Incorporation of SBEDS Single-Degree-of-Freedom Analysis Methodology into VAPO

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Abstract

The capability to determine building component response and damage from blast loads using a single-degree-of-freedom (SDOF) analysis will be added to the VAPO (Vulnerability Assessment and Protection Option) V3.0 program. Applied Research Associates (ARA) and Protection Engineering Consultants (PEC) are integrating the SDOF analyses methodologies from SBEDS V3.1 (SDOF Blast Effects Design Spreadsheets) into VAPO for the Defense Threat Reduction Agency (DTRA). This will allow VAPO users to determine building component response to blast loads and damage more accurately than pressure-impulse (P-i) diagrams currently used in the program. SBEDS is a large spreadsheet that calculates properties for the equivalent single-degree-of-freedom (SDOF) model representing an input structural component and dynamic response to the blast load for twelve different component types. The maximum SDOF response is converted into an equivalent component support rotation and ductility ratio and compared against criteria from the U.S. Army Corps of Engineers Protective Design Center (PDC) to determine the component damage level in VAPO. The SBEDS spreadsheet was developed for, and is distributed by, the PDC.

Introduction

VAPO is a vulnerability assessment tool that allows for the rapid modeling of geo-referenced sites and facilities. These sites can be assessed for a variety of threats including high explosives, chemical, biological, and radiological bombs. The integration of SBEDS into VAPO will allow users to perform SDOF calculations on both entire facilities and specific structural components to determine component blast damage. Currently, VAPO uses P-i diagrams to determine component damage, which are fast-running but include inherent assumptions on the applied blast load shape and structural component response. The SDOF methodology allows the VAPO program to define the blast load and component response characteristics more specifically with a more accurate and detailed response output. VAPO V3.0 will allow users to analyze the response of designated building components with the SDOF-based analysis procedures in SBEDS. The maximum component deflection calculated with the SDOF analysis is converted to an equivalent ductility ratio and support rotation and compared to response criteria from the PDC (PDC-TR 06-08) to determine a component damage level, which is reported to the user.

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The SBEDS program has been developed by Baker Engineering and Risk Consultants for the PDC in a multi-year effort (Nebuda and Oswald, 2004). It is distributed by the PDC from their website with unlimited distribution. The foundations of SBEDS are its methods to calculate the dynamic properties for equivalent SDOF systems representing a wide variety of structural component types and response modes and an SDOF numerical integration scheme capable of analyzing a very general resistance function. It also has the capability to determine blast loads from surface burst explosion scenarios, including both positive and negative phase blast load, and to calculate a range of pressure-impulse (P-i) diagrams and charge weight-standoff (R-W) diagrams for the input component.

Blast Loads

VAPO uses the TNT Standard method to calculate blast loads from an explosion in free-air and non-linear shock pulse addition laws to add together blast load pulses at the point of interest from reflecting surfaces including the ground (Jerrett, et al, 2006). For building components with line-of-sight to the threat, the blast load is calculated at nine points on each component and averaged using a Gaussian integration scheme to get the overall blast load. For components that are incident to the threat, a single point is used to determine the blast load on the component. This blast load is used as the applied load in the SDOF analysis of component response. The VAPO airblast model captures physical airblast phenomena including reflection, diffraction, and internal airblast propagation. These phenomena are illustrated in Figure 1.

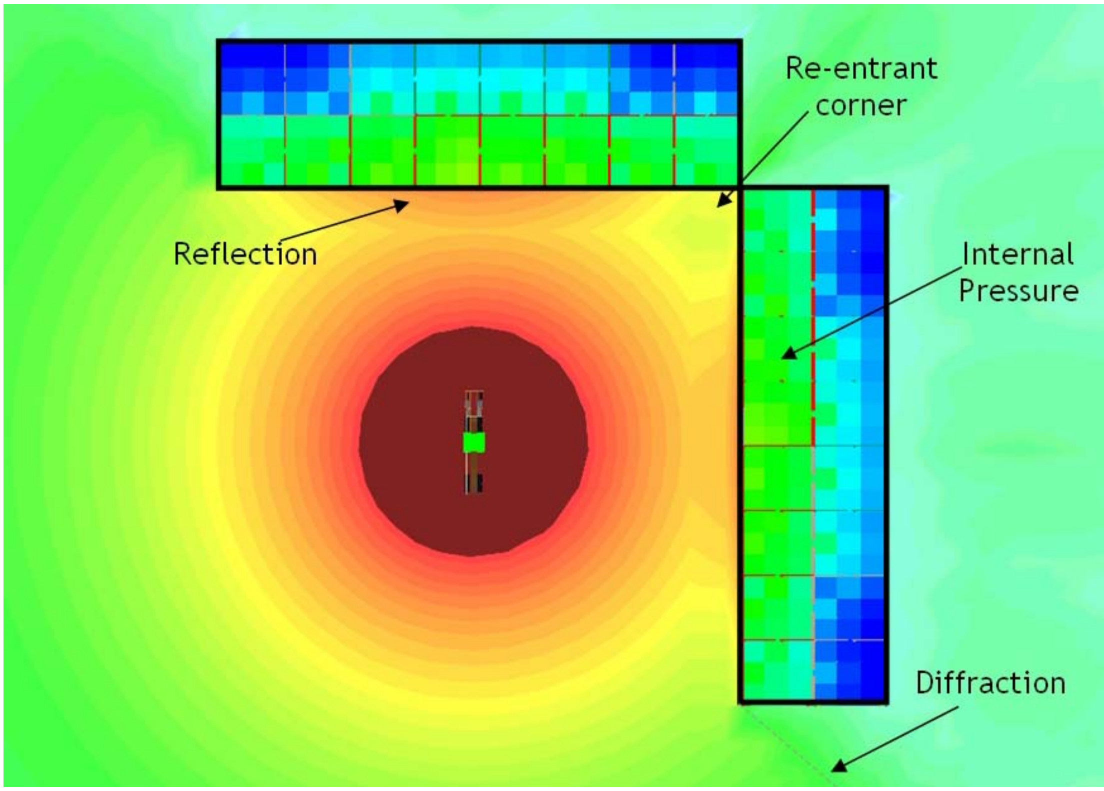

Figure 1. VAPO Airblast Model

Component Types

SBEDS determines the dynamic properties of equivalent SDOF systems for numerous common construction components. This is shown in Table 1. For each component a number of support and loading conditions can be considered, as indicated in Table 1. Table 2 shows the response modes that can be considered for each component. P-delta effects can also be included in the SDOF analysis for a number of the components. In this case, SBEDS calculates an equivalent lateral load at each time step causing approximately the same moment as an input constant compressive load acting with the deflection of the maximum component deflection at that time step. This lateral blast load is added to the applied blast load at the next time step. SBEDS also allows the user to directly define the properties of the equivalent SDOF system with a General SDOF input option. Detailed descriptions of the spreadsheet inputs and methodologies used to define the dynamic properties of the equivalent SDOF systems for each component type and response type are provided in the SBEDS Help document (PDC-TR 06-02) and SBEDS Methodology Manual (PDC-TR 06-01) distributed with the SBEDS spreadsheet. Capabilities from SBEDS that will be programmed into VAPO V3.0 are indicated in Table 1.

Response Modes

The primary component response mode assumed for SDOF analyses in VAPO is ductile flexural response, which represents the large majority of cases where conventional building components respond to blast load. 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) function is used. The parameters for these functions are based on the methodology found in TM 5-1300 (1990) and UFC 3-340-01 (2002). For unreinforced masonry, the brittle flexural response that accounts for axial load shown in Figure 3 is used. The initial resistances, r_1 and r_2 in Figure 3, represent flexural response.

Equation 1 shows the calculation procedure for the peak resistance from axial load, which acts after brittle flexural yielding at the maximum flexural resistance (r_2). This model is consistent with the methodology in the Wall Analysis Code (WAC, 2003). VAPO assumes that unreinforced masonry components have brittle flexural response with axial load arching for SDOF analyses.

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[2]		X	X
	One-Way Reinforced Masonry[2]		X	X
	One-Way Unreinforced Masonry[3]		X	X
	One-Way Wood Panel		X	
	One-Way Steel Beam or Beam-Column[2]	X	X	X
	One-Way Reinforced Concrete Beam or Beam-Column[2]	X	X	X
	One-Way Wood Beam or Beam-Column[2]	X	X	X
	Prestressed Concrete Beam or One-way Slab		X	
	Metal Stud Wall[2]	X	X	X
Four/Three/Two Adjacent Sides Supported – Fixed Four/Three/Two Adjacent Sides Supported – Simple Two Opposite Sides Fixed, Other Two Sides Simple	Two-Way Steel Plate		X	
	Two-Way Reinforced Concrete Slab[2]		X	X
	Two-Way Reinforced Masonry		X	X
	Two-Way Unreinforced Masonry		X	X
	Two-Way Prestressed Concrete Slab		X	
	Two-Way Wood Panel		X	
Simple-Simple	Open-Web Steel Joist[2]		X	
N/A	General SDOF System		X	X

Note 1: Concentrated load located at end of cantilever members, midspan for other support conditions.
Note 2: These component types can be analyzed as equivalent SDOF systems in VAPO for ductile flexural response to uniformly applied blast load.
Note 3: These component types can be analyzed as equivalent SDOF systems in VAPO for brittle flexural response with axial load arching with uniformly applied blast load.

Table 2. Available Response Modes

Component Types	Flexure[1,2]	Tension Membrane	Compression Membrane	Axial Load Arching[4]
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		X[3]	X
Wood Panel	X			
Wood Beam or Beam-Column	X			
Prestressed Concrete	X			
Metal Stud Wall	X	X		X (for masonry veneer)
General SDOF System	N/A, user directly inputs resistance function			

Note 1: Elastic, perfectly plastic flexural response. Flexural response available with combined tension and compression membrane response for designated component types.
Note 2: User optional shear-controlled flexural response (shear controls ultimate resistance) if calculated shear force exceeds calculated shear strength (N/A for open web steel joists)
Note 3: Includes effects of user input gap at top of wall
Note 4: Brittle flexure w/ axial load softening

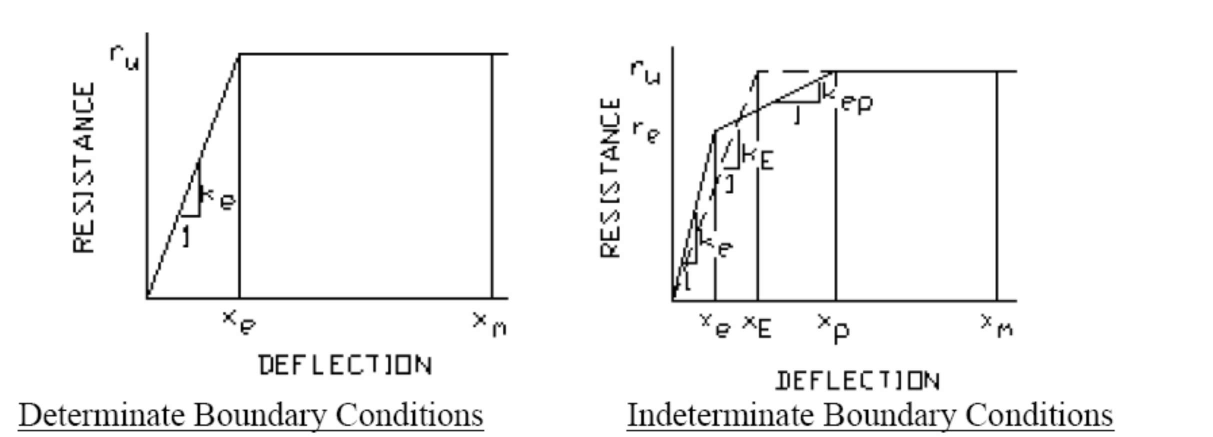

Figure 2. Resistance-Deflection Curve For Ductile Flexural Response

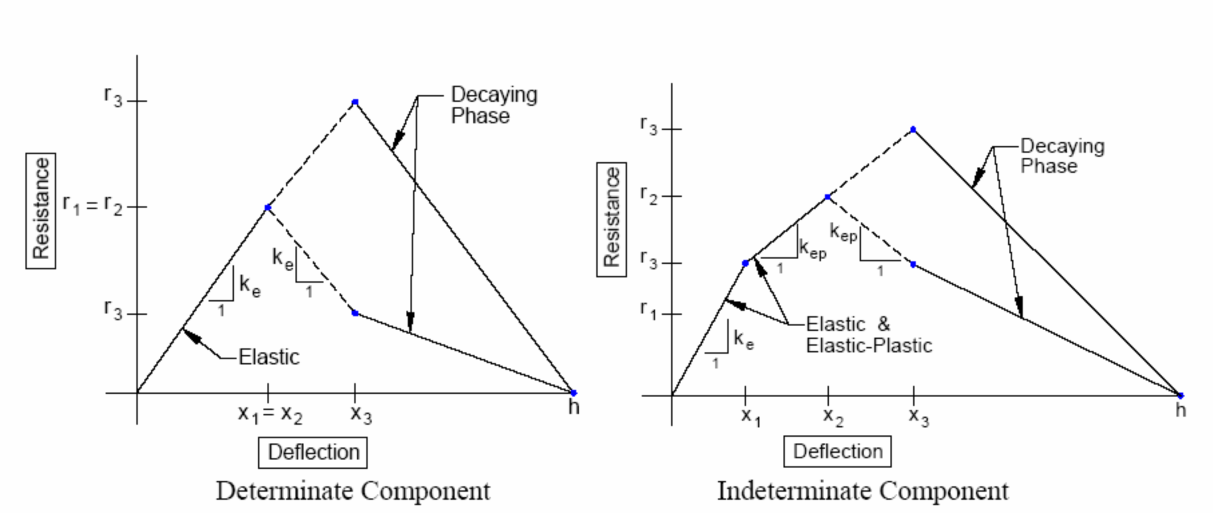

Figure 3. Resistance-Deflection Curves for Brittle Flexural Response and Axial Load

$$r_3 = \frac{8}{L^2}(h - x_2)\left(P + \frac{WL}{2}\right)$$

Equation 1

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_{axial}
W = areal self-weight and supported weight of wall
L = span length equal to wall height

Resistance-Deflection Function

SBEDS can determine the response of an equivalent SDOF system with a resistance function having up to five linear segments for initial inbound response and five linear segments for rebound. This scheme, which allows for perfectly plastic response and softening in either phase, is illustrated in Figure 4 for a general case with softening. The transition from one stiffness region to the next in SBEDS is based on the maximum or minimum resistance of the region (depending on the sign of the stiffness), except for regions with zero slopes. The transition in these regions is based on a maximum or minimum deflection. For elastic, perfectly plastic flexural response, this deflection is very large so that there is no upper bound transition. The complete resistance function is determined by SBEDS based on the component type and user specified information including the component response mode except for the General SDOF input option, where the user completely defines all the properties of the equivalent SDOF system.

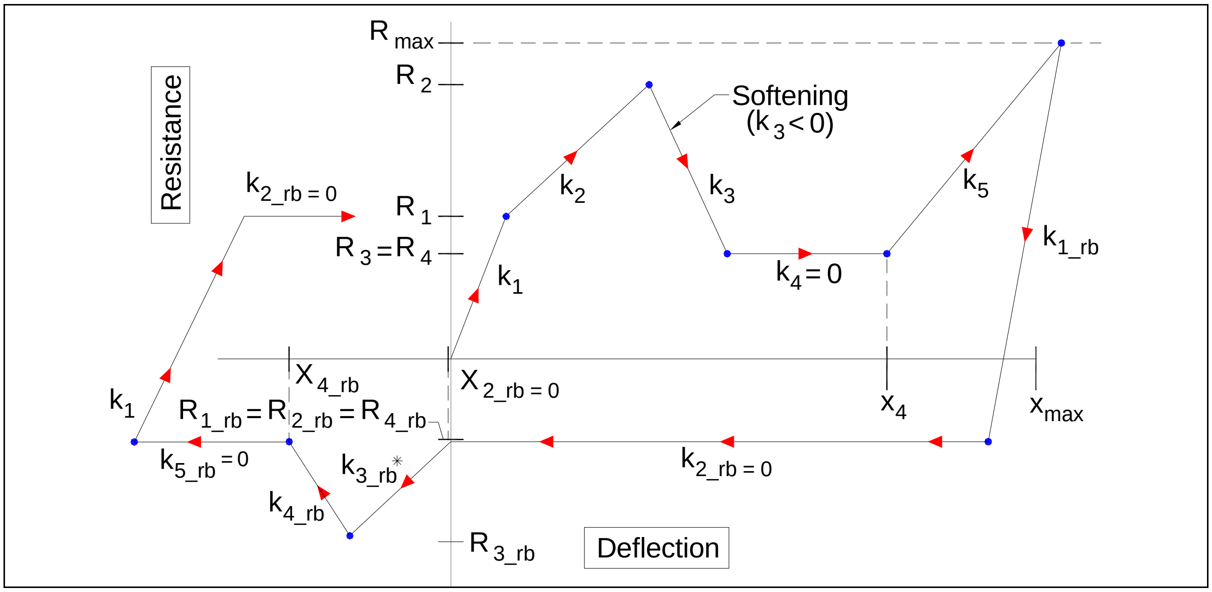

Figure 4. General Resistance-Deflection Diagram with Softening

The SBEDS resistance function has limited dependence on component type to the extent that it will check for flexural yielding of unreinforced masonry during initial response to blast load and, if this is the case, no flexural yielding will occur in rebound or subsequent inbound response. Also, compression membrane response during rebound can only begin after the component deflection becomes negative. This is illustrated in Figure 4, where K_{3_rb} is the compression membrane slope during rebound that begins after the deflection becomes negative. Rebound response of different types of structural components to blast load has not been studied experimentally or theoretically to anywhere near the extent of initial inbound response. This is due in large part because maximum component response to blast load almost always occurs during the first inbound response. The rebound response and inbound response after first rebound that are calculated in the SBEDS methodology are based on a number of assumptions related to the resistance-deflection diagram that are explained elsewhere (PDC-TR 06-01), (PDC-TR 06-02). These assumptions can all be overridden with a user defined resistance-deflection relationship in the General SDOF option of SBEDS. The VAPO dynamic link library is written to consider the general SBEDS resistance function, although VAPO V3.0 will only consider resistance functions for response modes as defined in Table 1.

SDOF Solution Scheme

The equation of motion for the equivalent SDOF system to the blast load is solved at each time step in SBEDS using a constant velocity numerical integration scheme, as generally recommended in EM 1110-345-415 “Principles of Dynamic Analysis and Design” and Biggs (1964). 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. This is based on comparisons against two other SDOF based computer programs and finite element calculations (Nebuda and Oswald, 2004). SBEDS results were generally within 1%-2% of comparable analyses with the SOLVER (NCEL, 1989) and Wall Analysis Code (WAC, 2003) for numerous cases (27) with multiple yield and stiffness combinations. It was within 15% of finite element analyses that modeled elastic and plastic response of beams with rectangular and I shaped cross sections. Most of this difference was due to the fact SBEDS does not explicitly model the gradual transition of the cross section from elastic to completely plastic stresses.

Summary

A methodology to determine blast damage of structural components based on SDOF analyses will be incorporated into VAPO V3.0. This will allow VAPO users to determine building component response to blast loads and damage more accurately than P-i diagrams currently used in the program. This methodology will be based on the SBEDS spreadsheet, which calculates properties for an equivalent SDOF model representing an input structural component and the dynamic response of the equivalent system to the blast load. Equivalent SDOF systems can be calculated for twelve different common structural component types. The maximum SDOF response is converted into an equivalent component support rotation and ductility ratio and compared against criteria from the PDC to determine the component damage level in VAPO. The SBEDS spreadsheet was developed for, and is distributed by, the PDC. A Methodology Manual and Help Manual are distributed with SBEDS, along with support rotation and ductility ratio criteria from the PDC to determine component damage levels and building levels of protection.

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