SBEDS as a Tool for Computation of Blast Response for Explosives Safety

David Rodriguez, P.E. and Chuck Oswald, Ph.D., P.E.
Baker Engineering and Risk Consultants, Inc.

Abstract

The governing design code for explosive safety design UFC 3-340-02, Structures to Resist the Effects of Accidental Explosions, presents methods of design for protective construction used in government and commercial explosive facilities. The UFC 3-340-02 provides a comprehensive methodology that includes analysis charts for elasto-plastic dynamic response and charts and tables to determine properties for Single-Degree-of-Freedom (SDOF) systems representing flexural response of one-way reinforced concrete (RC) elements and two-way RC slabs. The design methodology for two-way RC slabs requires 32 charts and 4 tables to calculate SDOF properties and shear demands.

Using these charts and tables for "hand" calculations is a requirement for calculation submittals to verify that an explosive safety design complies with UFC 3-340-02; however, performing these hand calculations is inefficient and prone to human error that can potentially affect an entire design.

The Single-Degree-of-Freedom Blast Effects Design Spreadsheets (SBEDS) V5.1 distributed by the U.S. Army Corps of Engineers Protective Design Center (USACE PDC), and previous versions, use a simplified method to calculate SDOF properties for two-way spanning components with flexural response including the response of shear forces at the supports. The SBEDS V6.2 software distributed by the USACE PDC includes an option to select the "Simplified UFC 3-340-02 Design Methodology" that fully complies with the UFC 3-340-02 methodology for two-way RC slabs but is much quicker to perform, as it automates the calculation of SDOF properties for both one-way and two-way RC slabs in accordance with UFC 3-340-02.

This paper will discuss a parametric analysis that provides Independent Verification and Validation (IV&V) of the SBEDS V6.2 software for compliance of one-way and two-way RC slabs SDOF property calculations and dynamic analysis. This IV&V includes the calculation of shear forces at both the supports and at a distance "d" from those supports. This parametric IV&V intends to demonstrate that the SBEDS V6.2 with the "Simplified UFC 3-340-02 Design Methodology" option complies with UFC 3-340-02 and therefore can be utilized in explosive safety design to provide consistent, efficient, and cost-effective designs.

Introduction

Explosive safety design in U.S. Department of Defense facilities requires analysis and design to comply with UFC 3-340-02 [1]. High explosives, typically produced at specialized manufacturing facilities, generate impulsive blast loads that are characterized by high peak shock pressures followed by short duration quasistatic gas pressures. Reinforced concrete (RC) is often the preferred construction material for high explosive design applications due to its inherent mass, which provides inertial resistance, and the ductility of its steel reinforcement. Together, these properties make RC an efficient and resilient choice for structures that are designed to resist high explosive blast loads.

Accordingly, this paper presents a parametric Independent Verification and Validation (IV&V) of the one-way and two-way RC slab component implementation in SBEDS V6.2 [2] distributed by the U.S. Army Corps of Engineers Protective Design Center (USACE PDC). The IV&V analysis focuses on the "Simplified UFC 3-340-02 Design Methodology" option, which is derived from and compliant with UFC 3-340-02. An Excel-based spreadsheet, termed UFC Method Spreadsheet (UMS), was developed based on review of UFC 3-340-02 to compare independently calculated SDOF properties and dynamic analysis results from UMS against SBEDS V6.2. The spreadsheet directly incorporates all the applicable equations and curve-fits for all graphs directly taken from the Dplot curves of UFC 3-340-02.

Analysis Approach

The analysis approach was structured into two phases, the SDOF Properties phase and SDOF Analysis phase. During the first phase, SDOF properties of both the one-way and two-way RC components were compared between the independently developed UMS spreadsheet and SBEDS V6.2. For the second phase, SDOF dynamic analysis was performed for only the two-way RC components, and the SDOF results were then compared between UMS and SBEDS V6.2.

The intent of the IV&V was to focus only on the SDOF properties and SDOF response associated with Protection Category 1 – Personnel Protection (i.e., displacements less than 2 degrees support rotation.)

RC Components

The RC component matrix used for both phases of the parametric IV&V is provided in Appendix Table 1. Two-way and one-way RC components included in the analysis are Component IDs C01 through C11a, and C12 through C15, respectively.

The variables assessed in the two-way RC components included boundary conditions, aspect ratio of the horizontal and vertical spans, material strengths, and steel reinforcement layout. For the two-way RC components, most of the steel reinforcement analyzed was symmetric (i.e., there was equal reinforcement on each face of the component); however, RC Component IDs C10 through C11a deviated with negative moment steel reinforcement approximately twice as large as the positive moment steel reinforcement. Parametric analysis for the one-way RC components assessed the boundary condition, span, material strengths, and steel reinforcement layout.

Calculation of SDOF Properties

The SDOF properties calculated with UMS and SBEDS V6.2, where the UMS properties were calculated as explained in this section, were initially directly compared, and then used in comparable SDOF analyses that had the same blast loads as explained later in this paper. Gross moment of inertia and ultimate moment capacities were calculated using the independent UMS spreadsheet following UFC 3-340-02 Sections 4-15 and 4-17, respectively.

UMS spreadsheet and SBEDS V6.2 both utilized the cracked moment of inertia equation provided in PDC-TR 06-02 Rev 4 [3]. The equation for the cracked moment of inertia, commonly presented in undergraduate RC design textbooks [4], is derived from first principles of equilibrium and compatibility. This equation calculates both the cracked neutral axis location, from the extreme compression fiber, and the corresponding moment of inertia. This is a deviation from UFC 3-340-02 which uses the simplified chart lookup for the cracked moment of inertia shown in Figure 1.

Equation for the cracked neutral axis with compression steel:

$$n = \frac{E_s}{E_c} \tag{1}$$

$$B = \frac{b}{nA_s} \tag{2}$$

$$r = (n-1)A'_s/(nA_s) \tag{3}$$

$$kd = \frac{\left[\sqrt{2dB\left(1+\frac{rd'}{d}\right)+(1+r)^2}-(1+r)\right]}{B} \tag{4}$$

Equation for the cracked moment of inertia at the calculated cracked neutral axis:

$$\frac{bk^3d^3}{3} + nA_s(d-kd)^2 + (n-1)A'_s(kd-d')^2 \tag{5}$$

Where:

- A_s = Area of tension steel reinforcement
- A'_s = Area of compression steel reinforcement
- B = Spacing of flexural steel reinforcement at cross-section
- d = Distance to centroid of tension steel reinforcement measured from extreme compression fiber
- d′ = Distance to centroid of compression steel reinforcement measured from extreme compression fiber
- E_s = Steel reinforcement modulus of elasticity
- E_c = Concrete modulus of elasticity

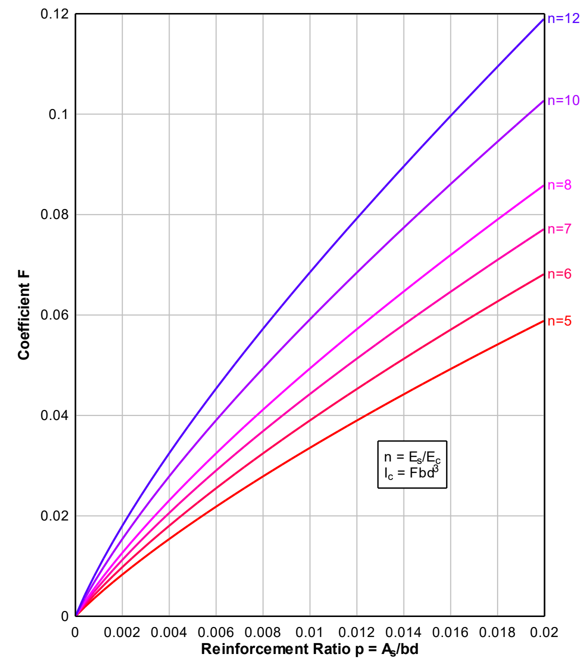

Figure 1. Coefficient for moment of inertia of cracked sections with equal reinforcement on opposite faces (UFC 3-340-02)

The first principles approach and the UFC 3-340-02 chart method yielded identical results when the modular ratio, *n*, corresponded to the discrete curve values specified in UFC 3-340-02 (e.g., 5, 6, 7, etc.) For values of *n* falling between these curves, interpolation required in the UFC 3-340-02 chart method introduced deviations, in the calculated cracked moment of inertia, of up to 2%. Since the average moment of inertia used for stiffness calculations is the average of the gross and cracked moments of inertia, deviations in the average moment of inertia are up to 1% when interpolating between the discrete *n* curves. Overall, a deviation in the average moment of inertia up to 1% is considered negligible.

Elastic and elasto-plastic stiffness and resistance values in the UMS spreadsheet were calculated using the methodologies outlined in UFC 3-340-02, Sections 3-12 and 3-13, respectively. Instead of using the tables and charts provided in UFC 3-340-02 for ultimate resistance calculations, values were derived from first principles, specifically virtual work and equilibrium, as described in UFC 3-340-02 Section 3-9.3. Shear reactions at supports and at distance *d* from the supports were calculated in accordance with UFC 3-340-02 Sections 3-15 and 4-27.2, respectively. Finally, load-mass factors were computed as prescribed in UFC 3-340-02 Section 3-17.3.

Blast Loads for Phase 2 (SDOF Analysis)

Blast loads were varied for the SDOF analyses of each Component Id in Table 1 to limit the maximum response to 2 degrees support rotation (i.e., Protection Category 1.) All blast loads had shapes relevant to explosive safety analysis and design. Identical blast loads were applied in comparable SDOF analysis with UMS and SBEDS V6.2.

Appendix Table 2 presents the two load scenarios developed for comparable SDOF analysis. Load ID L01 corresponds to the Test 02 configuration from the Internal Blast Test Series [5][6]. In this test that was part of a test program funded by the DoD Explosive Safety Board (DDESB), the front wall functioned as a frangible venting surface covered with a light-gauge metal panel, while all other surfaces were rigid. Load ID L02 features a similar setup to Load ID L01, but with half the charge weight. This reduced configuration allowed for the weaker two-way components to remain under the intended 2-degree support rotation.

Shock pressure loading for both Load IDS was calculated using SHOCK V2 [7]. To evaluate the influence of load shape, gas pressures were calculated using both the FRANG computer program [8] and the Gas Pressure History Calculation Spreadsheet, Gas-Calc V1 [9], developed by DDESB. Gas-Calc implements the Improved Methodology outlined by DDESB [10][11]. The Gas-Calc Improved Methodology is under evaluation by DDESB and has been included in this comparison due to its potential future adoption.

The combined shock and gas pressure history was subsequently applied in the SDOF analyses using both compared methods as stated: thus, UFC with a bilinear triangular profile, whereas the SHOCK/Gas-Calc load-shape consists of a triangular shock load superimposed with a gas pressure curve resembling a Weibull distribution. Load IDs L01-F and L02-F utilized the SHOCK/FRANG load shape, whereas Load IDs L01-GC and L02-GC utilized the SHOCK/Gas-Calc load shape.

The pressure histories for both Load IDs are shown in Figure 2.

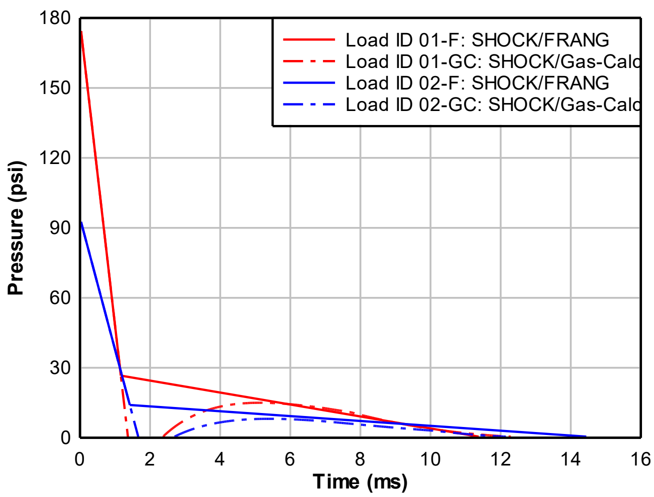

Figure 2. Load IDs 01 and 02 pressure histories

Results and Discussion

Results for the SDOF Properties phase and SDOF Analysis phase of the IV&V are presented in Appendix Table 3 through Table 6. To enhance readability of these results tables, the IDs in Column 1 of the tables referring to RC components are shown as in the example below:

C01-2FFFF

The Component ID, as described in Appendix Table 1, precedes the hyphen symbol. Immediately following the hyphen is a numeral, either 1 or 2, indicating whether the component behaves as a one-way or two-way element. This is followed by a sequence of letters, either ‘F’ or ‘S’, representing the number and type of support: F’ for fixed and ‘S’ for simple.

Results tables for the SDOF Analysis are provided with a similar ID scheme as in the following example:

C01-2FFFF_L01-F

The ID scheme prior to the underscore symbol is as previously described. Following the underscore symbol is the Load ID, as described in Figure 2. Following the Load ID and hyphen symbol is either an ‘F’ or ‘GC,’ representing SHOCK/FRANG or SHOCK/Gas-Calc blast load shapes, respectively.

The ratio between SBEDS V6.2 and the independently developed UMS spreadsheet is shown in the last three columns of all results tables. When this ratio exceeds 1.05 or falls below 0.95, the corresponding cell is highlighted in red. If the ratio lies within this range, the cell is highlighted in green. This color scheme is intended to help quickly identify cases where the difference between the two tools exceeds 5%.

The last three rows of each table present the average, maximum, and minimum for the respective columns. Since one-way RC components had identical SDOF Properties calculated with SBEDS V6.2 and the UMS spreadsheet, only the two-way components were included in the averaging process to avoid skewing the results.

Phase 1: Comparison of SDOF Properties

Two-way RC Components

The SDOF properties compared in the IV&V included load-mass factors, stiffness, resistance, and shear reactions. These properties are both critical inputs and outputs for a SDOF analysis. The resistance-deflection curves for two-way systems typically have three stiffness, or response regions, followed by ductile yielding of the component as a mechanism with zero stiffness. The three regions are delineated in the table column headers by the suffix value of 1, 2, or 3 for each step (i.e., stage) of response.

Appendix Table 3 presents the results for the IV&V of the load-mass factors. KLM1 and KLM2 values are in overall good agreement between the two tools; however, KLM3 for most of the two-way cases, except for two sides fixed and two sides simple (i.e., FFSS), are in poor agreement. This poor agreement is observed to occur from SBEDS V6.2 preemptively switching to the plastic load-mass factors in the final elasto-plastic stage of response (i.e., KLM3). The plastic stage of response does not occur for most of the two-way components until KLM4, which is not listed in this table. Hence, SBEDS V6.2 is applying the plastic load mass factor at one stage earlier than when the actual plastic response occurs. This underestimates the mass of the equivalent SDOF system during its dynamic response in this stiffness region.

The FFSS boundary condition only has two stages of response before a full plastic collapse mechanism occurs (i.e., ultimate resistance is achieved.) Hence, a plastic load-mass factor for KLM3 is appropriate for this boundary condition.

Appendix Table 4 provides the results for the stiffness comparison between SBEDS V6.2 and UMS. Stiffness results indicate an overall good agreement between the two tools except for Component IDs C11 and C11a. These two cases are two-way with two adjacent sides fixed.

These two cases are investigated further in Figure 3, Figure 4, and Figure 5. As shown in Figure 3, the overall difference between SBEDS V6.2 and UMS is not visually discernable (i.e., negligible). The K2 region of the resistance deflection curve is enlarged in Figure 4 to highlight the negligible deviation between SBEDS V6.2 and UMS.

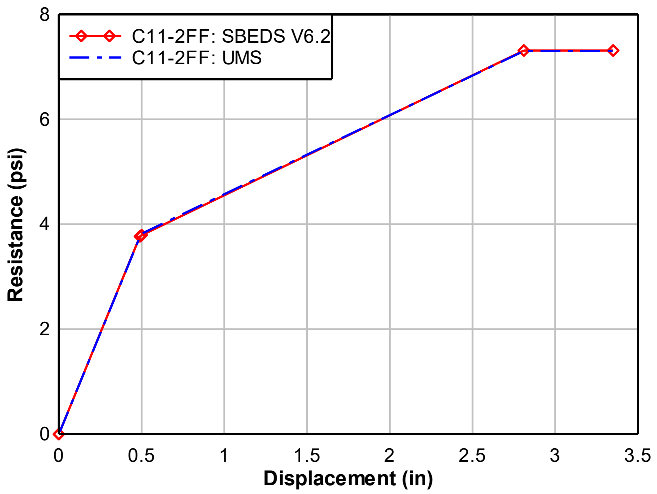

Figure 3. Component ID C11-2FF resistance-deflection curve

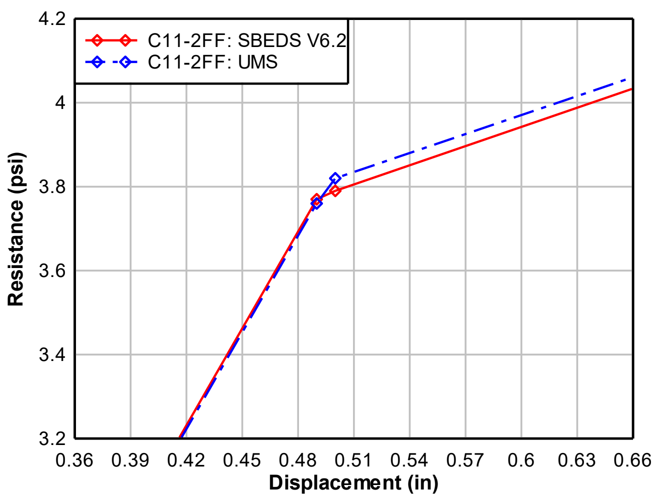

Figure 4. Component ID C11-2FF resistance-deflection curve with K2 region enlarged to show detail

Component ID C11a shows poor agreement in the K1 stiffness (i.e., elastic stiffness.) Since personnel protection is governed by a 2-deg rotation limit and this RC component is relatively stiff (i.e., elastic behavior occurs at small displacements relative to that limit) the visually noticeable difference observed in SBEDS V6.2 and UMS resistance deflection curves shown in Figure 5 is expected to have a negligible impact on the SDOF analysis of the component.

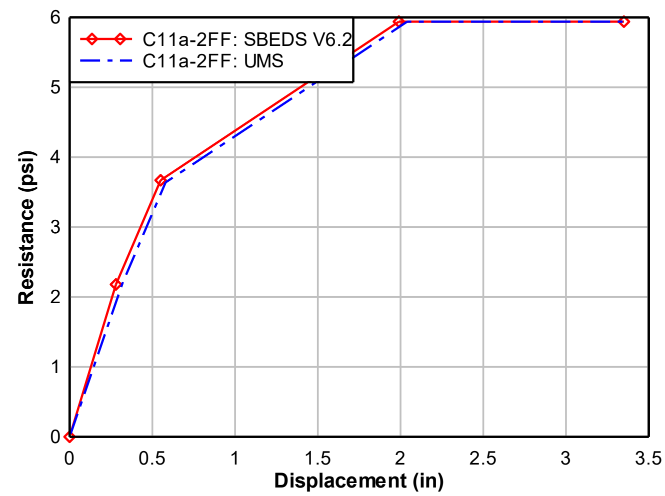

Figure 5. Component ID C11a-2FF resistance-deflection curve

Appendix Table 5 and Table 6 present the IV&V results for the resistance and shear reactions. Both tables illustrate good agreement between the two tools. The average values shown in these tables are a value of 1.00 for all three columns. Maximum and minimum values indicate that the difference in resistance and shear reactions is no greater than 2% and 3%, respectively.

The ultimate resistances (i.e., R3) for both tools are in exact agreement with a value of 1.00 for average, maximum, and minimum. Shear reactions at the supports are in good agreement with some variability measured in the shear at distance *d* from the support. In general, SBEDS typically overpredicts shear at distance *d* from the support by a minimal margin.

One-way RC Components

One-way component IDs C12 through C15 demonstrate an exact agreement in the calculated SDOF properties, as presented in Appendix Table 3 through Appendix Table 6. All components and regions have SBEDS/UMS ratios equal to unity in these tables. The implementation of one-way RC components in SBEDS V6.2 complies with UFC 3-340-02 for all cases in this study. Since the calculated SDOF properties are in perfect agreement for one-way components, Phase 2 will only focus on a detailed comparison of two-way RC components with SDOF analysis.

Phase 2: Comparison of SDOF Analysis Results

Two-way RC Component IDs C01 through C11a in Appendix Table 1 were analyzed with SDOF analyses using SBEDS V6.2 and UMS to determine the impact of differences observed in the SDOF Properties for load-mass factors and stiffness on calculated maximum dynamic deflections. The appropriate Load ID 01 or 02 was selected for each component to have a maximum response less than 2 degrees support rotation (i.e., Protection Category 1). SDOF analyses outputs recorded in this section are maximum response rotation, ductility, and displacement.

Appendix Table 7 presents the IV&V results comparing SBEDS V6.2 (As-is) to UMS. Maximum calculated support rotations and deflections from the SDOF analyses ranged from 0.34 deg to 2.45 deg and 0.43 in to 4.10 in, respectively. Only three of the twenty-six cases exceeded the 2-degree support rotation limit by a very limited amount. Therefore, the results for these cases were considered acceptable for the overall scope of the IV&V.

Significant differences are observable across all two-way boundary conditions analyzed. For the four-sides all fixed boundary condition, notable differences were observed under both the SHOCK/FRANG and SHOCK/Gas-Calc load shapes. The three sides and two sides supported RC components recorded significant differences for both load shapes analyzed.

The only boundary condition with good agreement for both load shapes was the four sides supported with two sides fixed and two sides simple (i.e., FFSS.) This good agreement suggests that SBEDS V6.2 applying the plastic load mass factor at one stage earlier than actual plastic response for RC components with three sides and two sides supported is significantly affecting the SDOF Analysis.

Appendix Table 7 demonstrates that discrepancies in *Xmax* greater than 5% are observed for eight cases with three out of these eight cases SBEDS V6.2 are unconservative. For all three of these cases, the unconservative instances occurred with the SHOCK/Gas-Calc load shape and the greatest deviation of 8% occurring in the Component ID *C11a-2FF_L02-GC*. Resistance, acceleration, and displacement time histories from the SBEDS and UMS SDOF analyses with both the SHOCK/Gas-Calc and SHOCK/FRANG loads were reviewed in detail for this Component ID.

The detailed review indicated that the SHOCK/Gas-Calc load shape was less severe than the SHOCK/FRANG load shape for both the SBEDS and UMS SDOF models. Consequently, both models remained in the elasto-plastic region for a longer duration under the SHOCK/Gas-Calc load shape. Specifically, both models remained in this region throughout the majority of the deceleration phase prior to peak deflection (i.e., region where accelerations are negative and slowing down the SDOF model prior to peak deflection).

The relevance of the timing for the final elasto-plastic stage within the deceleration phase of response is evident when reviewing the principles of the numerical analysis performed to solve a dynamic nonlinear SDOF system. The acceleration solved for at each time step in the SDOF numerical analysis with dynamic equilibrium is provided in Equation (6).

$$\ddot{y}_i = \frac{F(t)_i - c\dot{y}_i - k_i y_i}{K_{LM_i} M} \tag{6}$$

Where:

- $\ddot{y}$ = Acceleration at step i
- F(t) = Applied blast load force as a function of time at step i
- c = Numerical damping constant
- $\dot{y}$ = Velocity at step i
- k = Stiffness at step i
- y = Displacement at step i
- KLM = Load-mass factor at step i

As discussed in the Phase 1 Results, SBEDS V6.2 preemptively switches to plastic load-mass factors during the final elasto-plastic stage of response (i.e., KLM3). These plastic load-mass factors are smaller in magnitude than those used in the elasto-plastic region. As shown in Equation (6), a smaller load-mass factor in the denominator during the deceleration phase produces greater negative accelerations, which then decreases displacement at a faster rate. This behavior, combined with the less severe SHOCK/Gas-Calc load shape, which allows SDOF models to remain in the elasto-plastic region longer, results in SBEDS V6.2 producing less conservative peak deflections for the Gas-Calc load shape when compared to UMS.

SDOF properties previously calculated using the two-way RC slab program, with the "Simplified UFC 3-340-02 Design Methodology" option enabled, were transferred to the General SDOF program, with a correction applied to the KLM3 factor. This relatively minor change was made for all components included in the IV&V.

Appendix Table 8 presents the results from the revised KLM3 General SDOF models. The results for all SBEDS V6.2 components analyzed with the updated KLM3 factor show good agreement with UMS, indicating that the significant differences observed in the SBEDS V6.2 (As-is) comparison were due to the previously identified issue with the KLM3 load factor. This issue affects SDOF systems with more than two stages of response (i.e., more than one elasto-plastic stage)

Conclusions

This paper summarizes a parametric analysis to provide an Independent Verification and Validation (IV&V) of the SBEDS V6.2 "Simplified UFC 3-340-02 Design Methodology" option for its compliance with UFC 3-340-02. The UMS spreadsheet was developed to be fully compliant with the SDOF analysis methodology for one-way and two-way spanning components in UFC 3-340-02. The analysis was completed in two phases. The first SDOF Properties phase focused on the calculations of SDOF properties and shear reactions for one-way and two-way RC slabs. The second phase focused on SDOF analysis of two-way slabs.

For two-way slabs, thirteen components were analyzed in the SDOF Properties Phase 1. The results revealed significant differences in load-mass factors and stiffness between the two tools. For SDOF systems with more than two response stages (i.e., multiple elasto-plastic phases), SBEDS V6.2 applies the plastic load-mass factor one stage earlier than the actual onset of plastic behavior. Stiffness deviations were observed exclusively in slabs supported on two sides. Despite these differences, SBEDS V6.2 and UMS showed strong agreement in resistance, shear reactions at supports, and shear values at a distance *d* from the support.

In the SDOF Analysis Phase 2, discrepancies between the two tools were noted and ultimately traced to the load-mass factor implementation in SBEDS V6.2. The discrepancies showed that maximum dynamic deflections calculated with the SBEDS V6.2 program were conservative, when compared to the UMS spreadsheet, for five out of the eight cases with *Xmax* discrepancies greater than 5%. The remaining three out of eight cases, SBEDSV6.2 was unconservative for the SHOCK/Gas-Calc load shape exclusively. After the SDOF properties calculated by SBEDS V6.2 were imported with revised corrected load-mass factors into General SDOF models in SBDS V6.2, all discrepancies in SDOF analysis results between the two tools exceeding 2% were eliminated.

For one-way slabs, identical results were observed for all SDOF Properties calculated from SBEDS V6.2 and UMS. Hence, the implementation of one-way RC components in SBEDS V6.2 is in compliance with UFC 3-340-02 for all cases included in this study.

References

1. UFC 3-340-02, Change 2, "Structures to Resist the Effects of Accidental Explosions," Dept. of Defense, Washington, DC, USA, 2014.
2. SBEDS V6.2 software distributed by the USACE PDC.
3. PDC-TR 06-02. Revision 4, 2020. "User's Guide for the Single-Degree-of-Freedom Blast Effects Design Spreadsheets (SBEDS)," United States of America: U.S. Army Corps of Engineers Protective Design Center Technical Report.
4. Moehle, J., Seismic Design of Reinforced Concrete Buildings. McGraw Hill, New York, 2015.
5. Sheffield, Craig S. and Sellers, Cameron, "Internal Blast Test Series Final Test Report," DTRA FTR-21-64, Prepared by Applied Research Associates, Inc. for Defense Threat Reduction Agency (DTRA) Research and Development Directorate Enabling Capabilities Department, September 2021.
6. Oswald, C., "Quasistatic Pressure Testing for Confined Detonations with Large Vent Areas," presented at 2025 International Explosives Safety Summit and Exposition technical program, USA, December 9-12, 2025.
7. Donahue S., Abraham J., Stewart C., and Ayars J., "Computer Program SHOCK 2.0 Theory Manual," Technical Report TR-NAVFAC EXWC-SH-2201, NAVFAC Engineering and Expeditionary Warfare Center, Port Hueneme, California October 2021.
8. Kerrigan, C., "FRANG 2.0 Theory Manual," Technical Report TR-NAVFAC ESC-CI-1213, Naval Facilities Engineering Command (NCEL), Port Hueneme, California, April 2012.
9. EXWC Technical Report, "DoD Explosive Safety Board Technical Report – User's Guide for Gas-Calc Spreadsheet," September 2024.
10. Oswald, C., "Final Development of an Improved Method to Calculate Gas Pressure from Internal Detonations," Prepared by AG&E for APT Research, Inc., September 30, 2024.
11. Oswald, C., "An Improved Method to Calculate Quasistatic Pressure in the Detonation Room," presented at 2025 International Explosives Safety Summit and Exposition technical program, USA, December 9-12, 2025.

Contact Information

David A Rodriguez Jr., P.E.
drodriguez@bakerrisk.com
Office: +1-210-824-5960
3330 Oakwell Court, Suite 100, San Antonio, TX 78218-3024

Definitions/Abbreviations

BC	Boundary Condition
DDESB	Department of Defense Explosive Safety Board
E.F.	Each Face
f'_{dc}	Reinforced concrete dynamic compressive strength
f_{dy}	Steel reinforcement dynamic yield strength
H	Vertical span of two-way slab
hc	Thickness of concrete slab
K1, K2, K3	Stiffness in steps 1, 2, and 3 of SDOF model
KLM1, KLM2, KLM3	Load-mass factors in steps 1, 2, and 3 of SDOF model
L	Horizontal span of two-way slab or primary span of one-way slab
LS	Loaded side of slab for concrete cover to center of steel reinforcement
N.A.	Not applicable
neg	Negative moment steel reinforcement
NLS	Non-loaded side of slab for concrete cover to center of steel reinforcement
O.C.	On center
pos	Positive moment steel reinforcement
R1, R2, R3	Resistance in steps 1, 2, and 3 of SDOF model
Vu1	Shear along support H for two-way components and at fixed support for fixed-simple one-way components
Vu2	Shear along support L for two-way components and at simple support for fixed-simple one-way components
Vu at d	Maximum shear at distance d from support
Xmax	Maximum deflection calculated from SDOF analysis
θmax	Maximum support rotation calculated from SDOF analysis
μ	Maximum response ductility calculated from SDOF analysis

Appendix

Table 1. Test Matrix

ID	BC	L (ft)	H (ft)	Hc (in)	f'_{dc} (psi)	f_{dy} (psi)	Steel Reinforcement	Cover (in)
C01	2-Way: Four Sides - All Fixed	10	9.5	6	5,950	80,520	Parallel to L: 0.20in^2 @ 12in O.C. E.F. Parallel to H: 0.20in^2 @ 12in O.C. E.F.	Parallel to L: 1.50in NLS / 1.50in LS Parallel to H: 1.00in NLS / 1.00in LS
C02	2-Way: Four Sides - All Fixed	12	8	6	5,950	80,520	Parallel to L: 0.20in^2 @ 12in O.C. E.F. Parallel to H: 0.20in^2 @ 12in O.C. E.F.	Parallel to L: 1.50in NLS / 1.50in LS Parallel to H: 1.00in NLS / 1.00in LS
C03	2-Way: Four Sides - All Fixed	15	12	12	4,760	77,200	Parallel to L: 0.20in^2 @ 12in O.C. E.F. Parallel to H: 0.20in^2 @ 10in O.C. E.F.	Parallel to L: 1.50in NLS / 2.25in LS Parallel to H: 1.00in NLS / 1.75in LS
C04	2-Way: Three Sides - All Fixed	12	15	12	4,760	77,200	Parallel to L: 0.20in^2 @ 10in O.C. E.F. Parallel to H: 0.20in^2 @ 10in O.C. E.F.	Parallel to L: 1.50in NLS / 1.50in LS Parallel to H: 1.00in NLS / 1.00in LS
C04a	2-Way: Three Sides - All Fixed	12	15	12	4,760	77,200	Parallel to L: 0.20in^2 @ 10in O.C. E.F. Parallel to H: 0.11in^2 @ 10in O.C. E.F.	Parallel to L: 1.50in NLS / 1.50in LS Parallel to H: 1.00in NLS / 1.00in LS
C05	2-Way: Three Sides - All Fixed	20	14	15	4,760	80,520	Parallel to L: 0.20in^2 @ 11in O.C. E.F. Parallel to H: 0.20in^2 @ 11in O.C. E.F.	Parallel to L: 1.00in NLS / 1.00in LS Parallel to H: 1.00in NLS / 1.00in LS
C06	2-Way: Fixed One Span, Simple Other Span	12	8	6	5,950	80,520	Parallel to L (pos): 0.20in^2 @ 12in O.C. Parallel to L (neg): None Parallel to H: 0.20in^2 @ 12in O.C. E.F.	Parallel to L: 1.50in NLS / 1.50in LS Parallel to H: 1.00in NLS / 1.00in LS
C07	2-Way: Fixed One Span, Simple Other Span	15	12	12	4,760	77,200	Parallel to L (pos): 0.20in^2 @ 12in O.C. Parallel to L (neg): None Parallel to H: 0.20in^2 @ 10in O.C. E.F.	Parallel to L: 1.50in NLS / 2.25in LS Parallel to H: 1.00in NLS / 1.75in LS
C08	2-Way: Two Adj. Sides - Both Fixed	12	15	12	4,760	77,200	Parallel to L: 0.20in^2 @ 10in O.C. E.F. Parallel to H: 0.20in^2 @ 10in O.C. E.F.	Parallel to L: 1.50in NLS / 1.50in LS Parallel to H: 1.00in NLS / 1.00in LS
C09	2-Way: Two Adj. Sides - Both Fixed	12	8	6	5,950	80,520	Parallel to L: 0.20in^2 @ 12in O.C. E.F. Parallel to H: 0.20in^2 @ 12in O.C. E.F.	Parallel to L: 1.50in NLS / 1.50in LS Parallel to H: 1.00in NLS / 1.00in LS
C10	2-Way: Two Adj. Sides - Both Fixed	12	15	12	4,760	77,200	Parallel to L (pos): 0.20in^2 @ 12in O.C. Parallel to L (neg): 0.41in^2 @ 12in O.C. Parallel to H (pos): 0.20in^2 @ 12in O.C. Parallel to H (neg): 0.41in^2 @ 12in O.C.	Parallel to L: 1.00in NLS / 1.00in LS Parallel to H: 1.00in NLS / 1.00in LS
C11	2-Way: Two Adj. Sides - Both Fixed	12	8	6	5,950	80,520	Parallel to L (pos): 0.20in^2 @ 12in O.C. Parallel to L (neg): 0.41in^2 @ 12in O.C. Parallel to H (pos): 0.20in^2 @ 12in O.C. Parallel to H (neg): 0.41in^2 @ 12in O.C.	Parallel to L: 1.00in NLS / 1.00in LS Parallel to H: 1.00in NLS / 1.00in LS
C11a	2-Way: Two Adj. Sides - Both Fixed	8	12	6	5,950	80,520	Parallel to L (pos): 0.20in^2 @ 12in O.C. Parallel to L (neg): 0.41in^2 @ 12in O.C. Parallel to H (pos): 0.11in^2 @ 12in O.C. Parallel to H (neg): 0.22in^2 @ 12in O.C.	Parallel to L: 1.00in NLS / 1.00in LS Parallel to H: 1.00in NLS / 1.00in LS
C12	1-way: Fixed-Fixed	10	---	6	5,950	80,520	0.20in^2 @ 12in O.C. E.F.	1.50in NLS / 1.50in LS
C13	1-way: Fixed-Simple	10	---	6	5,950	80,520	0.20in^2 @ 12in O.C. E.F.	1.50in NLS / 1.50in LS
C14	1-way: Fixed-Fixed	20	---	15	4,760	80,520	0.20in^2 @ 11in O.C. E.F.	1.00in NLS / 1.00in LS
C15	1-way: Fixed-Simple	20	---	15	4,760	80,520	0.20in^2 @ 11in O.C. E.F.	1.00in NLS / 1.00in LS

Table 2. Internal Blast Test Series – Test 02 Configuration [5]

Load id	Explosive Charge		Nominal Dimension (ft)s	Room Volume (ft^3)	Loading Density (lb/ft^3)	No. of Vent Panels	Front Vent Wall	
	Weight (lb)	Type[1]					Type[1]	Dimensions (ft)[2]
L01	1.2	C4	5.5 x 7 x 6	231	0.0052	1	26-gauge metal	5.5 ft x7 ft
L02	0.6	C4	5.5 x 7 x 6	231	0.0052	1	26-gauge metal	5.5 ft x7 ft
Note 1: 1.05 psf aerial weight with four (4) Vent-All® fasteners designed to fail in tension at 175 lb force. Note 2: Vent panel height x width Note 3: Vent panel length x width								

Table 3. SDOF Properties: Load-Mass Factors Summary

ID	SBEDS V6.2			UMS			SBEDS / UMS Ratio		
	KLM1	**KLM2**	**KLM3**	**KLM1**	**KLM2**	**KLM3**	**KLM1**	**KLM2**	**KLM3**
C01-2FFFF	0.62	0.64	0.51	0.62	0.63	0.63	1.00	1.02	0.81
C02-2FFFF	0.69	0.71	0.55	0.69	0.70	0.70	1.00	1.01	0.79
C03-2FFFF	0.65	0.67	0.54	0.65	0.66	0.66	1.00	1.02	0.82
C04-2FFF	0.75	0.77	0.59	0.75	0.76	0.76	1.01	1.01	0.77
C04a-2FFF	0.75	0.77	0.61	0.75	0.75	0.75	1.01	1.03	0.82
C05-2FFF	0.70	0.71	0.54	0.70	0.70	0.70	1.01	1.01	0.77
C06-2FFSS	0.70	0.71	0.58	0.70	0.70	0.59	1.00	1.01	0.99
C07-2FFSS	0.66	0.67	0.57	0.66	0.66	0.57	1.00	1.02	0.99
C08-2FF	0.65	0.66	0.52	0.65	0.66	0.66	1.00	1.00	0.79
C09-2FF	0.65	0.66	0.54	0.65	0.66	0.66	1.00	1.00	0.82
C10-2FF	0.65	0.66	0.52	0.65	0.66	0.66	1.00	1.00	0.79
C11-2FF	0.65	0.66	0.54	0.65	0.66	0.66	1.00	1.00	0.82
C11a-2FF	0.65	0.66	0.57	0.65	0.66	0.66	1.00	1.00	0.86
C12-1FF	0.77	0.78	0.66	0.77	0.78	0.66	1.00	1.00	1.00
C13-1FF	0.78	0.78	0.66	0.78	0.78	0.66	1.00	1.00	1.00
C14-1FF	0.77	0.78	0.66	0.77	0.78	0.66	1.00	1.00	1.00
C15-1FF	0.78	0.78	0.66	0.78	0.78	0.66	1.00	1.00	1.00
(Two-way components only) Average							1.00	1.01	0.83
Maximum							1.01	1.03	0.99
Minimum							1.00	1.00	0.77

Table 4. SDOF Properties: Stiffness Summary

ID	SBEDS V6.2			UMS			SBEDS / UMS Ratio		
	K1 (psi/in)	**K2 (psi/in)**	**K3 (psi/in)**	**K1 (psi/in)**	**K2 (psi/in)**	**K3 (psi/in)**	**K1 (psi/in)**	**K2 (psi/in)**	**K3 (psi/in)**
C01-2FFFF	184	129	58.6	188	129	58.0	0.98	1.00	1.01
C02-2FFFF	233	97.0	65.9	236	97.4	67.1	0.99	1.00	0.98
C03-2FFFF	389	314	117	395	314	119	0.98	1.00	0.99
C04-2FFF	226	55.2	53.2	228	55.2	53.1	0.99	1.00	1.00
C04a-2FFF	221	261	52.1	224	263	52.2	0.98	0.99	1.00
C05-2FFF	58.8	25.1	17.5	60.3	25.1	16.7	0.98	1.00	1.05
C06-2FFSS	209	65.9	0.00	211	67.1	0.00	0.99	0.98	1.00
C07-2FFSS	315	118	0.00	315	119	0.00	1.00	0.99	1.00
C08-2FF	12.1	6.29	3.08	12.1	6.30	3.03	1.00	1.00	1.02
C09-2FF	7.27	5.46	1.44	7.26	5.47	1.43	1.00	1.00	1.00
C10-2FF	12.4	6.45	3.15	12.4	6.46	3.11	1.00	1.00	1.01
C11-2FF	7.68	3.01	1.52	7.64	5.75	1.51	1.01	0.52	1.01
C11a-2FF	7.81	5.57	1.58	6.85	5.62	1.57	1.14	0.99	1.01
C12-1FF	78.3	15.7	0.00	78.3	15.7	0.00	1.00	1.00	1.00
C13-1FF	37.7	15.7	0.00	37.7	15.7	0.00	1.00	1.00	1.00
C14-1FF	67.4	13.5	0.00	67.4	13.5	0.00	1.00	1.00	1.00
C15-1FF	32.5	13.5	0.00	32.5	13.5	0.00	1.00	1.00	1.00
(Two-way components only) Average							1.00	0.96	1.01
Maximum							1.14	1.00	1.05
Minimum							0.98	0.52	0.98

Table 5. SDOF Properties: Resistance Summary

ID	SBEDS V6.2			UMS			SBEDS / UMS Ratio		
	R1 (psi)	R2 (psi)	R3 (psi)	R1 (psi)	R2 (psi)	R3 (psi)	R1 (psi)	R2 (psi)	R3 (psi)
C01-2FFFF	8.53	8.88	18.3	8.57	9.02	18.3	1.00	0.98	1.00
C02-2FFFF	9.26	10.3	20.0	9.36	10.3	19.9	0.99	1.00	1.00
C03-2FFFF	10.7	11.1	23.7	10.7	11.2	23.6	1.00	0.99	1.00
C04-2FFF	9.41	11.5	17.5	9.42	11.5	17.5	1.00	1.00	1.00
C04a-2FFF	7.73	9.34	15.8	7.70	9.34	15.9	1.00	1.00	1.00
C05-2FFF	4.33	5.34	10.7	4.34	5.36	10.7	1.00	1.00	1.00
C06-2FFSS	8.63	16.7	16.7	8.62	16.7	16.7	1.00	1.00	1.00
C07-2FFSS	9.54	19.6	19.6	9.57	19.5	19.5	1.00	1.00	1.00
C08-2FF	2.31	2.43	6.25	2.27	2.39	6.25	1.02	1.02	1.00
C09-2FF	1.71	1.88	4.55	1.69	1.91	4.55	1.01	0.99	1.00
C10-2FF	4.05	4.13	8.12	3.98	4.06	8.12	1.02	1.02	1.00
C11-2FF	3.77	3.79	7.31	3.76	3.82	7.30	1.00	0.99	1.00
C11a-2FF	2.18	3.67	5.94	2.20	3.64	5.94	0.99	1.01	1.00
C12-1FF	4.88	6.51	6.51	4.88	6.51	6.51	1.00	1.00	1.00
C13-1FF	3.26	4.88	4.88	3.26	4.88	4.88	1.00	1.00	1.00
C14-1FF	4.21	5.62	5.62	4.21	5.62	5.62	1.00	1.00	1.00
C15-1FF	2.81	4.21	4.21	2.81	4.21	4.21	1.00	1.00	1.00
(Two-way components only) Average							1.00	1.00	1.00
Maximum							1.02	1.02	1.00
Minimum							0.99	0.98	1.00

Table 6. SDOF Properties: Shear Reaction Summary

ID	SBEDS V6.2			UMS			SBEDS / UMS Ratio		
	Vu1 (lbf/in)	Vu2 (lbf/in)	Vu at d (lbf/in)	Vu1 (lbf/in)	Vu2 (lbf/in)	Vu at d (lbf/in)	Vu1 (lbf/in)	Vu2 (lbf/in)	Vu at d (lbf/in)
C01-2FFFF	621	653	587	621	651	600	1.00	1.00	1.02
C02-2FFFF	648	682	609	647	684	620	1.00	1.00	1.02
C03-2FFFF	1,044	1,164	989	1,042	1,168	1,010	1.00	1.00	1.02
C04-2FFF	1,010	1,025	887	1,005	1,026	916	1.00	1.00	1.03
C04a-2FFF	971	728	834	965	728	824	0.99	1.00	0.99
C05-2FFF	877	882	775	881	880	790	1.00	1.00	1.02
C06-2FFSS	420	630	566	420	629	570	1.00	1.00	1.01
C07-2FFSS	684	1,065	914	683	1,066	914	1.00	1.00	1.00
C08-2FF	579	613	563	578	612	573	1.00	1.00	1.02
C09-2FF	310	305	295	309	305	297	1.00	1.00	1.01
C10-2FF	761	782	718	761	781	727	1.00	1.00	1.01
C11-2FF	507	485	481	506	485	484	1.00	1.00	1.01
C11a-2FF	428	342	406	427	341	405	1.00	1.00	1.00
C12-1FF	390	390	361	391	391	361	1.00	1.00	1.00
C13-1FF	366	219	344	366	220	344	1.00	1.00	1.00
C14-1FF	674	674	595	674	674	596	1.00	1.00	1.00
C15-1FF	632	379	573	632	379	573	1.00	1.00	1.00
(Two-way components only) Average							1.00	1.00	1.01
Maximum							1.00	1.00	1.03
Minimum							0.99	1.00	0.99

Table 7. IV&V SDOF Analysis: Results Summary Using SBEDS V6.2 As-is

ID	SBEDS V6.2			UMS			SBEDS / UMS Ratio		
	θmax (deg)	μ	Xmax(in)	θmax (deg)	μ	Xmax(in)	θmax (deg)	μ	Xmax(in)
C01-2FFFF_L01-F	1.64	10.41	1.63	1.56	10.03	1.55	1.05	1.04	1.05
C01-2FFFF_L01-GC	1.39	8.81	1.38	1.37	8.78	1.35	1.02	1.01	1.02
C02-2FFFF_L01-F	1.52	8.89	1.27	1.45	8.73	1.22	1.05	1.02	1.04
C02-2FFFF_L01-GC	1.23	7.18	1.03	1.23	7.39	1.03	1.00	0.97	1.00
C03-2FFFF_L01-F	0.44	5.50	0.56	0.42	5.37	0.53	1.04	1.02	1.06
C03-2FFFF_L01-GC	0.34	4.25	0.43	0.35	4.45	0.44	0.94	0.94	0.96
C04-2FFF_L01-F	0.59	5.75	0.74	0.58	5.61	0.73	1.03	1.03	1.02
C04-2FFF_L01-GC	0.54	5.24	0.68	0.55	5.38	0.70	0.96	0.95	0.94
C04a-2FFF_L01-F	0.68	7.73	0.85	0.65	7.41	0.81	1.06	1.05	1.05
C04a-2FFF_L01-GC	0.61	6.95	0.76	0.62	7.08	0.78	0.95	0.95	0.96
C05-2FFF_L01-F	0.61	4.06	1.28	0.58	3.80	1.21	1.07	1.08	1.07
C05-2FFF_L01-GC	0.65	4.29	1.35	0.58	3.79	1.21	1.05	1.06	1.04
C06-2FFSS_L01-F	2.09	12.67	1.53	2.12	13.01	1.55	0.99	0.98	0.99
C06-2FFSS_L01-GC	1.86	11.27	1.36	1.87	11.45	1.36	0.99	0.98	0.99
C07-2FFSS_L01-F	0.67	7.63	0.68	0.68	7.81	0.69	0.99	0.98	0.99
C07-2FFSS_L01-GC	0.59	6.67	0.60	0.59	6.76	0.60	1.01	0.98	0.99
C08-2FF_L01-F	1.31	3.02	3.30	1.22	2.76	3.08	1.07	1.09	1.07
C08-2FF_L01-GC	1.43	3.28	3.59	1.25	2.82	3.15	1.04	1.06	1.04
C09-2FF_L02-F	2.45	2.72	4.10	2.31	2.58	3.87	1.06	1.05	1.06
C09-2FF_L02-GC	2.28	2.54	3.83	2.12	2.37	3.55	0.99	0.99	0.99
C10-2FF_L01-F	1.03	2.29	2.58	1.03	2.25	2.58	1.00	1.01	1.00
C10-2FF_L01-GC	1.09	2.44	2.75	1.05	2.29	2.63	0.96	0.98	0.96
C11-2FF_L02-F	1.71	1.55	2.87	1.79	1.63	3.00	0.95	0.95	0.96
C11-2FF_L02-GC	1.60	1.46	2.69	1.67	1.52	2.81	0.93	0.93	0.93
C11a-2FF_L02-F	1.83	2.40	3.07	1.87	2.32	3.13	0.98	1.03	0.98
C11a-2FF_L02-GC	1.69	2.21	2.82	1.72	2.13	2.88	0.93	0.98	0.92
						Average	1.00	1.00	1.00
						Maximum	1.07	1.09	1.07
						Minimum	0.93	0.93	0.92

Table 8. SDOF Analysis: SBEDS V6.2 with Revised KLM3 Summary

ID	SBEDS V6.2			UMS			SBEDS / UMS Ratio		
	θmax (deg)	μ	Xmax(in)	θmax (deg)	μ	Xmax(in)	θmax (deg)	μ	Xmax(in)
C01-2FFFF_L01-F	1.55	9.57	1.53	1.56	10.03	1.55	0.99	0.95	0.99
C01-2FFFF_L01-GC	1.36	8.97	1.35	1.37	8.78	1.35	0.99	0.96	0.99
C02-2FFFF_L01-F	1.44	8.59	1.20	1.45	8.73	1.22	0.99	0.99	0.99
C02-2FFFF_L01-GC	1.23	7.34	1.03	1.23	7.39	1.03	0.99	0.99	1.00
C03-2FFFF_L01-F	0.42	5.27	0.53	0.42	5.37	0.53	1.00	0.98	1.00
C03-2FFFF_L01-GC	0.35	4.40	0.44	0.35	4.45	0.44	0.99	0.99	0.99
C04-2FFF_L01-F	0.57	5.50	0.72	0.58	5.61	0.73	0.99	0.98	1.00
C04-2FFF_L01-GC	0.55	5.33	0.69	0.55	5.38	0.70	0.98	0.99	1.01
C04a-2FFF_L01-F	0.64	7.26	0.80	0.65	7.41	0.81	0.99	0.99	0.99
C04a-2FFF_L01-GC	0.62	7.07	0.78	0.62	7.08	0.78	1.00	1.00	1.00
C05-2FFF_L01-F	0.56	3.67	1.17	0.58	3.80	1.21	0.98	0.98	0.98
C05-2FFF_L01-GC	0.57	3.72	1.19	0.58	3.79	1.21	0.98	0.98	0.98
C06-2FFSS_L01-F	2.09	12.67	1.53	2.12	13.01	1.55	0.99	0.98	0.99
C06-2FFSS_L01-GC	1.86	11.27	1.36	1.87	11.45	1.36	0.99	0.98	0.99
C07-2FFSS_L01-F	0.67	7.63	0.68	0.68	7.81	0.69	0.99	0.98	0.99
C07-2FFSS_L01-GC	0.59	6.67	0.60	0.59	6.76	0.60	1.01	0.98	0.99
C08-2FF_L01-F	1.21	2.80	3.05	1.22	2.76	3.08	0.98	1.01	0.99
C08-2FF_L01-GC	1.24	2.87	3.12	1.25	2.82	3.15	0.99	1.01	0.99
C09-2FF_L02-F	2.29	2.55	3.85	2.31	2.58	3.87	0.99	0.99	0.99
C09-2FF_L02-GC	2.11	2.34	3.53	2.12	2.37	3.55	1.00	0.99	1.00
C10-2FF_L01-F	1.02	2.26	2.55	1.03	2.25	2.58	0.99	1.00	0.98
C10-2FF_L01-GC	1.04	2.30	2.60	1.05	2.29	2.63	0.99	1.00	0.99
C11-2FF_L02-F	1.79	1.62	3.00	1.79	1.63	3.00	1.00	0.99	1.00
C11-2FF_L02-GC	1.67	1.52	2.81	1.67	1.52	2.81	1.00	0.99	1.00
C11a-2FF_L02-F	1.84	2.40	3.07	1.87	2.32	3.13	0.98	1.03	0.98
C11a-2FF_L02-GC	1.69	2.20	2.82	1.72	2.13	2.88	0.98	1.03	0.98
						Average	0.99	0.99	0.99
						Maximum	1.01	1.03	1.01
						Minimum	0.98	0.95	0.98