Overview of Simplified Methods and Research for Blast Analysis

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Abstract

Recent terrorist bomb attacks on buildings have resulted in increased interest in the protection of key buildings. Various research programs have provided improved design and analysis techniques as well as new mitigation methods. Advanced finite element methods provide the best analytical results because they can take into account the time varying load, dynamic structural response, non-liner material properties, and the non-linear interaction of various response modes (e.g., shear and flexure). These methods require not only time but also specialized expertise to obtain good results. They are therefore generally unpractical for typical blast design problems. Simplified methods can provide reasonable approximations that are adequate for design. A variety of types of simplified models exist. Typical models include single or multi-degree-of-freedom, pressure-impulse (P-I) diagrams, and response surfaces developed from finite element analyses. This paper describes some recently developed simplified models and associated research.

Introduction

In an explosion, a large amount of energy is released in a very short time. A typical blast pressure wave increases very rapidly to a peak and decays in roughly an exponential manner. The duration of the positive pressure is on the order of milliseconds to tens of milliseconds depending on the size of the bomb and distance from the explosion. Although the pressures can be very high, the duration is short. A building, or building component will respond dynamically. Analysis techniques must consider the dynamic behavior of the structure and possibly nonlinear material behavior, strain rate effects, and large deformations.

Advanced finite element methods (FEM) provide the best analytical results because they can take into account the time varying load, dynamic structural response, non-liner material properties, large displacements, and the non-linear interaction of various response modes (e.g., shear and flexure). These methods require not only time but also specialized expertise to obtain good results. They are therefore generally unpractical for typical blast design problems. Simplified methods can provide reasonable approximations that are adequate for design. A variety of types of simplified models exist. Typical models include single or multi degree-of-freedom models, pressure-impulse diagrams, and response surfaces developed from finite element runs or test data. This paper describes some recently developed simplified methods.

Single-Degree-of-Freedom Model

The number of dynamic degrees-of-freedom is the number of displacement components which must be considered to represent the effects of inertia forces of a structural element subjected to dynamic loading. All real structures and their basic elements are multi-degree of freedom systems. However, many of them can be approximated by Single-Degree-of-Freedom (SDOF) models with acceptable accuracy.

In an SDOF model the structural element of interest is idealized as shown in Figure 1 by lumping its mass at a single point. The mass is then allowed to displace in only one direction with an equivalent spring. The basic dynamic equilibrium equation for an undamped SDOF idealization is of the following form:

$$F_e(t) - K_e\, y = M_e\, dy/dt^2$$

where $F_e(t)$ = equivalent dynamic load,
K_e = equivalent stiffness,
y = displacement,
M_e = equivalent mass, and
dy/dt^2 = acceleration.

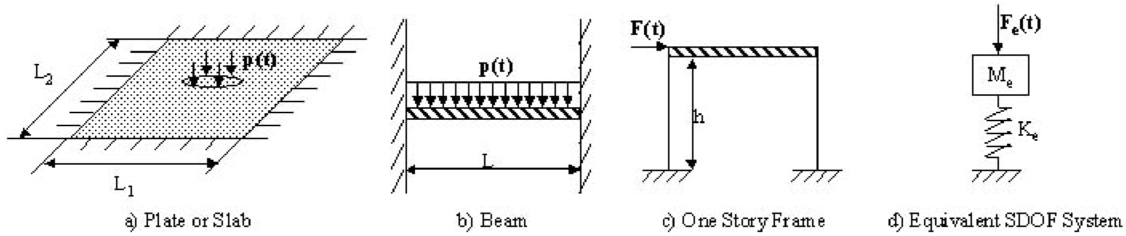


Figure 1, Undamped SDOF Idealizations

The equivalent load, stiffness and mass are obtained by multiplying the dynamic load, and stiffness and mass of the real structure by transformation factors, which are functions of the displaced shape of the structure under static application of the load. These transformation factors are established to maintain kinetic energy, strain energy, and external work between the real system and the equivalent system. Transformation factors for beams and plates with varying support and load conditions can be found from charts and tables in reference manuals and books dedicated to dynamic design. (See Biggs[3], 1964)

The SDOF formulation in most blast calculations is sufficiently simple to be solved by hand calculations. However, to expedite the calculations, several SDOF computer codes are available for automated analysis. Some codes available for the government and its contractors include SPAN32[6], WAC[8], HazL[7], WINLAC[1], and WINGARD[2].

To simplify hand calculations of elastic systems, response spectra as shown in Figure 2 are utilized. In this figure, t_d/T is the ratio of the dynamic pulse time to the period of vibration of the structure. DLF is the Dynamic Load Factor, which is the ratio of maximum dynamic displacement to deflection of the structure if the load (peak pressure) were applied statically.

For hand calculation of elasto-plastic systems, response spectra as shown in Figure 3 are utilized. In this figure, the ductility of the structure (μ), which is the ratio of the maximum dynamic displacement to the maximum elastic displacement of the structure (y_m/y_{el}), is obtained as a function of the dynamic pulse time to the period of vibration of the structure (t_d/T), the plastic resistance function (R_m), and the peak pressure (F_1).

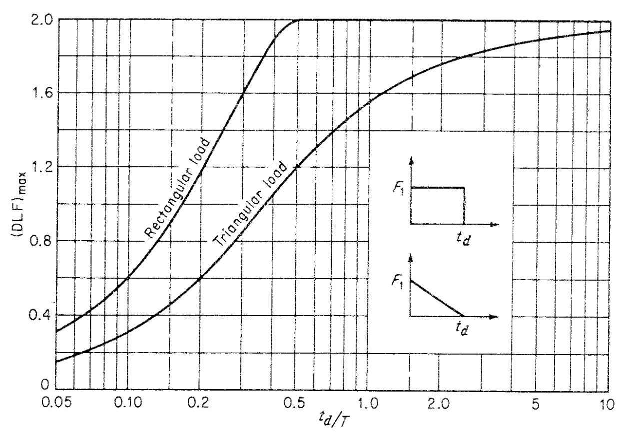


Figure 2: Elastic Response Spectra[5]

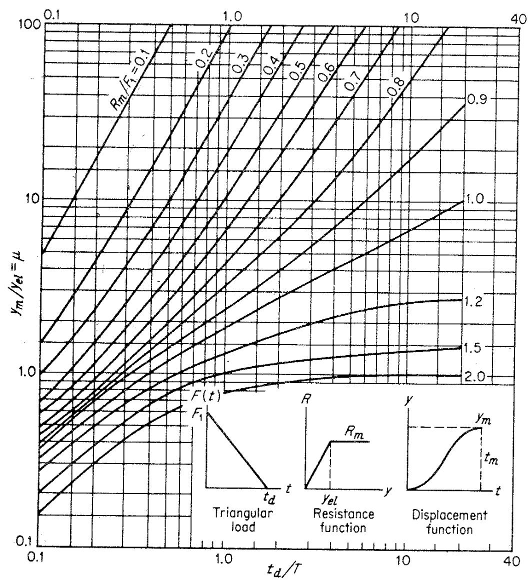


Figure 3: Elasto-Plastic Response Spectra[5]

SDOF Example – Structural Muntin Window Design Method

In an effort to develop aesthetically acceptable blast resistant designs, the US Department of State, Bureau of Diplomatic Security (DS) built on the common practice of installing architectural muntins behind large windows to visually separate a single sheet of glazing into multiple lites. In addition to the aesthetic value of a traditional muntin, DS's structural muntin provides blast protection by acting as a catch system for specially designed glazings. The system is constructed by backing relatively thin laminated glass with vertical and horizontal steel tubes securely fastened to the wall. The window system is intended to protect office occupants from large vehicle bombs. Figure 4 shows a prototype of an installed muntin window system prior to full-scale blast testing. The upper photo shows the single sheet of glazing from the outside. The lower photo shows the two muntin tubes from inside of the test structure.

Figure 4: Installed Muntin System[9]

In their research and development effort, DS relied on the use of SDOF models to design the muntin window. Their design methodology summarized in Reference 9 treats the window system as two, decoupled, SDOF models as shown in Figure 5. The glass plate resting on the muntin tubes is one of the SDOF models. The second model is for the muntin tubes deforming under the dynamic reaction of the glass plate. This de-coupling is reasonable because the period of the two systems in most cases differs by a factor of 2. Otherwise a two-degree-of-freedom model would have been necessary.

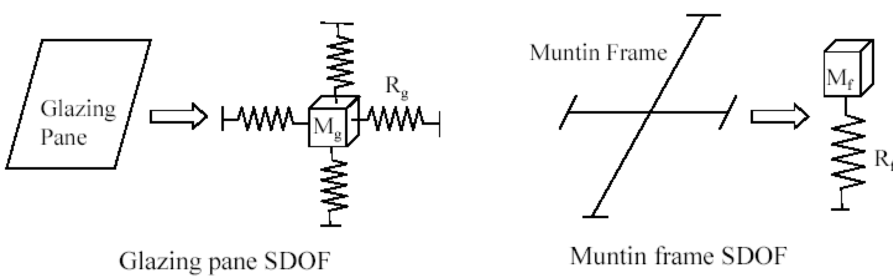


Figure 5: SDOF Models[9]

The DS design methodology recommends analyzing the glass plate with SDOF models for glazing like WINLAC or HazL. The dynamic reaction forces for the glass generated by these codes can then be applied as dynamic loads on the SDOF model of the muntin tubes. In the DS design methodology, it is recommended to solve the SDOF model for the muntin tube numerically.

Figure 6 shows the deflection of the muntin bar system, shown in Figure 4, measured during the blast test. The measurement was taken at the muntin bar intersection point with a peak deflection of 287mm (11.3 inches.) For comparison, the design methodology predicted a peak deflection of 284mm (11.2 inches.) This is remarkable considering the complexity of the muntin window system, and demonstrates the validity of the model.

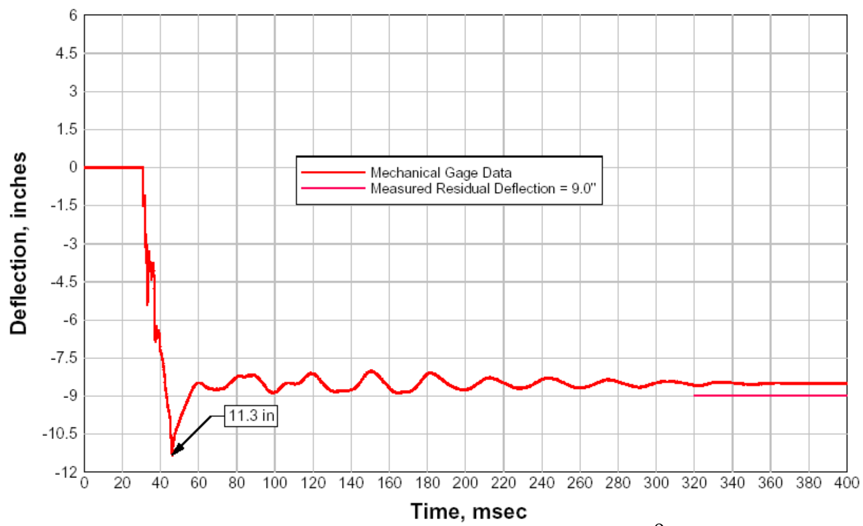


Figure 6: Deflection Measurements[9]

Pressure-Impulse Diagrams

A common approach for estimating damage to structural components is with pressure-impulse (P-I) diagrams. These diagrams provide a quick graphical tool for estimating damage. In this method, curves of equal damage (iso-damage curves) are plotted in a pressure-impulse space. The pressure axis represents the peak overpressure of a blast wave. The impulse axis is the total positive phase impulse from the blast wave. A typical iso-damage curve is shown in figure 7(a). A given curve could represent the onset of damage, onset of collapse, etc. A typical curve will have an impulse asymptote in the impulse sensitive region and a pressure asymptote in the pressure sensitive region. The transition between the two is called the dynamic region. In the impulse-sensitive part of the curve, the blast duration is typically short compared to the time of response of the structural component. The total impulse is therefore what is important in the response of the component. This would be the case for smaller bombs. If the duration of the blast load is long relative to the natural period of the structural component, then the peak pressure will tend to dominate the response. This would be the case for larger yield bombs that have relatively more impulse for the same peak pressure.

Every point in a pressure-impulse space represents a unique bomb size and standoff. Figure 7(b) shows an overlay of curves of equal charge weight and lines of equal standoff. A specific threat (bomb size and standoff) can be plotted on the P-I

Diagram and compared to the curves. If the point is below or to the left of a curve, the damage would be less than indicated by the curve. If the point is above and/or to the right, the structural component would receive more damage than indicated by the curve.

Pressure-Impulse diagrams can re-plotted in the form of range-to-effect curves (figure 8). These curves are very convenient, particularly for non-technical people because no knowledge of blast effects is needed. The axes represent distance from the bomb to the building (range) and bomb yield.

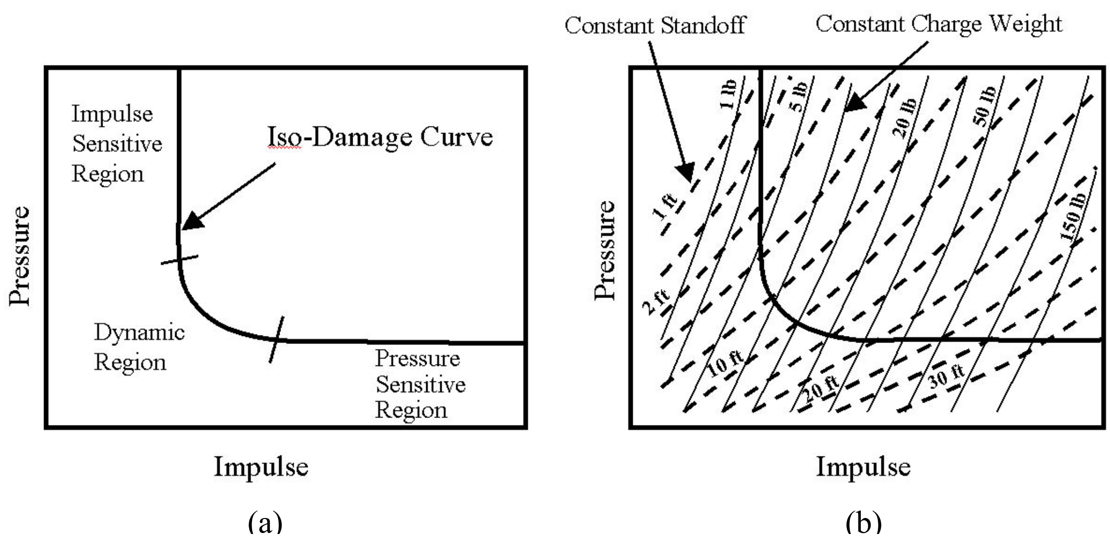


Figure 7 Pressure-Impulse Diagram

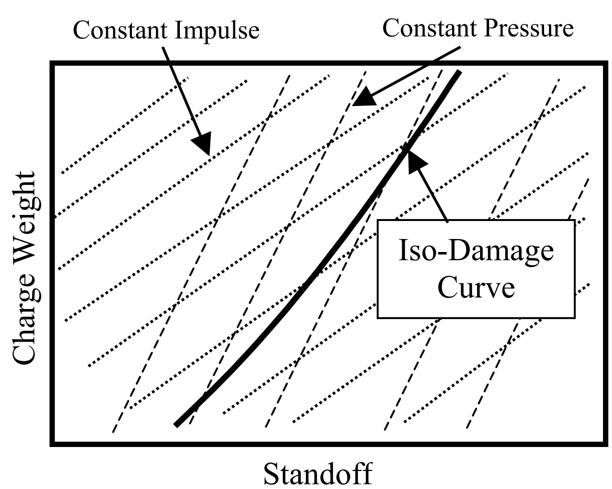


Figure 8: Range to Effect Curve

Example - Concrete Masonry Unit Methodology
Pressure impulse diagrams can be generated analytically using simple or high fidelity models, or can be developed as curve fits to experimental data. This section will provide an example of the latter.

The Facility and Component Explosive Damage Assessment Program (FACEDAP) [4] provides damage response curves for a variety of building components in a dimensionless pressure-impulse space. Concrete masonry unit (CMU) wall data was non-dimensionalized using the flexural capacity of the wall panel. This provides a convenient way of comparing data on the same graph. The original FACEDAP curves were based on very limited data. Since that time, testing has been accomplished by a number of organizations on various walls.

The Technical Support Working Group (TSWG) sponsored a project to gather all of the CMU wall data into a database, determine where gaps in the data exist, fill the gaps with simulated blast testing (shock tube), and update the FACEDAP damage curves using the data. [13] Of the 29 additional shock tube tests conducted in this project, the majority were conducted to improve the data population within the dynamic response regime of the P-I curves, with emphasis on the outer limits of this region towards both the impulse and pressure sensitive regions. Results from those tests were classified as 'reuse', 'replace', 'collapse', or 'blowout', as demonstrated in figure 9.

A total of 308 dynamic tests were compiled into the database. Figure 10 shows an example P-I diagram with the data and iso-damage curves. Notice the curves do not have the traditional shape as shown in Figure 7(a), but have a "layover" in the impulsive region. This can be attributed to the negative phase of the blast. When the duration of the positive phase of the blast is short compared to the response time of the wall, the negative phase will reduce the net applied impulse, and thus cause the layover effect. This new set of PI diagrams provides a significant step in eliminating the excessive conservatism from the FACEDAP curves for CMU walls.

(a) Reuse (b) Replace (c) Collapse (d) Blowout

Figure 9: Wall Damage Classifications[13]

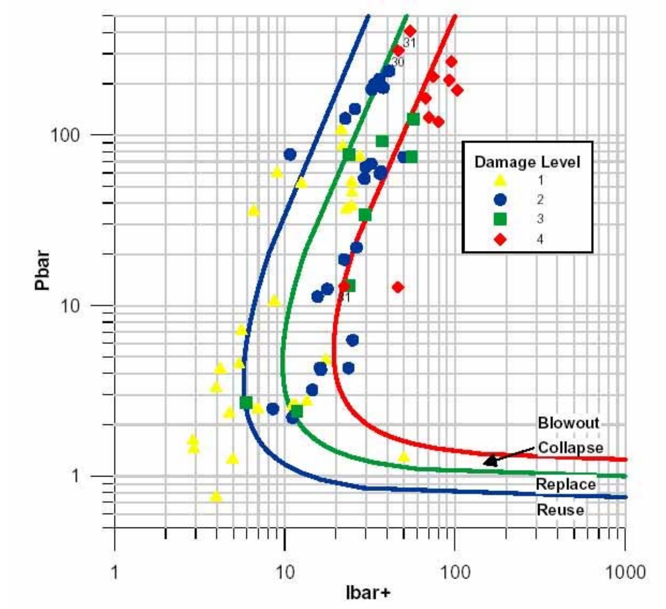


Figure 10: CMU Wall P-I Diagram[12]

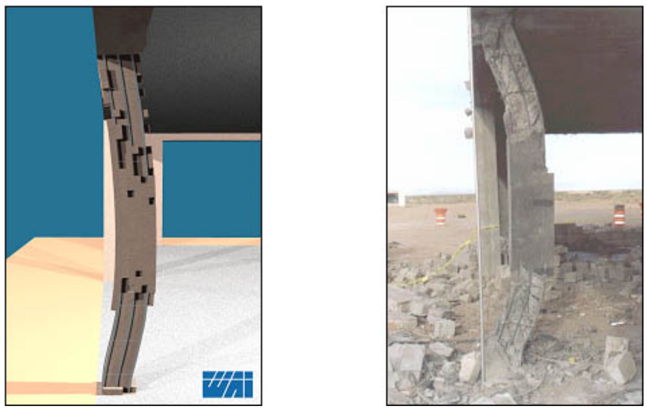
Response Surface

To create a simplified method, simplifying assumptions are used to approximate or disregard some of the physics of the problem. These simplifications will create inaccuracies in the results. However, when done correctly, within a validated range of parameters, these inaccuracies are minimal (or within an acceptable range), and the method is suitable for the particular problem. Often, conservatism is built into the model to account for uncertainties. Many times though, there are not adequate test data to fully validate a model over the range of parameters where the model is used. It may not be known whether the model is conservative or unconservative in a particular case. This could be as a result of complicated phenomenon that the model cannot handle. For example, a column may be subjected to both flexure and shear at the same time. These response modes interact in a non-linear manner that is difficult to capture in an SDOF model. They are often therefore handled separately.

Advanced finite element methods can handle these complex interactions and other details that cannot be handled in SDOF codes. These codes are not widely available, require a level of expertise to run and to properly interpret the results, and are often too time consuming for use in typical blast design problems. One way to take advantage of the higher fidelity solutions of FEM codes is to use them to create "analytical experiments" that can be used as data for development or validation of other methods. One technique is to create response surfaces where the data is fit to multi-dimensional curves. This provides a high fidelity solution in a fast running tool that does not require the experience in FEM modeling of blast effects. The major limitation of this method is that the input parameters must be within the bounds of the FEM runs.

Example - Reinforced Concrete Column Analysis Code

As part of the Divine Buffalo test series, a full-scale test building was constructed, in part, to examine the behavior of columns subjected to blast and to examine the potential for progressive collapse. This structure provided the first opportunities to validate high-fidelity finite element codes on typical buildings (most previous validation was on heavy construction such as bunkers, missile silos, etc.). A pretest prediction was generated with the FLEX[10] code and compared to the test as shown in Figure 11. The test results demonstrated the capability of this code to predict the complex behavior of a preloaded column subjected to a severe blast environment. Both flexure and shear modes of the column were captured in the analysis.

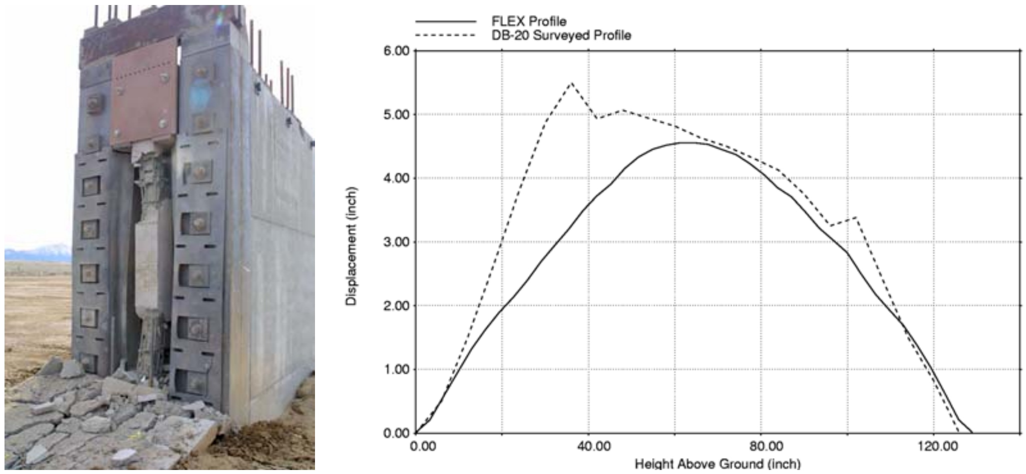


(a) Prediction (b) Results

Figure 11: Divine Buffalo 6 Pre-Test Prediction and Post-Test Result

To exploit this development, TSWG sponsored an initiative to create an improved column analysis method using FLEX results as analytical experiments. The approach was to first create a database of typical column designs, to then determine the response of the columns to various blast loads using finite element methods, and finally create a code that interpolates between the data to determine the response of a column to a particular blast environment. The column design database was created by first designing about 3300 buildings. The attributes of the columns on the first floor were examined and a subset of representative columns was included in the database. These columns were then analyzed in various blast environments using FLEX. Four cases were picked for further validation of the FLEX code using a component test reaction structure to test the columns in blast environments. The comparisons with the FLEX runs provided further confidence in the methodology (Figure 12). Then, about 11,400 analyses were completed and the results included into a database. The database was then fitted using a neural network approach.

Figure 13 shows the difference between an SDOF analysis and one from this methodology. Notice that the SDOF cannot account for lateral reinforcement, and therefore can range from conservative to unconservative depending on the reinforcement patterns.



(a) Column Test Structure

(b) Measured Displacement Profile v. Flex PreTest Prediction[11]

Figure 12. Divine Buffalo 20 Results

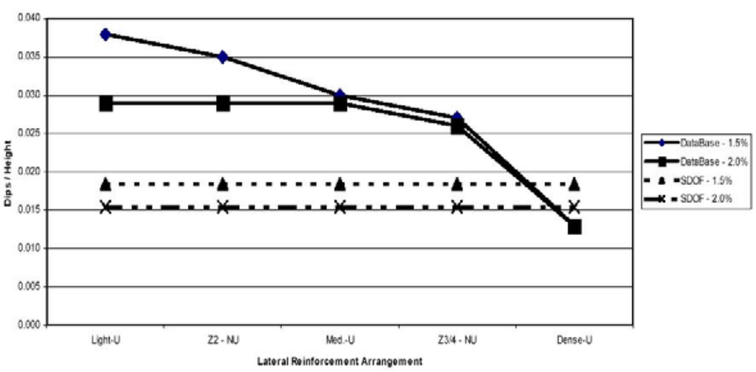


Figure 13. Comparison of SDOF and Response Surface Displacement Predictions[11]

Conclusion

Although simplified methods cannot consider the entire physics of a structure subjected to blast to the degree that high-fidelity finite element analyses (FEA) can, they are more than adequate for the average design process. The improbability of a terrorist attack against the designed building, coupled with the inability to predict the terrorist's weapon, limit the usefulness of an expensive FEA for antiterrorism design. As such, advancing the fidelity, usability and accessibility of simplified methods is our best method of ensuring antiterrorism considerations are fully integrated into the design process.

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