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Protective Design Center Technical Report

Single-Degree-of-Freedom Blast Effects Design Spreadsheets *(SBEDS)*

WBE Project

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Omaha District

https://pdc.usace.army.mil/software/sbeds

SBEDS
(Single degree of freedom Blast Effects Design Spreadsheets)

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Abstract

SBEDS is an Excel® based tool for design of structural components subjected to dynamic loads, such as airblast, using single degree of freedom (SDOF) methodology. This paper summarizes the key features and processes of SBEDS. SBEDS allows the user to choose from 10 common structural components and enter readily available parameters related to material properties and geometry and allow the workbook to calculate the SDOF properties or directly enter the SDOF properties. Masonry, reinforced concrete, steel, cold-formed metal, and wood components are included. Dropdown menus with common member sizes, material properties, boundary conditions, and other inputs allow for quick model setup. Various support conditions can be selected. A flexure resistance function is used with compression membrane and/or tension membrane contributions where applicable. P-delta effects on components subject to axial load can also be modeled. SBEDS follows the guidance contained in Army TM 5-1300, "Structures to Resist the Effects of Accidental Explosions", and Unified Facilities Criteria (UFC) 3-340-0 (FOUO), "Design And Analysis Of Hardened Structures To Conventional Weapons Effects", as applicable. Either uniformly distributed or concentrated loadings are accommodated. The workbook will read an ASCII file containing pressure/force time pairs or the user can enter a piecewise linear load consisting of up to 8 segments. Additionally, a uniform distributed pressure from detonation of a high explosive hemispherical surface burst that accounts for negative phase loading can be generated within the workbook by specifying the charge weight and standoff distance. Numeric integration of the equation of motion is accomplished using a constant velocity method with user specified dampening considered. Maximum and minimum displacements, maximum support rotation, ductility, and peak reactions are reported. Additionally, histories for displacement, resistance, reactions, and load are available. Shear capacity of the component is evaluated and reported. All input and output can be in a prescribed set of English or Metric units. A detailed Help/Users Guide is hot-linked to the program that includes all the information in this paper and additional information. SBEDS is a product of the U.S. Army Corps of Engineers Protective Design Center and was developed by Baker Engineering and Risk Consultants, Inc. (BakerRisk).

Background

UFC 4-010-01, "DoD Minimum Antiterrorism Standards for Buildings", requires inhabited structures not meeting minimum standoff requirements be designed to resist the airblast effects from an explosive device detonated at the reduced standoff distance provided. Currently, several programs need to be run to accomplish the design. Many of these existing programs were developed for the design of structures to resist wartime (conventional and nuclear) threats. As such, these programs are more suited for robust components such as heavily reinforced concrete and steel plate systems. Use of such programs when designing more conventional components, i.e. rolled steel shapes, cold-formed steel members, concrete masonry units, etc. are quite involved. Providing designers a more efficient tool suitable for satisfying the UFC requirements is the reason for the development of SBEDS.

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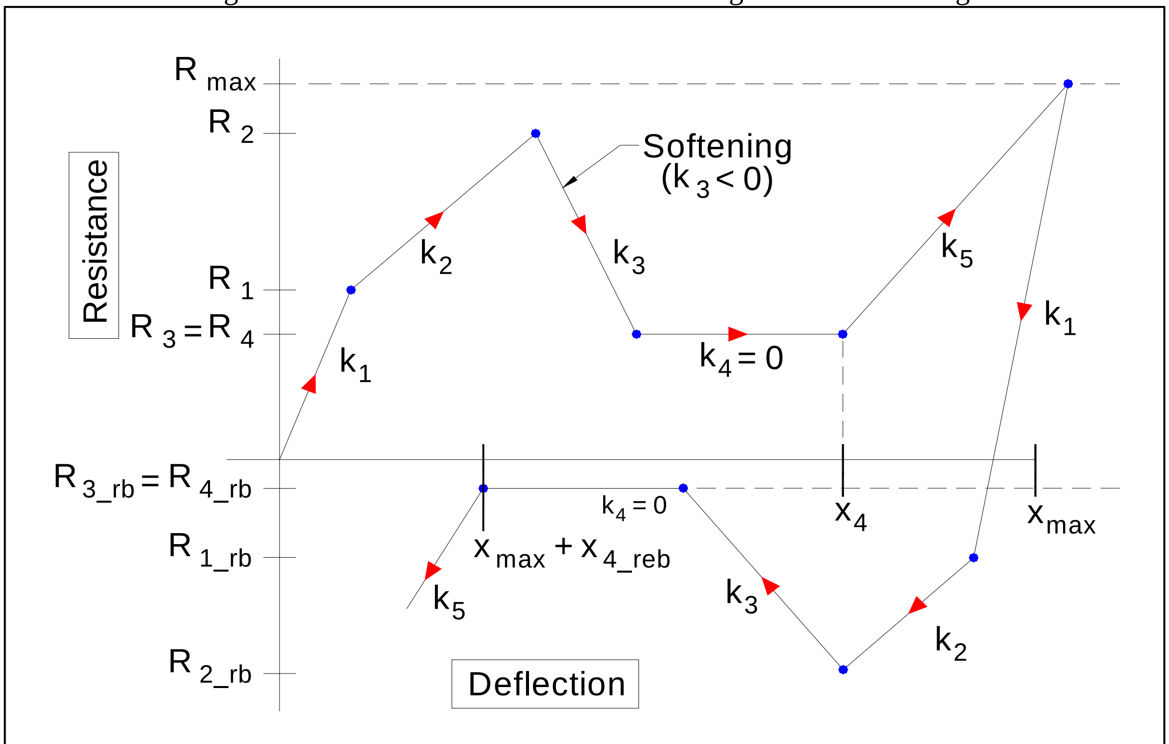
Systems Modeled

The foundation of SBEDS is an SDOF numerical integration scheme capable of analyzing a resistance function with five linear segments for initial response and five linear segments for rebound. This scheme, which allows for softening in either phase, is illustrated in Figure 1.

Figure 1. General Resistance-Deflection Diagram with Softening



Note: **k_i** are input stiffness for stiffness regions i = 1 to 5: k_i>=0
r_i are input inbound resistances for stiffness regions i = 1 to 5: r_i>=0
Δr_i = (r_i - r_{i_reb})
r_{i_reb} are input rebound resistances for stiffness regions i = 1 to 5: r_{i_reb}<0
x_i are input inbound maximum deflections for stiffness regions i = 1 to 5: x_i>0
x_{i_reb} are input rebound maximum deflections for stiffness regions i = 1 to 5: x_i<0
Note 1: x_i and x_{i_reb} are only used if k_i = 0

This solution scheme allows SBEDS to determine the response of numerous common construction components/response modes as well as a general SDOF system. The component types available in SBEDS are shown in Table 1. For each component a number of support and loading conditions can be selected. A constant axial load for P-Δ effects can also be specified for a number of the components. SBEDS calculates an equivalent lateral load at each time step based on the P-Δ induced moment. Table 1 also shows the support and loading options for the various components and Table 2 shows the response modes that can be consider for each component.

Table 1. Available Components, Support Conditions, and Loadings

Supports Conditions	Component Types	Loading		
		Conc[1]	Uniform	P-Delta
Cantilever Fixed-Fixed Fixed-Simple Simple-Simple	One-way Corrugated Metal Panel		X	
	One-Way Steel Plate		X	
	One-Way Reinforced Concrete Slab		X	X
	One-Way Reinforced Masonry		X	X
	One-Way Unreinforced Masonry		X	X
	One-Way Wood Panel		X	
	One-Way Steel Beam or Beam-Column	X	X	X
	One-Way Reinforced Concrete Beam or Beam-Column	X	X	X
	One-Way Wood Beam or Beam-Column	X	X	X
Four/Three/Two Adjacent Sides Supported – Fixed Four/Three/Two Adjacent Sides Supported – Simple	Two-Way Steel Plate		X	
	Two-Way Reinforced Concrete Slab		X	X
	Two-Way Reinforced Masonry		X	X
	Two-Way Unreinforced Masonry		X	X
	Two-Way Wood Panel		X	
Simple-Simple	Open-Web Steel Joist		X	
N/A	General SDOF System		X	X

[1] – Concentrated load located at end of cantilever members, midspan for other support conditions.

Table 2. Available Response Modes

COMPONENT TYPES	FLEXURE	TENSION MEMBRANE	COMPRESSION MEMBRANE
Corrugated Metal Panel	X	X	
Steel Plate	X	X	
Steel Beam or Beam-Column	X	X	
Open-Web Steel Joist	X		
Reinforced Concrete Slab	X	X	X
Reinforced Concrete Beam or Beam-Column	X	X	X
Reinforced Masonry	X	X	X
Unreinforced Masonry	X[1]		X[2]
Wood Panel	X		
Wood Beam or Beam-Column	X		
General SDOF System	N/A, user directly inputs resistance function		

[1] - Brittle flexure w/ axial load softening or ductile flexure
[2] - Rigid arching only with user input gap at top of wall

Response Modes

The resistance functions for ductile flexural response are shown in Figure 2. For determinate boundary conditions a two-stage (elastic-plastic) function is used. For indeterminate boundary conditions a three stage (elastic-elastoplastic-plastic) is used. The parameters for these functions are based on the methodology found in TM 5-1300 and UFC 3-340-01. If compression membrane or tension membrane response is considered with indeterminate boundary conditions the three-stage resistance function is converted to an equivalent elastic-plastic system for the initial behavior. For unreinforced masonry the brittle flexural response that accounts for axial load shown in Figure 3 is used. This model is consistent with the methodology in the Wall Analysis Code (WAC).

Figure 2. Resistance-Deflection Curve For Ductile Flexural Response

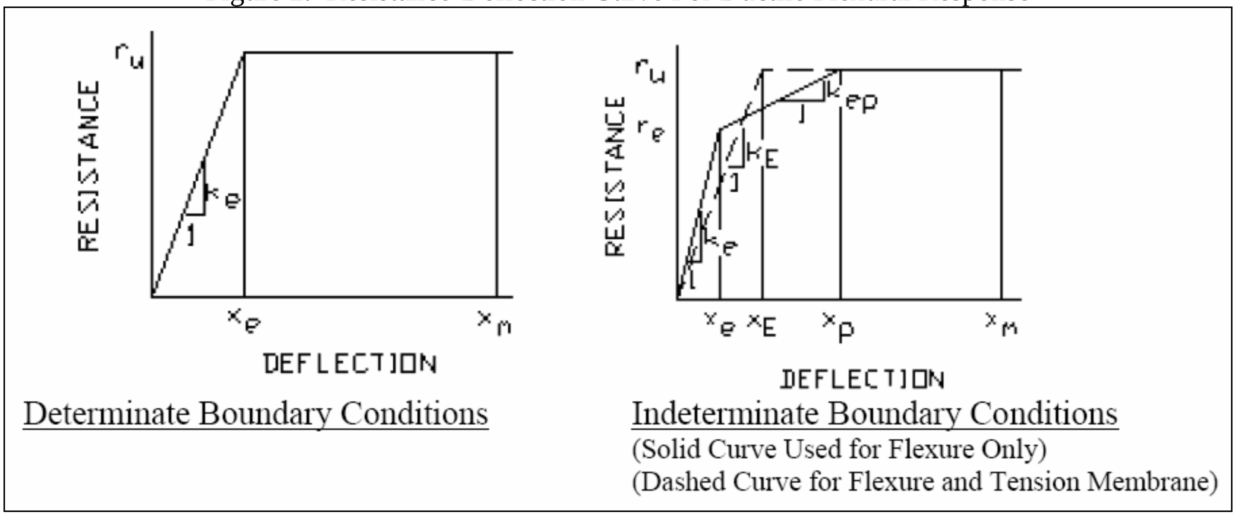
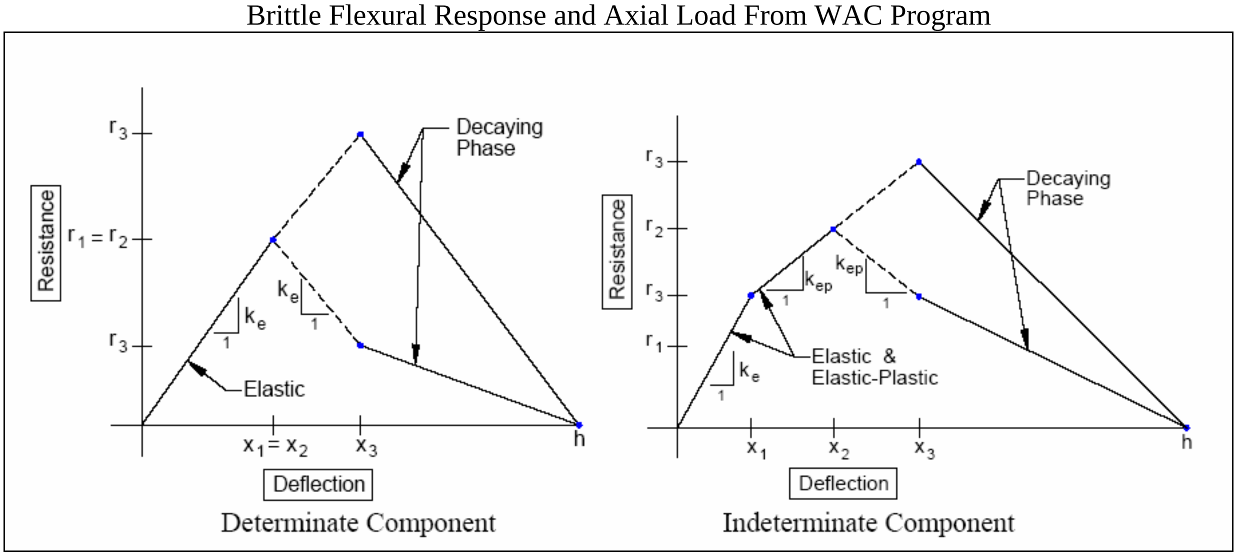


Figure 3. Resistance-Deflection Curves for Unreinforced Masonry with Brittle Flexural Response and Axial Load From WAC Program



The tension membrane resistance function for steel members and compression and tension membrane resistance function for reinforced concrete and masonry members follow the methodology of UFC 3-340-01. The steel resistance function is illustrated in Figure 4 for a component with flexural and tension membrane response. The tension membrane response after yield is based on the lesser of an input in-plane connection capacity or the dynamic axial tension strength of the cross section. In almost all practical cases, the in-plane connection capacity controls. The resistance function for reinforced concrete and reinforced masonry components with flexure, compression membrane, and tension membrane, which is the most general case, is shown in Figure 5. Flexure with either tension membrane, or compression membrane, can also be specified by the user.

Figure 4. Resistance Deflection Curve for Steel Components with Tension Membrane

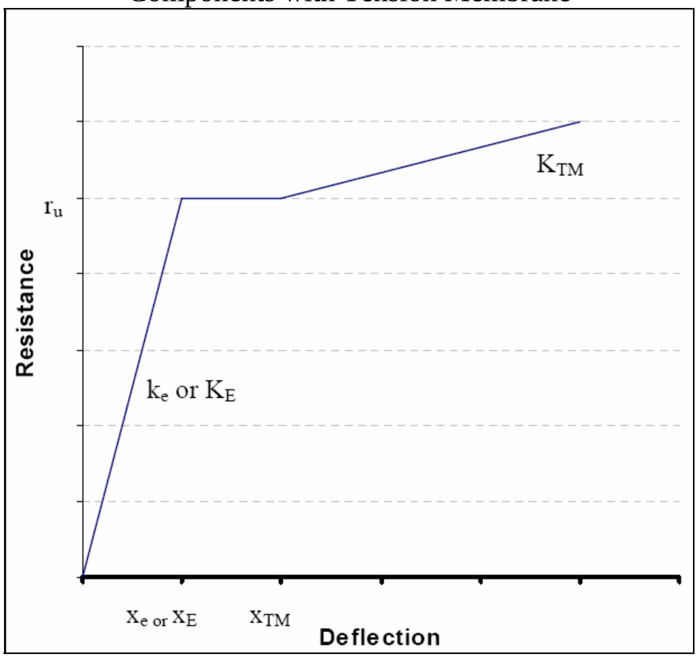
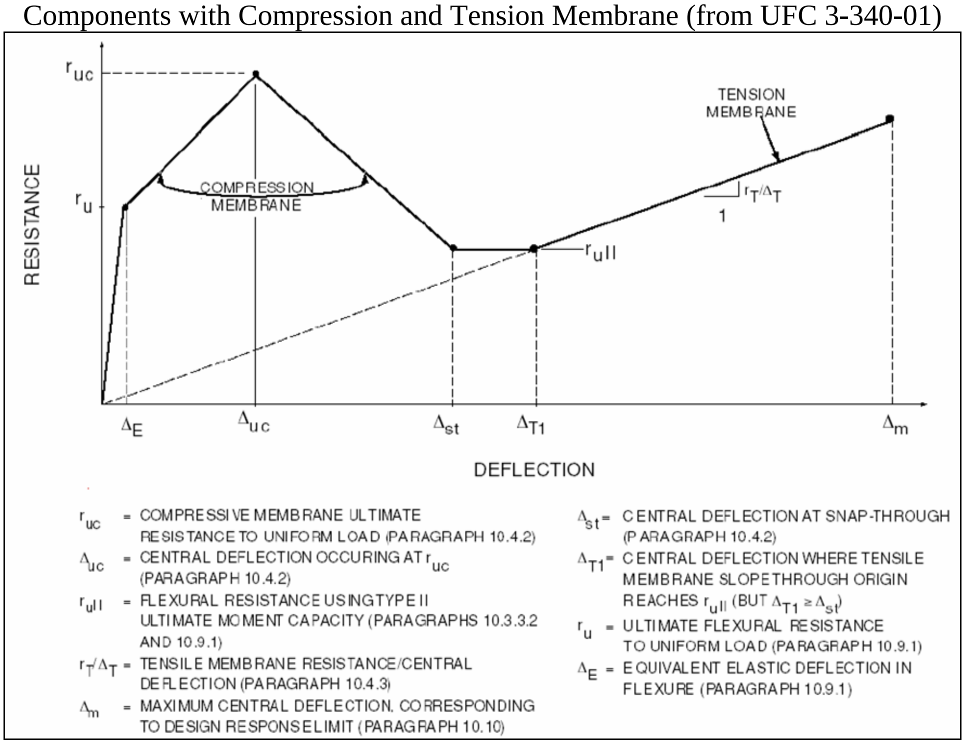
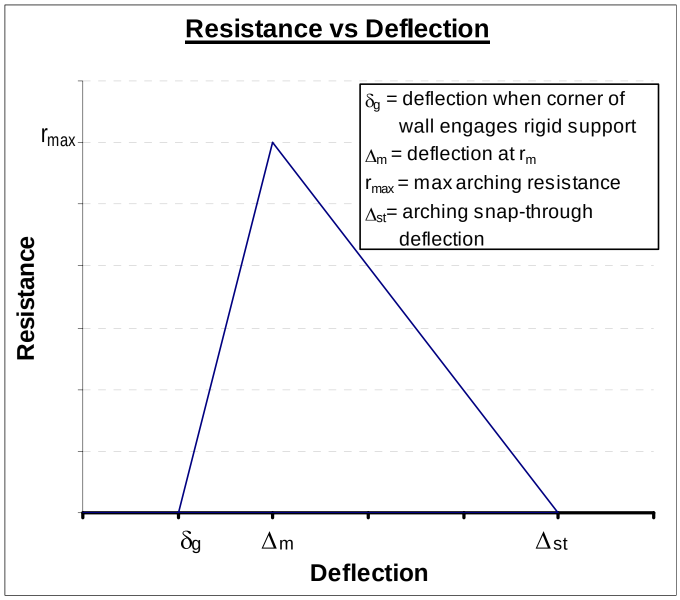


Figure 5. Resistance-Deflection Curve for Reinforced Concrete and Masonry Components with Compression and Tension Membrane (from UFC 3-340-01)



For arching of unreinforced masonry, the equations for compression membrane from Park and Gamble, "Reinforced Concrete Slabs", were modified to allow for a gap between wall and rigid support for non-solid components, such as ungrouted CMU. The resulting resistance function is shown in Figure 6.

Figure 6. Arching Resistance-Deflection Curve for Unreinforced Masonry Wall with Gap Between Wall and Rigid Support



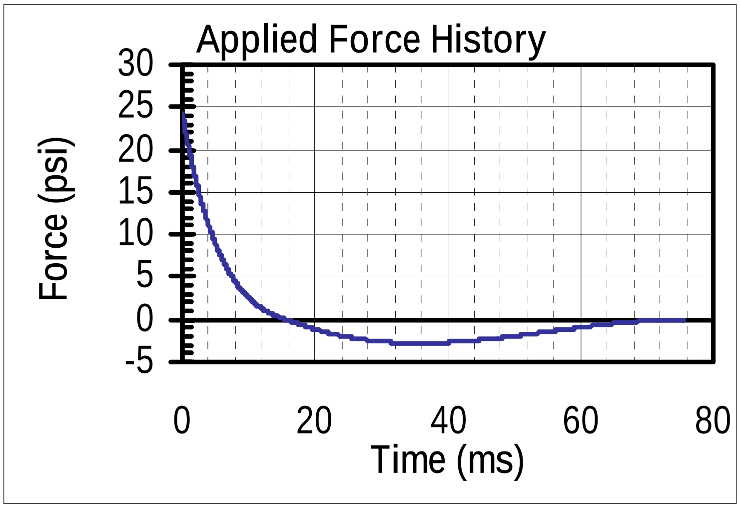
Loading

The user has three options for inputting the load used to drive the SDOF system. The user can directly enter up to 8 pressure-time pairs into the workbook to represent a piecewise-linear load. SBEDS can also read a file with up to 2000 pressure-time pairs where each line contains one pair, comma separated, per line. This file format is consistent with the ASCII file option in DPLOT. In the third option the user specifies a TNT equivalent charge weight and standoff distance and SBEDS calculates the pressure history for a hemispherical surface burst.

When the charge weight-standoff distance option is used, the user can elect to use either side-on or fully reflected pressure history and also elect to use both positive and negative phases (Figure 7) or positive phase only. Peak pressures and impulses for positive and negative phases are calculated from curve-fits to Figures 5-6 and 5-7 of UFC 3-340-01. The shape of the positive phase blast load is based on the exponential decay equation used in ConWep, Equation 1. The shape of the negative blast pressure history is from the DM 2.08, "Blast Resistant Structures", (Figure 8). This shape is used for both reflected and side-on loads, subject to the modification factor Cp- in Equation 2 that is required because the shape equation in Figure 8 does cause an impulse that is exactly equal to the impulse from Figure 5-7 of UFC 3-340-01. The calculated pressure histories are point-wise linear functions with 500 points each for the positive and negative phases.

For cases where axial load is applied with the lateral blast load, SBEDS can calculate an "equivalent" lateral P-Δ load (w_{equiv}) causing a moment distribution in the component similar to that caused by the P-Δ effect, where Δ is the midspan deflection at each time step and P is a constant input axial load. The moment distribution has a midspan moment equal to P(Δ)and no end moments at the ends of the span. Equation 3 is used to calculate w_{equiv}, at each time step and this load is added to the input applied load at the next time step. The w_{equiv} load vs. time is plotted separately in the output. This P-delta approach is approximate and it matches relatively well against limited static validation, but should be validated against dynamic finite element analyses. Table 3 shows a comparison of the equivalent lateral load method in SBEDS to theory where elastic, essentially static lateral loads were input in SBEDS with axial load.

Figure 7. Example of Positive and Negative Phase Loading



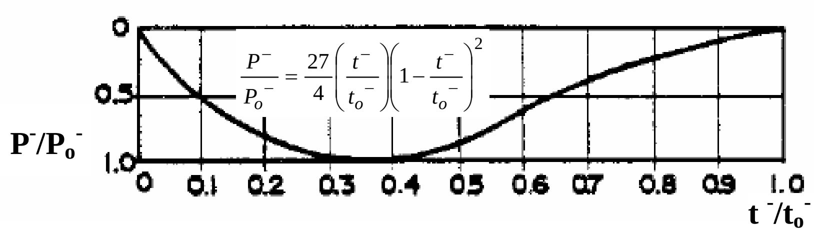
Equation 1. Positive Phase Pressure-Time Relationship

$$P(t) = P_{\max} \cdot (1 - t/t_o) \cdot e^{(-\alpha \cdot t/t_o)}$$

where:

- P(t) = pressure at time t after arrival
- P_{max} = peak pressure
- t_o = positive phase duration
- α = decay coefficient

Figure 8. Negative Wave Shape Used in SBEDS from DM 2.08



P^-_o = peak negative pressure

$t^-_o = 2*i^-/P^-_o$

i^- = negative phase impulse

Note: Used for reflected and side-on blast loads

Equation 2. Negative Phase Time Correction

$$t^- = t'^- * Cp^-$$

$$Cp^- = \frac{i^-}{i'^-}$$

where:

i'^- = impulse calculated with equation for negative pressure history in Figure 8
i^- = actual negative phase impulse from UFC 3-340-01 charts
t'^- = negative phase times after first negative pressure from equation for negative pressure history in Figure 8
t^- = corrected negative phase times used in SBEDS calculations

Equation 3. Equivalent P-Δ Lateral Load

$$w_{equiv} = W_F \Delta(t)$$

$$W_F = \frac{KP}{bL^2}$$

where:

w_{equiv} = equivalent lateral load with same spatial distribution as blast load causing P-Δ moments in component (added to applied blast load)
W_F = equivalent P-Δ load factor
K = 8 for component supported top and bottom
= 2 for a cantilever
L = span length (in direction of axial load for 2-way spanning components)
b = supported width of component loaded by blast
P = axial load
Δ(t) = displacement at each time step in SDOF calculations

Table 3. Calculated Deflections from SBEDS for W12x40 Beam-Column Compared to Theoretical Values (Moment Magnifier)

Boundary Condition	**Span (ft)**	**Effective Length (ft)**	**Calculated with SBEDS**	**Theoretical (Calculated with Moment Magnifier Method*)**	**SBEDS/Theoretical**
Fixed-Fixed	50	25	1.25	1.11	1.13
	40	20	1.16	1.02	1.14
	30	15	1.09	0.94	1.16
Fixed-Simple	50	35	1.46	1.45	1.01
	40	28	1.33	1.28	1.04
	30	21	1.19	1.13	1.05
Simple-Simple	50	50	1.81	1.78	1.02
	30	30	1.45	1.43	1.01
	15	15	1.11	1.11	1.00

*C_m=0.85 for fixed support, C_m=1.0 for simple support, C_m estimated as 0.93 for fixed simple support
Note: Static uniform lateral load in SBEDS was 50% of load causing first yield and axial load was 50% of axial load capacity in all cases above for W12x40 where weak axis had continuous lateral support.

Solution Scheme

SDOF calculations in SBEDS are performed using a constant velocity numerical integration scheme as generally recommended in EM 1110-345-415 "Principles of Dynamic Analysis and Design", and Biggs, "Structural Dynamics", to solve the SDOF equation of motion at each time step. The constant velocity method offers very stable solutions if small enough time step used. Based on numerous trials, this simple method is stable and accurate for a wide variety of resistance-deflection cases provided the time step is small enough, which is typically possible with the 2900 time steps in SBEDS. When checked against the SOLVER and WAC codes for numerous cases (27) with multiple yield and stiffness combinations, SBEDS results were generally within approximately 1%-2%. The constant velocity method has also been validated against finite element calculations performed by BakerRisk in Table 4.

Table 4. Comparison of Constant Velocity Methodology to Higher Order Analysis

Analysis Description	**Response Range**	**SDOF Model**		**ADINA Model**		**Percent Difference**
		Maximum Displacement (in)	**Time of Max. Displacement (msec)**	**Maximum Displacement (in)**	**Time of Max. Displacement (msec)**	
Rectangular Beam	μ=3	5.507	35	5.232	33	5.0
	μ=10	17.17	51	15.19	47	11.5
	μ=20	33.73	65	28.58	58	15.3
	μ=20	26.11 SDOF based on Z	55	28.58	58	-9.5
I-Shaped Beam (W8x24)	Elastic	2.297	23	2.250	24	2.0
	μ=2	5.962	29	5.853	29	1.8
	μ=10	29.81	51	26.26	47	11.9
	μ=20	59.55	66	49.98	58	16.1

SBEDS offers a recommended time step based on the minimum of the parameters listed in Table 5. SBEDS will also accommodate initial velocities, dampening, and will calculate dynamic shear history when user inputs appropriate constants.

Table 5. Recommended Time-Step Factors

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)

SBEDS Structure

The SBEDS distribution consists of the five files listed in Table 6. All user input and results reporting is in the SBEDS.XLS workbook. SBEDS.xls consists of the nine sheets discussed in Table 7. An example of member input, for a steel beam or beam column, is shown in Figure 9. SBEDS make extensive use of dropdown menus to ease input. A list of inputs where dropdown menus are used is included in Table 8. All drop-downs automatically insert properties of selected size/type into spreadsheet. Dropdowns for material properties and members have a user-defined option that allows for modeling of non-library materials and members. All input and output can be in a prescribed set of English or Metric units.

Table 6. SBEDS Files

FILE	DESCRIPTION
SBEDS.xls	Workbook where user inputs required parameters, calculations are performed, and results are reported. See Table 7 for file structure.
SBEDS_templates.xls	Contains the input templates for the various components and general SDOF options. When a component is selected in SBEDS.xls, the appropriate template is copied from this file.
SDOFLicense.dll	A dynamic link library requiring registration with the PDC.
SBEDS_Help.pdf	Contains guidance on specific input items in SBEDS along with information on methodologies employed in SBEDS.
READ_ME_1ST.pdf	Contains important information on configuring Excel to run SBEDS and information on registration of SDOFLicense.dll.

Table 7. SBEDS.xls Sheets

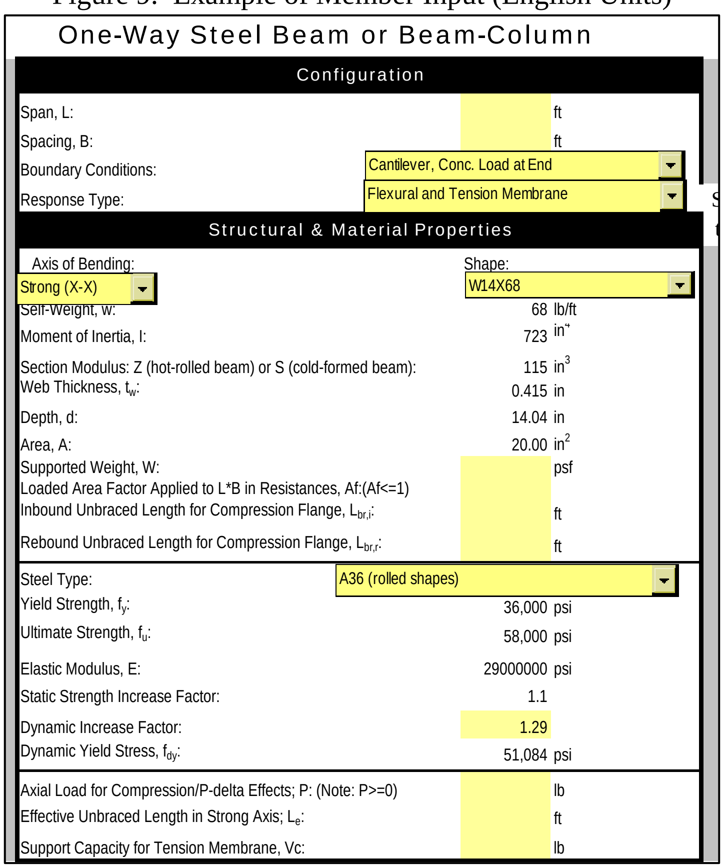
SHEET	FUNCTION
ReadMe	General administrative information
	Support information
Intro	Component selection
	Units selection
	Link to User's Guide for discussion of methodology and many of the inputs
	Workbook instructions
	Discussion of workbook design
Input	Separate component and units specific input sheets for each component
	Input sheets show all required input parameters and calculated resistance-deflection relationship
	Applicable input sheet pulled into main SBEDS workbook by macro from separate workbook (SBEDS_templates.xls)
	Reports calculated equivalent SDOF system, maximum response parameters, results of shear capacity check
	Model can be saved/recalled from this sheet
Results	Maximum response parameters
	Response histories (deflection, resistance, equivalent P-Δ, dynamic shear) and resistance vs. displacement
SDOF (hidden)	Equivalent SDOF system
	Time-stepping SDOF solution
Database	Properties of library members
	SDOF constants
PositivePhased Load (hidden)	Positive phase blast parameters
NegativePhase Load (hidden)	Negative phase blast parameters

Table 8. Dropdown Menus

Subject	Dropdown Options
Support conditions	Variety of one-way and two-way support conditions with uniform load and concentrated midspan load depending on component type
Response mode	Flexure, tension membrane, and compression membrane depending on component type
Steel beam cross section input	AISC and cold-formed girts/purlins sizes
Open web steel joist size and strength input	K and LH series
Masonry type	Brick, European block, and Heavy-Medium-Lightweight CMU
Corrugated metal panel	Various MBCI and Vulcraft deck type including traditional corrugated steel deck and standing-seam deck
Steel material properties	Typical steel plate, beam, and rebar material properties

Figure 10 shows the detailed results presented on the Results sheet in SBEDS. The response maximums and minimums are presented along with the response histories for displacement, applied force resistance, equivalent P-Δ lateral load (for input axial load acting with lateral blast load), dynamic shear, and resistance-displacement. Figure 11 shows results summary from the Input sheet in SBEDS for a reinforced concrete slab. Response maximums and minimums, reactions, shear capacity, and warning messages are provided. Required stirrups are calculated for reinforced concrete and masonry elements when shear capacity is not sufficient. Figure 10 and Figure 11 show input and output in the English unit system. Corresponding input and output templates are provided in the Metric unit system based on the user selected unit system.

Figure 9. Example of Member Input (English Units)


One-Way Steel Beam or Beam-Column

Configuration		
Span, L:		ft
Spacing, B:		ft
Boundary Conditions:	Cantilever, Conc. Load at End	
Response Type:	Flexural and Tension Membrane	

Structural & Material Properties		
Axis of Bending: Strong (X-X)	Shape: W14X68	
Self-Weight, w:	68	lb/ft
Moment of Inertia, I:	723	in^4
Section Modulus: Z (hot-rolled beam) or S (cold-formed beam):	115	in^3
Web Thickness, t_w:	0.415	in
Depth, d:	14.04	in
Area, A:	20.00	in^2
Supported Weight, W:		psf
Loaded Area Factor Applied to L*B in Resistances, Af:(Af<=1)		
Inbound Unbraced Length for Compression Flange, $L_{br,i}$:		ft
Rebound Unbraced Length for Compression Flange, $L_{br,r}$:		ft
Steel Type:	A36 (rolled shapes)	
Yield Strength, f_y:	36,000	psi
Ultimate Strength, f_u:	58,000	psi
Elastic Modulus, E:	29000000	psi
Static Strength Increase Factor:	1.1	
Dynamic Increase Factor:	1.29	
Dynamic Yield Stress, f_{dy}:	51,084	psi
Axial Load for Compression/P-delta Effects; P: (Note: P>=0)		lb
Effective Unbraced Length in Strong Axis; L_e:		ft
Support Capacity for Tension Membrane, Vc:		lb

Figure 10. Example of Detailed Results

Results Summary

θ_{max} =	0.2	deg.		
μ =	0.96			
X_{max} =	0.31	in	at time =	10.05 msec
X_{min} =	-0.07	in	at time =	23.22 msec
R_{max} =	17.41	psi	at time =	10.05 msec
R_{min} =	-10.26	psi	at time =	23.22 msec

Reactions

Peak Dynamic Reactions		
$V_{max,Long}$ =	3.83	psi
$V_{max,Short}$ =	3.83	psi
Strain Rate to First Yield*		
For Steel	0.704	1/ sec
For Concrete	0.529	1/ sec

* First yield, or maximum response if no yield

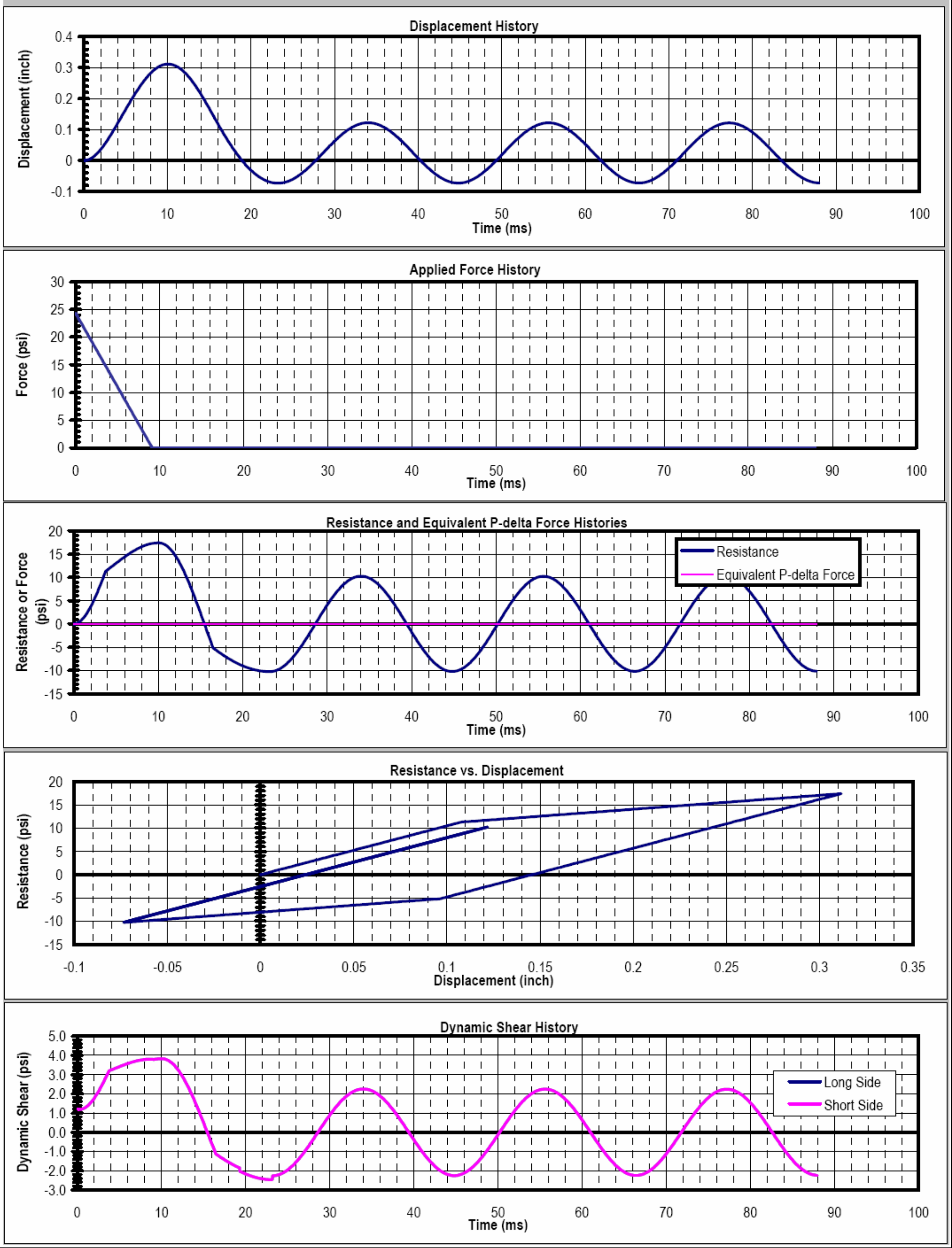
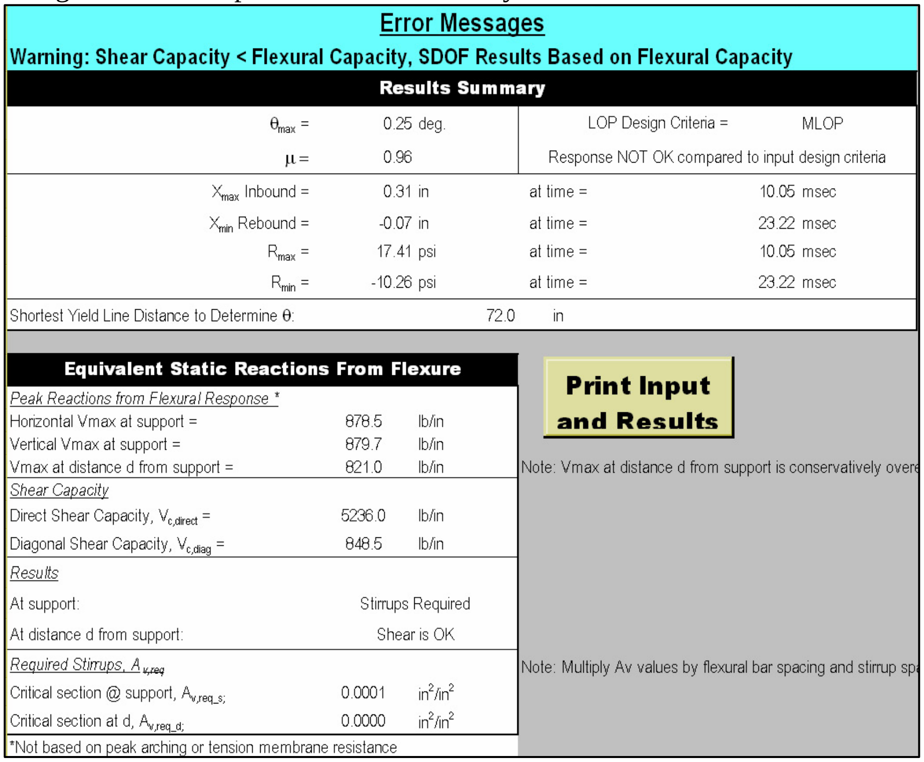


Figure 11. Example of Results Summary for Reinforced Concrete Slab



Distribution

SBEDS carries Distribution Statement A, Approved for public release; distribution is unlimited. SBEDS can be downloaded from the USACE Protective Design Center website: https://pdmcx.pecp1.nwo.usace.army.mil/software/sbeds/index.php. This site also provides links for user support.

References

"Blast Resistant Structures," Naval Facilities Engineering Command Design Manual 2.08, December, 1986.

ConWep, US Army Engineer Research & Development Center, May, 2003.

"Design and Analysis of Hardened Structures to Conventional Weapons Effects," DoD UFC 3-340-01 (FOUO), June 1, 2002.

"Design of Structures to Resist the Effects of Atomic Weapons - Principles of Dynamic Analysis and Design," Department of the Army Engineering Manual (EM) 1110-345-415, March, 1957

"DoD Minimum Antiterrorism Standards For Buildings," DoD UFC 4-010-01, October 8, 2003.

DPLOT, US Army Engineer Research & Development Center, May, 2001.

"Structural Dynamics," J.M. Biggs, 1964.

SOLVER, Naval Civil Engineering Laboratory, August, 1989.

"Structures to Resist the Effects of Accidental Explosions," Department of the Army Technical Manual TM 5-1300, Department of the Navy Publication NAVFAC P-397, Department of the Air Force Regulation AFR 88-22, Departments of the Army, the Navy and the Air Force, Revision 1, November 1990.

Wall Analysis Code (WAC), US Army Engineer Research & Development Center, July, 2003.