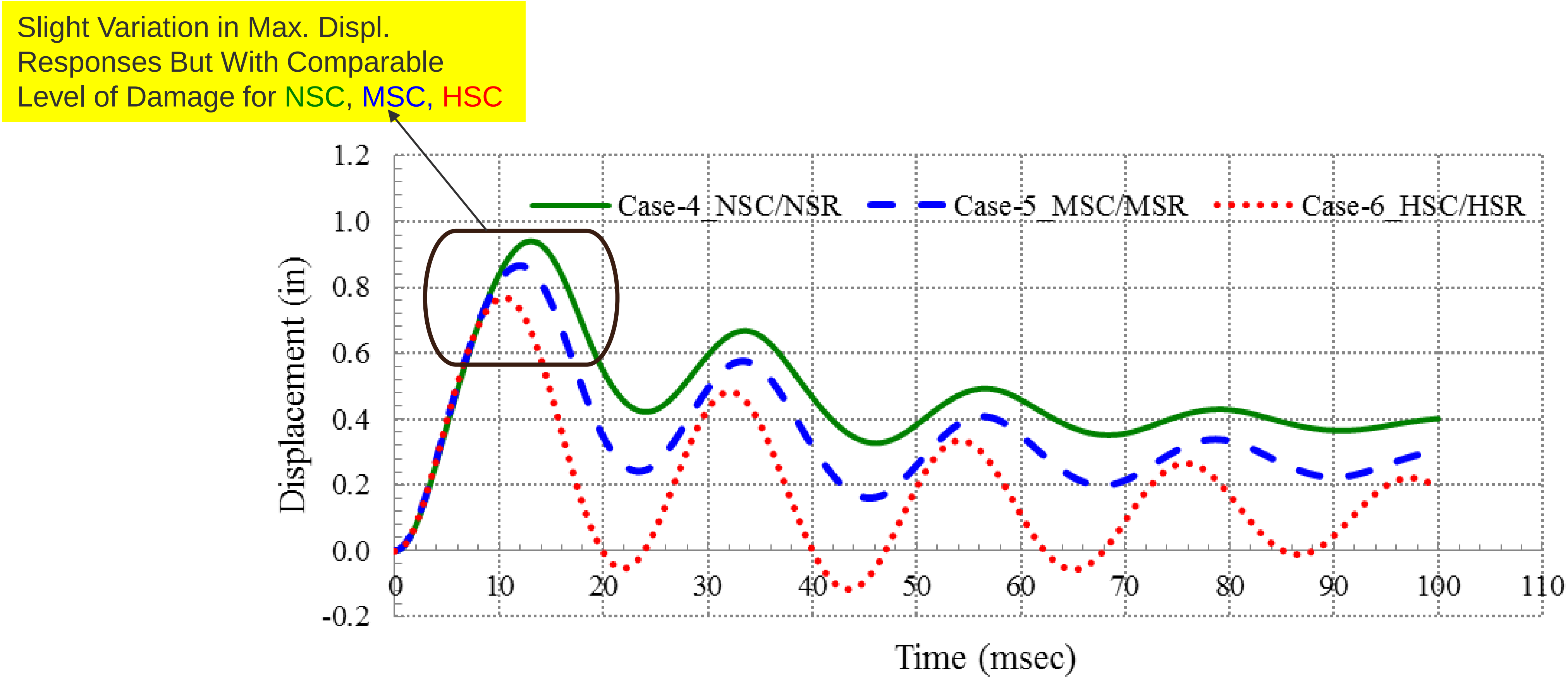
Residual Displ. MSC

Almost Elastic Response HSC

**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**

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

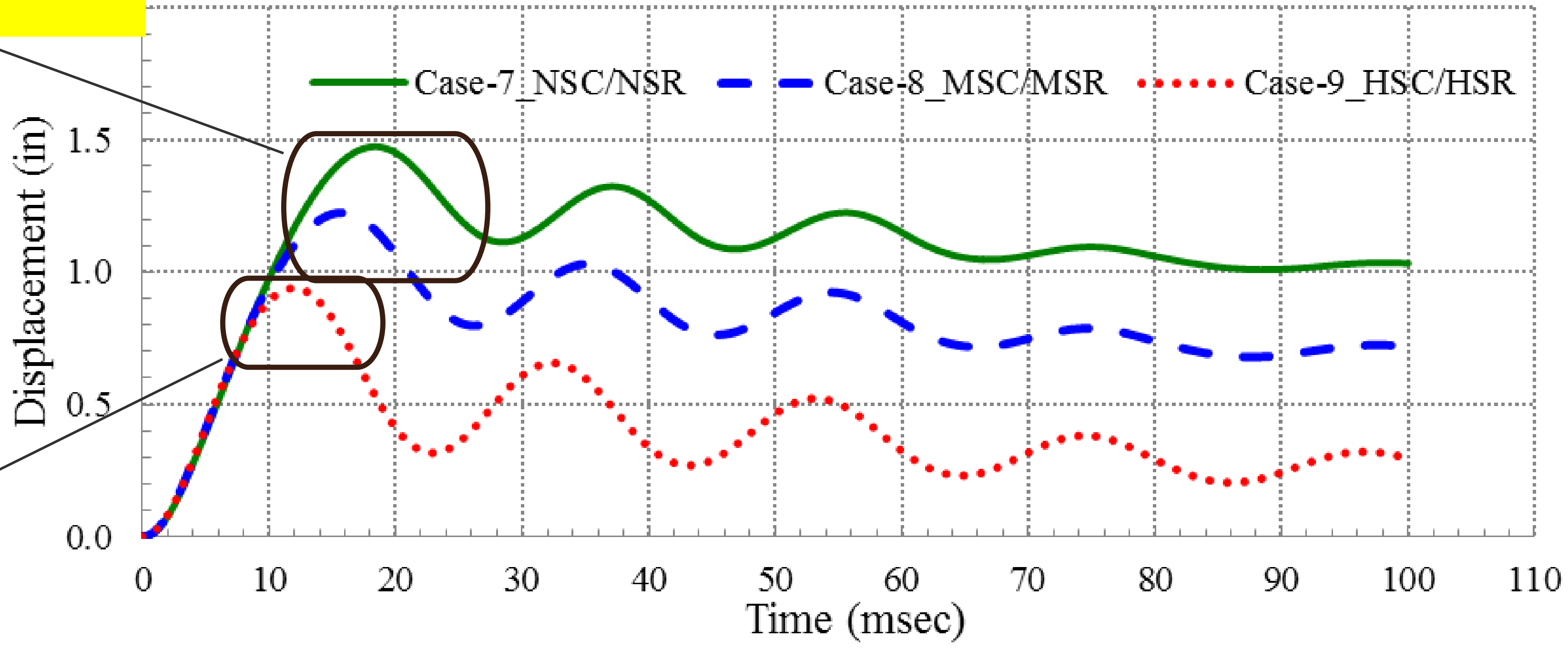



**Simple** Supports **Low** Pressure/ **Medium** Duration Blast $T/T_N \approx 1.06$ , $P/r_u \approx 1.15$

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

# Response to LP/LD Blast (S-S)

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

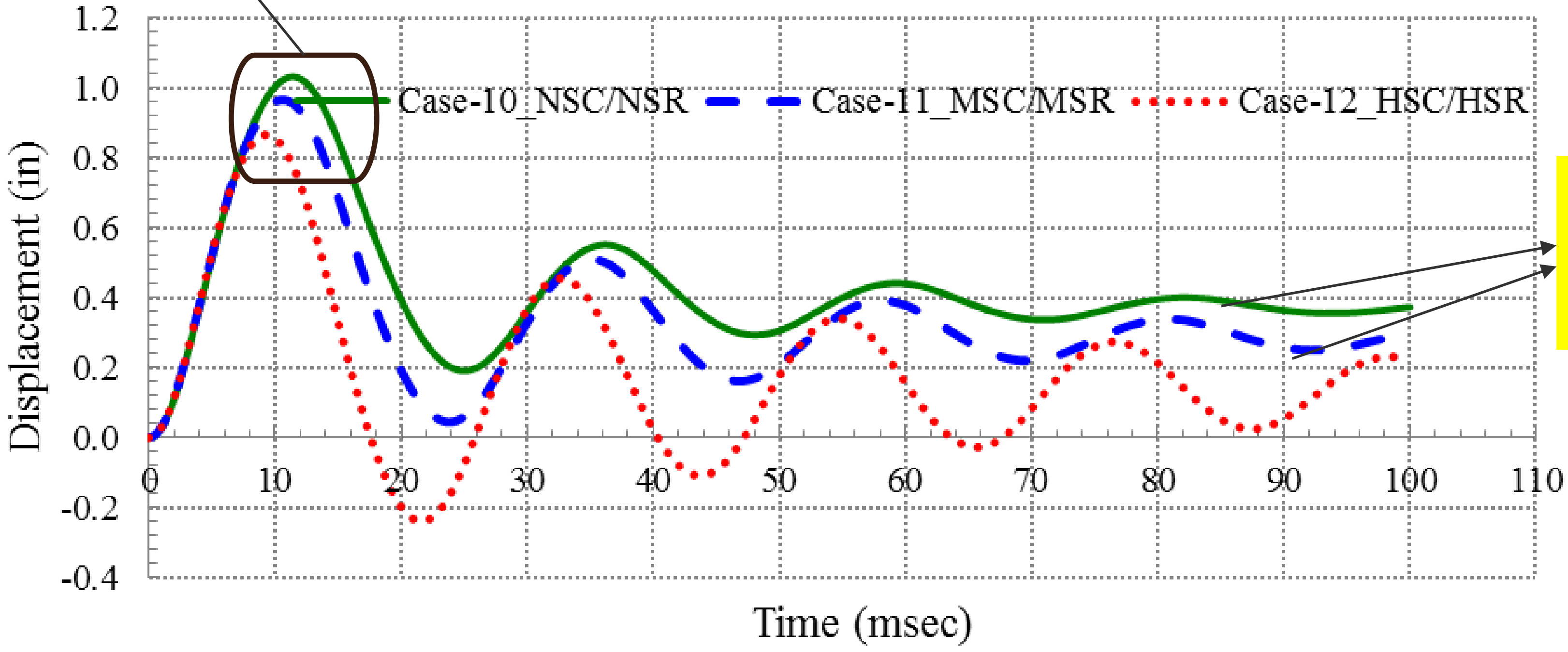
**Simple** Supports **Low** Pressure/ **Long** Duration Blast **$T/T_N \approx 2.04$, $P/r_u \approx 1.15$**

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



# Response to MP/SD Blast (S-S)

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



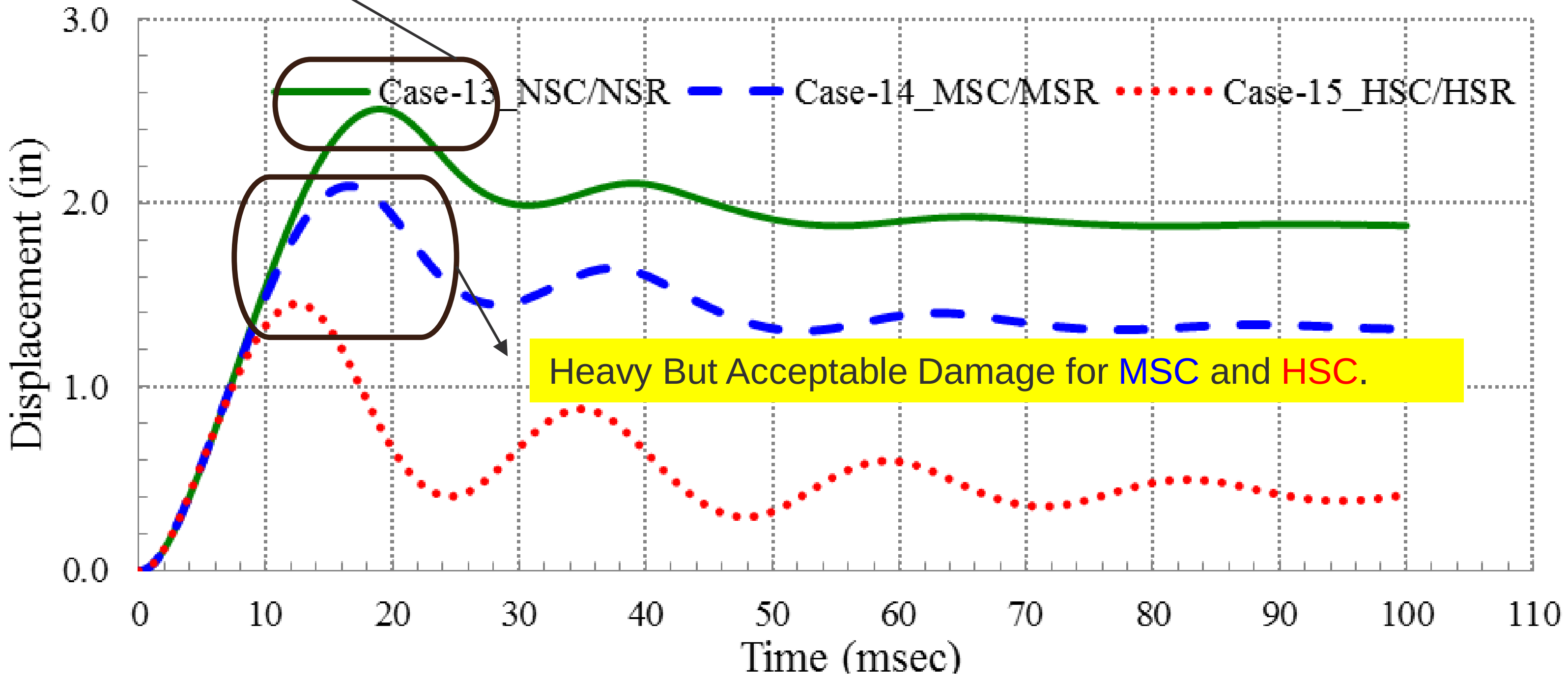

Close Similarity of Max. and Resid. Response for NSC and MSC. No Advantage in Using MSC

**Simple** Supports **Medium** Pressure/ **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**

# Response to MP/MD Blast (S-S)

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

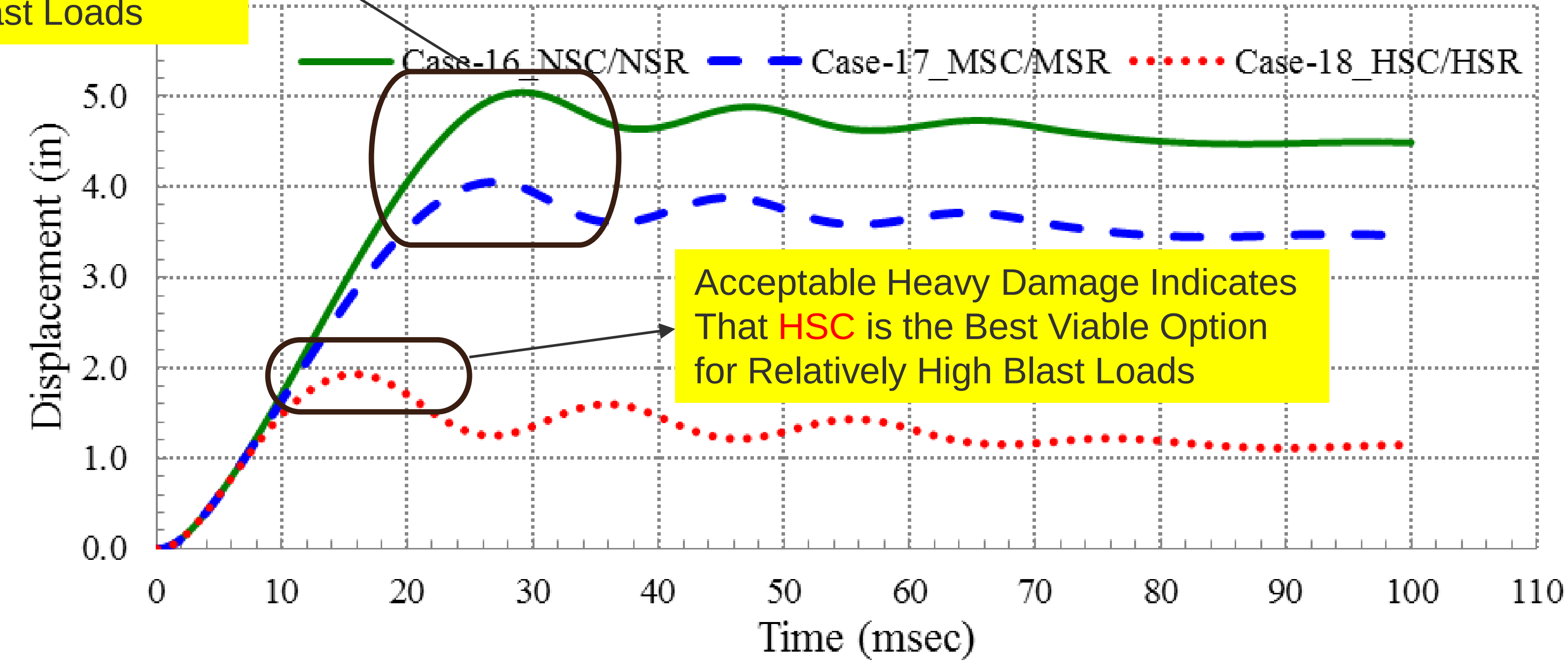



**Simple** Supports **Medium** Pressure/ **Medium** Duration Blast **$T/T_N$ ≈ 1.06 , $P/r_u$ ≈1.73**

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

# Response to MP/LD Blast (S-S)

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



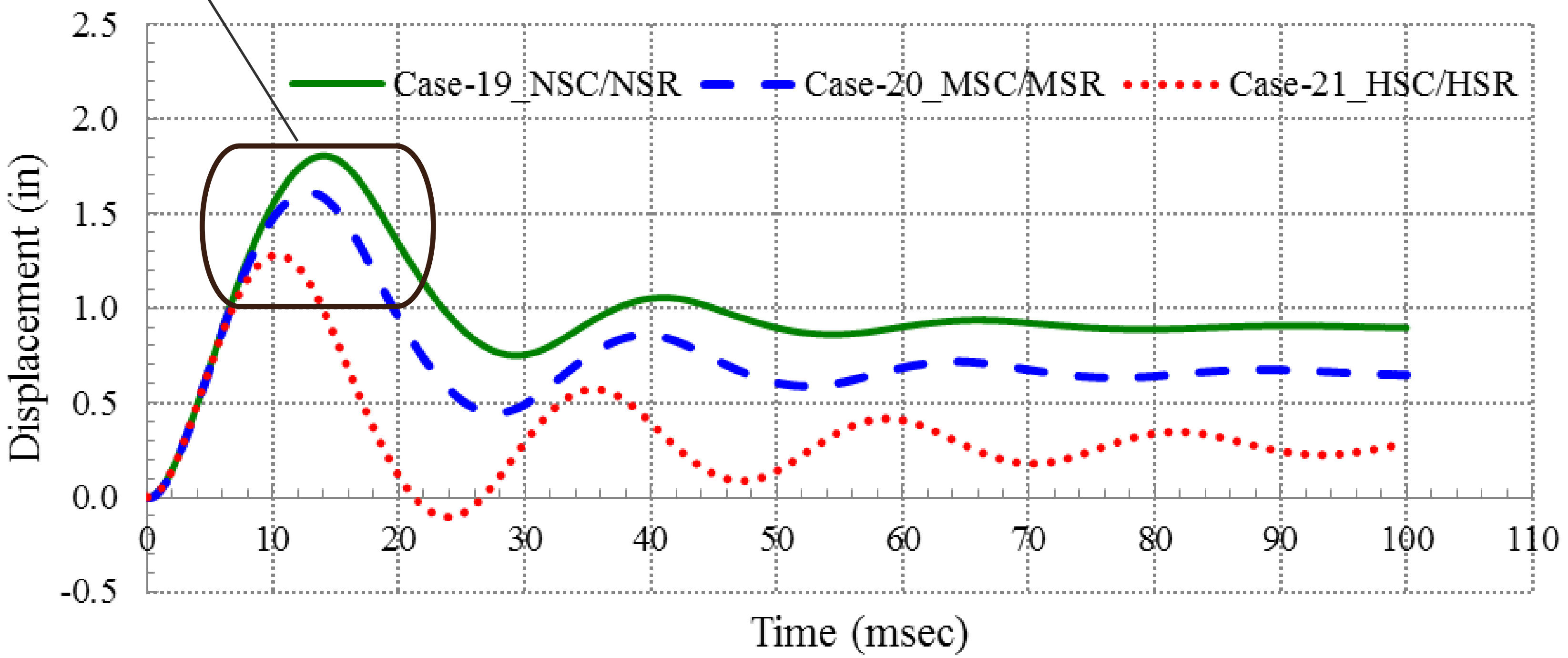

Acceptable Heavy Damage Indicates That HSC is the Best Viable Option for Relatively High Blast Loads

**Simple** Supports **Medium** Pressure/ **Long** Duration Blast $T/T_N \approx 2.04$ , $P/r_u \approx 1.73$

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

# Response to HP/SD Blast (S-S)

Slight Variation in Max. Displ. Responses But With Comparable Levels of Damage for NSC, MSC, HSC

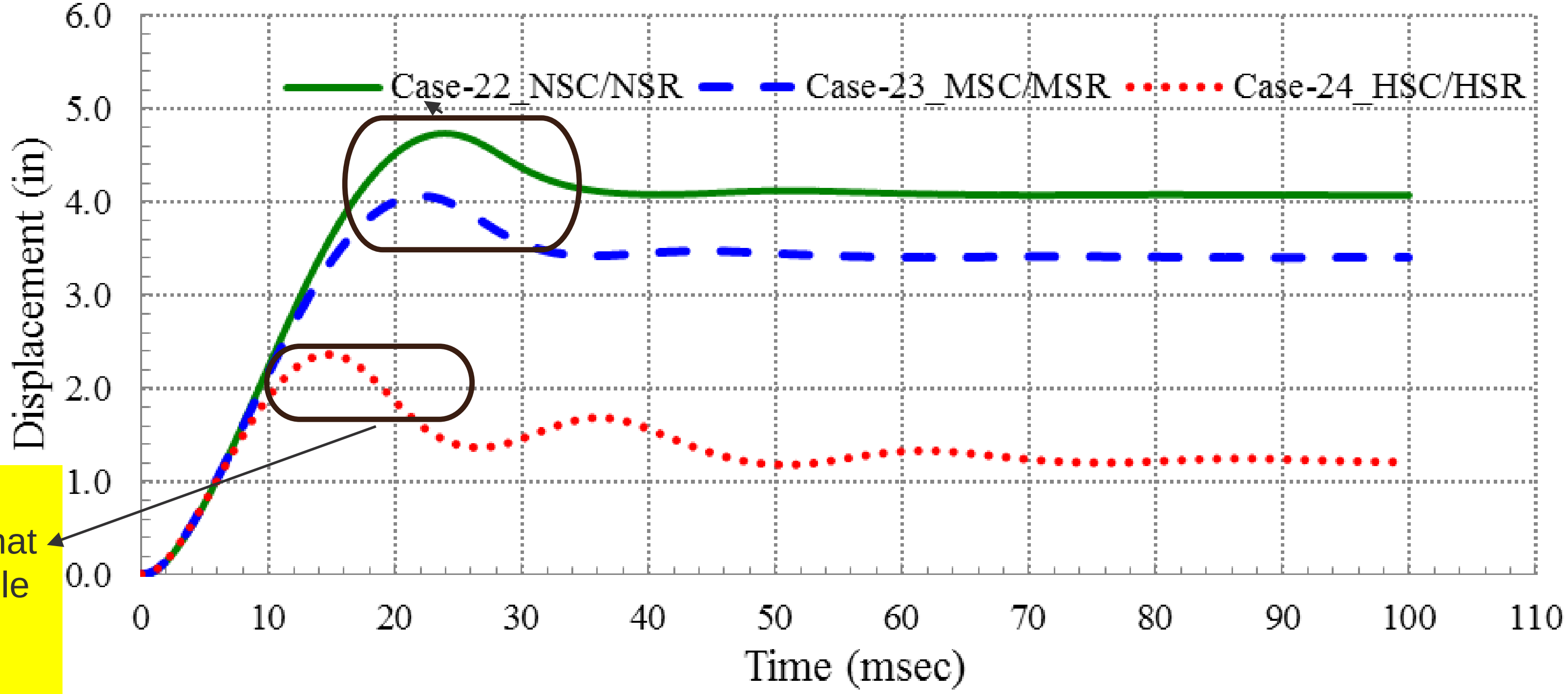



**Simple** Supports **High** Pressure/**Short** Duration Blast **$T/T_N \approx 0.50$ , $P/r_u \approx 2.31$**

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



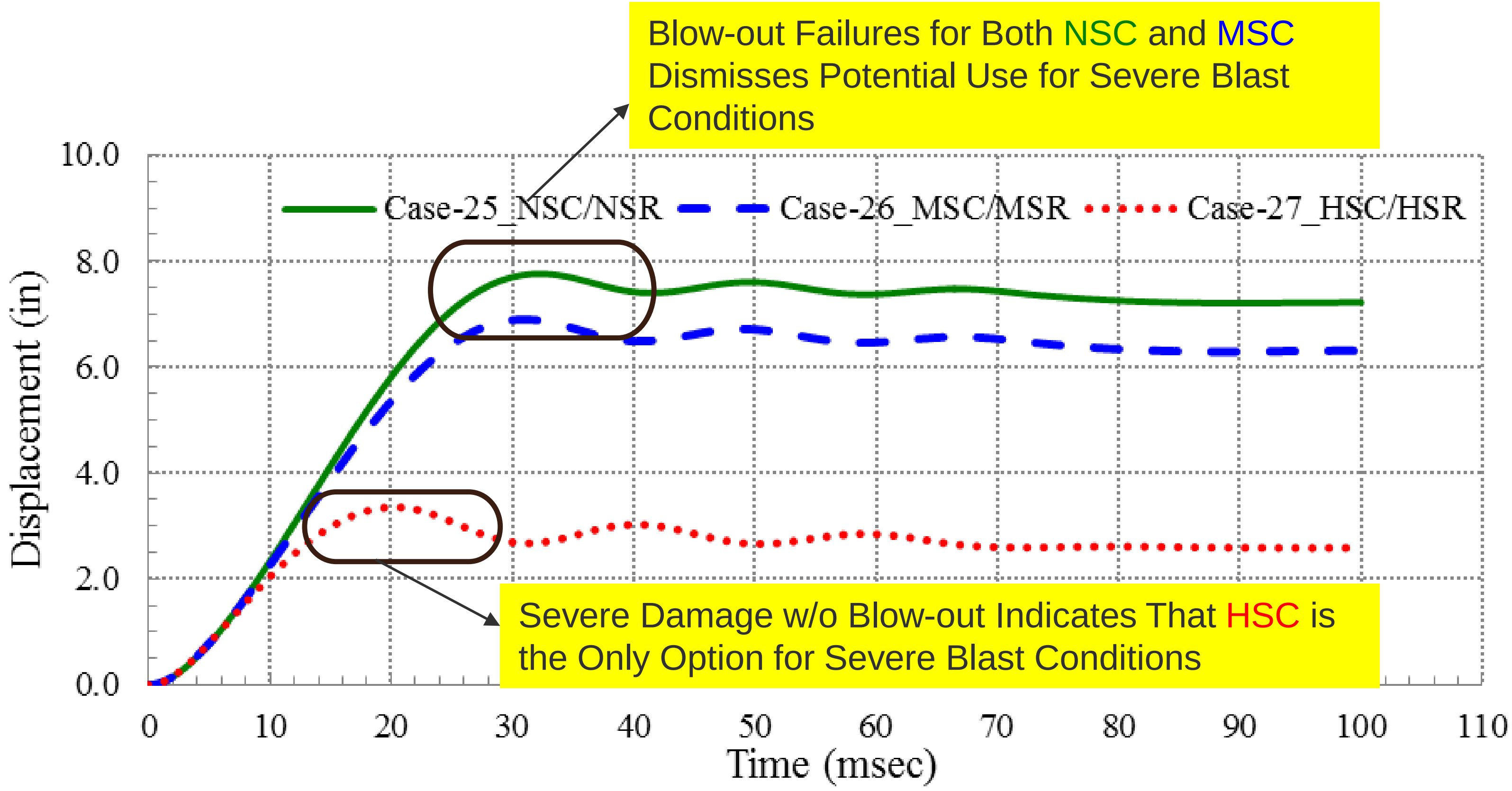

Acceptable Heavy Damage Indicates That HSC is the Best Viable Option for Relatively High Blast Loads

**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**


Louis Berger

# Response to HP/LD Blast (S-S)




**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**



# 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**.

**PLASTIC RESPONSE**

| $P/r_u$ | SD (T/T$_N$ 0.00–0.75) | MD (T/T$_N$ 0.75–1.50) | LD (T/T$_N$ 1.50–2.25) |
|---|---|---|---|
| HP (1.75–2.25) | NSC/NSR | HSC/HSR | HSC/HSR |
| MP (1.25–1.75) | NSC/NSR | MSC/MSR | HSC/HSR |
| LP (0.00–1.25) | NSC/NSR | NSC/NSR | NSC/NSR |

$T/T_N$

# FIXED SUPPORT SLABS

- 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.

**PLASTIC RESPONSE**

| $P/r_u$ | SD (0.00–1.50) | MD (1.50–3.0) | LD (3.0–4.50) |
|---|---|---|---|
| HP (0.60–0.80) | NSC/NSR | NSC/NSR | NSC/NSR |
| MP (0.40–0.60) | NSC/NSR | NSC/NSR | NSC/NSR |
| LP (0.00–0.40) | NSC/NSR | NSC/NSR | NSC/NSR |

$T/T_N$

# FIXED SUPPORT SLABS

- 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**.

## ELASTIC RESPONSE

| $P/r_u$ | SD ($T/T_N$ 0.00–1.50) | MD ($T/T_N$ 1.50–3.0) | LD ($T/T_N$ 3.0–4.50) |
|---|---|---|---|
| HP (0.60–0.80) | HSC/HSR | | |
| MP (0.40–0.60) | HSC/HSR | HSC/HSR | |
| LP (0.00–0.40) | MSC/MSR | HSC/HSR | HSC/HSR |

# PRESENTATION OUTLINE

1 INTRODUCTION

2 STUDY PARAMETERS

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4 BLAST RESPONSE

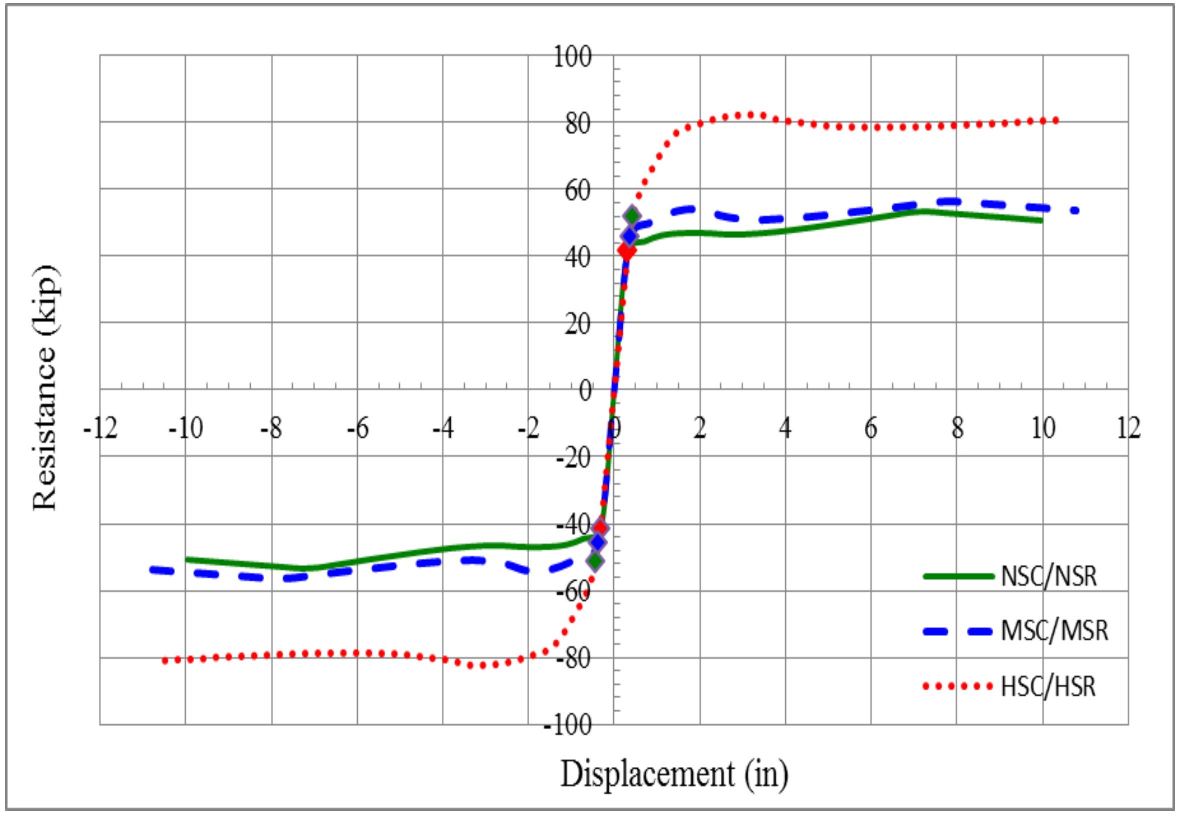
**5 CONCLUDING REMARKS**

6 QUESTIONS



# CONCLUDING REMARKS

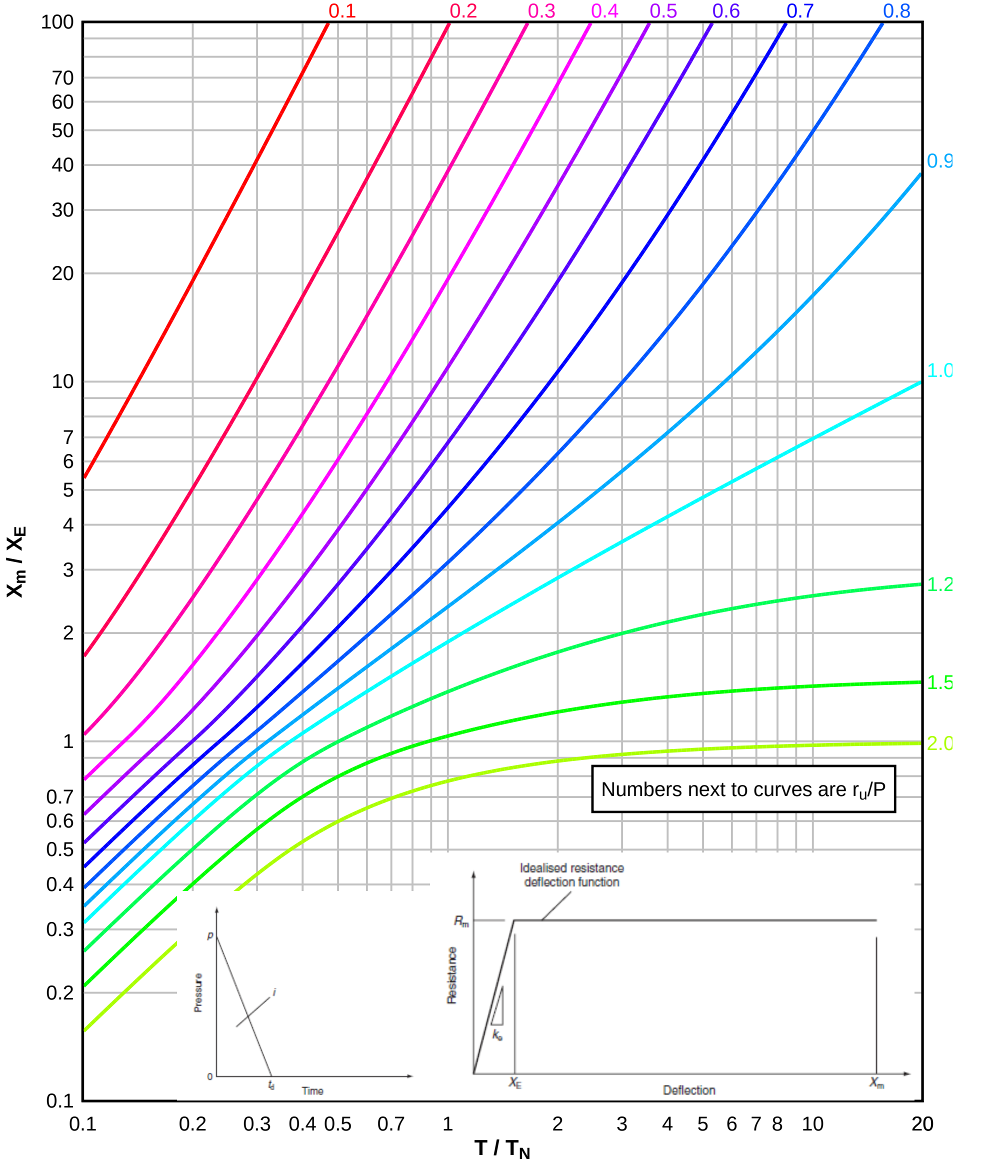
- Favorable changes in the primary **Dynamic Properties** are not linearly proportional to the **Material Strength**. Therefore the emphasis of **Efficient** Blast-Resistant Reinforced Concrete Design should Not be on the use of **Stronger** materials. Rather the focus should be on the use of **Tougher** materials and **Ductile** detailing




# CONCLUDING REMARKS

- The **Most Influential** non-dimensional parameters affecting the structural response to shock loading are:
  - Load Duration-to-Fund. Period Ratio (**$T/T_N$**)
  - Load Intensity-to-Resistance Ratio (**$P/r_u$**)
- **SODF** approaches that adequately capture response dependence on these parameters **can be used successfully** for Blast-Resistant Design

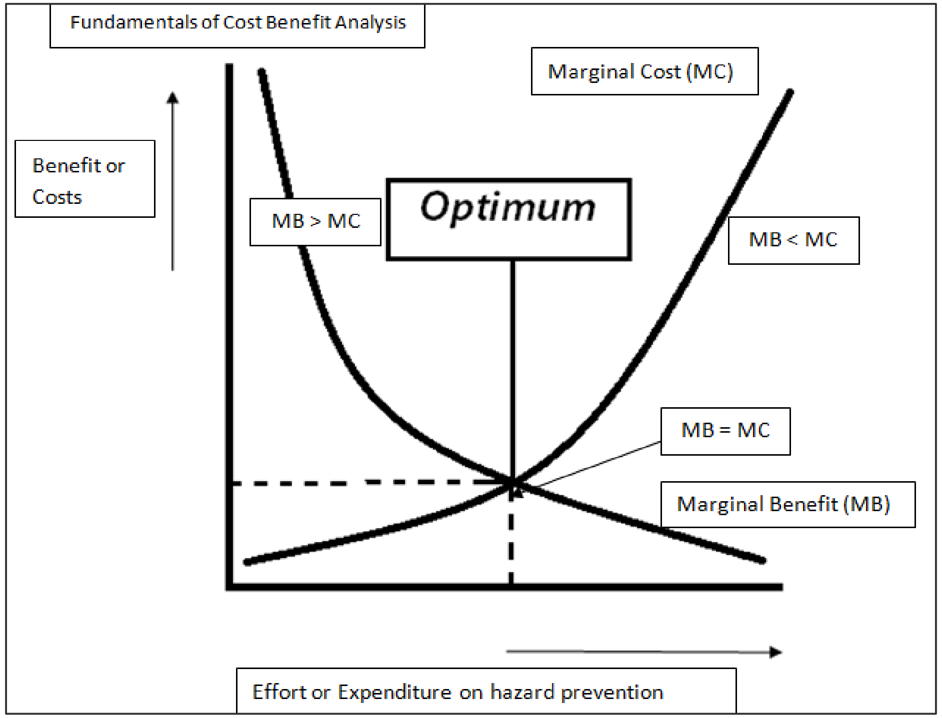
Figure 3-54. Maximum deflection of elasto-plastic, one-degree-of-freedom system for triangular load




# 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)

| Strength Class / Relative Cost | (Normal) NSC/NSR | (Medium) MSC/MSR | (High) HSC/HSR |
|---|---|---|---|
| Comp Strength $f_c'$<br>Yield Strength $f_y$ | **5000** psi<br>**60000** psi | **10000** psi<br>**75000** psi | **15000** psi<br>**100000** psi |
| **Concrete**<br>Cost/ unit Volume | 1.00 | 1.25 | 1.60 |
| **Reinforcing Steel**<br>Cost/ unit Weight | 1.00 | 1.20 | 1.50 |
| **Reinforced Concrete**<br>Cost / unit Area | **1.00** | **1.23** | **1.56** |



# PRESENTATION OUTLINE

1 INTRODUCTION

2 STUDY PARAMETERS

3 DYNAMIC ANALYSIS

4 BLAST RESPONSE

5 CONCLUDING REMARKS

6 **QUESTIONS**

Louis Berger

# Questions