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Advancing concrete knowledge

Blast and Impact Loading Response of Concrete Structures Part 2 of 2

ACI Fall 2010 Convention
October 24 - 28, Pittsburgh, PA

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Blast and Impact Loading Response of Concrete Structures Part 2 of 2

ACI Fall 2010 Convention
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William Zehrt is a Safety Engineer with the Department of Defense Explosives Safety Board (DDESB) in Alexandria, Virginia. He is chair of DDESB's Technical Working Group to Revise UFC 3-340-02, "Structures to Resist the Effects of Accidental Explosions" and is responsible for verifying that protective construction designs developed by the Services satisfy DoD explosives safety requirements.

Prior to joining DDESB, Bill was a Senior Structural Engineer and Branch Chief with the US Army Engineering and Support Center, Huntsville. During his 17 years at Huntsville Center, Bill worked on a wide range of programs including Chemical Demilitarization, National Missile Defense, Training Ranges, Maglev, and Ordnance & Explosives. He has extensive experience in blast analysis and design, co-authoring more than 30 technical papers on various explosive safety topics. Bill earned BSCE and MSCE degrees from the University of Illinois at Urbana-Champaign. He is a registered professional engineer in the state of Alabama.

Summary of the New Reinforced Concrete Blast Design Provisions in UFC 3-340-02, "Structures to Resist the Effects of Accidental Explosions"

William H. Zehrt, Jr., PE, US Department of Defense Explosives Safety Board
and
Patrick F. Acosta, PE, US Army Engineering and Support Center, Huntsville

Presentation Outline

- **TM 5-1300/UFC 3-340-02 Overview**
- **Comparison of DoD Explosives Safety and Anti-Terrorism Protective Designs**
- **UFC 3-340-02 Development**
- **Chapter 4 Revisions**
- **Future Work**
- **Conclusions**
- **Questions???**

TM 5-1300/UFC 3-340-02 Overview

- **Army TM 5-1300/NAVFAC P-397/AFR 88-22, published in 1969, based upon results of an extensive DoD explosives testing program of protective construction.**
- **Revision 1, published in 1990, greatly expanded content.**
- **UFC 3-340-02, issued 5 Dec 2008, converts manual to UFC format and incorporates significant revisions to chapter 4's reinforced concrete design guidance.**
- **Manual has always been approved for public release; as a result, it has been used throughout the world to design blast resistant government, commercial, and industrial structures.**
- **Specifically written to facilitate use by first-time blast designers.**
- **Step-by-step examples in chapter appendices include references to applicable equations, figures, and tables.**

TM 5-1300/UFC 3-340-02 Overview

- Proponent: DoD Explosives Safety Board (DDESB)
- Primary Objective: Establish design procedures and construction techniques whereby the propagation of an explosion or a mass detonation can be prevented and DoD personnel and valuable equipment can be protected.
- Applicability
  - Present methods of design for protective construction used in facilities for development, testing, production, storage, maintenance, modification, inspection, demilitarization, and disposal of explosives materials.
  - Provide equivalent protection to satisfy DoD 6055.09-M, "DoD Ammunition and Explosives Safety Standards" (4 August 2010), and Service explosive safety standards.

Comparison of DoD Explosives Safety and Anti-Terrorism (AT) Protective Designs

- While both the explosives safety and AT design communities typically use SDOF models to analyze and design structural elements, the levels of protection and resulting design requirements for each community differ markedly. While AT protection criteria focus on the prevention of mass casualties, explosives safety criteria are written to provide specific levels of protection to personnel, to property, and to ammunition and explosives.
- AT design procedures focus heavily upon protecting personnel from the relatively low overpressures and impulses of far range, lower NEW, external blast events. In comparison, explosives safety design guidance considers close-in blast loads and places detailed requirements on internal blast designs where structural elements often must provide the mandated protection while under combined axial tension and flexure loads.

Comparison of DoD Explosives Safety and AT Protective Designs

- In light of the AT community's philosophy that an appropriate level of protection can be provided for all DoD personnel at reasonable cost, AT design procedures and requirements often are based upon enhancing the blast resistance of conventional structural elements. In comparison, explosives safety designs are usually "custom designed' and "custom built" to satisfy specific, operational, maximum credible events and their corresponding low charge standoff distances.
- Based upon the foregoing, DDESB only allows use of AT software, such as SBEDS, for preliminary flexural design and element sizing. Final protective construction designs for explosives safety applications, including calculation of blast loads and development of SDOF analytical models, must be prepared in accordance with UFC 3-340-02 criteria and requirements.

UFC 3-340-02 Development

- FY 02 TM 5-1300 users survey indicated strong support for revision; many respondents recommended areas for update and expansion.
- DDESB established Technical Working Group to Revise Army TM 5-1300/NAVFAC P-397/AFR 88-22 (TWG) in early 2003.
- Funding provided by DDESB, HQUSACE, USATCES, and NAVFAC-Atlantic.
- Short Term Objective: Develop an interim UFC incorporating limited changes to previously identified outdated and/or overly conservative requirements.
  - Base all changes upon existing research.
  - Align explosives safety, hardened structure, and AT/FP requirements, where feasible.
  - Retain English units and open distribution.

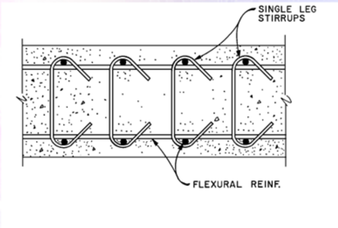
UFC 3-340-02 Development

- Due to its widespread use, conservative design requirements and high construction cost, focused on revisions to reinforced concrete guidance (chapter 4).
- At 2006 DoD Explosives Safety Seminar, DDESB presented several papers outlining the more significant changes to the manual and soliciting technical community comments.
- In FY 07, TM 5-1300 TWG members reviewed draft final revision; DDESB incorporated comment resolutions in FY 08.
- UFC 3-340-02 issued on 5 Dec 08; available through Whole Building Design Guide website (www.wbdg.org).

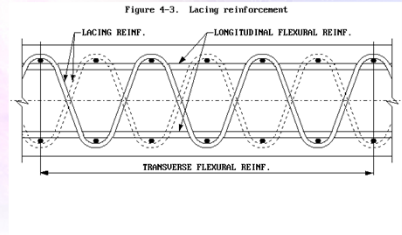
History of Diagonal Tension Reinforcement Requirements

- TM 5-1300 – 1969
  - Single leg stirrups only allowed for Type I elements with a design support rotation $\leq$ 2.0 degrees.
  - Detailing guidance considered lacing only.
- TM 5-1300, Revision 1 – 1990
  - Single leg stirrups defined as straight bar with a hook of at least 135 degrees at each end.
  - Support rotation limits increased (4 degrees under flexural action; 8 degrees under tensile membrane action).
  - Lacing required if $z < 1.0$.

Single Leg Stirrups (TM 5-1300, revision 1)



Lacing Reinforcement

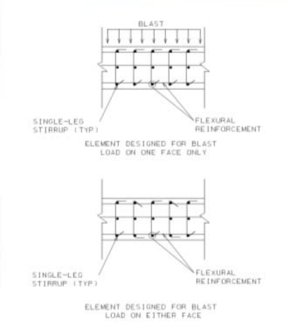


Example: ANCDF Constructability Claim

Stirrup/Lacing Revisions

- **UFC 3-340-02 defines 3 single leg stirrup configurations with the following usage limits.**
  - **Type A – 90-135 degree hooks**
    - **Scaled charge distance, z > 1.0 ft/lb$^{1/3}$**
    - **Design support rotation, θ < 2-degrees**
    - **Concrete spalling prevented IAW section 4-55**

Placement Requirements for Type A Single Leg Stirrups (Figure 4-101)



Stirrup/Lacing Revision

- **Type B – 135-135 degree hooks**
  - **z > 1.0**
  - **Design support rotation, θ ≤ 12-degrees**
- **Type C – 180-180 degree hooks**
  - **May be used at all scaled distances allowed by UFC 3-340-02**
  - **Design support rotation, θ ≤ 12-degrees**

Expand Material Properties Data and Update References to ACI 318 Building Code

- **Expand Dynamic Material Properties Data**
  - **Dynamic Increase Factor design curves added for 6,000 psi compressive strength concrete, Grade 40 steel and Grade 75 reinforcing steel.**
  - **ASTM A706 steel allowed.**
    - o **f_{dy} = 66,000 psi**
    - o **f_{du} = 80,000 psi**
- **Revise Category II response limits for walls/slabs to agree with UFC 3-340-01, "Design and Analysis of Hardened Structures to Conventional Weapons Effects".**

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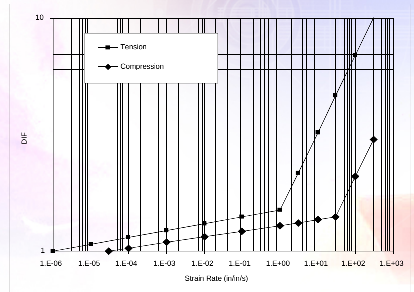
Plot of Dynamic Increase Factor versus Strain Rate (f'c = 6,000 psi)

New Figure 4-9b



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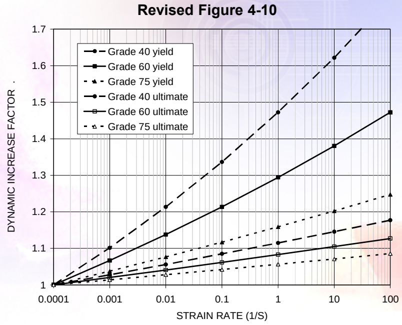
Plot of Dynamic Increase Factor versus Strain Rate – Reinforcing Steel

Revised Figure 4-10



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Add ACI 318 References and UFC 3-340-01 Spall and Breach Data

- **If a design/detailing requirement is taken directly from ACI 318, the latest version of code is now referenced.**
- **Spall and breach data for reinforced concrete walls updated to incorporate analytical procedures from UFC 3-340-01, "Design and Analysis of Hardened Structures to Conventional Weapons Effects," Appendix D.**

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Future Work Priorities

- **Due to funding constraints, the new analysis/design guidance in UFC 3-340-02 was limited to reinforced concrete.**
- **Continuing need to update and expand UFC 3-340-02 content.**
- **High priorities:**
  - **Update and expand masonry, precast/prestressed concrete and structural steel design guidance (chapters 5 and 6).**
  - **Revise gas pressure calculation procedure for partial containment cells (chapter 2).**
- **Development of new sections recommended.**
  - **Retrofit of existing structures**
  - **Innovative structural systems and materials**

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Conclusions

- **Since its initial publication in 1969, TM 5-1300 has provided uniquely practical and straightforward procedures for analyzing and designing blast resistant structures.**
- **UFC 3-340-02 is the only blast resistant design manual approved by US Department of Defense/DDESB for explosives safety applications.**
- **UFC 3-340-02 incorporates much needed updates to chapter 4's reinforced concrete analysis and design procedures, significantly enhancing constructability and reducing construction cost.**
- **Additional revisions are needed – Update/expansion of masonry design guidance is underway; publication anticipated in FY 11.**

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Thank You

Questions

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Khaled El-Domiaty received his M.Sc. Degree in Civil Engineering from the University of Misouri-Rolla and is a licensed engineer in the State of Virginia. Mr. El-Domiaty is the lead supervisor for the Structures Division at the BakerRisk Washinton, DC office. Mr. El-Domiaty has spent the last ten years assessing blast effects on both conventional and hardened structures from deliberate and accidental explosions. He has performed assessments and retrofit mitigation designs with conventional and innovative materials for government agencies, commercial clients and petrochemical facilities.

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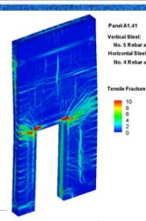

Constitutive Concrete Material Model Comparison to Tested Reinforced Slabs Subjected to Blast Loads

2010 ACI Fall Convention, Pittsburgh, PA

James Wesevich, PE, SE and Barry Bingham, PE (San Antonio, Texas)
David Bogosian, PE and Alex Christiansen (Los Angeles, California)
Johan Magnusson (Toronto, Canada)

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Background

- Recent years have seen the increased and widespread use of explicit finite element (FE) models to represent the response of structural components to blast loading
  - reinforced concrete structural elements have been the focus of extensive research, using both analytical and experimental techniques
- Numerous nonlinear constitutive material models have been developed for use in finite element codes to represent the anisotropic nature of concrete response under blast loading
  - shear, tension, compression
  - enhancement of capacities due to strain rate effects

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Study Overview

- Evaluate the ability of three different constitutive concrete models to predict the response of reinforced concrete slab specimens subjected to blast loads
  - The Applied Engineering Cap Model with Three Invariants (AEC-3I)
    - implemented into DYNA-3D under a license/collaboration agreement with Lawrence Livermore National Laboratory
  - Material 72 (MAT72R3)
    - in the LS-DYNA material library (Version 971)
    - Release 3
  - Material 159 (MAT159)
    - in the LS-DYNA material library (Version 971)
- Two well-controlled blast experiments on a simple one-way reinforced concrete slab
  - one tested to moderate damage, 7.7 psi [53 kPa]/60 ms
  - one tested to a high level of damage, 10.4 psi [72 kPa]/60 ms

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Shock Tube Component Testing

- 45 psi capacity
- Used for validating GSA, DoD, and DoS windows, doors, and wall component responses
- Accommodates up to 10 ft x10 ft samples
- Consists of two major sections
  - a driver section and an expansion section
  - separated by a rupture diaphragm

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Reinforced Concrete Slab Makeup

- Slabs 8.5 ft tall by 8.0 ft wide and 5.5 in thick [2.6 m tall by 2.4 m wide by 140 mm thick]
- Nominal 28-day compressive strength of 4,000 psi [27.6 MPa]
- Reinforcement consisted of No. 5 steel reinforcing bars spaced at 12 inches on center spanning in the vertical direction and at mid-depth
  - No. 4 bars spaced at 12 inches on center spanning in the horizontal direction adjacent to mid-depth vertical reinforcement
  - nominal steel yield strength was 60,000 psi [414 MPa]
- Slab was supported at the top and bottom to achieve vertical one-way flexural behavior

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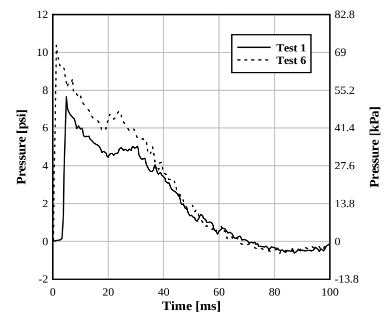
Applied Blast Load Histories



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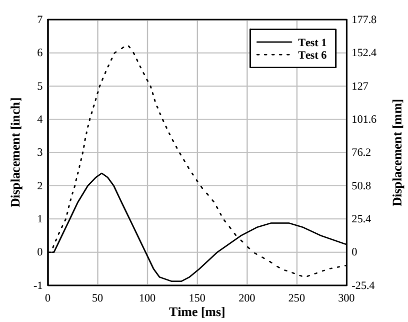
Measured Midspan Displacement Histories



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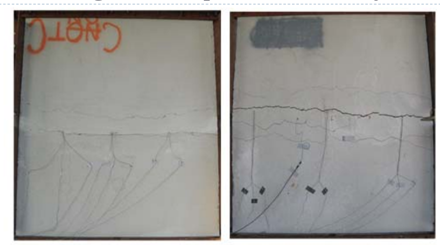
Test Loading and Response Summary



Test 1 Test 6

Test No.	Applied Pressure (psi) – [kPa]	Applied Impulse (psi·ms) – [MPa·ms]	Peak Deflection (in) – [mm]	Peak Support Rotation (°)
1	7.7 – [53]	217 – [1.50]	2.4 – [61]	2.7
6	10.4 – [72]	297 – [2.50]	6.2 – [157]	7.1

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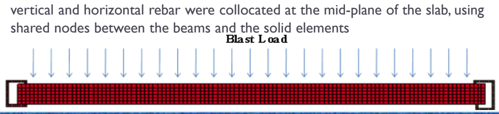
FEA Model Summary

- A 3D finite element model was defined to represent the test slab and its supports
  - simple-simple without arching
- A single mesh was used in all the analyses, independent of the three concrete constitutive models
- Hexahedral (solid brick) elements were used to represent the concrete, with six elements through the slab's thickness
  - concrete element size is slightly less than 1 inch in each dimension, or 0.96×0.96×0.92 inch [24.3×24.3×23.4 mm]
- Beam elements were used to represent the reinforcing
  - vertical and horizontal rebar were collocated at the mid-plane of the slab, using shared nodes between the beams and the solid elements



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Steel Reinforcement Material Model

- Elastic-plastic model (MAT3 in the LS-DYNA and DYNA3D material libraries)
- Steel strength was increased from its nominal value with a static increase factor of 1.1 to better represent realistic vs. minimum strength properties as recommended by UFC3-340-2 and ASCE for ASTM A615, Grade 60
- Dynamic increase factor of 1.22 applied to strength based on estimated strain rate effects as recommended by UFC3-340-02
- A tangent modulus of 230 ksi [1,590 MPa] was included to represent post-yield hardening behavior
- Failure was not included in the steel model as the rebar did not reach significant strains approaching strain at ultimate strength

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AEC-3I Model

- Applied Engineering Cap Model with Three Invariants
- Models material plasticity with a unified shear yield and cap surface that can harden from an initial yield position to ultimate strength, and then soften to residual surfaces under continued loading
  - The cap portion of the yield surface only hardens and does not soften
  - uses a non-associated flow rule in the form of normal stress correction to the yield surfaces
  - dilation and shear compaction are controlled through relative strain hardening parameters of the shear yield surface and cap
- The decohesion algorithms model the formation of crack planes with defined orientation, and controlled growth based on material fracture energy
  - crack growth is represented with decohesion strain components resulting in anisotropic material behavior
  - elements cannot carry traction forces across a fully formed crack plane, and subsequent compressive forces are not engaged until the crack has closed
  - any number of crack failure planes can form and grow within any element
  - orientation of crack plane initiation is based on principal-stress Rankine criteria
- Model does not incorporate strain rate effects on material properties
  - dynamic strength enhancement is modeled by explicit (offline) application of an increase factor to the compressive and tensile strength values

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MAT72R3 Model

- Model consists of three shear failure surfaces, the initial yield surface, the maximum yield surface and the residual yield surface
  - during initial loading, the deviatoric stresses are elastic until the initial yield surface is reached
  - stresses can then increase further until these reach the maximum yield surface
  - beyond the maximum yield surface, the response can soften to the residual surface or be perfectly plastic
  - Shear dilatancy occurs as concrete approaches failure
- A softening model for concrete in tension is also included in the material model
  - Does not track cracking planes, smeared crack so entire element fails
- Two separate curves defining the dynamic increase factor as a function of strain rate
  - one curve for tension and another for compression

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MAT159 Model

- Model has a smooth intersection between the failure surface and the hardening cap and is often referred to as a Continuous Surface Cap Model
  - shear dilatancy occurs as concrete approaches failure
  - softening of concrete after the peak stresses have been reached is modeled using a damage formulation
  - this formulation models strain softening and modulus reduction for both tensile and compressive hydrostatic pressures
- Includes strain rate dependence for tensile and compressive states of stress, as well as for fracture energy

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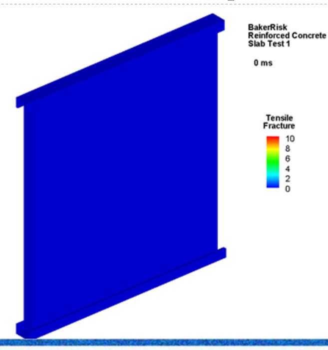
Test 1 AEC-3I Model Response



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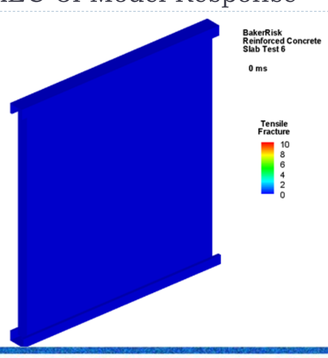
Test 6 AEC-3I Model Response



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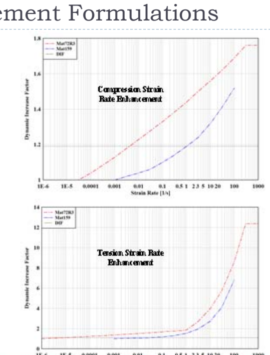
Material Model Dynamic Rate Enhancement Formulations



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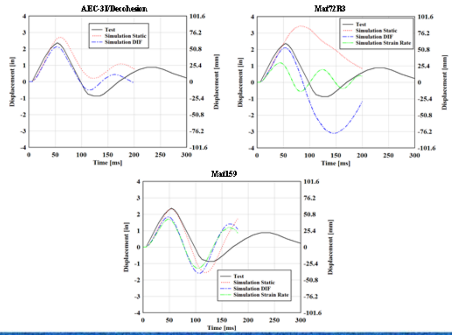
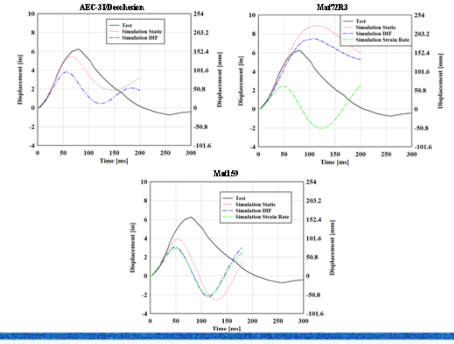
Test 1 Material Model Response Comparison



Test 6 Material Model Response Comparison



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Conclusions

- All three models predicted the peak positive deflection within a factor of 2
- All three models were generally better at predicting a lower damage response level since the results were more comparable to Test 1 than Test 6
- MAT72R3 is clearly the least accurate for Test 1, but it does as well as the others for Test 6
- AEC-31 is comparable to MAT159 for both tests
- Addition of more sophisticated methods of addressing rate enhancement in the concrete constitutive models did not result in greater predictive accuracy
- The AEC-31 and MAT159 models are the least sensitive to variations in how one represents the rate sensitivity of the concrete

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