SBEDS
(Single degree of freedom Blast Effects Design Spreadsheets)

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Protective Design Center
Presentation Outline

- Background & general description
- SBEDS technical capabilities
- Tour of workbook
- Obtaining SBEDS
- Future enhancements
Background

- Implementation of DoD antiterrorism construction standards requiring more blast design of ‘conventional’ facilities
- Existing blast resistant structural design tools developed for design of more robust structures and are cumbersome for design of more conventional structures
- USACE Protective Design Center, through Baker-Risk, developed SBEDS as a designer friendly tool for more typical construction
- SBEDS v1.0 released May 2004, v2.0 released June 2005
SBEDS - General

- SBEDS is an Excel© workbook that combines all steps to design/analyze a wide variety of blast-loaded structural components
- User inputs basic information related to geometry, boundary condition, material property, response mode, & blast load for component
- SBEDS calculates equivalent SDOF parameters & determines dynamic response w/ time-stepping SDOF calculator
- 11 types of structural components available
  - Also allows for input of general SDOF system
- Outputs maximum response parameters and response history plots
SBEDS – General (continued)

- Also performs shear check
  - stirrup design for concrete & CMU components
- Iteratively develops pressure-impulse (P-i) relationship and associated charge weight-standoff diagrams
- Designated metric or English units
- Detailed Users Guide hot-linked to workbook
- Based on Army TM 5-1300 & UFC 3-340-01 guidance but draws on other sources for best methodologies
Available Component Types

- One-way corrugated metal panel
- One-way or two-way steel plate
- Steel beam or beam-column
- One-way open-web steel joist
- One-way or two-way reinforced concrete slab
- Reinforced concrete beam or beam-column
- Prestressed concrete beam or panel
- One-way or two-way reinforced masonry
- One-way or two-way unreinforced masonry
- One-way or two-way wood panel
- One-way wood beam or beam-column
- General SDOF system
Available Response Modes

- Flexure
- Tension membrane
- Compression membrane
- Brittle flexure w/ axial load softening
- Arching with gap & non-solid section
- General
Flexure Resistance Functions

- TM 5-1300/UFC 3-340-01
- Option for shear based resistance for concrete slabs & masonry elements

All components

Determinant Boundary Conditions

Indeterminate Boundary Conditions
(Solid Curve Used for Flexure Only)
(Dashed Curve for Flexure and Tension Membrane)

Figure 4. Resistance-Deflection Curve For Flexural Response
Tension Membrane Resistance Function

- UFC 3-340-01
- One-way corrugated metal panel
- One-way or two-way steel plate
- Steel beam or beam-column

![Graph of Tension Membrane Resistance Function](image)

\[ \phi_{TM} = \tau_e + \frac{4TL^2}{\pi^2 EA} \quad \text{where} \quad T = \text{Minimum}\left[\frac{f_y A}{V_0}\right] \]

\[ K_{TM,1} = \frac{8T}{bL^3} \]

\[ K_{TM,2} = \frac{T\pi^4}{4L^2 \sum_{n=1,2} \left(\frac{1}{n^4}(-1)^{n+1/2}\right) A} \quad \text{where} \quad A = 1 - \frac{1}{\cosh\frac{n\pi L_x}{2I_y}} \quad \text{and} \quad I_x > I_y \]

Equation 2

Where:
- \( \phi_{TM} \): assumed deflection at beginning of linear tension membrane response adding to flexural response for one and two-way response
- \( K_{TM,i} \): linear tension membrane slope for one-way (\( i=1 \)) or two-way (\( i=2 \)) response
- \( \tau_e \): equivalent elastic yield deflection
- \( f_y \): dynamic yield strength
- \( A \): component cross sectional area within loaded width \( b \)
Compression & Tension Membrane Resistance Function

- UFC 3-340-01
- User’s option to consider compression only, tension only, or both
- One-way or two-way RC slab
- RC beam or beam-column
- One-way or two-way reinforced masonry

Figure 18. Resistance-Deflection Curve for Reinforced Concrete and Masonry Components with Compression and Tension Membrane (from UFC 3-340-01)
Brittle Flexure w/ Axial Load

Softening Resistance Function

- Wall Analysis Code (WAC)

- One-way or two-way unreinforced masonry

Figure 25. Resistance-Deflection Curves for Unreinforced Masonry with Brittle Flexural Response and Axial Load From WAC Program

\[ r_3 = \frac{4}{L^2} \left( h - \Delta \left( P + \frac{WL}{2} \right) \right) \]

Equation 7

where:
- \( r_3 \) = maximum resistance from axial load effects
- \( x_3 \) = flexural deflection at \( r_2 = (r_3 - r_2) / K_{ep} \)
- \( K_{ep} \) = elastic-plastic stiffness for indeterminate components, otherwise equal to elastic stiffness
- \( h \) = overall wall thickness
- \( P \) = input axial load per unit width along wall, \( P_{ned} \)
- \( W \) = areal self-weight and supported weight of wall
- \( L \) = span length equal to wall height
Arching With Gap & Non-Solid Cross Section Resistance Function

- Park and Gamble’s Reinforced Concrete Slabs modified for gap between wall and rigid support for non-solid cross section
- One-way or two-way unreinforced masonry

![Resistance vs Deflection](Image)

Figure 26. Arching Resistance-Deflection Curve
General Resistance Function

- Up to 5 segments
- Systems with or without ‘softening’
- Different stiffness in rebound allowed
- Rules for rebound stiffness in systems using compressive membrane and arching

Figure 2. General Resistance-Deflection Diagram Without Softening

Figure 3. Typical Resistance-Deflection Diagram With Softening (See Figure 2 and Table 1 for Definition of Terms in Figure)
Available Boundary Conditions

- One-way components
  - Cantilever
  - Fixed-fixed
  - Fixed-simple
  - Simple-simple (only condition for open web joists)

- Two-way components
  - Four sides supported (all fixed or all simple)
  - Three sides supported (all fixed or all simple)
  - Two adjacent sides supported (both fixed or both simple)
Available Loadings

- Uniform loading for all components
- Concentrated loads for beam or beam-column components
  - load at free end of cantilevered elements
  - load at midspan for all other support conditions
- P-Δ
  - RC components except prestressed
  - Reinforced masonry
  - Unreinforced masonry
  - Wood beam or beam-column
  - General SDOF
Equivalent $P-\Delta$ Load

- SBEDS calculates the lateral force on component causing same maximum moment as $P-\Delta$ effect at each time step
  - $P-\Delta$ load based on axial load, geometry, and boundary conditions/load type of component and deflection at each time step
- Equivalent $P-\Delta$ load history is added to input load history and separately plotted in output
- Approach is consistent with other dynamic analyses methods considering $P-\Delta$ effects including FEA based approaches
SBEDS Structure

- ReadMe sheet
- Intro sheet
- Input sheet
- Results sheet
- P-i Diagram sheet
- SDOF Output sheet

- SDOF sheet (hidden)
- Database sheet
- Positivephasedload sheet (hidden)
- Negativephasedload sheet (hidden)
- Wait sheet


SBEDS Structure

- ReadMe sheet
  - General admin info
  - Support info
- Intro sheet
- Input sheet
- Results sheet
- P-i Diagram sheet
- SDOF Output sheet
- SDOF sheet (hidden)
- Database sheet
- Positivephaseload sheet (hidden)
- Negativephaseload sheet (hidden)
- Wait
SBEDS Structure

- ReadMe sheet
- Intro sheet
  - Component selection
  - Units selection
  - Workbook instructions
  - Discussion of workbook design
- Input sheet
- Results sheet
- P-i Diagram sheet
- SDOF Output sheet
- SDOF sheet (hidden)
- Database sheet
- Positivephaseload sheet (hidden)
- Negativephaseload sheet (hidden)
- Wait
SBEDS Structure

- ReadMe sheet
- Intro sheet
- Input sheet
  - Discussed later
- Results sheet
  - Discussed later
- P-i Diagram sheet
  - Discussed later
- SDOF Output sheet
  - Sample shown later
- SDOF sheet (hidden)
- Database sheet
- Positivephasedload sheet (hidden)
- Negativephasedload sheet (hidden)
- Wait
SBEDS Structure

- ReadMe sheet
- Intro sheet
- Input sheet
- Results sheet
- P-i Diagram sheet
- SDOF Output sheet

- SDOF sheet (hidden)
  - Time-stepping SDOF solution
- Database sheet
  - Properties of library members
  - SDOF constants
- Positivephasedload sheet (hidden)
- Negativephasedload sheet (hidden)
- Wait
## Component Input

### Configuration
- Span, L: 50 ft
- Spacing, B: 20 ft
- Boundary Conditions: Fixed-Fixed, Uniformly Loaded
- Response Type: Flexural

### Structural & Material Properties
- Axis of Bending: Strong (X-X)
- Shape: W12×50
- Self-Weight, w: 50.0 lb/ft
- Moment of Inertia, I: 384 in
- Section Modulus, Z: 72.4 in
- Web Thickness, t_w: 0.37 in
- Depth, d: 12.19 in
- Area, A: 14.70 in
- Supported Weight, W: 3 psf
- Load Area Factor - Enter 1.0 for Uniform Load: 1
- Inbound Unbraced Length for Compression Flange, L_23L: 0 ft (0 for fully braced)
- Rebound Unbraced Length for Compression Flange, L_23R: 0 ft (0 for fully braced)

#### Steel Type
- A992, A313, A572, A529 (All Gr. 50) rolled shapes

#### Calculated Properties
- Inbound Moment Capacity, M_y: 4,523,190 lb-in
- Rebound Moment Capacity, M_y: 4,523,190 lb-in
- Rebound/Inbound Moment Capacity Ratio, MR: 1.00
SBEDS Drop-Down Menus

- Support conditions
- Response mode
- Beam sizes (AISC and cold-formed girts/purlins)
- Open web steel joist sizes (K and LH series)
- Masonry (Brick, European block, Heavy-Medium-Lightweight CMU)
- Corrugated metal panel sizes (MBCI and Vulcraft sizes, traditional and standing-seam deck)
- Typ. steel plate, beam, and rebar material properties
- All drop-downs automatically insert properties of selected size/type into spreadsheet
- User-defined option available for all drop-down menus
Calculated Resistance-Deflection Relationship on Input Sheet

### SDOF Properties

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<th>Property</th>
<th>Inbound</th>
<th>Rebound</th>
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<td>psi-ft-in</td>
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<td>0.00</td>
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<td>psi</td>
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</table>

Graph:

**Resistance vs Deflection**

- Resistance ranges from 0 to 0.9 psi.
- Deflection ranges from 0 to 25 in.

The graph shows the calculated resistance-deflection relationship on input sheet.
Loading Options

- Directly input up to 8 time-pressure pairs defining a piecewise linear pressure history
- User inputs charge weight and standoff distance
  - Pressure history for hemispherical surface burst is calculated based on Kingery-Bulmash parameters
  - Side-on or reflected load
    - angle of incidence can be specified for reflected loads
  - With or without negative phase
  - With or without clearing effects
- User designated file with up to 2,000 time-pressure pairs
  - One time-pressure pair separated by commas per line
  - Consistent with DPLLOT file saved using the ASCII file option
- Member orientation
SBEDS Generated Loading

- Exponential decay in positive phase pressure-history using curve-fit to decay constant from CONWEP
- Curve-fit to negative phase using method from Navy document "Blast Resistant Structures, Design Manual 2.08, December 1986" (see below)

![Graph showing force history over time](image)

Note: Used for reflected and side-on blast loads
### Solution Options

#### Dynamic Shear Factors

<table>
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<tr>
<th>Shear Constant</th>
<th>Elastic</th>
<th>Plastic</th>
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<tbody>
<tr>
<td>F (long side)</td>
<td>0.14</td>
<td>0.11</td>
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<tr>
<td>R (long side)</td>
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<td>0.36</td>
</tr>
<tr>
<td>F (short side)</td>
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<td>0</td>
</tr>
<tr>
<td>R (short side)</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

*Note: Dynamic shear factor input is optional*

#### Solution Control

- **Inbound Natural Period:** 145.95 ms
- **Rebound Natural Period:** 145.95 ms
- **Max Recommended Time Step:** 0.40 ms
- **Time Step:** 0.2 ms
- **% of Critical Damping:** 0%
- **Initial Velocity:** 0 m/s

#### Input Design Criteria

- **θ (deg):** 2
- **μ:** 5
- **Design LOP:** MLOP

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Solution Options (continued)

- Response limits/level of protection desired (optional)
  - Does not effect calculations, bookkeeping aid

- Dynamic shear constants (optional)

- Damping
  - 0.05% of critical used by default, greater values can be input

- Initial velocity

- Time step (recommended value provided)
Recommended Time Step – Smallest Value Based On:

- 10% of the natural period
- 10% of the smallest time increment in a manually input blast load
- 3% of the equivalent triangular positive phase duration or 1.5% of the equivalent triangular negative phase duration of an input charge weight-standoff blast load
- 3% of the smallest calculated time between local maxima and minima points of a input blast load file
- The total 2900 time steps in the time-stepping SDOF method in SBEDS divided by 8 natural periods (but not less than 0.01 ms)
SDOF Solver in SBEDS

- Constant velocity integration method used to numerically solve SDOF equation of motion at each time step
  - Very stable solutions if small enough time step used
- 2900 time steps in program so very small time steps are usually recommended (less than 1 ms)
Validation

- Generally within 1%-2% when checked against the SOLVER and WAC codes for numerous cases (27) with multiple yield and stiffness combinations
- Constant velocity method has also been validated against finite element calculations performed by BakerRisk

<table>
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<th>Analysis Description</th>
<th>Response Range</th>
<th>SDOF Model</th>
<th>ADINA Model</th>
<th>Percent Difference</th>
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<td>Mu = 10</td>
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<td>Mu = 10</td>
<td>29.81</td>
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<td>26.26</td>
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<td>Mu = 20</td>
<td>59.55</td>
<td>66</td>
<td>49.98</td>
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SBEDS Output

- Maximum deflection and resistance in inbound/outbound response
  - Maximum support rotation, ductility ratio, strain rate(s), and equivalent static and dynamic shears
- Response history plots for deflection, resistance, equivalent P-Δ load, and dynamic shear and resistance-deflection plot
### SBEDS Results Summary

#### Results Summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
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<tbody>
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<td>deg.</td>
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<td>$\mu$</td>
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<td>LOP Design Criteria</td>
<td>MLOP</td>
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<td>Response</td>
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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
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<tr>
<td>$X_{\text{max}, \text{Inbound}}$</td>
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<td>$X_{\text{max}, \text{Rebound}}$</td>
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<td>$R_{\text{max}}$</td>
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<td>psi</td>
</tr>
<tr>
<td>$R_{\text{min}}$</td>
<td>-0.79</td>
<td>psi</td>
</tr>
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</table>

Shortest Yield Line Distance to Determine $\theta$: 300.0 in

#### Equivalent Static Reactions

**Peak Reactions from Flexural Response**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
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<td>$V_{\text{max}, R}$</td>
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**Shear Capacity**

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**Results:** Shear is OK

---

*Based only on larger of $R_{\text{max}}$ or $R_{\text{min}}$, not including tension membrane*
SBEDS Detailed Output
(Results Sheet)
Peaks

Results Summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>$\theta_{\text{max}}$</td>
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<td>$\mu$</td>
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<tr>
<td>$X_{\text{min}}$</td>
<td>-5.05 in at time = 122.00 msec</td>
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<tr>
<td>$R_{\text{max}}$</td>
<td>0.81 psi at time = 47.20 msec</td>
</tr>
<tr>
<td>$R_{\text{min}}$</td>
<td>-0.79 psi at time = 122.00 msec</td>
</tr>
</tbody>
</table>

Reactions

- Peak Dynamic Reactions
  - $V_{\text{max,Long}}$ = 0.52 psi
  - $V_{\text{max,Short}}$ = 0.00 psi

Strain Rate to First Yield*

- Strain Rate = 0.082 1/sec

* First yield, or maximum response if no yield
Displacement History
Resistance and Equivalent P-Δ Force History
Resistance – Displacement Function
Dynamic Shear History
### SDOF Output Sheet

<table>
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<tr>
<th></th>
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P-i & CW-S Diagrams

Deflections Calculated with Positive & Negative Phase Reflected Loads from Charge Weight-Standoff.

- Max. Defl. = 7.43 in
- Max. Defl. = 14.85 in
- Max. Defl. = 22.28 in
- Max. Defl. = 29.71 in

- Pressure (psi)
- Impulse (psi-ms)
- Charge Weight (lb)
- Standoff (ft)
User specifies ductility and/or support rotation for up to four levels of response
  - if ductility and support rotation are entered, the one resulting in the smallest deflection is used

Negative phase is optional

User selects either P-i, CW-S for side-on loading, or CW-S for fully reflected loading

Clearing and angle of incidence are not considered

SBEDS iterates to determine the charge weight and standoff resulting in the specified level of response and then plots either the P-i or CW-S point
SBEDS Availability

- Distribution Statement A – Approved for public release; distribution is unlimited
- [https://pdc.usace.army.mil/](https://pdc.usace.army.mil/)
- Registration required (Armadillo protection)
- Limited support available
  - PDC website has FAQ, discussion forum, & issue tracker
Future

- Methodology manual
- Routine to transfer graphic output to DPlot
- Additional boundary condition options for 2-way concrete, steel, and masonry slabs and plates
- Cavity wall component (unreinforced masonry)
- Metal stud w/ fascia component
- Account for openings in two-way members
Summary

- SBEDS is a valuable tool for implementing DoD antiterrorism standards
- Designer friendly tool for conventional construction that combines all steps to design/analyze a wide variety of blast-loaded structural components
- SBEDS calculates single degree of freedom (SDOF) response for 11 types of structural components
  - Also allows for input of general SDOF system
- Based on Army TM 5-1300 & UFC 3-340-01 guidance but draws on other sources for best methodologies
- Approved for public release and available from https://pdc.usace.army.mil/
CEDAW
(Component Explosive Damage Assessment Workbook)
Background

- DODI 2000.16 requires vulnerability assessments of installations that include the consideration of explosive threats
- P-i methodology provides a means of rapidly assessing expected damage to structural components
- Many blast assessment tools utilize the P-i methodology in the PDC FACEDAP (1991)
- Recent developments have left FACEDAP ‘dated’
  - refined SDOF techniques considering more complex response modes
  - more test data for component response to blast loads
  - better understanding of importance of the negative phase
- These factors accounted for in CEDAW, as well as incorporation of the new DOD definitions for LOP
CEDAW Methodology

- P-i relationships developed from scaled relationships specifically for defined DoD levels of protection
- Near instantaneous results (not an iterative process as used in SBEDS)
CEDAW Components

- One-way corrugated metal panel
- Steel beam or beam-column
- Metal stud wall
- Open-web steel joist
- One-way or two-way reinforced concrete slab
- Reinforced concrete beam
- One-way reinforced masonry
- One-way or two-way unreinforced masonry
- Wood stud wall
- Steel column (assuming connection failure)*
- Reinforced concrete column
CEDAW P-i Output

Open Web Steel Joists P-i Diagram for test test test
Range = 50 ft, Charge Weight = 500 lb TNT

P\textsubscript{so} = 24.89 psi
l\textsubscript{o} = 0.096 psi-sec
P\textsubscript{r} = 79.45 psi
l\textsubscript{r} = 0.246 psi-sec

- HLOP Upper Bound
- MLOP Upper Bound
- LLOP Upper Bound
- Onset of Blowout

*See "LLOP descriptions" worksheet
CEDAW CW-S Output

Open Web Steel Joists Reflected CW-Standoff Graph for test test test
Range = 50 ft, Charge Weight = 500 lb TNT

- Upper Bound of HLOP*
- Upper Bound of MLOP*
- Upper Bound of LLOP*
- Onset of Blowout*
- Situation

For a charge weight = 500 lb TNT
- Upper Bound of High LOP = 220 ft
- Upper Bound of Medium LOP = 140 ft
- Upper Bound of Low LOP = 84 ft
- Lower Bound of Blowout = 42 ft

* See "LOP descriptions" worksheet
** From Unconfined Hemispherical Surface Burst
CEDAW Availability

- Distribution Statement A – Approved for public release; distribution is unlimited
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