Use of SBEDS for Blast Resistant Design in accordance with UFC 3-340-02

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Abstract

The SBEDS workbook was developed by BakerRisk for the U.S. Army Corps of Engineers Protective Design Center as a tool to be used by structural design engineers to satisfy Department of Defense (DoD) antiterrorism standards. It is intended to be used by structural engineers experienced in structural dynamics and blast effects for designs in accordance with the "Minimum Antiterrorism Standards for Buildings (UFC 4-010-01).

SBEDS can also be used by structural engineers to analyze or design structures that are subject to accidental explosions at facilities housing explosives operations. This is a reasonable extension of the code's application, as dynamic analyses performed by both the explosion safety and antiterrorism community are based on Single-Degree-Of-Freedom (SDOF) methods. SBEDS is a very useful tool that not only performs the dynamic analysis, but also simplifies the user input by including a wide range of section and material properties, performing most of the calculations necessary to determine the required SDOF system properties (i.e., mass, stiffness, and resistance). However, there are differences between the methods defined in UFC 3-340-02 ("Structures to Resist the Effects of Accidental Explosions") for accidental explosion and those defined in UFC 3-340-01 ("Design and Analysis of Hardened Structures to Conventional Weapons Effects") for antiterrorism design. The major differences between these two design philosophies as related to the use of SBEDS will be discussed in this paper.

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14. ABSTRACT
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1.0   Introduction

SBEDS[1,2] is an Excel-based tool used to perform Single-Degree-of-Freedom (SDOF) dynamic analyses of structural components subjected to blast loads. It was developed for the U.S. Army Corps of Engineers Protective Design Center to meet Department of Defense (DoD) Antiterrorism standards.[3]

The Unified Facilities Criteria (UFC) 3-340-02,[4] (formerly known as the tri-service document[5] Army TM5-1300, Navy NAVFAC P-397, or Air Force AFR 88-22) presents methods of design for protective construction used in facilities for development, testing, production, storage, maintenance, modification, inspection, demilitarization, and disposal of explosive materials. A major portion of its contents deals with procedures to analyze structural components subjected to blast loads. This includes characterization of structural components as equivalent SDOF systems and evaluation of the response of SDOF systems.

SBEDS follows the same basic procedures that are presented in UFC 3-340-02, with some variations to better meet the requirements for antiterrorism standards. As a spreadsheet, it provides a very simple tool to solve the equation of motion to predict the dynamic response of structural components subjected to blast loads. It also provides a very user friendly "preprocessor" to allow the user to simply enter basic geometry and section information, and the program will determine the equivalent SDOF system parameters. However, in order to use SBEDS to meet the requirements of UFC 3-340-02, it is necessary to understand the differences between the procedures used in SBEDS and those specified in UFC 3-340-02.

In this paper, the major differences between the SBEDS and UFC3-340-02 methodologies will be highlighted. Although SBEDS has the capability to be used to analyze a wide range of component types, including masonry, wood, and prestressed concrete, and can consider various response modes, such as tension membrane, compression membrane, and brittle-flexural response (for masonry), the focus of this paper will be flexural response of normally reinforced concrete and steel components. It should be noted that this paper should not be considered to provide a validation of the program.

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[1] "User's Guide for the Single-Degree-of-Freedom Blast Effects Design Spreadsheets (SBEDS)," U.S. Army Corps of Engineers Protective Design Center Technical Report, PDC TR-06-02 Rev 1, September 2008.

[2] "Methodology Manual for the Single-Degree-of-Freedom Blast Effects Design Spreadsheets (SBEDS)," U.S. Army Corps of Engineers Protective Design Center Technical Report, PDC TR-06-01 Rev 1, September 2008.

[3] Design and Analysis of Hardened Structures to Conventional Weapons Effects," UFC 4-010-01, 1 June 2002.

[4] "Structures to Resist the Effects of Accidental Explosions," UFC 3-340-02 (TM5-1300), December 2008.

[5] "Structures to Resist the Effects of Accidental Explosions," U.S. Army Technical Manual TM5-1300, Department of the Navy Publication NAVFAC P-397, Department of the Air Force Manual AFM 88-22, November 1990.

2.0   Blast Loads

SBEDS allows for three means to enter blast load information:

- Manual Entry – using up to eight time-pressure pairs
- Data File – with up to 2,000 time-pressure pairs, consistent with DPLOT file
- Calculate pressure history for hemispherical surface burst

Analyses performed in accordance with UFC 3-340-02 will often use the manual entry. An external load, consisting of only a shock loading phase, will typically be entered as a triangular pulse, with an instantaneous rise to the peak pressure and a linear decay; this load function can be entered using two time-pressure pairs. An internal load, consisting of a shock and gas, or quasi-static loading phase, will require three time-pressure pairs to define a piecewise bilinear pressure time history.

For cases when BlastX[6] is used to predict blast loads, the data file input option can be used to read the time-pressure history file.

When the explosion source can be characterized as a hemispherical surface burst, SBEDS can calculate the blast loads applied to the structural component. Options are available to predict positive phase loads only or positive and negative phase loads. Reflection effects can be accounted for based on the angle of incidence. Clearing can also be considered.

Positive phase, side-on, pressure and impulses are calculated using the scaled curves from Figure 5-6 in UFC 3-340-01. Reflected pressures are calculated based on the angle of incidence, using Figure 5-3 in UFC 3-340-01. Reflected impulses are calculated in a similar way using Figure 2-194 in UFC 3-340-02. The positive phase impulses for reflected blast loads with clearing are calculated from input building wall dimensions based on Section 9.23.3 in UFC 3-340-01. This approach is generally consistent with UFC 3-340-02; note that the approach in SBEDS combines the effects of clearing with the negative phase loads, which is not specifically addressed in UFC 3-340-02.

Negative phase peak pressure and impulse on side-on and fully reflected blast loads are calculated from Figure 5-6 and Figure 5-7 in UFC 3-340-01. The shape is based on Figure 4 from the Navy Design Manual 2.08.[7] For angles of incidence less than 45 degrees, reflected loads are used; otherwise, side-on loads are used. If clearing is used and the clearing time occurs prior to the start of the negative phase, side-on loads are used for the negative phase. Note that UFC 3-340-02 does not provide guidance on the application of negative phase loads considering clearing and angle of incidence.

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[6] BlastX Version 6.4.2.2, developed by Science Applications International Corporation, sponsored by US Army Engineer Research and Development Center, Geotechnical and Structures Laboratory.

[7] "Blast Resistant Structures," Navy Design Manual DM2.08, 1 Dec 1986.

3.0   SDOF Analysis Routine

UFC 3-340-02 discusses two approaches for performing numerical integration to solve the equation of motion: the average acceleration method and the acceleration impulse extrapolation method. SBEDS uses the acceleration impulse extrapolation method, called the constant velocity method in the SBEDS Methodology Manual, which provides very accurate solutions when using small time steps as recommended.

When developing the equations of motion for the equivalent SDOF systems, transformation factors are used to determine the equivalent mass, stiffness, resistance, and load. The transformation factors, or the load factors, mass factors, and load-mass factors used in SBEDS are identical to those defined in UFC 3-340-02.

The dynamic reactions or support shears of blast loaded sections are a function of the applied load and the maximum resistance attained by an element, its geometry, and yield line location. However, UFC 3-340-02 notes that for short duration blast loads, the reactions can be reasonably estimated using only the resistance. The formulas provided in UFC 3-340-02 are based on static equilibrium.

While SBEDS has the ability to calculate dynamic reactions, the calculated maximum support shears are based on static equilibrium relationships, assuming that the maximum resistance is equal to the ultimate resistance, even if the predicted response is elastic. Thus, the support reactions calculated with SBEDS are consistent with UFC 3-340-02.

For reinforced concrete, the concrete shear stresses must also be checked. For most externally loaded structures, and for some internally loaded geometries, the critical section for concrete shear is at d from the support. Note that the user must determine which section is critical. The formulas used in SBEDS for 1-way sections match those provided in UFC 3-340-02. For 2-way sections, SBEDS uses a simplified, conservative approach to calculate the shears at d from the support, simply substituting (x-d) for x and (y-d) for y in the support shear formulas.

Finally, SBEDS is programmed with the response limits recommended by the Protective Design Center for Antiterrorism design. Since these limits differ from those specified in UFC 3-340-02, users must not rely on the response checks performed in SBEDS.

4.0   Equivalent SDOF Systems

Analysis of SDOF systems requires the definition of the resistance-deflection function for the structural component being analyzed. Figure 1 shows a typical resistance-deflection curve for a component with an elastic, elastic-plastic, and plastic response range. Although SBEDS generally follows the same approach as discussed in UFC 3-340-02, and the calculation in SBEDS for the resistance and stiffness for 1-way components (assuming flexural response) exactly matches the approach in UFC 3-340-02, there are a few differences for 2-way

components that must be considered. Note that the discussion in this paper only addresses flexural behavior, although SBEDS does have the capability to include other response modes.
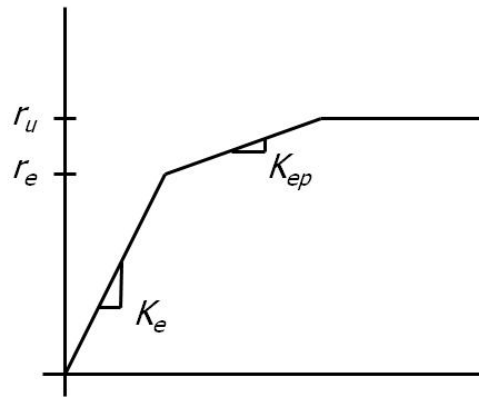

Figure 1. Resistance Deflection Curve

The ultimate resistance for 2-way components is calculated following the same basic procedure defined in UFC 3-340-02 that is based on yield line locations. However, the ultimate resistance is increased by 8% in SBEDS. The formulas in Table 3-2 in UFC 3-340-02, which are used to calculate the ultimate resistance, are based on an assumption that 2/3 of the moment capacity acts in the corners. The 8% increase was included in SBEDS based on studies[8] that indicated that these formulas give conservative estimates of the ultimate resistance by 6 to 10%.

The remaining differences in SBEDS are to simplify the resistance-deflection curve so that it can be defined with no more than two resistance and two stiffness values, as shown in Figure 1. For 2-way sections with fixed supports along three or four edges, the method in UFC 3-340-02 will require three or four resistance and stiffness values to define the resistance deflection curve. For example, see Figure 2, which is taken from Example 3A-2 in UFC 3-340-02.

For these cases, the initial stiffness is equal to the elastic stiffness from Figure 3-23 through Figure 3-38 in UFC 3-340-02. The elastic resistance is defined using the formulas in Table 10-5 of UFC 3-340-01. Since this table does not list values for sections with two adjacent edges supported and two edges free, the elastic resistance is assumed to be 60% of the ultimate resistance when the two supported edges are fixed. The elastic-plastic stiffness is set equal to the elastic stiffness for the same component, but with simple supports. If the component only has simple supports, the resistance-deflection curve will be characterized with a single resistance and stiffness value. Figure 3 shows example resistance-deflection curves comparing curves from SBEDS with a curve following the procedures in UFC 3-340-02. The parameters were taken from Example 3A-2 in UFC 3-340-02.

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[8] Morrison, C., "Dynamic Response of Walls and Slabs by Single-degree-of-freedom Analysis – A Critical Review and Revision," Intl. J. Imp. Engrg. 32 (2006) 1214-1247.
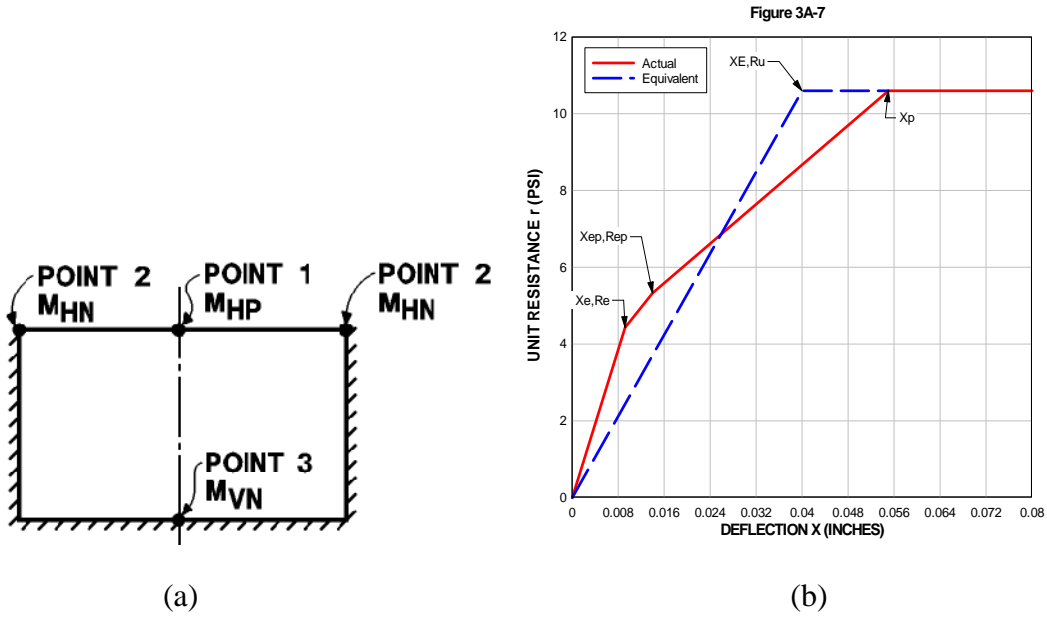
(a)   (b)
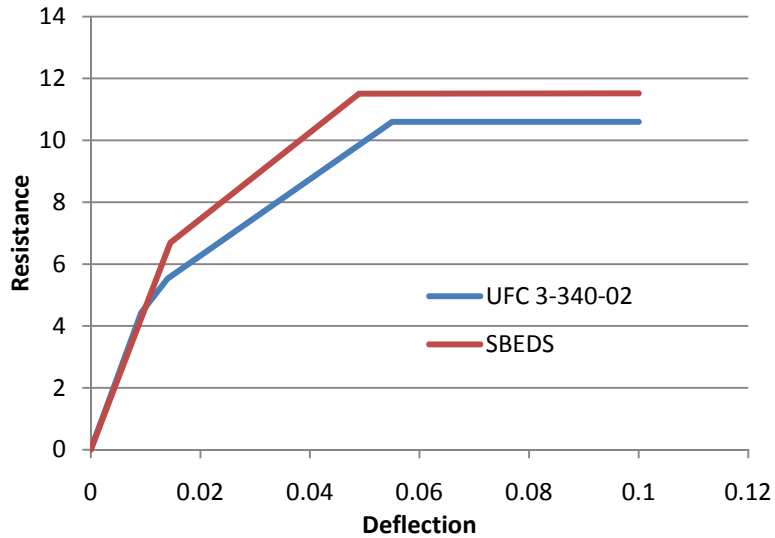
Figure 2. Resistance-Deflection Curve for 2-Way Section

Figure 3. Example Resistance-Deflection Curve comparing UFC 3-340-02 to SBEDS approach

5.0   Reinforced Concrete

Dynamic Material Strength

For reinforced concrete sections, the formulas in SBEDS to calculate the dynamic concrete and reinforcement strength are based on the approach in UFC 3-340-01, which differs from the

approach in UFC 3-340-02. Table 1 provides a comparison between the two approaches. It should be noted that if K_e and K_a are set to 1.0 for the dynamic concrete strength and 1.1 for the dynamic steel strength, and if the DIFs are set to the recommended values in UFC 3-340-02, the material strengths in SBEDS will match those calculated following the procedures in UFC 3-340-02.

UFC 3-340-02 allows the dynamic material strengths to be increased for larger deflections to account for strain hardening that could take place. This increased strength is calculated with a weighted average of the dynamic yield strength and the dynamic tensile strength. SBEDS does not have this type of procedure programmed. The user can manually modify the material strengths to make these adjustments in SBEDS.

Table 1. Dynamic Design Stresses

Item	SBEDS	UFC 3-340-02
Dynamic Concrete Strength	$f'_{dc} = f'_c K_e K_a (DIF)$ where f'_c minimum specified concrete compressive strength K_e static increase or average strength factor, typically 1.1 K_a concrete aging factor, conservatively 1.1 (DIF) dynamic increase factor	$f'_{dc} = f'_c (DIF)$ where f'_c minimum specified concrete compressive strength (DIF) dynamic increase factor For flexure, the recommended *DIF* is 1.19 and 1.25 for far range and close-in range, respectively.
Dynamic Reinforcement Strength	$f_{dy} = f_y K_e (DIF)$ where f_y minimum specified steel yield strength K_e static increase or average strength factor, typically 1.1 (DIF) dynamic increase factor	$f_{dy} = f_y (DIF)$ where f_y average steel yield strength (DIF) dynamic increase factor For flexure, the recommended *DIF* is 1.17 and 1.23 for far range and close-in range, respectively.

Moment capacity

SBEDS has the capacity to consider both Type 1 and Type 2 cross-sections when determining the moment capacity of a section. When the response of a section exceeds 2-degree support rotations, the section can automatically transition from a Type 1 to Type 2 section. This transition takes place from rotations of 2 to 2.2 degrees, allowing for a smooth transition in the moment capacity calculation. It should be noted that UFC 3-340-02 does not state how the transition from a Type 1 to Type 2 section should occur, but the approach used in SBEDS is considered a reasonable approach.

Diagonal Tension Shear Capacity

UFC 3-340-01 and UFC 3-340-02 also have different formulas for calculating the diagonal tension shear capacity of concrete. SBEDS uses a simplified, intermediate approach, as shown in Table 2. As indicated, UFC 3-340-02 recommends a *DIF* of 1.0 for diagonal tension shear.

Table 2. Diagonal Tension Shear Capacity Formulas

SBEDS	UFC 3-340-02
$v_c = \dfrac{\sqrt{f'_{dc}}}{6}$	$v_c = \begin{cases} 2(f'_{dc})^{0.5} \\ 1.9(f'_{dc})^{0.5} + 2500\rho \le 3.5(f'_{dc})^{0.5} \end{cases}$
where f'_{dc} dynamic concrete compressive strength used for flexure (MPa)	where f'_{dc} $f'_c(DIF)$ f'_c minimum specified concrete compressive strength (psi) (DIF) dynamic increase factor ρ reinforcement ratio For diagonal tension shear, the recommended *DIF* is 1.0.

For comparison, SBEDS will calculate a diagonal tension shear capacity of 139 psi for concrete with a minimum compressive strength of 4000 psi (27.6 MPa), assuming a *DIF* of 1.19 for far range design. Using the simple formula $(2(f'_{dc})^{0.5})$ in UFC 3-340-02 results in a diagonal tension shear capacity of 126 psi. Thus, SBEDS uses a capacity that is about 10% greater than the UFC 3-340-02 approach.

The above discussion ignores the effect of axial load on the shear capacity. For sections in tension, the diagonal tension capacity of the concrete is reduced, and for sections in compression, the diagonal tension capacity of the concrete is increased. SBEDS does not account for axial loads when calculating the shear capacity of the concrete.

Direct Shear Capacity

The formula used both in SBEDS and in UFC 3-340-02 for the concrete direct shear capacity are the same. However, UFC 3-340-02 states that the direct shear capacity is zero when the section is in net tension or if the support rotations exceed 2 degrees (for fixed supports only). When designing bays with internal explosions, the user must account for this requirement when determining the requirements for diagonals.

Other Considerations

- SBEDS has the capability to enter a static or dynamic axial load that is used to include P-Δ effects. P-Δ effects are not addressed in UFC 3-34-02; consideration of these effects in SBEDS will provide conservative results.

- SBEDS does not calculate the requirements for tension steel. When designing internally loaded bays, such as containment cells, the user must calculate these requirements separately.

- SBEDS only has the capacity to consider sections with fully fixed or fully simple supports. If the moment capacity varies at opposite supports, the effect on the resistance-deflection curve must be calculated independently.

- SBEDS does not have the ability to consider the effect of openings or reactions applied from doors or windows at openings.

6.0   Steel

This section discusses the similarities and differences in steel analysis and design in the UFC 3-340-02 and SBEDS. The UFC 3-340-02 methodology references the 1989 Manual of Steel Design ASD, Chapter N Plastic Design.[9] Where SBEDS differs from the UFC, the methodology references the 1999 AISC Manual of Steel Construction LRFD.[10] While the differences may appear significant, this section serves to show that the documents are quite similar. Plates, hot-rolled beams and beam-columns, open web steel joists, and cold-formed panels are discussed. Discussion of cold formed beams, doors, frames, fragment penetration, and tension membrane are outside the scope of this paper.

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[9] American Institute of Steel Construction. (1989). Steel Construction Manual.

[10] American Institute of Steel Construction. (1999). Steel Construction Manual.

Material Properties

Both UFC 3-340-02 and SBEDS recommend the same dynamic increase factors and strength increase factors for steel analysis and design.

Plates

The flexural capacity calculation of plates is based on the same equations in UFC 3-340-02 Section 5-28. The moment capacity is determined based on the average of the elastic and plastic section modulus. However, UFC 3-340-02 recommends a reduction of the moment capacity due to end shear reactions. According to the SBEDS Methodology Report,[2] the reduction is not used in SBEDS because "it rarely applies for structural plates." A graph of the factor as a function of the ratio of the shear reaction to the shear capacity is presented in Figure 4. The same reduction factor is cited in the UFC 3-340-02 for beams with a rectangular cross section or built-up beams. As an example, consider a ¼-inch thick, simply supported steel plate subjected to a blast load that results in a 2° support rotation. The V/V_p ratio of 0.016 correlates to a reduction factor of about 1. Similarly, a simply supported steel beam subjected to a blast load that resulted in a 3° support rotation has a V/V_p ratio of 0.03, which correlates to a reduction factor of about 1. Thus, the simplification in SBEDS is considered reasonable for most cases.
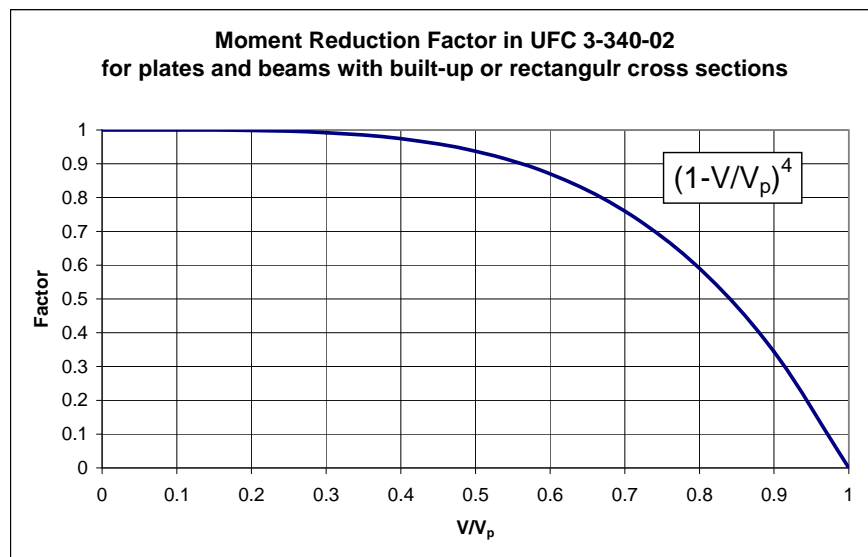

Figure 4. Moment Reduction Factor as a Function of Shear

Hot-Rolled Beams

The flexural capacity calculation of beams in UFC 3-340-02 Section 5-20.3 differentiates between the elastic and the plastic modes of behavior. If the member ductility, μ, is less than or equal to 3, which is essentially in the region between elastic and fully plastic, then the moment capacity is calculated similar to plates where the section modulus is taken as the average of the elastic and plastic section modulus. When $\mu > 3$, in the plastic realm, the moment capacity is

calculated using the plastic section modulus. However in SBEDS, the moment capacity is always calculated with the plastic section modulus. Although there may be cases where beams are designed with μ < 3, the difference in moment capacity is about 7% for typical hot-rolled beams.

UFC 3-340-02 provides bracing requirements depending on the response level for both the inbound and rebound directions. More stringent criteria are provided for μ > 3, when more significant plastic deformation occurs. SBEDS uses the same unbraced length limits formulas in both the inbound and rebound direction, but allows the user to input different unbraced lengths in inbound and rebound. The SBEDS approach is more conservative.

SBEDS and UFC 3-340-02 have minor differences to account for shear in hot-rolled sections. Generally, the allowable shear stress is given by $f_{dv} = 0.55f_{ds}$. For I-shaped beams, UFC 3-340-02 uses this formula with no adjustments to the allowable flexural stresses. However, as previously mentioned, in beams with rectangular cross sections or built-up beams, the shear may reduce the moment capacity similar to plates. Since this effect is typically small, SBEDS ignores the possible moment capacity reduction. SBEDS also performs slenderness checks to reduce the shear capacity of sections with large h/t ratios. UFC 3-340-02 only requires these checks for cold-formed sections. The approach in SBEDS is conservative.

Beam-Columns
The capacity of beam-columns with combined axial and bending loads is determined with the same two interaction diagram equations for yielding/max strength and stability/column slenderness in both UFC 3-340-02 Section 5-37.3 and SBEDS.

To assess the axial capacity, the UFC 3-340-02 uses the ASD equations while SBEDS uses the LRFD equations. The equations are essentially the same with a slight difference in non-slender columns, which are most commonly used in blast design. In the 2005 AISC, the ASD and LRFD methods are essentially the same with formulas adjusted for consistency.[11] The slight difference in the two methods is shown in Figure 5. The 2005 ASD solid line is analogous to the LRFD method. The effective length factor, K is the same in both documents.

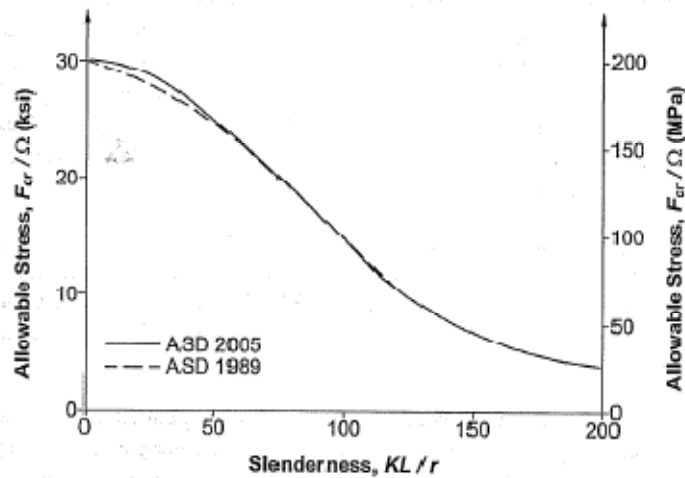[11] American Institute of Steel Construction. (2005). Steel Construction Manual.

Figure 5. Comparison of Axial Capacity Calculation Methods used in the UFC and the PDC[11]

Open Web Steel Joists

SBEDS calculates the inbound capacity of open web steel joists following the approach used in UFC 3-340-02 Section 5-33. However the rebound capacity is determined differently. In UFC 3-340-02, the inbound capacity is different than the rebound capacity. In rebound, the UFC specifies that the lower chord must be checked as a column or beam column while the top chord must be checked as a tension member. In SBEDS, the same methodology is used to calculate both the inbound and rebound response, citing that the unaccounted-for tension membrane response would make up for any reduction in capacity in rebound, based on test observations.[12]

Cold-Formed Panels

Both the flexural and shear capacity of cold-formed panels is based on the same equations in both UFC 3-340-02 Section 5-34 and SBEDS. However, to account for web crippling, the UFC specifies an additional limitation for support reactions in "sections that provide a high degree of restraint against rotation of their webs," which SBEDS does not include.

7.0   Conclusions

The overall analysis approach used in SBEDS is generally consistent with the requirements in UFC 3-340-02. However, there are differences that could impact the design requirements. Users of SBEDS must carefully review SBEDS results to ensure that they are complying with the requirements of the UFC, and if necessary, provide supplementary calculations.

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[12] Coltarp, D.R., Simmons, L., and Bogosian, D.D., "Blast Response Evaluation of a Lightweight Steel Roof," Proceedings of the 9th International Symposium on Interaction of the Effects of Munitions with Structures, Berlin-Strausberg, Federal Republic of Germany, May, 1999.

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By

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BAKERRISK

Introduction

- SBEDS
  - Excel-based program
  - Perform dynamic SDOF analysis of blast loaded components
  - Developed for US Army COE PDC to meet DoD antiterrorism standards
  - Approved for public release, distribution is unlimited
- UFC 3-340-02 (formerly TM5-1300)
  - Provides guidance for the design of protective construction for explosives safety
  - Structural response heavily based on SDOF methods

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Objective of Paper and Presentation

▶ Answer this question:

- When using SBEDS to support an analysis or design to meet UFC 3-340-02 requirements, what are the major methodology differences in SBEDS that could lead to unconservative results?

▶ This is not a validation of SBEDS
▶ The focus includes only flexural response of concrete and steel sections

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Blast Loads

- Input Options
  - Manual Entry
  - Data File – Consistent with DPLOT ASCII file output
  - Calculate load for hemispherical surface burst
- Calculated loads are derived generally following procedures in UFC 3-340-02
  - Exponential load shape is used for cases without clearing
    - Positive phase uses curve shape in CONWEP
    - Negative phase uses curve shape from DM2.08

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Blast Loads

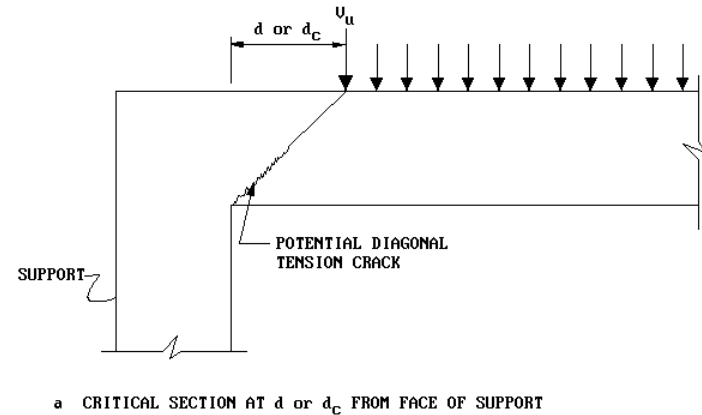- Positive Phase Only
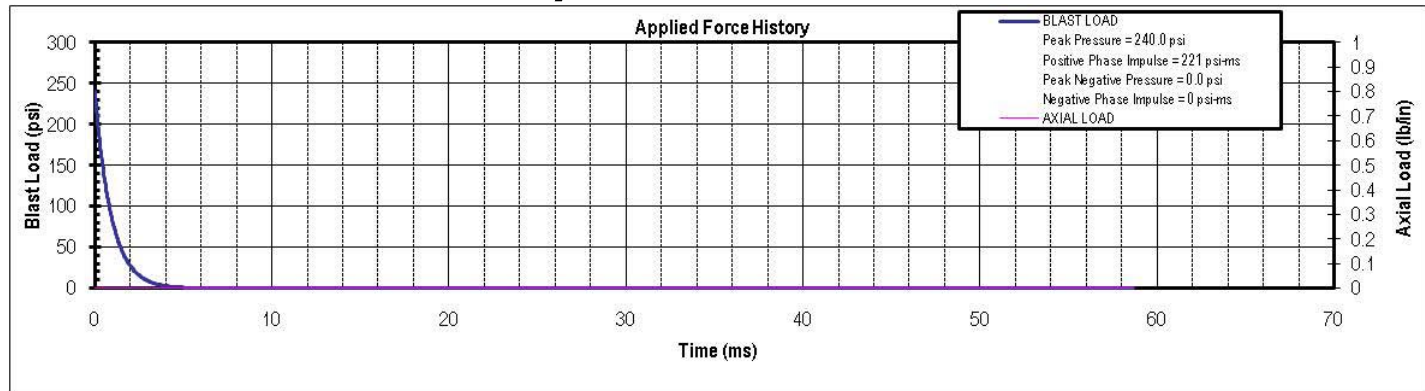
- Positive and Negative Phase

Blast Loads

▶ With Clearing

Applied Force History

BLAST LOAD
Peak Pressure = 28.0 psi
Positive Phase Impulse = 343 psi-ms
Peak Negative Pressure = -1.7 psi
Negative Phase Impulse = -218 psi-ms
AXIAL LOAD
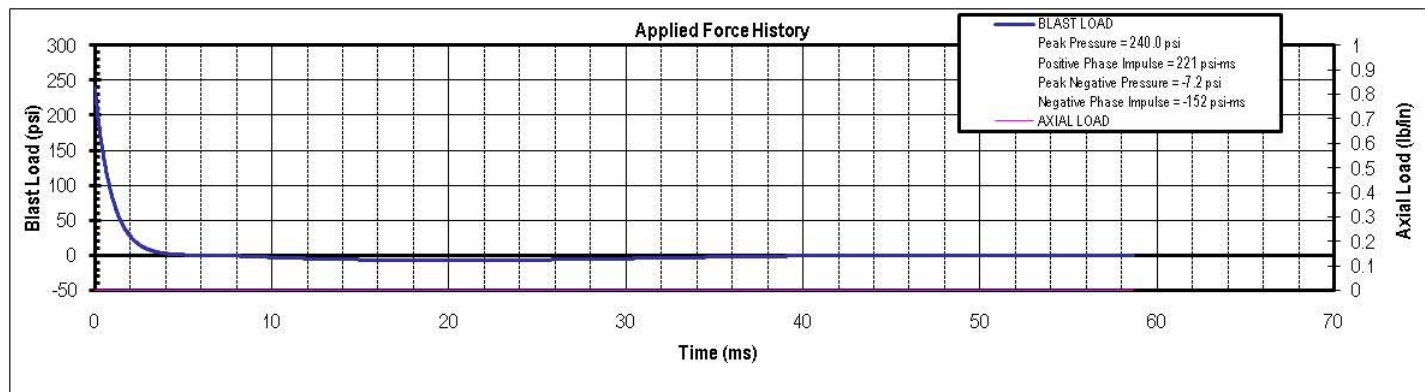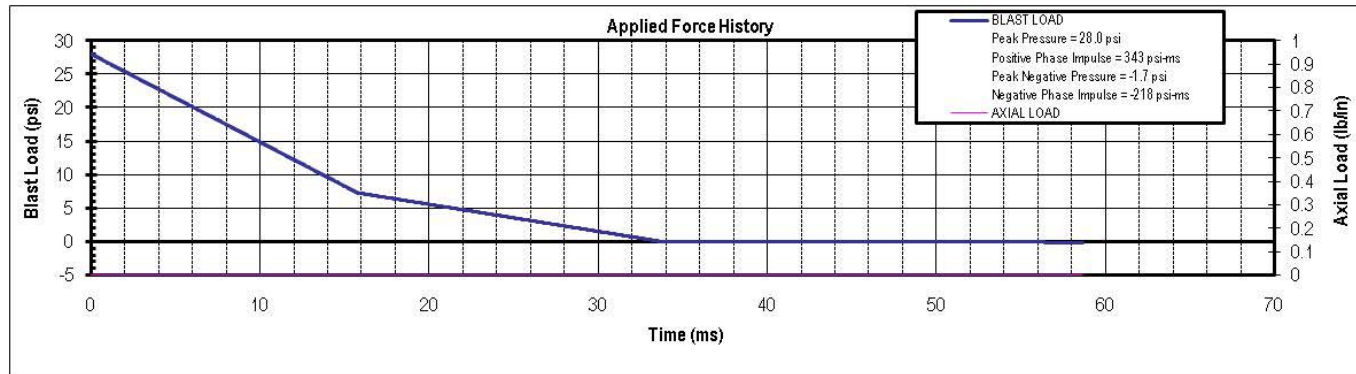
Calculated Reactions

- Two approaches in SBEDS
  - Dynamic reactions
  - Based on static equilibrium
- UFC 3-340-02 states that for short duration blast loads, the reactions can be reasonably estimated using only the resistance treated statically
- When SBEDS determines reactions based on static equilibrium, the ultimate resistance is used, not the maximum resistance
  - This approach is conservative for flexural response

Diagonal Tension Shear

- Concrete shear stress must be checked in reinforced concrete
- If critical section is at d from support:
  - For 1-way sections, SBEDS matches UFC 3-340-02
  - For 2-way sections, SBEDS uses a simplified, conservative approach
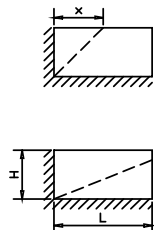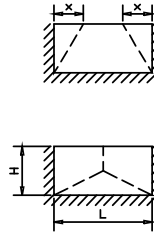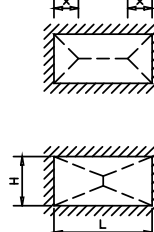
Figure 4-14. Location of critical sections for diagonal tension

a   CRITICAL SECTION AT d or d_c FROM FACE OF SUPPORT

POTENTIAL DIAGONAL TENSION CRACK

d or d_c

V_u

SUPPORT

POTENTIAL DIAGONAL TENSION CRACK

SUPPORT

V_u

b. CRITICAL SECTION AT FACE OF SUPPORT
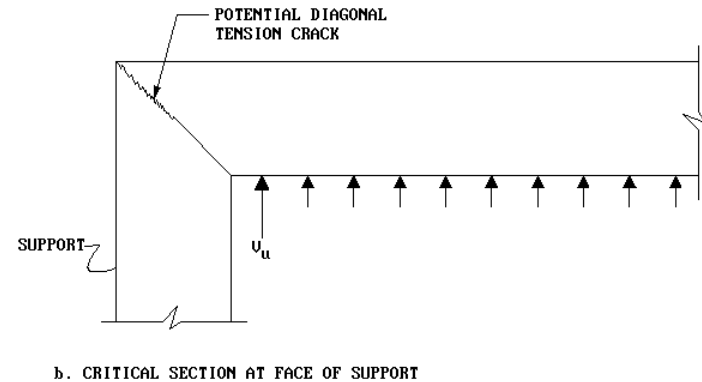
Diagonal Tension Shear

- SBEDS conservative simplification for 2-way
  ◦ Substitute (x–d) for x
  ◦ Substitute (y–d) for y

Table 3-10   Ultimate Support Shears for Two-Way Elements (Symmetrical Yield Lines)

Edge Conditions	Yield Line Locations	Limits	Horizontal shear, V_{sH}	Vertical shear, V_{sV}
Two adjacent edges supported and two edges free		$x \leq L$	$\dfrac{3r_u x}{5}$	$\dfrac{3r_u H(2-\frac{x}{L})}{(6-\frac{x}{L})}$
		$y \leq H$	$\dfrac{3r_u L(2-\frac{y}{H})}{(6-\frac{y}{H})}$	$\dfrac{3r_u y}{5}$
Three edges supported and one edge free		$x \leq \frac{L}{2}$	$\dfrac{3r_u x}{5}$	$\dfrac{3r_u H(1-\frac{x}{L})}{(3-\frac{x}{L})}$
		$y \leq H$	$\dfrac{3r_u L(2-\frac{y}{H})}{2(6-\frac{y}{H})}$	$\dfrac{3r_u y}{5}$
Four edges supported		$x \leq \frac{L}{2}$	$\dfrac{3r_u x}{5}$	$\dfrac{3r_u H(1-\frac{x}{L})}{2(3-\frac{x}{L})}$
		$y \leq \frac{H}{2}$	$\dfrac{3r_u L(1-\frac{y}{H})}{2(3-\frac{y}{H})}$	$\dfrac{3r_u y}{5}$

Response Limits

- SBEDS
  - From PDC–TR 06–08
  - Based on Level of Protection (LOP)
- UFC 3–340–02
  - Based on protection category
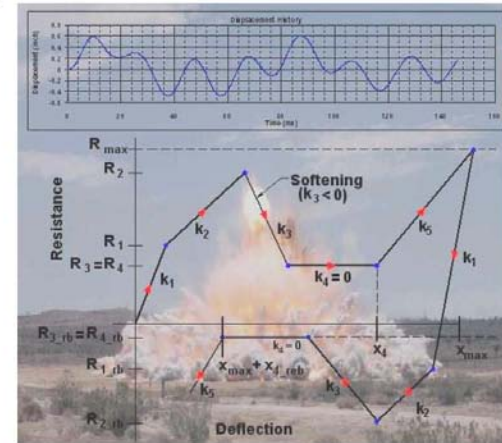 - Generally more conservative than antiterrorism standards

PDC-TR 06-08
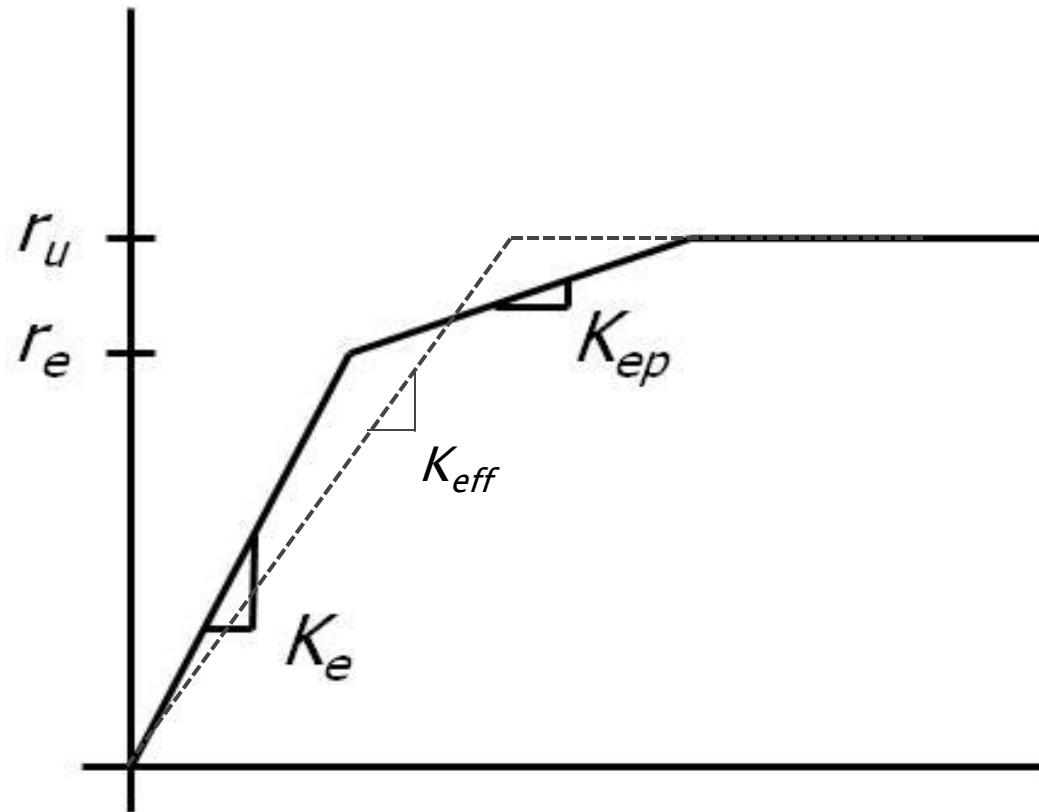20 October 2006

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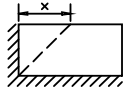**Single Degree of Freedom Structural Response Limits for Antiterrorism Design**
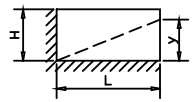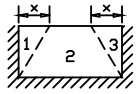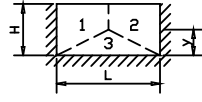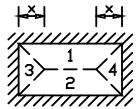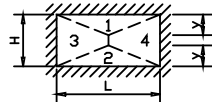
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Typical Resistance Deflection Curve

Resistance–Deflection Curve

- **1-way components**
  - SBEDS matches UFC 3-340-02
- **2-way components**
  - Ultimate Resistance
    - Follows procedure in UFC 3-340-02 based on yield line locations
    - Increase r_u by 8% based on study by Morrison

| Edge Conditions	Yield Line Locations	Limits	Ultimate Unit Resistance
Two adjacent edges supported and two edges free		$x \leq L$	$\dfrac{5(M_{HN}+M_{HP})}{x^2}$ OR $\dfrac{6LM_{VN}+(5M_{VP}-M_{VN})x}{H^2(3L-2x)}$
		$y \leq H$	$\dfrac{5(M_{VN}+M_{VP})}{y^2}$ OR $\dfrac{6HM_{HN}+(5M_{HP}-M_{HN})y}{L^2(3H-2y)}$
Three edges supported and one edge free		$x \leq \dfrac{L}{2}$	$\dfrac{5(M_{HN}+M_{HP})}{x^2}$ OR $\dfrac{2M_{VN}(3L-x)+10xM_{VP}}{H^2(3L-4x)}$
		$y \leq H$	$\dfrac{5(M_{VN}+M_{VP})}{y^2}$ OR $\dfrac{4(M_{HN}+M_{HP})(6H-y)}{L^2(3H-2y)}$
Four edges supported		$x \leq \dfrac{L}{2}$	$\dfrac{5(M_{HN}+M_{HP})}{x^2}$ OR $\dfrac{8(M_{VN}+M_{VP})(3L-x)}{H^2(3L-4x)}$
		$y \leq \dfrac{H}{2}$	$\dfrac{5(M_{VN}+M_{VP})}{y^2}$ OR $\dfrac{8(M_{HN}+M_{HP})(3H-y)}{L^2(3H-4y)}$

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Resistance–Deflection Curve

◦ 2-way components (cont)

- Elastic Resistance
- Determine stiffness from curves in UFC 3-340-02 to formation of 1st yield line

$$K_e = \frac{r}{X} = \frac{D}{\gamma H^4}$$

$$D = \frac{EI}{1 - v^2}$$

Figure 3-33. Moment and deflection coefficients for uniformly-loaded, two-way elements with all edges fixed.
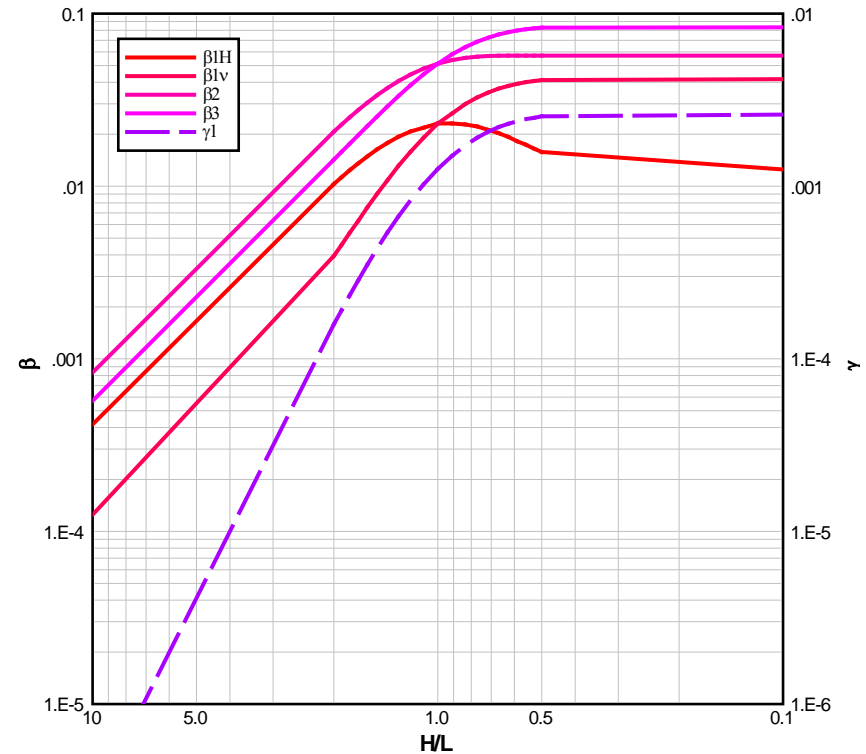
Resistance-Deflection Curve

- 2-way components (cont)
  - Elastic Resistance
    - From formulas in Table 10-5 in UFC 3-340-01
  - Elastic-Plastic Stiffness
    - Similar to elastic stiffness
    - Use curves assuming all supports are simple

- Example
  - Compare SBEDS results to Example 3A-2 in UFC 3-340-02

Chart: Resistance (y-axis, 0 to 14) vs Deflection (x-axis, 0 to 0.12). Two curves shown: UFC 3-340-02 and SBEDS.

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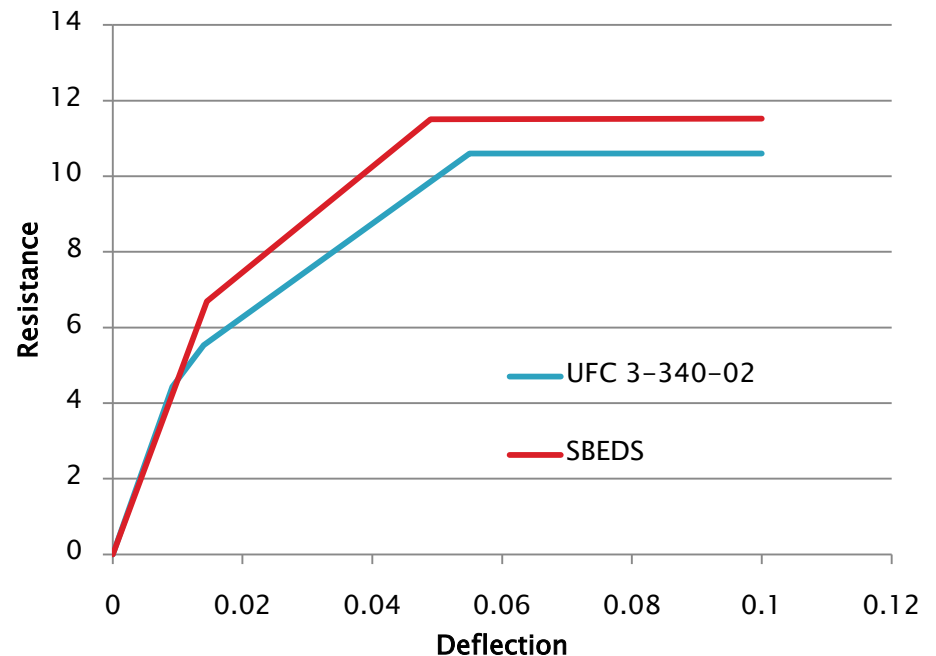
Dynamic Concrete Strength

SBEDS	UFC 3-340-02
$$f'_{dc} = f'_c \cdot K_e \cdot K_a \cdot (DIF)$$ where f'_c minimum specified concrete compressive strength K_e static increase, or average strength factor, typically 1.1 K_a concrete aging factor, conservatively 1.1 *DIF* Dynamic Increase Factor	$$f'_{dc} = f'_c \cdot (DIF)$$ where f'_c minimum specified concrete compressive strength *DIF* Dynamic Increase Factor For flexure, the recommended DIF is 1.19 and 1.25 for far range and close-in range, respectively.

Dynamic Reinforcement Strength

SBEDS	UFC 3-340-02
$$f_{dy} = f_y \cdot K_e \cdot (DIF)$$ where	$$f_{dy} = f_y \cdot (DIF)$$ where
$f_y{'}$ minimum specified steel yield strength	f_y average steel yield strength
K_e static increase, or average strength factor, typically 1.1	(66 ksi for 60 ksi rebar)
DIF Dynamic Increase Factor	*DIF* Dynamic Increase Factor
	For flexure, the recommended DIF is 1.17 and 1.23 for far range and close-in range, respectively.

Reinforced Concrete Moment Capacity

▸ SBEDS can determine moment capacity assuming section is either a Type I or Type II cross-section

▸ Transition is assumed to take place between support rotations of 2 degrees and 2.2 degrees

Resistance vs Deflection

Reinforced Concrete Diagonal Tension Shear Capacity

SBEDS	UFC 3-340-02
$v_c = \dfrac{\sqrt{f'_{dc}}}{6}$ where $f_{dc}{}'$ dynamic concrete compressive strength used for flexure (Mpa)	$v_c = \begin{cases} 2 \cdot \sqrt{f'_{dc}} \\ 1.9 \cdot \sqrt{f'_{dc}} + 2500 \cdot \rho \le 3.5 \cdot \sqrt{f'_{dc}} \end{cases}$ where $f'_{dc} = f'_c \cdot (DIF)$ $f_c{}'$ minimum specified concrete compressive strength (psi) *DIF* Dynamic Increase Factor ρ reinforcement ratio For diagonal tension shear, the recommended DIF is 1.0

For 4000 psi concrete, SBEDS gives a shear strength of 139 psi, while UFC 3-340-02 gives 126 psi

Reinforced Concrete Direct Shear Capacity

▸ Both SBEDS and UFC 3-340-02 use the same formula for the concrete direct shear capacity

$$V_d = 0.16 f'_{dc} bd$$

▸ However,

◦ UFC 3-340-02 states that $V_d = 0$ if the section is in net tension or if the support rotation exceeds 2 degrees

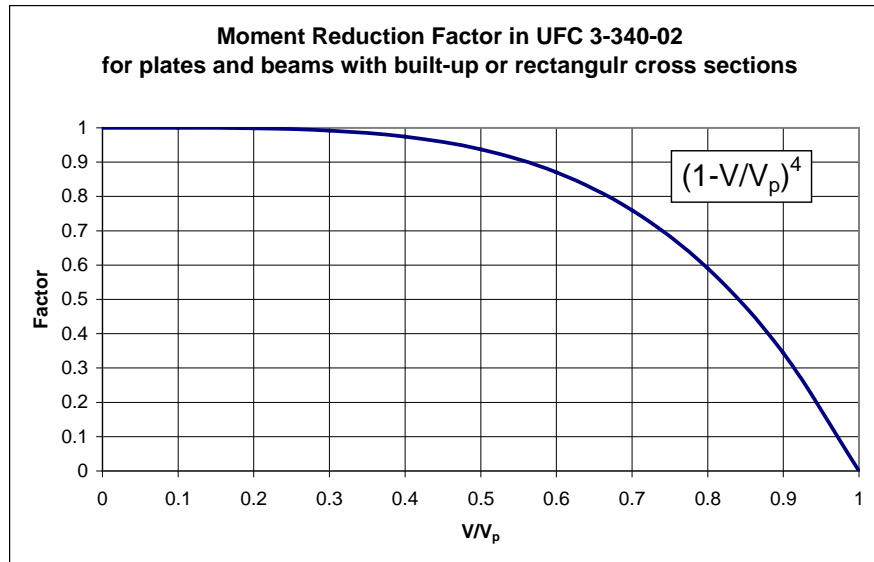◦ User must account for this when determining the need for diagonals

BakerRisk

Reinforced Concrete
Other Consderations

- SBEDS can include P-Δ Effects
  - Static
  - Dynamic
- User must evaluate Tension Steel requirements
- SBEDS cannot consider sections with different moment capacities at opposite ends.
- SBEDS does not have ability to assess effects from openings or reactions applied at openings (from doors or windows).

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Steel Plates

- Moment Capacity Reduction Due to Shear
  - UFC 3-340-02 includes a reduction factor
  - SBEDS does not include factor in code

Moment Reduction Factor in UFC 3-340-02 for plates and beams with built-up or rectangulr cross sections

$(1-V/V_p)^4$

  - Example: ¼" plate, 2° support rotation, $V/V_p=0.016$, reduction factor=1

Steel Beams

- Moment Capacity
  - μ≤3
    - UFC 3-340-02: $M = \dfrac{S+Z}{2} \cdot f_{dy}$
    - SBEDS: $M = Z \cdot f_{dy}$
    - For typical hot-rolled beams, difference of about 7%
  - Bracing Requirements
    - UFC provides different requirements depending on response realm and in inbound and rebound
      - More stringent requirements in plastic realm when μ>3
    - SBEDS uses same requirements inbound and rebound, user can input different lengths in inbound and rebound
   - More conservative

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Steel Beams

- Shear

$$f_{dv} = 0.55 \cdot f_{ds}$$

   ◦ Effect of shear stresses on moment capacity
     - UFC 3-340-02
       - I-beams: Does not reduce moment capacity based on shear stress
       - Rectangular beams or built-up beams, shear reduces moment capacity with factor, similar to plates
     - SBEDS
       - Does not reduce moment capacity
       - As noted for plates, this effect is small

   ◦ Shear capacity of slender sections
     - SBEDS performs slenderness checks for all sections to reduce shear capacity of sections with large h/t ratios
     - UFC 3-340-02 only performs these checks for cold-formed sections
     - SBEDS is conservative

Steel Beam-Columns

- UFC 3-340-02 and SBEDS use same Interaction Diagram Equations
- Axial Capacity
  - UFC: 1989 AISC ASD equations
  - SBEDS: 1999 AISC LRFD equations
  - Slight difference at low values of KL/r (non-slender), 2005 AISC
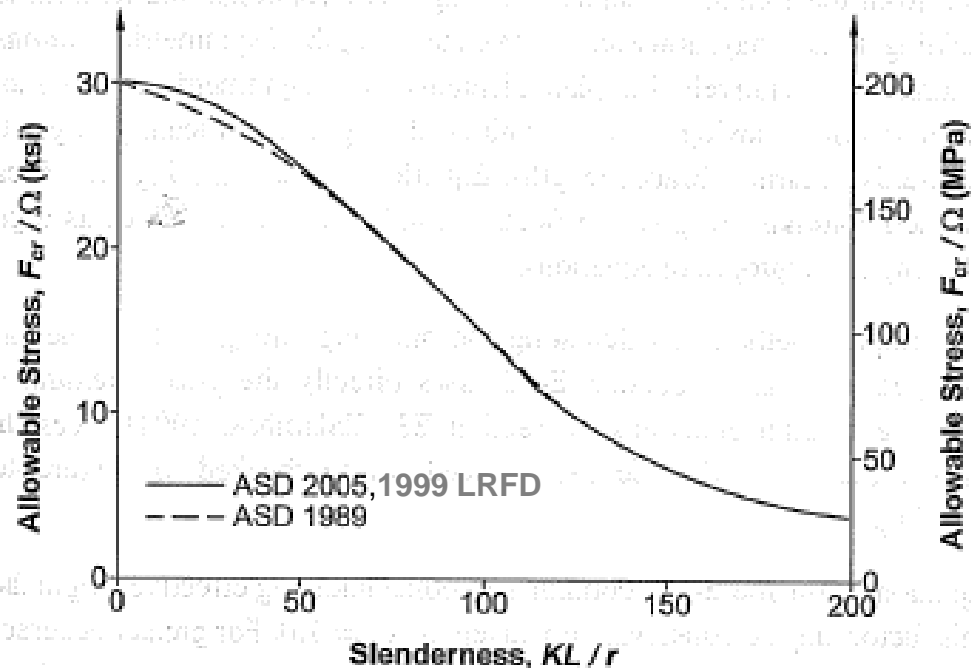
Conclusions

- Generally, SBEDS is consistent with UFC 3-340-02
  - But there are differences that could impact the design
- Users may be required to provide supplementary calculations to address differences between SBEDS and UFC 3-340-02