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Reinforced Concrete Columns with High-Strength Concrete and Steel Reinforcement, Part 1

ACI Fall 2012 Convention
October 21 – 24, Toronto, ON

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Blast Behaviour of Ultra High Strength CRC Columns

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October 22nd, 2012

uOttawa www.uOttawa.ca

Outline of Presentation

1. Introduction – UHPC and CRC
2. Why use CRC in blast resistant design ?
3. Literature Review
4. Blast Loading & UOttawa Shocktube
5. Experimental Program
6. Results / Discussion
7. Analysis
8. Conclusions

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Concrete, a versatile material but …

- **Plain Concrete** : weak and brittle in **tension / flexure**

- **High strength Concrete** : brittle in **compression**

- **Reinforced concrete:** susceptible to deterioration

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What is UHPC ?

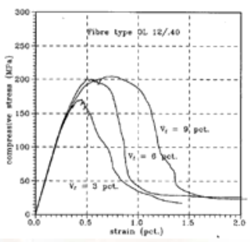
- Ultra High Performance Concrete is a **new** and **innovative** class of concrete material.
- When compared to "traditional" concretes :
  - **High compressive strength**
  - **Good flexural / tensile strength**
  - **Superior ductility**
  - **Excellent durability**
  - hence the term *Ultra-High Performance*.

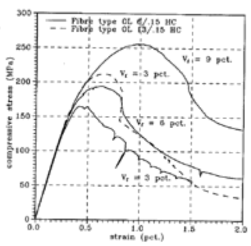
Compact Reinforced Composite (CRC)

- UHPC developed by Cement and Concrete Laboratory of Aalborg Portland in 1986, now marketed by **CRC Technology** (Denmark)
- High **compressive** strength (140 MPa – 400 MPa)
- Good **Flexural** strength (10 – 30 Mpa)
- **Steel Fibers**: 2-6% fibers ... Toughness, Ductility

Compact Reinforced Composite (CRC)

- Behaviour in **compression**

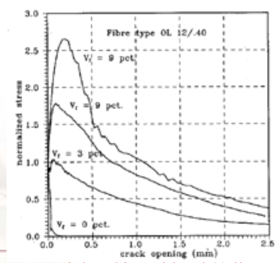




(Adapted from Nielson (1995))

Compact Reinforced Composite (CRC)

- Behaviour in direct **tension**



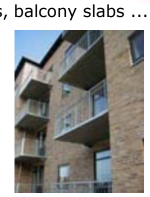
(Adapted from Nielson (1995))

Compact Reinforced Composite (CRC)

- Behaviour in **fresh state** (without fibers)

Compact Reinforced Composite (CRC)

- Some current applications: staircases, balcony slabs ...

Compact Reinforced Composite (CRC)

- Potential for use in heavily loaded structures

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Why CRC in blast resistant design?

- Increasingly important to ensure that strategic buildings are blast resistant.
- **Failure of ground-storey columns** in buildings can lead to **progressive collapse**.

(source: FEMA)

(source: FEMA)

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Why CRC in blast resistant design?

- Columns need to be properly detailed
  - Ductility ☺
  - Highly congested sections ☹
- Use of **CRC:**
  - Improve **performance ?**
  - Improve **constructability ?**

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SFRC and UHPFRC at high stress rates:

SFRC	CRC & other UHPFRC
•Research data is conflicting •Performance improvements absent at high stress rates ???	•Limited research shows improved performance when compared to traditional concrete and SFRC
Limited research on Blast performance of SFRC and UHPC structural components	

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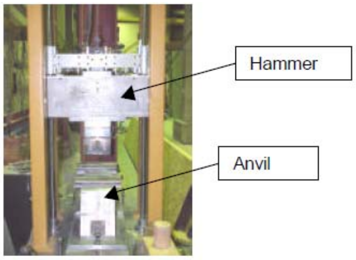
Bindiganavile et al. (2002)



(Adapted from Bindiganavile et al. (2002))

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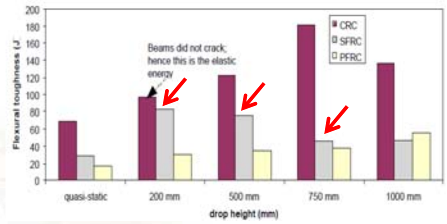
Bindiganavile et al. (2002)

SFRC



(Adapted from Bindiganavile et al. (2002))

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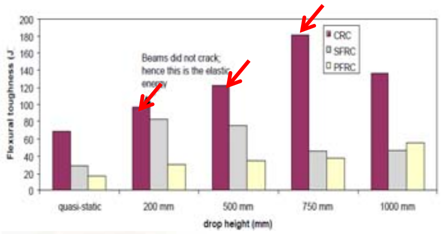
Bindiganavile et al. (2002)

CRC



(Adapted from Bindiganavile et al. (2002))

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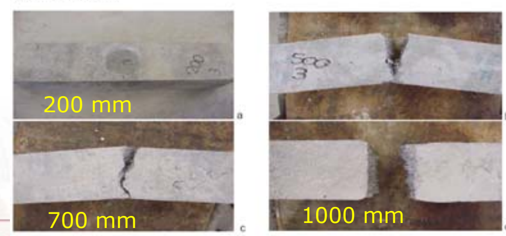
Bindiganavile et al. (2002)

- CRC specimens at different drop-heights

Figure 10. Photographs of CRC Failure in Impact under Various Drop Heights, a) 200 mm, b) 500 mm, c) 750 mm & d) 1000 mm



(Adapted from Bindiganavile et al. (2002))

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CRC – impact (Projectile test)

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CRC – impact (Projectile test)

Concrete after impact (total thickness 100 cm)

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CRC – impact (Projectile test)

CRC after impact (total thickness 40 cm)

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Idealized Blast Pressure-Time History

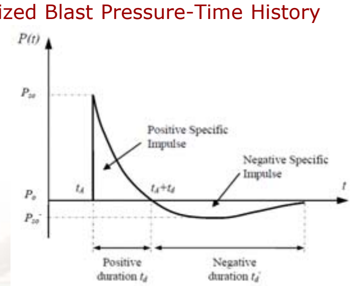

Figure 2: Blast wave pressure – Time history

(Adapted from Ngo et al. 2007)

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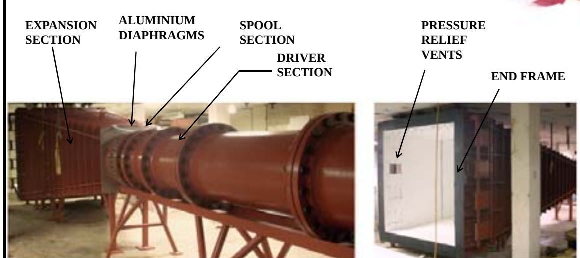
University of Ottawa Shock Tube



a) Shock tube driver section and expansion chamber

b) Shock tube end frame

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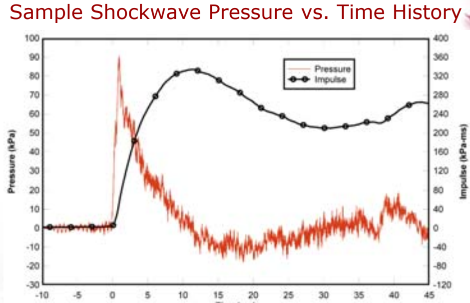
Sample Shockwave Pressure vs. Time History



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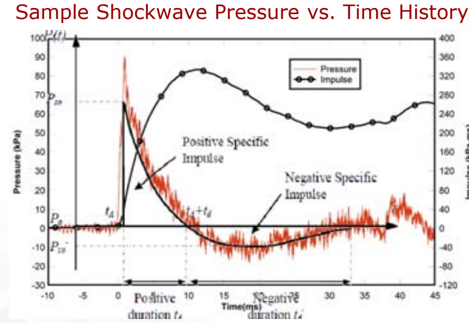
Sample Shockwave Pressure vs. Time History



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Experiments Program:

- Half-scale columns tested under simulated blast loading
- Effect of :
  - **Seismic detailing ?**
  - **CRC ?**
  - **Fibers (SCC + fibers) ?**

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Nomenclature

SCC - 0% - 75

CRC - 2% - 38

Concrete type

V_f (%)

Tie Spacing(mm)

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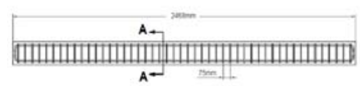
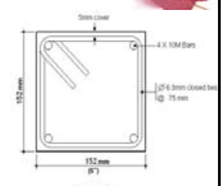
Test Specimens - Reinforcement





s=75mm
(Non-Seismic Detailing)

s=38mm (h/4)
(Seismic Detailing)

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Columns – SCC Series

Column	Fibre Type	Compressive Strength (MPa)	Remarks
SCC-0%-75	-	**52**	**Non-Seismic Control**
SCC-0%-38	-	**52**	**Seismic Control**
SCC-0.5%-75	ZP-305	54	V_f =0.5%, Non-Seismic
SCC-1%-75	ZP-305	46	V_f =1%, Non-Seismic
SCC-1.5%-75	ZP-305	57	V_f =1.5%, Non-Seismic

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SCC - Concrete

- KING MS-self Consolidating concrete
  - Strength:50 Mpa
  - 10 mm max aggregate size
  - SuperP, VMA : dry powder
  - Prepackaged bags (add water)

- For specimens with fibers:
  - 30 mm hooked-end fibers
  - 0.5%-1.5%

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Columns – CRC Series

Column	Fibre Type	Compressive Strength (MPa)	Remarks
CRC-2%-75	OL-12/.40	145	CRC, V_f =2%, Non-Seismic
CRC-2%-38	OL-12/.40	149	CRC, V_f =2%, Seismic
CRC-4%-75	OL-12/.40	153	CRC, V_f =4%, Non-Seismic
CRC-6%-75	OL-12/.40	166	CRC, V_f =6%, Non-Seismic

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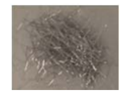
CRC – Concrete

- CRC:
  - Strength:140 Mpa +
  - *Densit* Binder – cement and microsilica
  - Water-Binder ratio 0.18
  - Prepackaged bags (add water, fibers)
- Fibers:
  - *Stratec OL – 12/0.40*
  - *Smooth/straight*
  - *12mm Length, 0.40mm Diameter*
  - *Content : 2% to 6% by volume*



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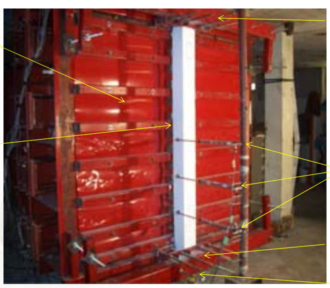
Test Procedure and Instrumentation



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Test Procedure

Name	Driver Pressure Psi (kPa)	Driver Length ft (mm)	Average Reflected Pressure kPa	**Average Reflected Impulse** kPa*msec	Average Positive Phase Duration msec
Blast 1	10 (69)	9 (2743)	13.28	**125**	21.36
Blast 2	30 (207)	9 (2743)	42.75	387	22.95
Blast 3	80 (552)	9 (2743)	78.90	748	26.21
Blast 4	100 (689)	9 (2743)	96.28	893	25.09
Blast 5	100 (689)	14 (4267)	81.54	1355	33.04

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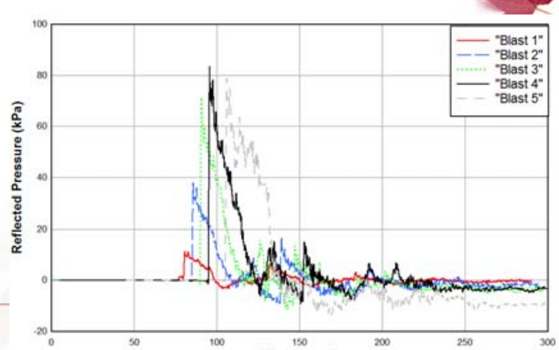
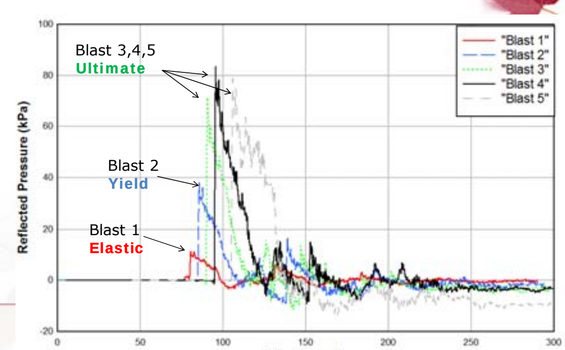
Test Procedure



Test Procedure



Outline of Presentation

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Effect on:

Mid-Span Displacements

(Maximum and Residual)

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Mid-span displacements

- Blast 1 (elastic shot) … no trend emerges
- Blast 2 (just to yield) … no trend emerges

- Blast 3 … can be used to study effect of test parameters

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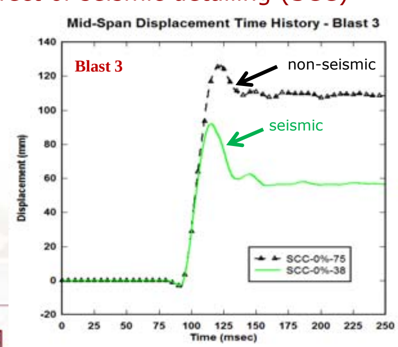
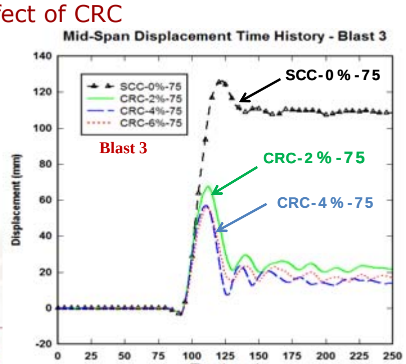
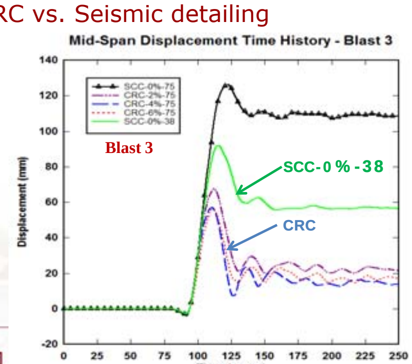
Effect of seismic detailing (SCC)



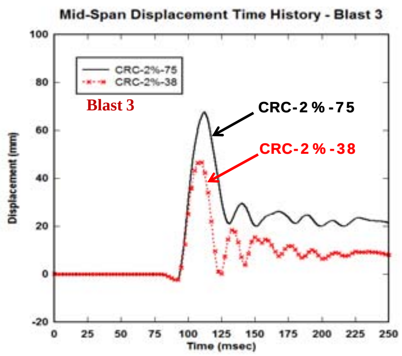
Effect of CRC



CRC vs. Seismic detailing



CRC + seismic detailing



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Effect on:

Failure mode

Damage tolerance

Secondary Blast Fragments

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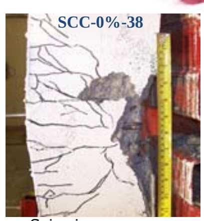
SCC vs. SCC/Seismic – **Blast 3**

Non-seismic
-Buckling of rebar
-Fails at Blast 3



Seismic
-Prevents Buckling
-Fails at Blast 4

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SCC vs. CRC-4% – **Blast 3**

•Damage tolerance
•Prevents buckling

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SCC/Seismic vs. CRC-4% – **Blast 3**

CRC-4%-75

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SCC/Seismic vs. CRC-4% – **Blast 4**

CRC-4%-75

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CRC - Failure Blasts …

2% fibers

4% fibers

2% fibers +seismic

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CRC – Failure mode …

•Rupture of tensile steel
•Fibers pullout at single crack

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Secondary fragments:

SCC vs. CRC

(a) SCC-0%-75

(b) CRC-2%-75

Blast 3

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Secondary fragments:

SCC/seismic vs. CRC@2%

(a) SCC-0%-38 –Blast 4

(b) CRC-2%-75 – Blast 4

Blast 4

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Blast 3 … SCC-0%-75

SCC - 0% - s=75mm

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Blast 3 … SCC-0%-38 (seismic)

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Blast 3 ... CRC-4%-75

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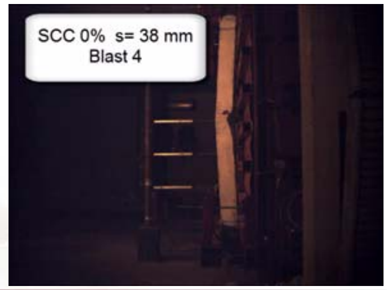
Blast 4 ... SCC-0%-38 (seismic)



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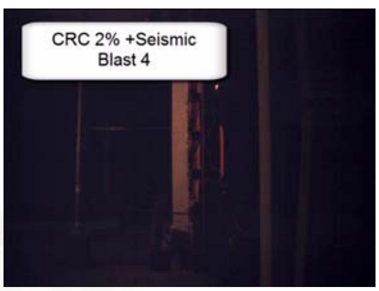
Blast 4 ... CRC-2%-38 (seismic)



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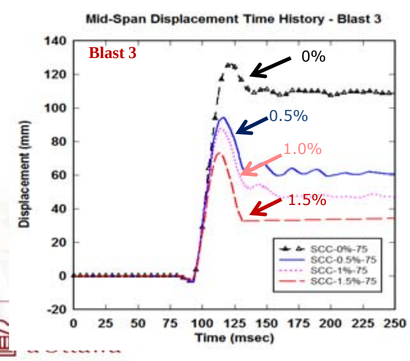
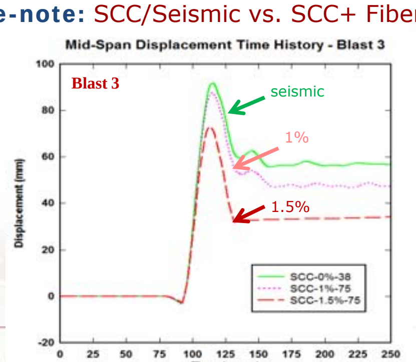
Side-note: SCC vs. SCC + fibers



Side-note: SCC/Seismic vs. SCC+ Fibers



Side-note: SCC vs. SCC + Fibers

Improved damage tolerance

Does not prevent rebar buckling (fails at Blast 3)

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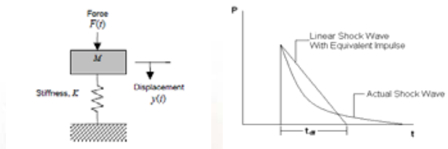
SDOF Analysis

- SDOF analysis used to determine the maximum mid-span displacement of the columns subjected to triangular pulse load



$$K_{LM} m\ddot{u}(t) + ku(t) = AP_r(t)$$

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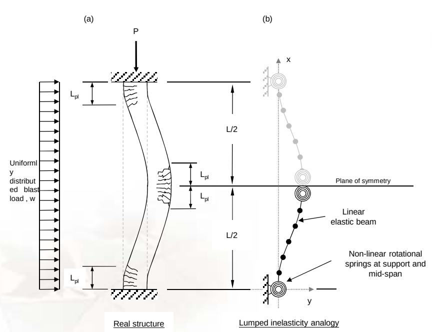

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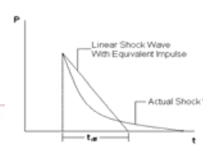
SDOF Analysis

RCBlast
Blast analysis software

RCBlast (Jacques et al., 2011)

1. User inputs include material and cross sectional properties, axial load
2. Generates moment-curvature diagrams
3. Computes hinge rotation and rotational spring stiffness
4. Generate Resistance Function and Load-Mass Factors
5. SDOF analysis using idealized Blast load

$$K_{LM} m\ddot{u}(t) + ku(t) = AP_r(t)$$



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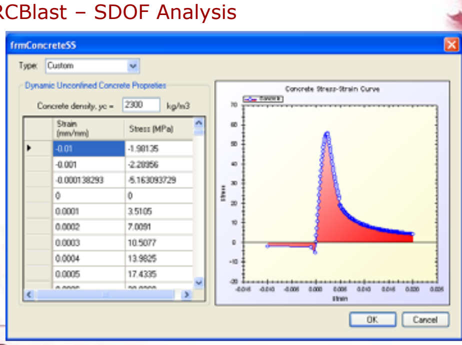
RCBlast – SDOF Analysis



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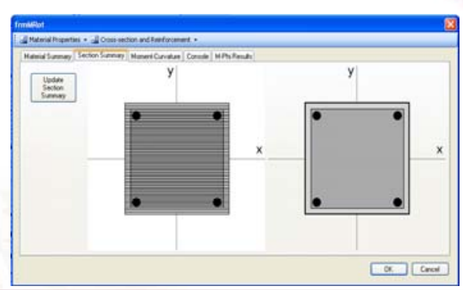
RCBlast – SDOF Analysis



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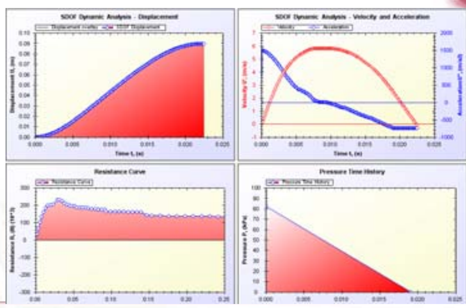
RCBlast – SDOF Analysis



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Material Modeling

CONCRETE	Unconfined	Confined	Tension	DIF
SCC	Hognestad (1951)	Légeron & Paultre (2003)	-	1.19
CRC	Based on cylinder tests	Paultre et al. (2010)	Lok and Pei (1998)	-

STEEL	Tension	Compression	DIF
-	Based on coupon tests	Yalcin & Saatcioglu	1.17 (upto ultimate) 1.05 (after)

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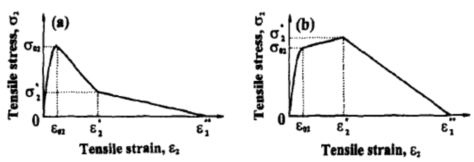
Tension Model – Lok and Pei



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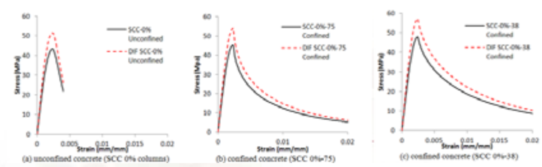
Concrete …



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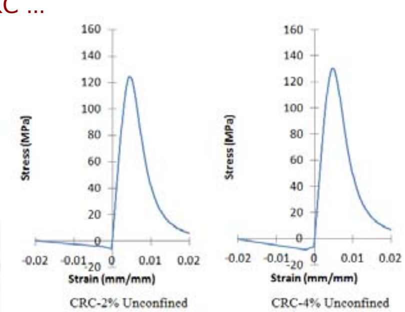
CRC …



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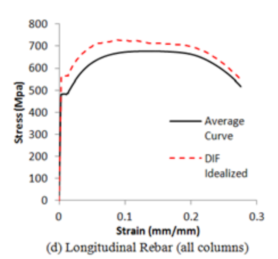
Steel…



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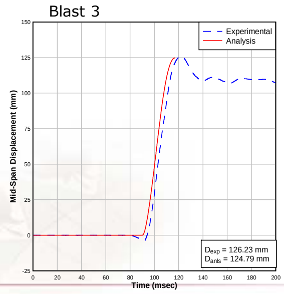
Analytical Results – SCC-0%-75



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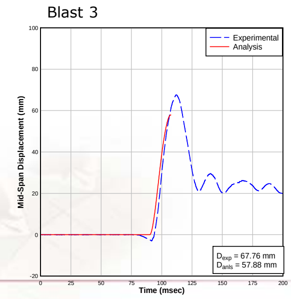
Analytical Results – CRC-2%-75



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Conclusions

- Seismic detailing provides increased confinement and ductility:
  - reduces **max. & resid. displacements** to structural members subjected to blast loading
- Use of CRC:
  - reduces **max. & resid. displacements** to structural members subjected to blast loading
  - increases **damage tolerance**
  - reduces amount of **secondary blast fragments**
  - improves **blast performance**
- SDOF analysis can predict the maximum displacement of structural members constructed of **SCC** and **CRC**

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