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A Dissertation

Presented to

the faculty of the School of Engineering and Applied Science

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In Partial Fulfillment

of the requirements for the Degree

Doctor of Philosophy (Civil Engineering)

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ABSTRACT

STOCHASTIC ANALYSIS OF FACILITIES HARDENED AGAINST CONVENTIONAL WEAPONS EFFECTS

A procedure is developed which returns a probability of kill of a hardened facility taking into account two types of uncertainties: weapon delivery accuracy and structural characteristics or intelligence uncertainties. The kill criteria are based on the structural response of the facility exceeding predetermined limits which represent the achievement of the attack objective. Perfect knowledge is rarely known about the structural characteristics of a target once a conflict is initiated. Analyst tasked to perform pre-attack weapons analysis and post-attack weapons effectiveness must be able to report to their superiors realistic probabilities of achieving the objective of an airborne strike on a target. Current methodologies do incorporate weapon delivery accuracy, however they overlook uncertainties in target structural characteristics which can make a dramatic difference in a probability of kill prediction.

A nonlinear, nondimensional, continuous hysteretic beam model is developed to represent a section of a hardened facility subjected to conventional weapons effects. The model returns response calculations across the height of the section as required to provide information for determining the kill state of a hardened target. The nondimensionalization allows for ease of parameter input and serves the stochastic analysis well where structural characteristics are continuously changed.

Existing empirical models which generate conventional weapon blast pressure time histories as a function of the TNT equivalent throw weight are modified to become a function of space as well as time. A new model is generated which returns the pressure

at any point up a wall section as a function of time, space and angle of incidence. This type of load representation is required to feed the continuous beam model referenced above. The combination of the beam model and the load model is termed the NONLIN model.

Robust statistical models or response surfaces (RS) are derived from NONLIN results calculated using typical combinations of weapon throw weight and range, target wall heights, depths and concrete compressive strengths. The use of a design of experiments (DOE) or experimental design approach to the RS development ensured the RS closely replicated the input data across the parameter space of interest. The result was a multidimensional RS which returned the structural response given a set of the five parameters stated above.

Two Monte Carlo simulation programs are developed which take into account structural characteristics as random input variables in addition to the traditional weapon delivery accuracy. The first program utilizes the NONLIN model in the simulations whereas the second program replaced the full NONLIN model with several RS models valid over key parameter ranges. Use of the RS replacement models allowed the simulation to be run in less than 1% of the time required to run the simulation with NONLIN. This time saving is crucial to the use of this tool in a dynamic wartime environment.

This work demonstrates that uncertainties in the structural characteristics of a target may significantly effect its response to conventional weapons and the determination of the resulting probability of kill given an attack. The use of robust response surfaces to replace complex analytic procedures demonstrates that timely calculation of probabilities of damage may be generated in spite of using a simulation technique such as Monte Carlo. The methodology presented will accommodate studies to single out the most critical random structural variables and their ranges allowing the proper emphasis to be placed on variable significance in a targeting analysis and data gathering exercise.

DEDICATION

This dissertation is dedicated to my lovely wife Carol and my three wonderful kids Amanda, Justin and Cameron who have sufferd through my full time preoccupation with this project for the last seven years. Without their support and understanding I could never have finished. My final and ultimate gratitude is given to God for blessing me with the perseverance to complete this task.

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List of Symbols and Abbreviations

A_v	= cross sectional area of shear reinforcing steel
A_0	= post-yield to pre-yield moment curvature ratio
A_1, A_2	= hysteresis shape terms
a	= NDRC equation factors
A_s	= cross sectional area of flexural steel
b_w	= ROI width
b	= NDRC equation factors
C	= weapon case weight
c	= NDRC equation factor
CEP	= circular error probability, the
d	= depth of ROI (inches)
e_{11}	= typical residual term
FC	= concrete strength (psi)
L/T	= ROI length over thickness
M	= nonlinear, hysteretic portion of total moment
m(x,t)	= moment as a function of space and time
n	= hysteresis shape terms
N_μ	= number of moment terms in solution
N_v,	= number of displacement terms in the solution
P_{ki}	= probability of kill for each weapon, i
$P_{ki/Rih}$	= probability of kill for each weapon given the location of the weapon detonation (by response region)

P_{Rih} = probability of the weapon hitting in a response region

$P_{ref}(y)$ = reflected pressure as a function of distance up the ROI (psi)

P_{so} = peak positive incident pressure seen by the structure

P_f = probability of failure

$q_{ext}(x,t)$ = external load as a function of space and time

$q(\xi,\tau)$ = nondimensional load as a functionn of space and time

r,R = range from weapon detonation to region of interest

Rh 1-4 = response regions 1-4

ROI = region of interest, wall section modeled as a hysteretic beam

SS_{RESIDS} = residual sum of squares

SR = scaled range of weapon from ROI

t_a = time of arrival, after detonation, of the blast to the ROI (msec)

t_o = positive pressure phase duration of blast after arrival at ROI (msec)

v = beam deflection

v/L = deflection over length of ROI

V' and M' = shear and moment at critical shear section

V_n = nominal shear capacity of the ROI

W = TNT throw weight of the weapon of interest

XL = height or length of ROI

x = lateral distance of detonation location relative to the ROI (ft)

y = distance from ground level up the ROI

z = incident distance of detonation location relative to the ROI (ft)

α	=	angle of incidence
α_k	=	displacement solution coefficients
β_l	=	moment solution coefficients
μ	=	nondimensional moment
μ_x	=	mean value of the random variable x
ρ_w	=	percentage of flexural steel in ROI (equation 3.13)
υ	=	nondimensional displacement
ξ	=	nondimensional length
Φ_l	=	moment shape functions
ϕ_u	=	ROI ultimate curvature
Ψ_k	=	displacement shape functions
σ_x	=	standard deviation of the random variable x
τ	=	nondimensional time
$\bar{\tau}$	=	nondimensionalization factor for time

CHAPTER 1

Introduction

In the past twenty-five years there has been a resurgence of interest in the effects of conventional weapons on structures (Krauthammer,1987). This is due in part to the many uncertainties which characterize the loading and response process of a structure in a conventional weapon environment plus the realization that there is simply no future in the use of nuclear weapons. The occurrence of DESERT STORM further served to illustrate the effectiveness of advanced conventional weapons against targets which only two decades ago could only be held at risk with nuclear weapons. The introduction of precision guided munitions and tough, penetrating warheads has caused a re-thinking of the "near miss" mentality that has dominated "survivability designs" to date.

Concurrently, the methods by which "hostile" structures are targeted and weaponeered are also being redefined. In targeting, uncertainties in delivery accuracy are accompanied by uncertainties in the structural characteristics of the target, such as wall thickness (internal and external), percent of steel reinforcement, concrete strength, etc.. The target structural characteristics uncertainties above will be referred to as target intelligence uncertainties for the remainder of this dissertation. The ability to perform meaningful pre- and post-attack Battle Damage Assessment (BDA) is driven by the amount of information known about the target coupled with the analyst's capability to perform weapons effects calculations. Current probabilistic structural response methods do not incorporate target structural uncertainties into their probability of kill calculations.

The primary concern of commanders during a conflict is whether they accomplished their military objective with the fewest casualties. For air commanders this translates into answering the following question; Did an attack achieve the level of damage desired or do more pilots need to be sent in harm's way to re-strike the target? Combat decision makers require personnel to perform pre- and post-attack damage analysis and provide realistic assessment given whatever level of target intelligence is available. In a combat environment or in preparation for a contingency operation, damage predictions are required in near real time. A push is on to incorporate structural damage predictions and graphical representations into combat simulators and trainers therefore exacerbating the real time requirement. Realistic bounds are required for the structural characteristics presented in Table 4.2. The mean values and probability distribution of each variable will be based on known local design and construction practice. For example, it was found during on-site inspections following DESERT STORM that similarly designed aircraft shelters built in Iraq and Kuwait had very different quality control on concrete mix and placement. This was evident in the response of thick concrete burster layers to contact detonations and penetrating weapons. There is much work underway within the DoD community to quantify the sensitivity to variations in the design characteristics in Table 4.2 when subjected to blast fragment loadings as well as projectile penetrations. A procedure to apply a measure of effectiveness or probability of damage to this process is lacking in the community at this time. This work will present a methodology to combine the weapons effects and target intelligence uncertainties. This methodology will be illustrated for a single case, that of an above ground hardened structure targeted with non-precision weapons, however application to other scenarios are relevant and will be discussed.

A conventional weapon blast produces very high local pressures of very short duration. This is in contrast to the much higher and much longer pressure loading of a nuclear blast. In the conventional arena, structures are designed to withstand a specified weapon damage mechanism based on a threat assessment for that facility. For example, structures which house high value assets or critical mission functions will be designed to withstand the most potent weapon threat. The most threatening conventional weapons existing today are precision guided, penetrating weapons. Structures designed to resist such weapons will not be studied herein. Structures which house less than mission critical functions are traditionally constructed above ground and designed to withstand the primary damage mechanisms of unguided munitions, which are airbl. , and fragments. Unguided munitions may be delivered by tactical fighter-bomber aircraft (ie. F-111, F-15E, F-117) or strategic bombers (ie. B52, B1). The unguided munitions of interest are delivered in groups of up to eight in a "stick" for tactical aircraft and much larger numbers for strategic aircraft. The combination of throw weight of explosive and location of detonation determine the magnitude and duration of a conventional loading which may produce pressures on the order of 30,000 psi decaying exponentially to atmospheric pressure over a period of 1 to 4 milliseconds(msec). From a survivability standpoint, structures designed to withstand standoff loadings of this type are typically called "semihardened" and are traditionally constructed of reinforced concrete from 12 to 30 inches in thickness. In contrast, structures designed to withstand direct hits from conventional weapons are built completely or partially underground, with thicker walls

- Attack scenario
  - Duration of attack
  - Target priorities
    - Single target
    - Blanket bombing/multiple targets
  - Delivery method
    - Airborne
    - Surface
    - Naval
  - Multiple attacks
- Weapon type
  - Physical dimensions
    - Length/width ratio
    - Casing thickness
  - Throw weight (TNT equivalent)
  - Guidance system
  - Detonation method
    - Impact
    - Timed
    - Penetration
    - Delayed fuse
- Pressure-Time history
  - Pressure and casing fragment synergism
    - Spacial representation
    - Arrival and duration representation
- Initial condition representation

Table 1.1 Loading Uncertainties

and a burster barrier cover.

To fully define an attack, and the subsequent damage mechanism seen by a structure, one must start with the intent of the attack. Once a plan of attack is hypothesized, the probability of survival/damage of a structure can be developed by using computer models to predict the response. Predicting the response of a known structure to the threat weapons of interest is a random process due to the uncertainties in the structural material properties as well as inherent uncertainties in the simulation methodology. The random uncertainties associated with the attack/loading and structure/response events, given known structural characteristics, are shown in Tables 1.1 and 1.2.

The majority of work dealing with the response of individual structures to conventional weapons considers deterministic and often very simplistic models. Specifically, spatial variations in the loading are ignored and the structure is represented

- Physical properties
    - Material strength
        - Nonlinear response
    - Strength enhancement due to high stress, short duration loading
    - Composite action
    - Blast arresting device physical characteristics
        - Berms
        - Revetments
        - Sacrificial slabs
    - Multiple hits and strength degradation
        - Spalling/scabbing on front wall
        - Blast attenuation and spalling on inside wall
        - Local breaching
    - Workmanship
- Sophistication of model
    - Single degree of freedom(SDOF)
    - Multidegree of freedom(MDOF)
        - Continuous
        - Finite difference
        - Finite element
    - Support conditions
- Mode of failure
    - Shear
    - Flexure

Table 1.2 Structure Uncertainties

by a single degree of freedom model. The weapons effects objective of this dissertation is to provide an analysis technique which takes into account the stochastic loading and resistance characteristics of the system while using one dimensional continuous load and structure representations. The target intelligence uncertainties will be incorporated into the structure representation as well.

Chapter 2 reviews the current deterministic and stochastic methods of design and analysis of hardened as well as traditional facilities. Research on-going in these areas will be examined. Chapter 3 describes the development of the response statistic generator code to include the load and structural models and the solution technique. Chapter 4 describes the basis and implementation of the stochastic response analysis. Stochastic analyses are compared for various real-world delivery situations and structural variable distributions. Chapter 5 provides recommendations and conclusions.

CHAPTER 2

Background and Literature Review

2.1 Deterministic Design and Analysis of Protective Structures Against Weapons Effects

The methodology used by the Armed Forces in design and analysis of semi-hardened structures is outlined in the US Air Force manuals, "Protection From Nonnuclear Weapons"(Crawford,1971), "Structures to Resist the Effects of Accidental Explosions"(TM5-1300,1990), "Protective Construction Design Manual"(Drake et al.,1989) and the Army manual "Fundamentals of Protective Design For Conventional Weapons"(TM5-855,1986).

Drake et.al,1989 is the current authority for the U.S. Air Force. According to this manual, the three cases of interest for surface structures being considered are: (1) direct hits resulting in extreme damage, (2) close-in bursts causing extremely high and nonuniform overpressures and fragment loadings, and (3) bursts occurring far enough away for the pressure loadings to be approximately uniform. With the accuracy of modern weapons, (1) and (2) are becoming the events of interest. They are also the areas about which the least is known.

The steps in the analysis and design of hardened structures (Drake et al,1989) are given in Table 2.1. In the remainder of this section the current methodologies used to perform those steps will be discussed.

2.1.1 Loading Considerations

The empirical formulas refered to in Step 1 above, were developed to determine the minimum wall thickness required to prevent breaching from contact or near contact

Step 1 - As a preliminary analysis, use breaching curves (described below) to estimate the minimum standoff requirements of the wall section to resist breaching.

Step 2 - Perform a structural analysis assuming the weapon burst produces a uniform load, provided the total applied impulse to the structure is maintained. The equivalent uniform load is applied in a single degree of freedom (SDOF) analysis resulting in the maximum structural response at a specified location.

Step 3 - Perform a fragmentation analysis to determine if the design fragment, based on the design or threat weapon case characteristics, will perforate the wall.

Table 2.1 Steps in the Design and Analysis of Hardened Structures

bursts. These formulas are based on National Defense Research Committee (NDRC) tests (White,1946), supplemented by more recent test data (McVay,1988). These curves can be found in recent manuals (Drake et al,1989;DAHS,1993). Examples of these curves are shown in Figures 2.1.and 2.2 and were taken out of Hyde,1988. These curves are for cased and uncased explosives and are based, for the most part, on scaled model tests. It has been reported that strain rate effects (McVay,1988), cannot be modeled or scaled explicitly, causing model structures to withstand slightly less damage than otherwise equivalent full-scale structures. This fact may result in the under prediction of real world damage based on these curves. Breach and lower levels of damage may be read from these curves using the scaled wall thickness, $t/W^{1/3}$ and the scaled range $R/W^{1/3}$. For cased weapons the scaled range is multipled by $W/(W+C)$, where C is the case weight.

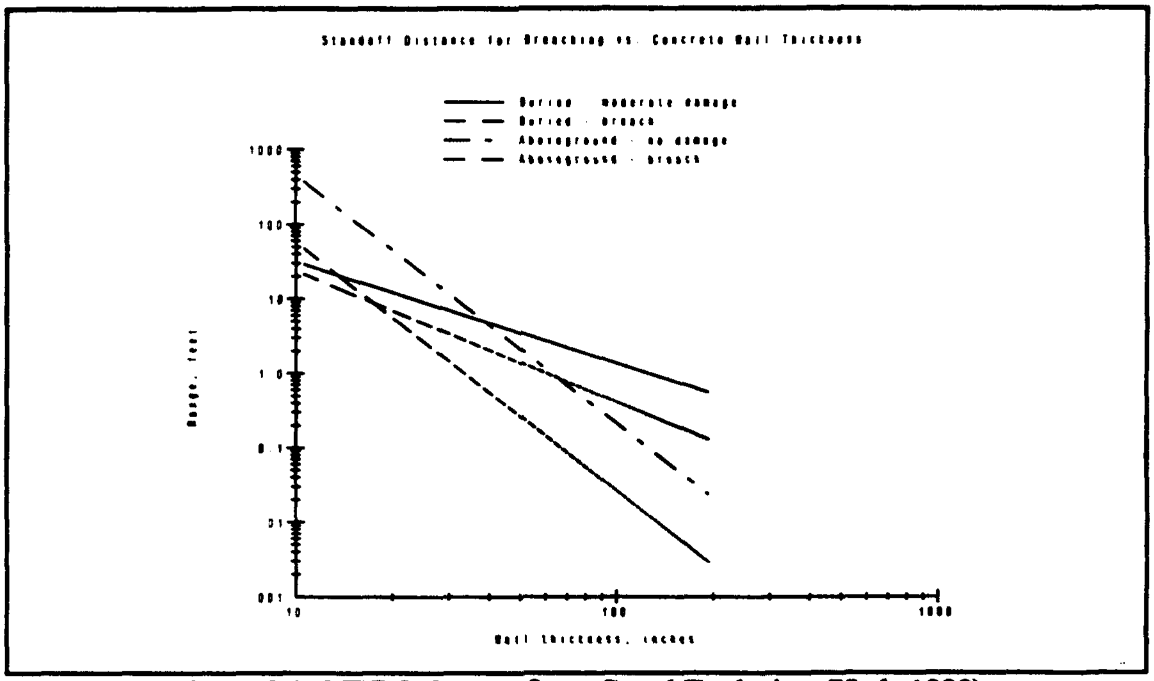

Figure 2.1 NDRC Curves for a Cased Explosive (Hyde,1988)

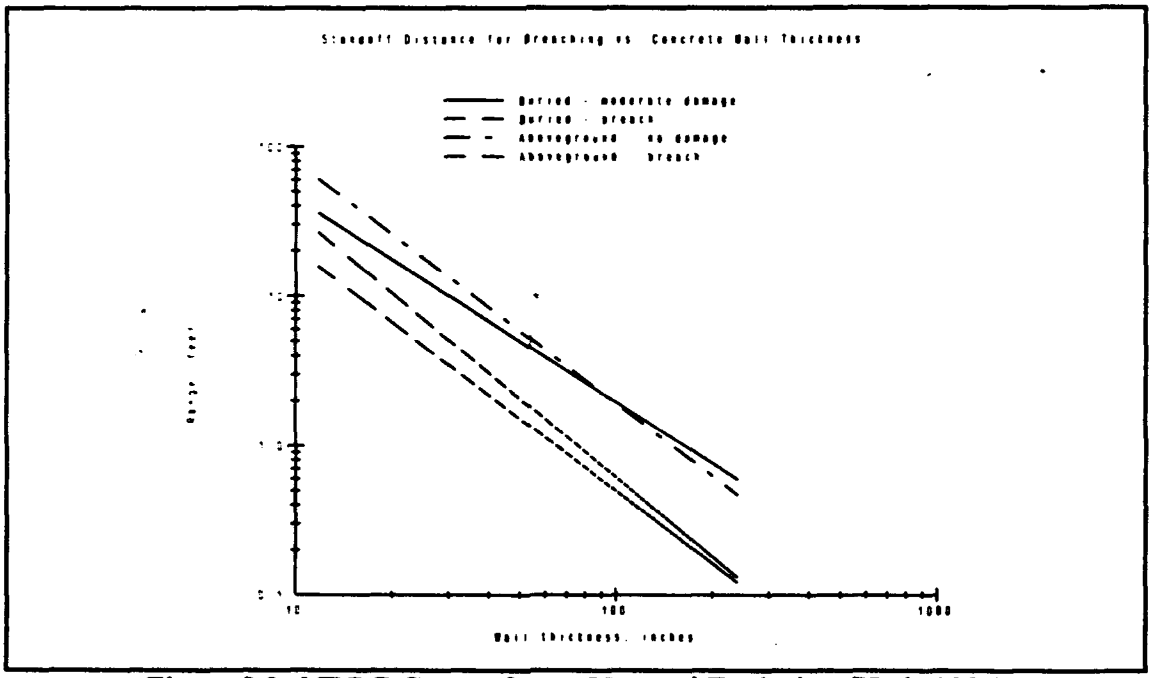

Figure 2.2 NDRC Curves for an Uncased Explosive (Hyde,1988)

The equation

$$\frac{t}{W^{1/3}} = a\left(\frac{R}{W^{1/3}}\right)^{-b} \left(\frac{W}{W+C}\right)^{-c} \tag{2.1}$$

was used to generate the curves of Figures 2.1and 2.2. Table 2.2 gives the values of a, b, and c used to generate those curves.

Descriptions of near field bursts have traditionally disregarded the nonuniformity of the blast loading as well as weapon casing effects (Crawford,1971; TM5-1300,1990). In fact, it has been shown that the blast loading is very concentrated about the centroid of the weapon. The effects of the weapon case on the load attributed to a weapon has been widely debated. One method of including such effects is to decrease the blast loading to account for the energy absorbed in case break-up. It is correct that the blast pressure seen by the structure from a given size cased explosive is less than if the charge

	a	b	c
No Damage Cased Weapon	0.43	0.3	0.3
Breach Cased Weapon	0.23	0.3	0.3
No Damage Bare Charge	0.3	0.62	0
Breach Bare Charge	0.13	0.62	0

Table 2.2 NDRC Equation Coefficents (Hyde,1988)

were uncased. In this method however, the impulse delivered by the fragments is ignored. This impulse has been shown in some cases to be very destructive (Hader,1983). The current method (Drake et al,1989;DAHS,1993) does not reduce the blast loading due to case break-up but does not explicitly account for the fragment loading. Only recently have researchers become very interested in the combined or synergistic effects of blast and fragments from cased explosives (Hader,1987; Marchand,1986; Kropatscheck,1983; Koos,1987). Studies to explictly model fragment loading and synergistic effects have been sponsored by various DoD agencies beginning in 1988 (Marchand,1988; Sues and Twisdale,1993).

2.1.2 Structural Response Considerations

The SDOF commonly selected is the midpoint deflection or support rotation of a slab representing the portion of the protective structure. The wall dimensions typical in protective construction in conjunction with observed response characteristics has led to the common modeling of wall sections as one-way slabs (Biggs,1964; TM-5-855-1,1986). Equivalent SDOF parameter representations of such structures are provided in tabular form in several publications (Biggs,1964; Crawford et al,1971; TM-5-855-1,1986).

The justification for use of the uniform load and SDOF models hinges on the uncertainties surrounding the loading and material responses not warranting elaborate and/or expensive analysis techniques (Biggs,1964). Additionally, in protective construction design, the main design driver has been maximum displacement, which has been shown to be modeled reasonably well with the SDOF representation for above ground and shallow buried structures (Coltharp et al,1985; Krauthammer,1986). The shortfalls of the SDOF method this dissertation addresses are:

1. Response characteristics generated for the designated degree of freedom only.

2. Spatial load variations, to include fragment effects, can not be analyzed.

3. Shear away from the supports can not be analyzed directly.

4. Significant participation of higher modes of vibration, typical under impulsive loadings, cannot be evaluated.

When under near field loading, shear failure has been shown to be prevalent (Ross and Krawinkler,1985; Krauthammer,1986) as well as the early achievement of the ultimate moment capacity at points away from the midspan. With the addition of fragment impacts and maximum nonuniform pressures near the bottom of the wall, shear failures away from the supports have been observed. This so called punching shear or vertical shear failure has been called an early time failure (Ross and Krawinkler,1985; Van Der Veen and Blaauwendraaad,1983; Krauthammer,1986). The failure occurs so early that there appears to be no flexural contribution. Thus it has been proposed that separate shear and flexural criteria can be used to predict failure once the response has been computed (Ross and Rosengren,1985; Krauthammer,1986). If the structure does not develop a critical shear response, it can fail later in flexure. The ultimate moment may occur away from the midspan if the pressures are sufficiently high and are concentrated in one area, normally the bottom half of the wall. In these cases yielding then propagates toward the midspan (Ross and Rosengren,1985; Krauthammer,1986).

2.2 Probabilistic Methods in Design and Analysis of Protective Structures Against Weapons Effects

2.2.1 General

Probabilistic analysis of protective structures was first used for hardened facilities, or facilities required to resist nuclear loads. In 1968 a program called FAST III was completed which modeled various elements of the hardened or strategic systems failure problem (Rowan,1977). Failure Analysis by Statistical Techniques (FAST) was developed to study nuclear attack survivability, using Monte Carlo simulation. Within the program simulations are run with probable attack scenarios and possible failure modes and probability statistics are computed. The code underwent several revisions (Rowan,1977) until it was replaced by Probability Assessment of Strategic Systems (PASS) code adopted by the Air Force in 1988 (Kung et al,1988). The new code, which covers a wider variety of scenarios and failure mechanisms than FAST, mirrors current technologies but uses the same Monte Carlo approach to derive response and survivability statistics.

Several air base attack simulation models use a probabilistic approach for assessing overall damage effects from a predetermined attack scenario. One such program is entitled TSARINA, and was developed by the RAND Corporation. The main objective of this code is to generate air base attack outcomes that exhibit realistic levels of damage across Monte Carlo trials. It was not designed to accurately estimate the damage to any particular target for a particular impact point and weapon. Damage assessment is accomplished using a "cookie-cutter" method based on weapon effectiveness data taken from the Joint Munitions Effectiveness Manuals/ Air to Surface (JMEM/AS) manual which will be discussed later in the chapter. For each kind of point impact weapon the code assigns an effective miss distance (EMD) according to each target type.

Semihardened type facilities would be one such target type. If a facility target falls within the radius of a weapons EMD after an attack, the fraction of the facility covered leads to the determination of the fractional damage to the facility. Cumulative damage from multiple point impacts may be attributed to a facility. Failure criteria for different types of facilities are based on reaching a certain fractional damage level.

The Effectiveness/Vulnerability Assessment in Three Dimensions (EVA3D), is a model developed under funding from the Air Force to assess the vulnerability of hard targets (Bessette,1988). The results of this code could feed an overall air base or theater conflict simulation model such as TSAR mentioned above. EVA3D is a Monte Carlo simulation model which seeks to provide a realistic assessment of damage to a structure and its contents. Either a structural kill or a functional kill may occur. The ability to predict a functional kill is much more dependent on the foreknowledge or intelligence available on that facility. Within the code a variety of predictive "tools" are available. The user has the ability to apply a force in one of four ways. They are: (1) laser-guided bomb delivery, (2) electro-optical guided bomb delivery, (3) unguided or stick bomb delivery and (4) Pk region analysis. Cases 1 and 2 both deal with precision guided munitions and are not relevant to this work. Case 4 is available to specifically provide output data that would be consistent with the data requirements of the TSAR/TSARINA model. The stick bomb delivery method is the one of choice for this effort and will be described in the context of its EVA3D application as background. EVA3D uses a MSBASIC program developed by the JMEM community for evaluating runway survivability from an attack by an aircraft carrying a stick of "dumb" bombs. A stick delivery is a method of bombing in which two or more bombs are released at a predetermined interval from one aircraft as a result of a single actuation of the bomb-release mechanism on the aircraft. Stick patterns or how the weapons are delivered relative to a reference point are generated using the JMEM/AS data that is fed into the Stickbomb code. The stick patterns are a function of delivery profile, the weapons loadout, intervelometer setting, and weapon aerodynamic/stability characteristics. These variables are inputs into the Stickbomb code. After the Stickbomb code returns a stick pattern relative to a reference point the EVA3D code determines the actual impact points by applying a procedure that accounts for aiming error and ballistic error. Each bomb also is evaluated for fuse reliability, that is one bomb in so many is considered a "dud." For the purposes of this work these "filters" will not be applied and the reference point cited above will become the aim point or center of the target. A sample stick pattern is shown in Figure 2.3.

Chou and Chang,1987 suggests using Markov chains to model the detonation locations of weapons during a sequence of attacks. This way the actual load seen by a structure may be approximated since the loading is directly proportional to the structures distance from the detonation point of the weapon.

Wong,1985, extended the first-order, second-moment method in attempting to quantify the uncertainties in the representation of dynamic soil-structure interaction(SSI). Dynamic SSI refers to the coupling between the response of a buried structure and the loading exerted by the medium on the structure after the detonation of a conventional weapon either above or below ground. The parameters modeled as uncertain are the

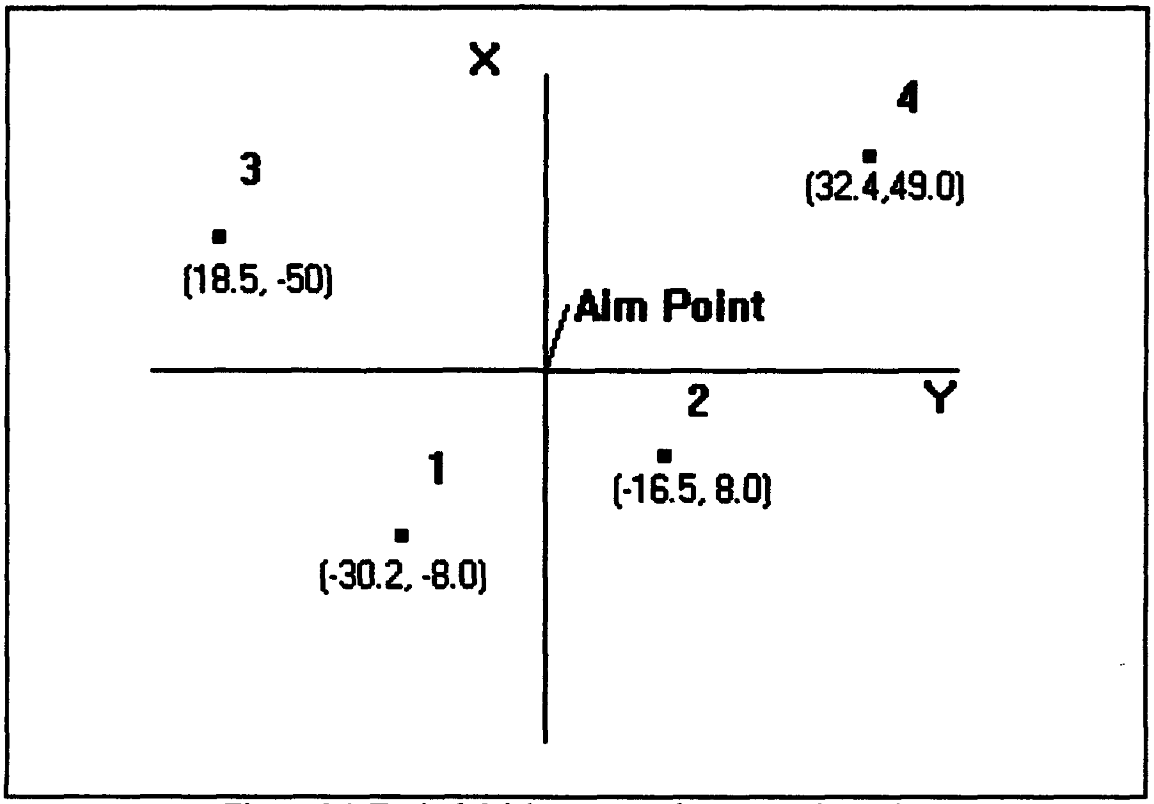

Figure 2.3 Typical Stick Pattern About An Aim Point

nominal overpressure loading, the loading moduli, the unloading moduli, the pressure rise time and the soil density.

Research funded by the Air Force has resulted in work on the feasibility and applications of stochastic methods in design and analysis of protective structures (Twisdale,et al.,1988; Ross, et al.,1988). Both reports recommend stochastic methods. Twisdale, et al.,1988, focused on developing a reliability based design for protective structures. Their main approach is based on defining limit states for probable failure modes. They recommend the use of a First-Order, Second-Moment method (Ang and Tang,1984) or Monte Carlo simulation as discussed earlier. Ross et al,1988, recommend the use of Monte Carlo simulation for assessing the influence of uncertainties in design.

Very recent emphasis in the conventional weapons effects community has been placed on increasing the ability to predict fragment loadings on structures (Hader, 1983; Koos, 1988; Marchand, 1988; Sues and Twisdale,1993). The work in this area centers around the ability to predict a design fragment and the loads generated from fragment applications. In protective construction design, a design fragment is specified for which a structural element must resist penetration, perforation and/or spalling. In the same study advances have been made in the area of fragment structure interaction to include predicting the loads on the structure due to penetrations versus ricochets. With current methods, given a weapon location relative to the structure, the number of fragments that penetrate and ricochet at each section can be predicted. In turn the load imparted to the structure may be predicted for either penetration, perforation, cratering, and ricochet. Predictive tools under development currently lack sufficient empirical data to allow reasonable verification of the results.

2.2.2 Application of Reliability Methods

The use of reliability methods in engineering design has significantly increased in recent years. Because of the large uncertainties in most engineering problems the measure of safety has shifted from simply applying a safety factor to developing probability based design factors which account for the probability of failure or survival in a systematic and accepted fashion (Ang & Tang,1984). Reliability problems aim to determine a probability of failure (P_f) for general engineering problem where failure is easily and traditionally defined. In the area of design and analysis of protective structures the definition of failure is not so well defined. These structures are designed to withstand a certain level of plastic response therefore generating a nonlinear problem. Where that nonlinearity crosses the level that renders the structural element under analysis unusable is debatable. Therefore, in lieu of determining a specific P_f it will be more useful to develop a cumulative distribution function (CDF) for each response parameter that might represent a failure mode that can be used for later development of one or more P_f's. It has been shown that these same reliability methods can be used to develop the desired CDF's (Wu, et al,1989).

The structural reliability methods alluded to above were developed by Hasofer and Lind,1974, Rackwitz and Feisler,1978, Hohenbichler and Rackwitz,1981, Tvedt,1983 and Madsen et al, 1986. The initial step in these methods is to define a limit state function or performance function. A typical performance function takes the form:

$$g(X) = g(X_1, X_2, \ldots, X_n) \tag{2.2}$$

in which the X_i 's represent a set of basic state variables that define the performance either explicitly or implicitly. In general the X_i 's may be correlated random variables . For the purposes of this discussion they are assumed to be uncorrelated and mutually independent.

The limit state may then be defined as $g(X) = 0$, which for reliability purposes states that if $g(X) < 0$ then the system is in a "safe state" and if $g(X) > 0$ the system is in a "failure state." The probability density function (PDF) of the state variables is defined as $f_X(x) = fx_{1,\ldots,}x_n\,(x_1\ ,\ldots,\ x_n\ )$. The cumulative distribution function (CDF) is further defined as

$$P(\mathbf{g} \leq g) = F_{\mathbf{g}}(g) = \int_{\mathbf{g} \leq g} f_{\mathbf{x}}(\mathbf{x}) d\mathbf{x} \tag{2.3}$$

This multiple integral is in general very difficult to evaluate since the function $g(X)$ is typically nonlinear.. The structural reliability community has overcome this difficulty by adopting and developing a variety of approximate methods for defining probability of safety or in more general terms the CDF described above. One alternative is a Monte Carlo simulation which requires a large number of computer runs. This is further complicated when $g(X)$ is not an explicit function as will be the case in the structural analysis of this work. Other approximate methods are summarized by stating that they rely on the determination of a most probable failure point (MPFP) to evaluate the integral above. The MPFP defined as the point on the failure surface generated by multiple evaluations of $g(x)$, that gives the minimum distance to the origin of a plot of that surface. Given a plot of the *g*-function, at the MPFP that function is further linearized if it is not by definition a linear function. In the case where *g* is not an explicit function, a polynomial or response surface representation of *g* must be determined by multiple runs of the implicit code that represents g. Prior to determining the MPFP the generally non-normal dependent random variables, X_i, are transformed into a set of independent, standard normal variables u_i.

NASA began a 10-year program in 1984 called PSAM (probabilistic structural analysis methods) for the purpose of developing probabilistic methods and structural analysis codes for the components of current and future reusable space propulsion systems. Southwest Research Institute (SwRI) of San Antonio is one of the key contractors in this effort. Under this program a probabilistic finite element code called NESSUS (Numerical Evaluation of Stochastic Structures Under Stress)(Wu and Wirsching,1987B) was developed by SwRI. NESSUS is designed specifically for predicting structural response caused by uncertain basic variables such as loads, material properties, geometry and boundary conditions.

SwRI has published numerous papers using what they call a new, fast probability analysis for reliability (Wu and Wirsching,1987A). They extend the FPI method of Rackwitz and Fiessler ,1978 and Chen and Lind,1983. Their new FPI method has been demonstrated to provide fast and accurate estimates of probability of failure for performance functions normally associated with engineering applications. They introduce an improved scheme for constructing the equivalent normal distributions and a quadratic approximation of the original limit state with log transformation options.

2.2.3 Joint Munitions Effects Manuals (JMEM)

The form of the weapon delivery accuracy adopted by the U.S. Department of Defense (DoD) is outlined in the *Joint Munitions Effectiveness Manual (JMEM)*. The process of estimating force requirements stems from the estimation of the effectiveness of the weapons systems the DoD maintains. These same methods may be used to estimate the probabilities associated with the effectiveness of an adversaries' weapons. The three conditions which lead to the determination of the weapon to be used for a specific attack scenario are:

1. Capabilities and Characteristics of Weapons and Fuses
2. Target Characteristics and Vulnerability

3. Weapon-system Effectiveness

Of these three the third will be of most importance in this work. It is assumed that the first two have been considered by the strategist and have lead to the selection of a certain weapon or type of weapon. Therefore, the structural analysis will be run against a specific weapon assuming it will be delivered in the most advantageous method. Weapon delivery accuracy is the prime measure of weapon-system effectiveness. This parameter will be the primary input information and it can be influenced by many unpredictable associated variables. The uncertainties associated with the manuals estimates are based on data derived from past experience, test results, and theoretical calculations. The probability of hit of a typical conventional weapon is characterized in the *JMEM* by the term Circular Error Probable or CEP. For a large number of bomb drops the impact points describe a normal distribution. The probability structure of the accuracy of a weapon may be described in one or two dimensions. When the target can be described by one dimension so may the weapon accuracy. An example would be the bombing of a highway where the accuracy may be characterized by the impact distance to the left or right of the roadway centerline. The *JMEM* states that the crosstrack and alongtrack values of bomb impacts are independent and normally distributed events. As such the probability of both events is the product of each individual event. The joint probability density function is shown as:

$$f(x,y) = \frac{1}{2\pi\sigma_x\sigma_y} e^{-[(x - \mu_x)^2 / 2\sigma_x^2 + (y - \mu_y)^2 / 2\sigma_x^2]} \tag{2.4}$$

Where the above function describes the probability structure of the weapon accuracy in rectangular coordinates, it has become convenient to describe it in circular coordinates. Making the appropriate transformations the distribution function above may be written as:

$$P = 1 - e^{-r^2/2\sigma^2} \tag{2.5}$$

with

$$r^2 = x^2 + y^2 \qquad\qquad \sigma_x = \sigma_y = \sigma \tag{2.6}$$

To find the value of r that will give a circle containing 50 percent of the impacts, P is set equal to 0.5. This results in:

$$0.5 = 1 - e^{(-r^2/2\sigma^2)} \tag{2.7}$$

or

$$e^{(-r^2/2\sigma^2)} = 0.5 \tag{2.8}$$

Taking the natural log and rearranging, yields:

$$r = \sigma\sqrt{2\ln(2)} = 1.1774\sigma = CEP \tag{2.9}$$

This is defined as the CEP or the radius of the circle in which 50 percent of the impacts will occur. Weapons and associated weapons systems or platforms are assigned CEPs for strategic planning purposes.

In most cases the distribution is noncircular or $\sigma_x \neq \sigma_y$. The delivery accuracy is therefore defined in terms of two normal variates. They are the range error, R, and the deflection error, D. The range error 'R' replaces the variable 'x' and the deflection error 'D' replaces the variable 'y'. Range error probable (REP) and deflection error probable (DEP) values are derived in the same manner as the CEP and can be found in the JMEM for calculating delivery accuracies. The values of REP and DEP are given in the JMEM and can be used to back out the first and second moments of the variables using the following relations developed in the manual:

$$REP = 0.6745\sigma_R \qquad DEP = 0.6745\sigma_D \tag{2.10}$$

Here σ_R and σ_D are the delivery-accuracy measures in range and deflection, respectively. To illustrate this, let the aimpoint be the target and let the flight path be over the target. If two parallel lines are drawn,one on either side of the flight path, at a distance DEP, an infinite strip would be formed that contained 50% of the impacts of the individually aimed and delivered weapon. Likewise, an infinite strip similarly constructed, at 90° to the first strip, having 2*REP as its overall width, would also contain 50% of the impacts. The intersection of these two strips about the target or aimpoint will contain 25% of the impacts.

2.3 Experimental Test Design

Experimental test design or design of experiments (DOE) is a method of tailoring experiments in order to extract the most meaningful information. The method is very useful when there are many variables that contribute to the design of a single experiment. One run of a computer program may be interpreted as a single experiment. The method prompts the user to evaluate the output requirements desired and up-front make decisions that can result in fewer runs, apply simpler analysis techniques and yield more information than undesigned experiments. The output is generally more reliable than the employment of traditional experimentation techniques which involve varying process inputs in an unsystematic way. This method often includes letting the results of one run determine the inputs to the next run which may tell you what you want to know or may in effect be very misleading. In contrast, experimental design requires careful considerations about all aspects of your experiment before you make a single run. This method can save a great deal of time that may be used in unguided runs that often lead the analyst down a long and unproductive road. What assumptions one makes before embarking on a systematic experimental process can be critical to the appropriateness and the validity of the results.

The stages of the experimental design process are as follows.

a) define the problem

b) specify the model

c) select a design

d) running the experiment

e) analyze the data

f) interpret the results

The following is a brief description of each stage

a) **Define the Problem**

Defining the problem requires the experimenter to become familiar with what he is trying to achieve. While defining the problem an objective must be determined. The factors or variables which will interact in a specified process to produce or accomplish that objective are determined. Finally, the response or responses of the process that measure whether the objective has been met are established. If a representation of the process over an entire operating range is desired the response surface methodology (RSM) is recommended.

b) **Specify the Model**

Proper modeling of the process in order to study the interactions and contributions of each factor to the observed response is the key of the method. The model will be a generic equation that will be used to predict the outcome of the process after initial data has been collected and analyzed. The model may be either linear or more complex. Through an analysis of a limited set of actual process runs the coefficients of the model equation are determined. The number of actual process runs required is determined based on the selected design method.

c) **Select a Design**

The design is the method of determining the actual runs required of an experiment to achieve the desired objective. The design and its specific form are determine on the overall objective, the number and type of factors and the order of the terms in the model. Classical and optimal are the two general categories of designs. The following are a few types of classical designs:

- Plankett-Burman
- Full Factorial
- Central Composite
- Fractional Factorial
- Box-Behnken
- Orthogonal Arrays

These classical designs are generally inflexible on the number of runs and variable settings required. Optimal designs are less conventional and use complex algorithms to determine a reduction of runs and variable settings. Although fewer runs are accomplished, the interpretation of the results is often more difficult. One of the most common optimal design is the D-optimal design. The D in D-optimal refers to a "determinant" manipulation. The maximizing of the value of the determinant of the coefficients is equivalent to minimizing the uncertainty in the coefficient values. RSM experiments generally require classical methods due to their complex coefficients.

d) **Run the Experiment**

Once the number of runs is determined along with the desired variable values associated with each run a worksheet is developed and the results are cataloged.

e) **Analyze the Results**

Regression techniques are used to fit the data to the model. Once the initial results are fit the model is evaluated and refined until the model results are reasonable.

f) **Interpret the Results**

With a satisfactory model it can be used to learn more about the basic process. In this case the model will be used to determine the probability structure of the response.

CHAPTER 3

Response Statistics Generation

3.1 Introduction

This chapter describes the development of load and structural models which together generate response statistics for typical hardened facilities subjected to conventional weapons effects. The load model is derived from coded blast environment prediction formulas and graphs found in the literature. The model presented extends current methods by incorporating the ability to predict loads on structures in both time and space. A typical wall unit is modeled as a continuous, hysteretic beam in order to accept the spatial/temporal load model input and produce response statistics across its height. The loading parameters as well as the structure equations of state are nondimensionalized within the code to allow investigations of various structural configurations with a minimum of input. The equations of state of the structure are solved by the method of weighted residuals, on an iterative basis. The combined load and structure models is termed the Response Statistics Generator (RSG) mode. RSG model results are compared to full and sub-scaled test results from the literature (Pyle and Baber,1991).

The following statements/assumptions are made as a preface to the remainder of this chapter:

1. The attack scenario posits the use of unguided munitions against the target. These unguided munitions are normally deployed in "sticks" from four to eight weapons per aircraft.

2. A wall of the above ground hardened structure considered in this study, subjected to blast and fragment loadings from a conventional weapon detonated in its vicinity, will respond as a one-way slab (Biggs,1964; Coltharp,1985; Hyde,1988). This assumption is based on the fact that a typical hardened structure wall has a length to height ratio which allows for this characterization. Therefore, typical wall units will be described as a series of beam models. The beam model will represent a section of the structure described as the region of interest (ROI) in this work (Figure 3 4).

3. The weapons to be investigated will be general purpose bombs which will be assumed to detonate at a near vertical orientation or perpendicular to the ground surface with the nose touching. Casings effects will not be considered explicitly but will be included by using the total weapon weight (explosive plus casing weight) for calculating blast loadings.

3.2 Loading Model

The blast environment from a surface detonation of a typical conventional weapon is depicted in Figure 3.1. In this Figure, taken from TM5-855,1986, the common approximation that the load is applied uniformly at the structure is depicted when in fact it varies rapidly over the height of the wall. In order to accurately represent the loading of a structure from the near field detonation of a conventional weapon, a model is required that can represent both the spatial and temporal characteristics of this phenomena. The free-field pressure-time history from conventional weapon detonation is shown in Figure 3.2, also from TM5-855. The program ConWep, a conventional weapons effects code developed by the Army Corp of Engineers, Waterways Experiment Station

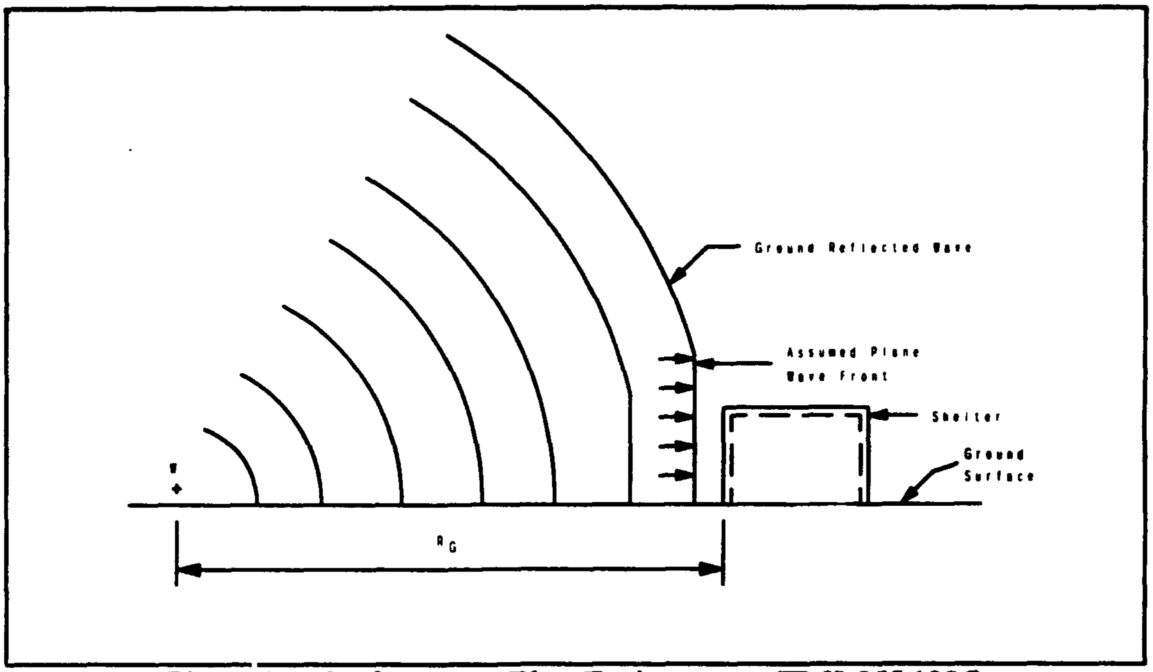

Figure 3.1 Surface Burst Blast Environment (TM5-855,1986)

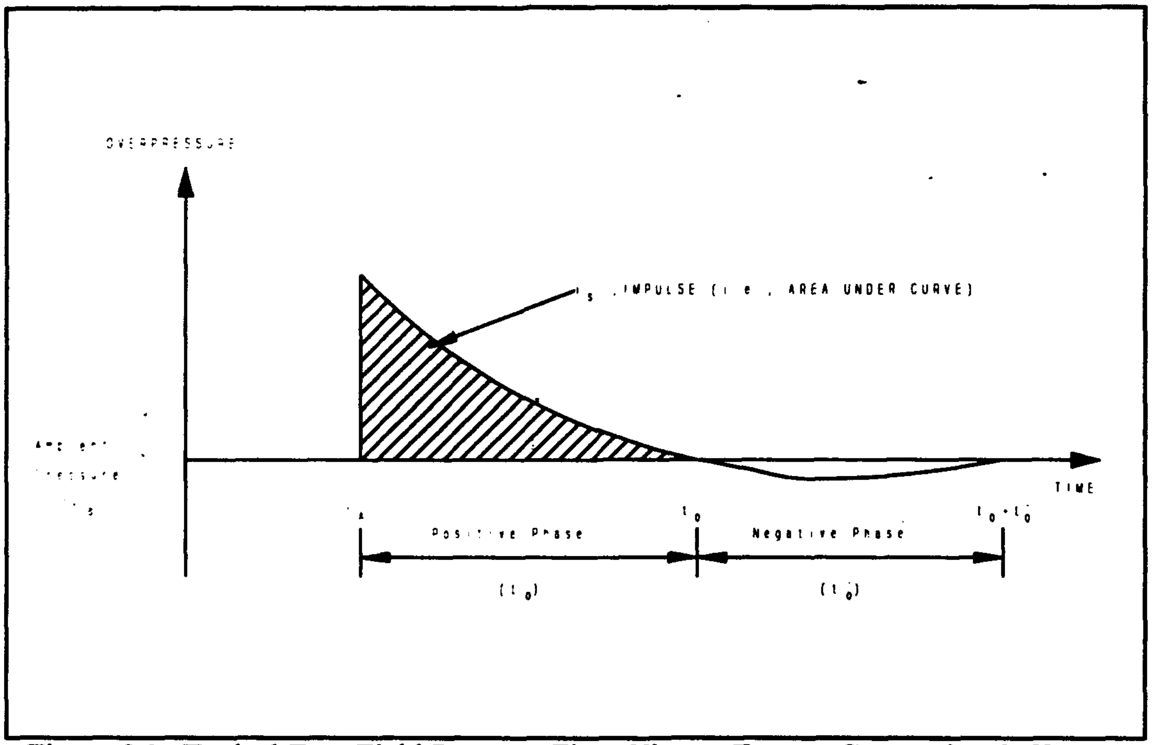

Figure 3.2 Typical Free-Field Pressure-Time History From a Conventional Weapon Detonation (TM5-855,1986)

(Hyde,1988), uses the physics described later in this section to predict the blast environment from a weapon detonation. The incident pressure-time history seen at the base, the mid-height and top of the ROI are shown in Figures 3.3 through 3.5. Clearly the blast seen by the wall is not uniform. This variation is further exaggerated by the higher reflection and magnification of the blast at the lower angles of incidence for the lower portions of the wall. It is argued that the variations are not critical for calculating the bending response of the section, however they seem to be critical for predicting shear failures away from the supports as was discussed in Section 2.1.

The principal parameters that can be taken from Figure 3.1 are:

(1) Time of arrival, after detonation, of the blast wave to the structure. (t_a, msec)

(2) Positive pressure phase duration of blast after arrival at structure. (t_o,msec)

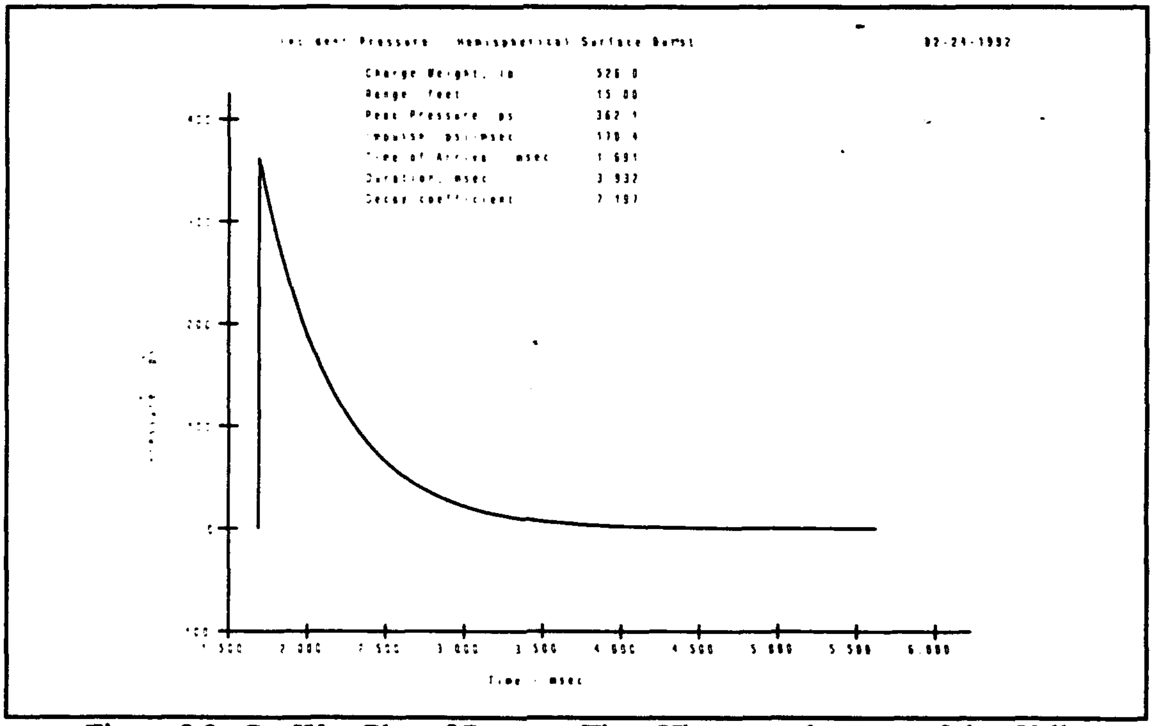

Figure 3.3 ConWep Plot of Pressure-Time History at the Base of the Wall

(3) Peak positive incident pressure seen by the structure. (P_{so}, psi)

(4) Positive incident impulse delivered to the structure. (i_s, msec*psi)

These parameters are presented in graphical and equation form in Kingery,1966. Figure 3.3 is an extract from Kingery,1966 and was constructed using the results of experimental tests accomplished with hemispherical surface bursts of payloads ranging from 5 to 500 tons. Cube root scaling and altitude corrections were made to bring the results to standard sea level conditions for a 1 pound TNT charge. The curves were then generated using standard curve fitting techniques. The required input for pulling information from this graph is the scaled range of the detonation. This is a combination of the location of the detonation relative to the facility or range (R) and the TNT equivalent throw weight (W) of the charge. The scaled range (SR) is defined as:

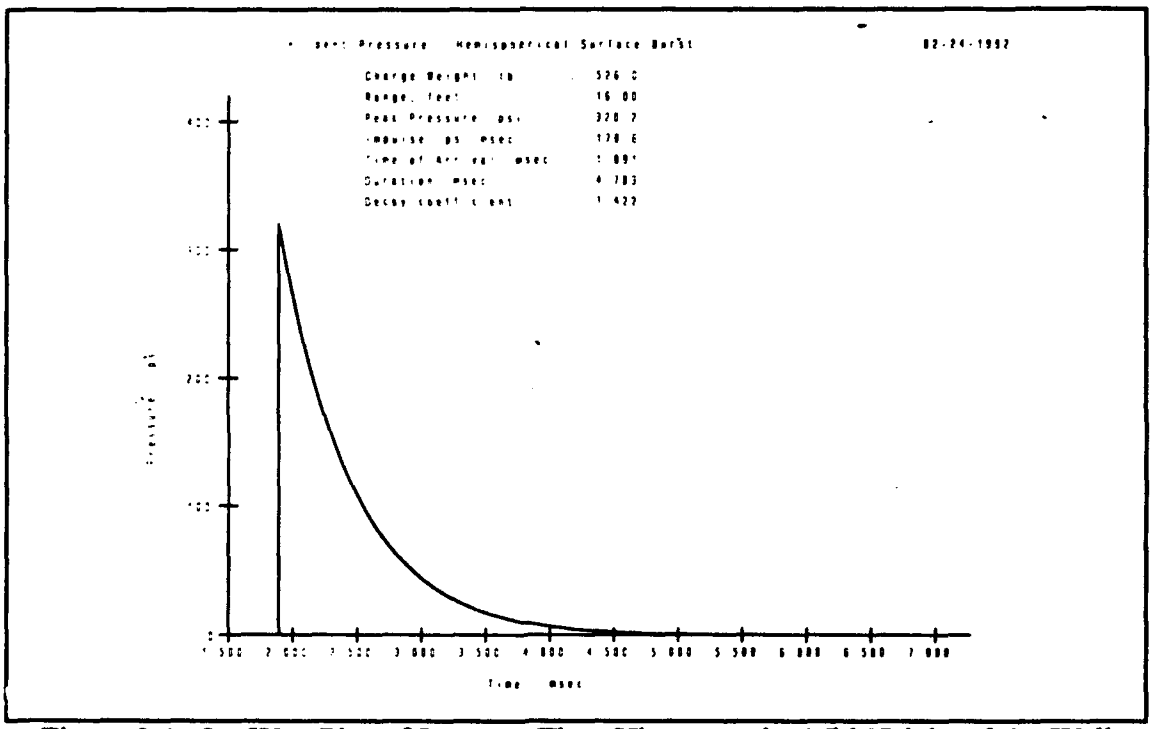

Figure 3.4 ConWep Plot of Pressure-Time History at the Mid-Height of the Wall

$$SR = \frac{(x^2+z^2)^{1/2}}{W^{1/3}} = \frac{R}{W^{1/3}} \tag{3.1}$$

This so called cube root scaling is attributed to Hopkinson,1915, and is well documented and accepted in the literature (Baker,1973; Kingery,1966).

The weapon used in this work is assumed to be a general purpose bomb detonating on impact at a near perpendicular angle to the surface of the ground. Explicit casing/fragment loading effects will be disregarded but will be accounted for by increasing the TNT throw weight of the weapon by the casing weight. The exclusion of the casing effects is not meant to infer its unimportance but is an initial simplifying assumption deemed necessary to set up the method. As discussed in Section 2.1, there is a great deal of interest in the community for further study of case fragment loadings

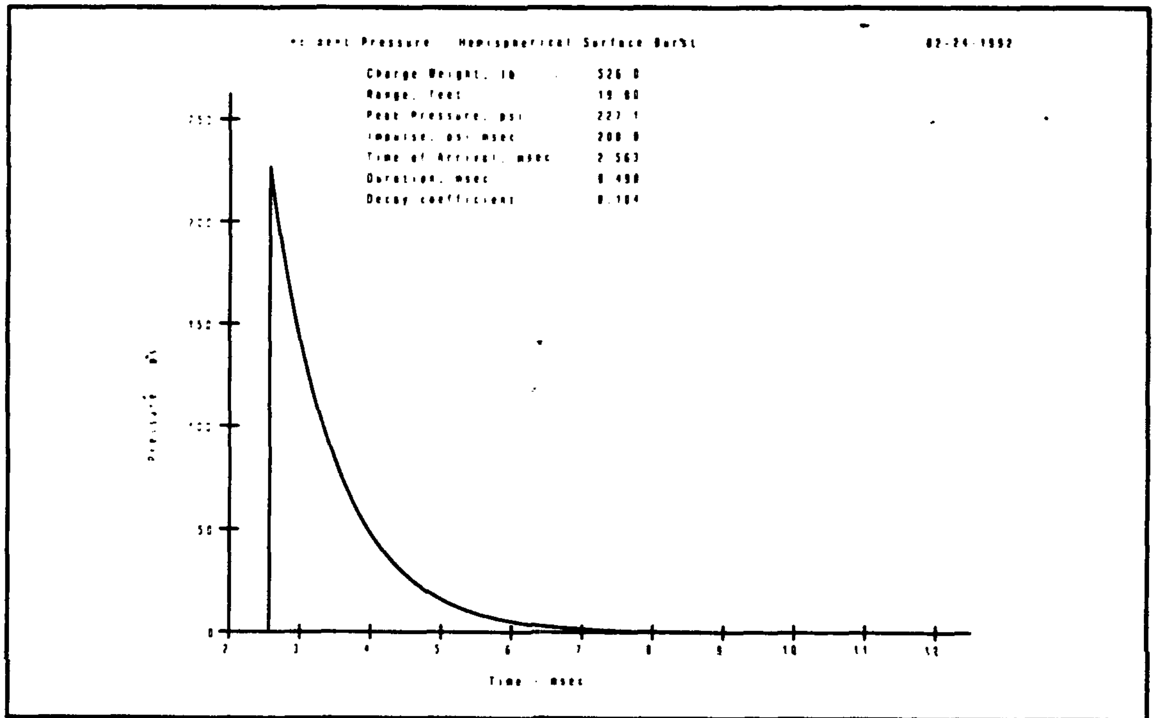

Figure 3.5 ConWep Plot of Pressure-Time History at the Top of the Wall

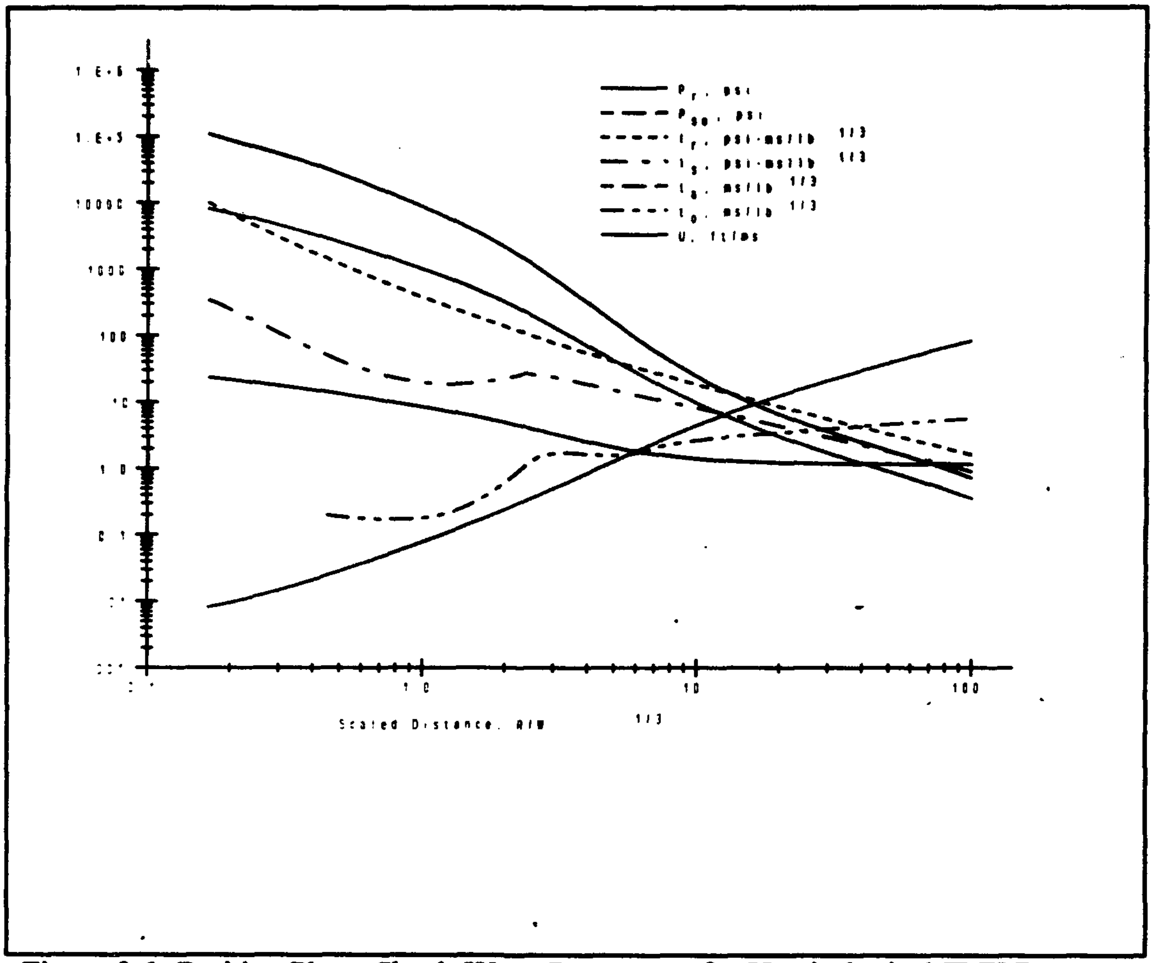

Figure 3.6 Positive Phase Shock Wave Parameters for Hemispherical TNT Bursts at Sea Level (TM5-855,1986)

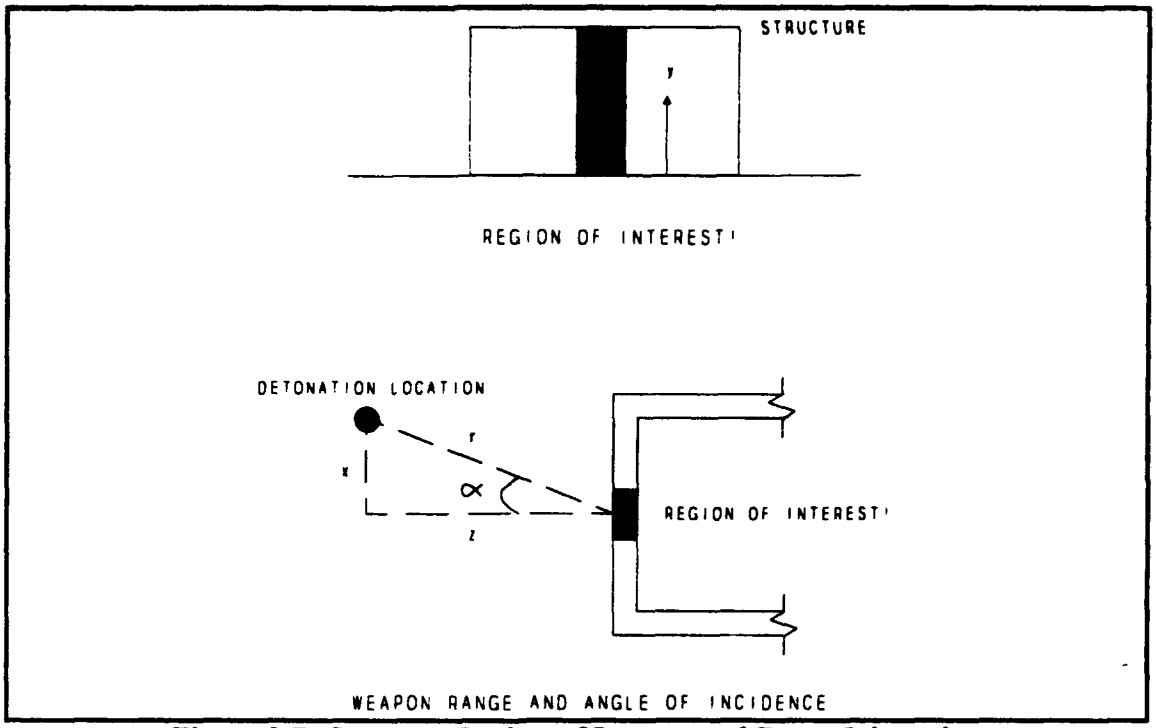

Figure 3.7 Structure Region of Interest and Burst Orientation

and the synergistic effect of blast and fragments. The technology to predict such effects is not available at present and in fact the new tri-service conventional weapons effects design manual, under development, uses the above assumption. The underlying premise in describing the distribution of fragments from a cased ordnance is based on a probability law and should lend itself to inclusion in subsequent work.

Given the attack scenario above, the burst location relative to the ROI, which will be further defined in Section 3.4, may be defined by the range (R) and angle of incidence (α), which are functions of the lateral and incident standoffs, x and z respectively as shown in Figure 3.7.

Segments of the program ConWep were modified and incorporated into the load models presented here. ConWep takes the weapon TNT equivalent throw weight and detonation location and calculates the scaled range. With the scaled range ConWep utilizes equations derived from the curves of Figure 3.6 to generate the parameters which may feed the empirically based modified Friedlander equation (Baker,1973) to produce the ideal blast pressure-time history in air. The modified Friedlander equation

$$P(t)=P_{so}*\left[1-\left(\frac{t-t_a}{t_o}\right)\right]*\exp\left[-A*\left(\frac{t-t_a}{t_o}\right)\right] \tag{3.2}$$

measures time from the time of arrival of the blast wave to the point in space of interest. Various forms of this equation are found in the literature and range from triangular representation with two variables, to this exponential equation with three variables to multiple exponential equations with five variables (Baker,1973). The choice of empirical representation is commensurate with the accuracy desired but that "probably the best compromise is the modified Friedlander equation, since it allows adjustment to conform to the most important blast wave properties and yet is not too complex," (Baker,1973).

When the blast wave hits a rigid surface the particle velocities are arrested and the pressure, density and temperature are increased above the values in the free field incident wave (Baker,1973). The magnification resulting from the reflection of the blast wave is a function of the incident wave pressure and the angle of incidence α. As defined, the lower the angle of incidence the higher the magnification factor. Magnification factor curves, as seen in Figure 3.8, have been developed and are common throughout the literature. These curves, which were generated from experimental data (Crawford,1971),

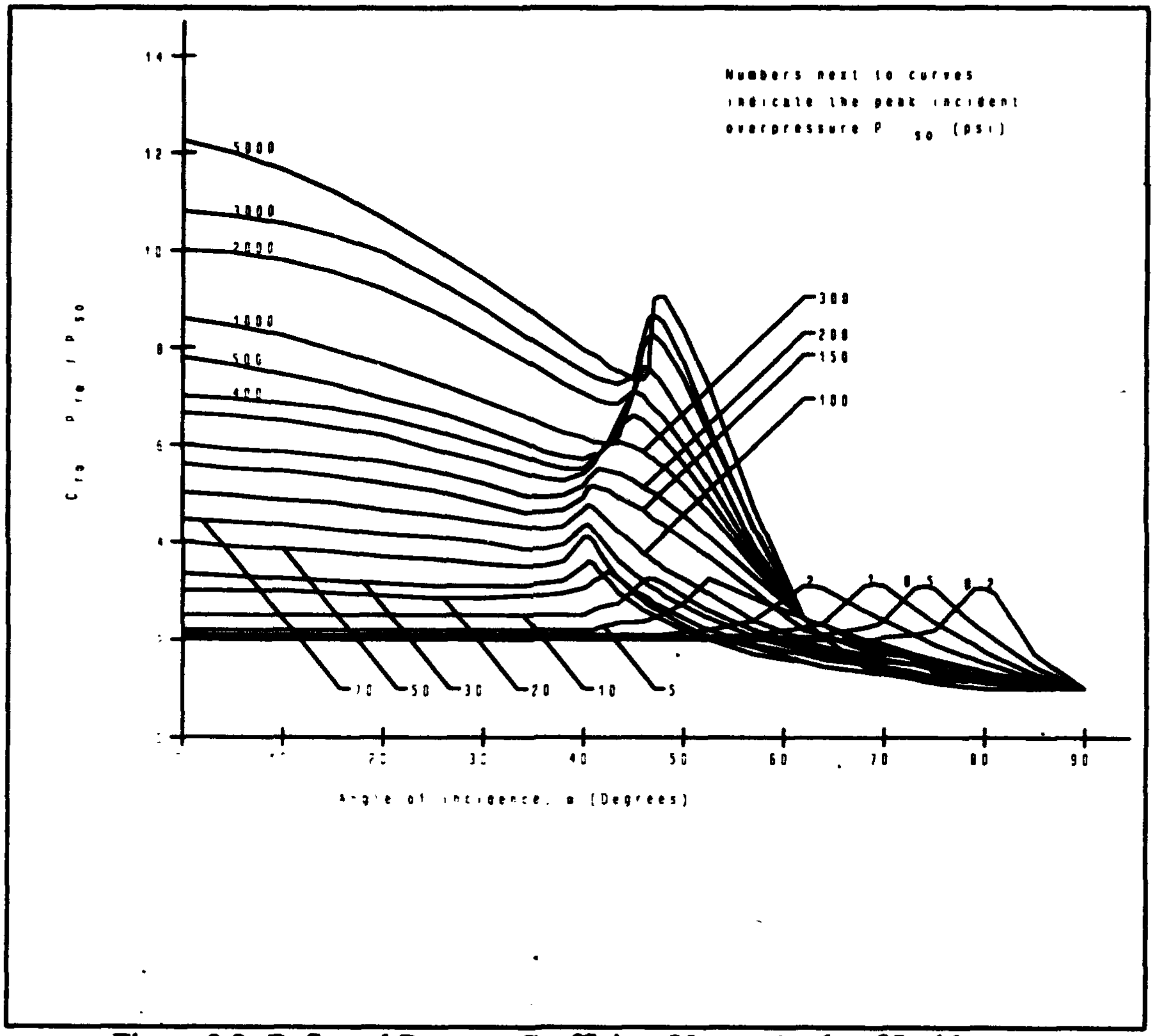

Figure 3.8 Reflected Pressure Coefficient Versus Angle of Incidence (TM5-855,1986)

are coded in ConWep and were also incorporated into the load models developed. Two load model representations were generated and investigated in this work. The goal of each model was to best represent the nonuniformity of the dynamic loading on a structure from a near field conventional weapon detonation and lend itself to interfacing with the structure model which was developed.

3.2.1 - Temporal Wave Form Model

In Coltharp et al,1985, a scaled test structure was subjected to the near field (5 to 15 feet) detonation of a typical conventional TNT throw weight (250 to 1000 lbs) weapon. The test structure was instrumented with pressure gauges as shown in Figure 3.9. The plot of the average pressures at various times along the vertical gage line is shown in Figure 3.10. These series of plots represent a typical set of blast profiles which would

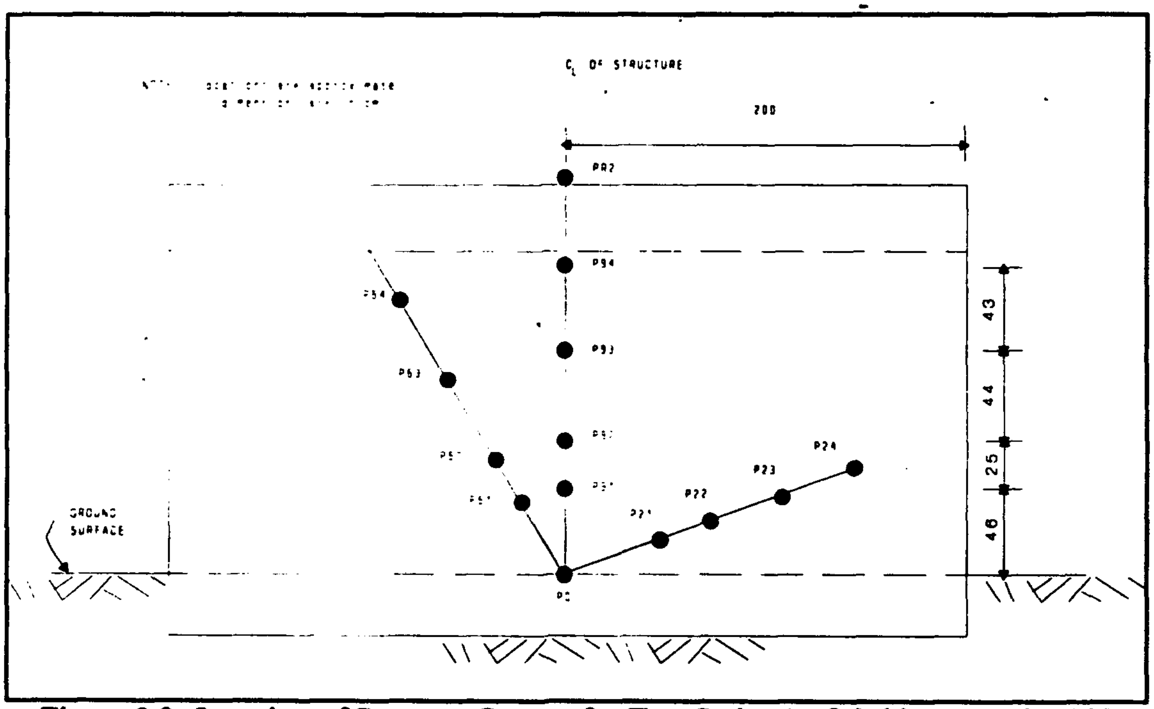

Figure 3.9 Location of Pressure Gauges for Test Series 1 of Coltharp, et al, 1985

be produced by a conventional weapon in the TNT throw weight and standoff ranges of interest in this study. The reproduction of these profiles, while varying the maximum pressure multiplier, represents a typical spatial and temporal loading sequence needed for input into the continuous beam model developed in section 3.2. The reproduction of these profiles for the purpose stated will be called the Temporal Wave Form (TWF) load model.

In development of the TWF load model, the plots of Figure 3.10 were reproduced by multiple order polynomials as shown in Figure 3.11. Based on an analysis of pressure time-histories for specific weapons employments (Coltharp et al,1985; Wright et al,1988; Hyde,1989) and running numerous simulations with ConWep, the number of profiles required to represent the temporal and spatial load history associated with the scaled ranges (range (R) over the cube root of the TNT throw weight) of interest, are shown Table 3.1. These allocations are based on the fact that the further from the structure the weapon detonates the more the load profile resembles a plane wave.

Scaled Range ($SR = R/W^{1/3}$)	Number of Profiles Required
SR < .75	6
.75 < SR < 1.25	5
1.25 < SR < 1.75	4
1.75 < SR < 2.25	3
SR > 2.25	2

Table 3.1 Scaled Range Versus Profiles Required

The prime indicator for allocating profiles and assigning pressure multipliers is a check of the total impulse imparted to the structure for a given loading scenario. The impulse imparted to the beam element is computed by summing the impulse applied by each profile. The individual profile impulse is determined by integrating each profile ploynomial over its assigned duration. The generated total impulse values are compared

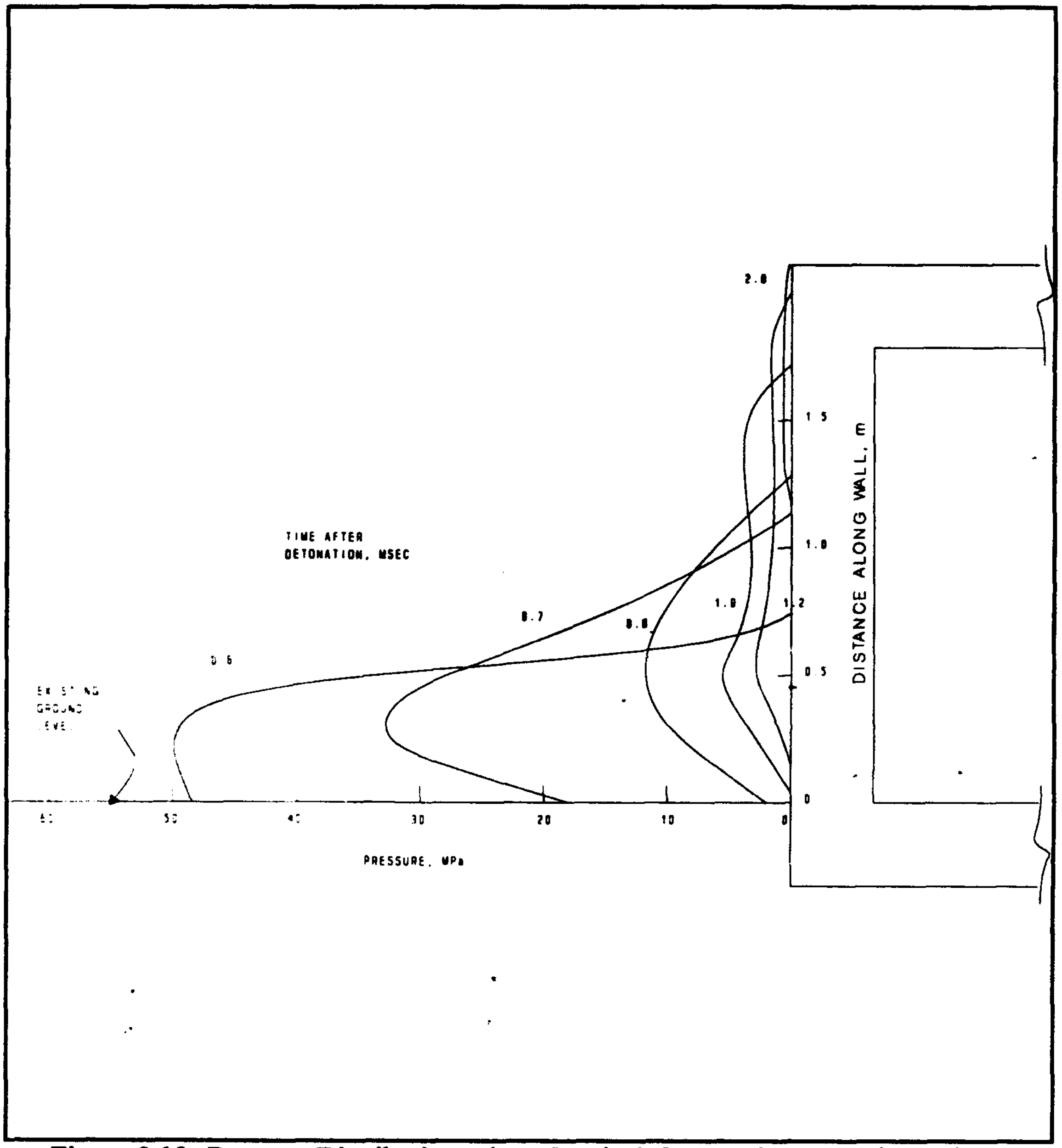

Figure 3.10 Pressure Distribution Along Vertical Gauge Line at Various Times (Coltharp, et al,1985)

to impulse calculations returned by the ConWep program. ConWep divides a structural element into sections and collects the impulse values shown in Figure 3.6 associated with the scaled range to each section. Table 3.2 shows the results of exhaustive comparisons of the type depicted above. This table shows the observed relation between the number of profiles required and the percentage of the maximum reflected pressure and positive phase duration allocated to each profile.

Given a scaled range, the TWF model determines the required number of profiles from Table 3.1. The TWF model then takes the calculated maximum reflected pressure

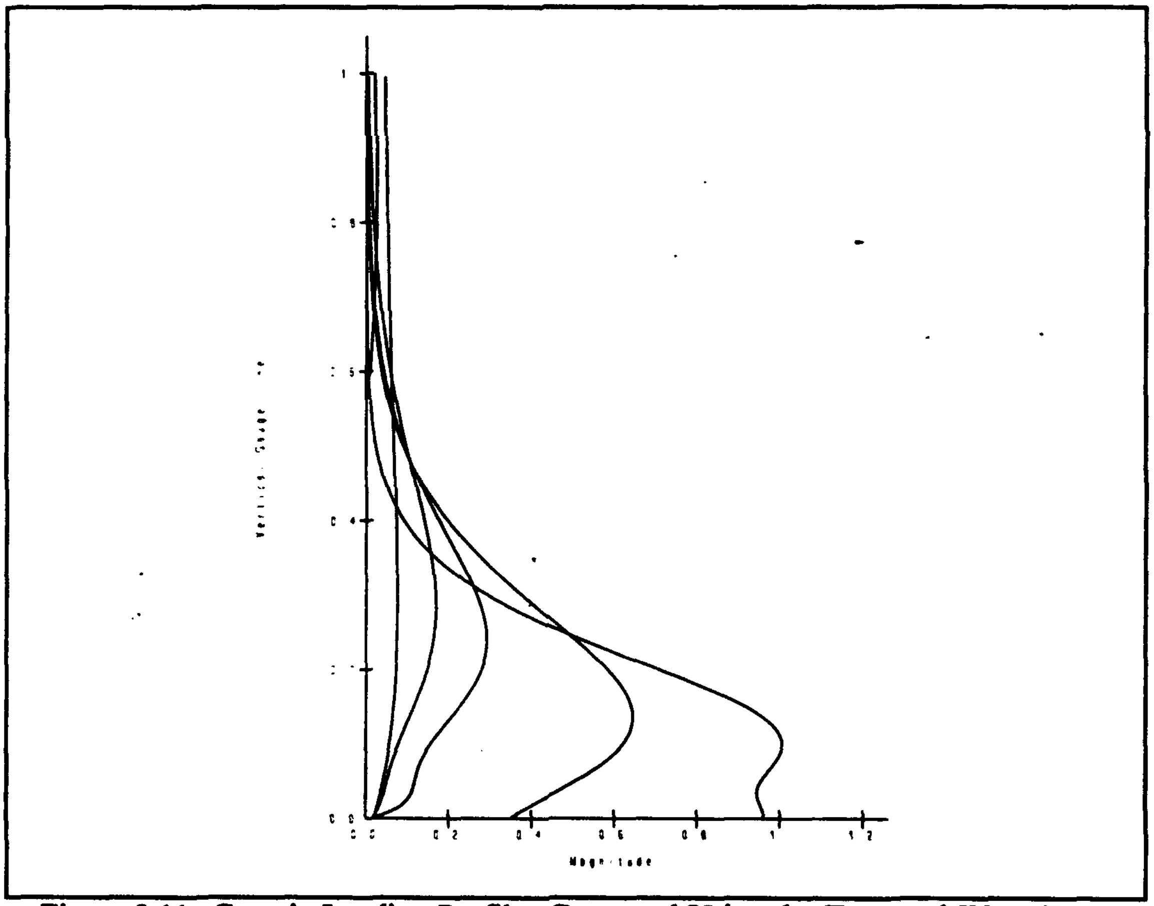

Figure 3.11 Generic Loading Profiles Generated Using the Temporal Wave Form Model

and positive phase duration and applies them to the appropriate set of profiles per Table 3.2. The RSG program calls the TWF model at each time step and applies the appropriate load to the structure model. Figure 3.11 is a plot of a case where five profiles were required to identify the loading based on the scaled range.

Total Number of Profiles	Profile Number	Percent of Maximum Pressure Per Profile	Percent of Positive Phase Duration Per Profile
6	6	100	5
	5	66	5
	4	34	10
	3	13	10
	2	7	10
	1	7	60
5	5	100	5
	4	37	10
	3	20	10
	2	10	20
	1	10	60
4	4	100	15
	3	54	15
	2	30	30
	1	30	40
3	3	100	35
	2	54	25
	1	54	40
2	2	100	40
	1	85	60

Table 3.2 Profile Allocations

3.2.2 - Spatial/Temporal Modified Friedlander Equation Model

The ability to vary the load spatially is added to the modified Friedlander equation by making the primary input parameters functions of the vertical location of the point of interest relative to the burst location. The time of arrival (t_a) and positive phase duration

(t_o) become functions of the three dimensional scaled range (TDSR) defined in equation 3.3, which includes now the distance up the ROI (y) from the ground surface. The incident pressure (P_{so}) also becomes a function of the TDSR . The resulted incident pressure is magnified by the appropriate reflection factor from Figure 3.8 using as input the angle of incidence calculated using the x,y and z coordinates of the point of interest. The input needed to generate the required parameters at any point along the ROI are the detonation location, x and z, the distance up the ROI, y, and the weapon throw weight, W. The TDSR to any point along the ROI is therefore:

$$TDSR = \frac{(x^2+z^2+y^2)^{1/2}}{W^{1/3}} \tag{3.3}$$

With this scaled range one can go to the curves of Figure 3.7 and read off the parameters identified above. The ability for spatial variation is coupled with the inherent temporal variability of the equation resulting in the spatial/temporal modified Friedlander equation:

$$\begin{aligned} P(y,t) = {} & P_{ref}(y) * H[t-t_a(y)] * \left[1-\left(\frac{t-t_a(y)}{t_o(y)}\right)\right] \\ & * \exp\left[-A(y) * \left(\frac{t-t_a(y)}{t_o(y)}\right)\right] \end{aligned} \tag{3.4}$$

The value $P_{ref}(y)$ is the reflected pressure seen at the point y up the wall, at time t. The Heaviside function $H[t - t_a(y)]$ ensures the loading at a specific point is not applied prior to its time of arrival.

As part of the nondimensionalization, the height of the ROI is normalized and it is given a unit width. Parameters are calculated at 70 locations up the wall with 50 falling on the lower half of the wall where the loading changes most rapidly. At each location an equation is generated and the parameters stored. For a typical 12 foot high wall, loaded by a 1000 pound bomb at a 15 foot perpendicular standoff, Figures 3.3-3.5 show the incident pressure time histories at the base of the wall, the mid point and the top. These figures were generated in the program ConWep. The reflected pressure may be calculated by multiplying the incident pressures on these curves by the angle of incidence multiplier taken from Figure 3.8. At each integration time step the model pulls

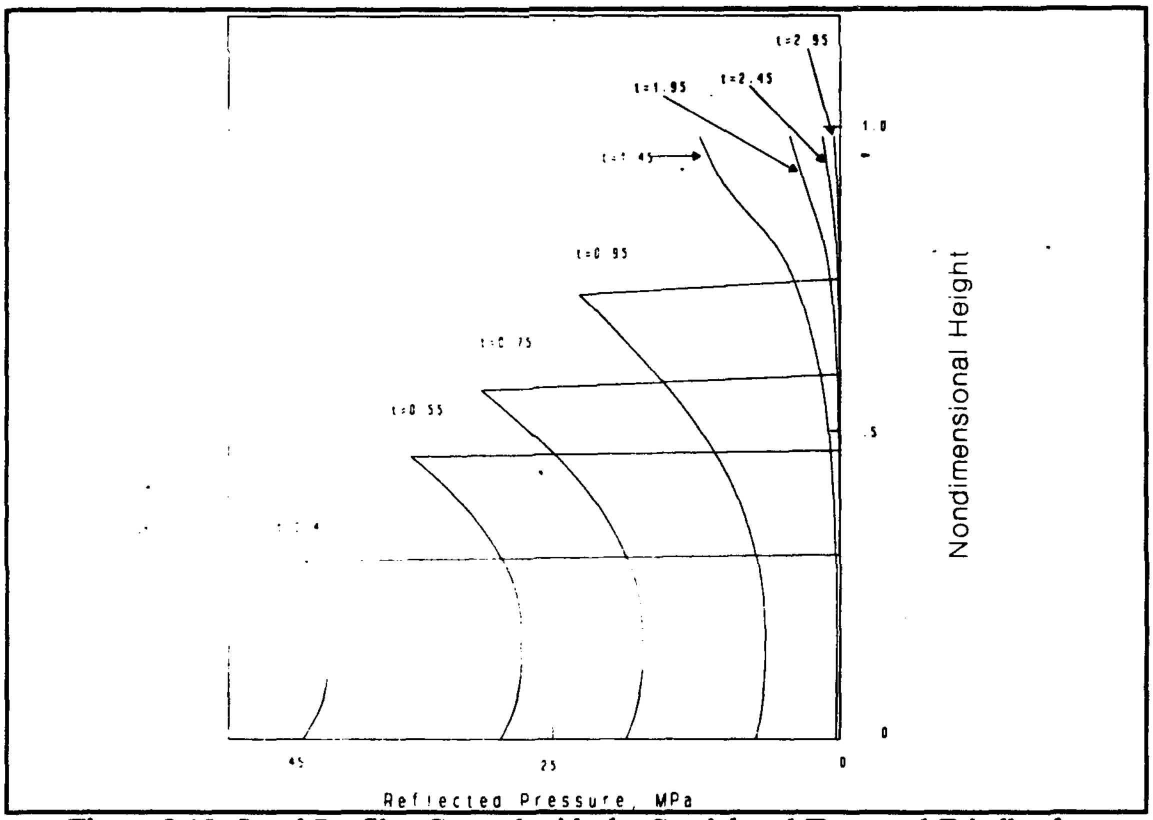

Figure 3.12 Load Profiles Created with the Spatial and Temporal Friedlander Equation Model

the current load on that segment of the ROI from the appropriate curve.

The Friedlander equation model can also be used to generate profiles similar to the ones recorded in Coltharp et al,1985. Figure 3.12 shows profiles generated from the Friedlander model using the test parameters from Coltharp et al,1985 as input.

3.3 Load Model Selection

For the purpose of this study the Spatial/Temporal Modified Friedlander Equation leant itself well to integration into the structure model and solution method chosen. The TWF model, though deemed applicable, did not lend itself to the weighted residual method used to solve the equations of state.

3.4 Structure Model

Reinforced concrete wall structures subjected to the conventional weapons effects of interest in this work have been shown to respond essentially as one way slabs, therefore the use of a beam model to represent the response characteristics is justified. It is desired to model the beam so that the response can be evaluated along its entire length in such a way as to include the higher modes of vibration. It is also desired that the model not be too detailed as to cause unwanted complexity requiring long and expensive computer runs, as in a nonlinear finite element analysis. The nonlinear response of the structure is therefore modeled as a continuous hysteretic beam. The beam model is taken to represent the vertically centered section of the wall referred to as the ROI in Figure 3.7.

The support conditions that best represent the response of similar structures has been characterized as being somewhere between fixed and simply supported (Ross and

Krawinkler,1985). To gain insight into the method proposed the example developed in this work assumes simply supported conditions. This assumption however is not unique as can be seen in the literature (Coltharp et al,1985; Biggs,1962). Other support conditions could be incorporated into the model at a later date.

If the system is modeled as a general beam the equation of motion of the system can be written as

$$m_{,xx} + \rho A v_{,tt} = q_{ext}(x,t) \tag{3.5}$$

where the comma and subscript letters represent the derivative of that term with respect to the subscripted letter. The moment curvature relationship can be defined in terms of linear and nonlinear portions. The moment term of equation 3.5 can be written as:

$$m(x,t) = A_0 EIv_{,xx} + (1-A_0)\mathrm{M} \qquad |A_0| \leq 1 \tag{3.6}$$

The term M represents the nonlinear, hysteretic portion of the total moment. The term A_0 can be interpreted as the post-yield to pre-yield moment-curvature ratio or for reinforced concrete, the post-yield to inital tangent ratio and it controls the degree of nonlinearity that the system will exhibit (see Figure 3.13). For example, if A_0 equals 1 the system is effectively linear while if A_0 equals = 0, the system is fully nonlinear hysteretic. Substituting equation 3.6 into equation 3.5 returns:

$$(1-A_0)\mathrm{M}_{,xx} + A_0 EIv_{,xxxx} + \rho A v_{,tt} = q_{ext}(x,t) \tag{3.7}$$

The term $q_{ext}(x,t)$ represents the load model input to the system. The hysteretic moment curvature relationship may be expressed in various ways. One particularly convenient form is the rate type smooth hysteretic system attributed to Bouc(1967),

$$\frac{M_{,t}}{M_u} = \frac{v_{,xxt}}{\phi_i} - A_1\left|\frac{v_{,xxt}}{\phi_i}\right|\left|\frac{M}{M_u}\right|^{n-1}\frac{M}{M_u} - A_2\frac{v_{,xxt}}{\phi_i}\left|\frac{M}{M_u}\right|^{n} \tag{3.8}$$

Here M_u is the ultimate moment, however, ϕ_i is the curvature where the initial tangent curve intercepts the horizontal ultimate moment curve. A typical hysteretic curve is shown in Figure 3.13. The terms A_1, A_2 and n of equation 3.8 control the shape of the hysteretic curve inorder to replicate the response history of a real world system (see Baber and Wen,1979 for studies on hysteresis shape control). This and similar models were developed to represent response of structures to seismic type dynamic loadings which would normally take it through several cycles. The model may also be modified to include system degradation. At this time there is not sufficient data to generate an appropriate degradation model for the types of loadings under consideration herein. The motion of the system is now totally defined by equations 3.7 and 3.8. Closed form solution of these equations is difficult, so a reasonable approximate solution is desired.

Prior to developing a solution technique the equations are nondimensionalized. This will allow the analysis of systems with various reinforcing and concrete configurations by manipulation of only three input variables. The equations become, after rearranging to solve for the derivative of the displacement with respect to time:

$$v_{,\tau\tau} = \bar{q}(\xi,\tau) - (1 - A_0)\mu_{,\xi\xi} - A_0 v_{,\xi\xi\xi\xi} \tag{3.9}$$

$$\mu_{,\tau} = v_{,\xi\xi\tau} - A_1|v_{,\xi\xi\tau}||\mu|^{n-1}\mu - A_2 v_{,\xi\xi\tau}|\mu|^{n} \tag{3.10}$$

The details of the nondimensionalization are in the Appendix A.

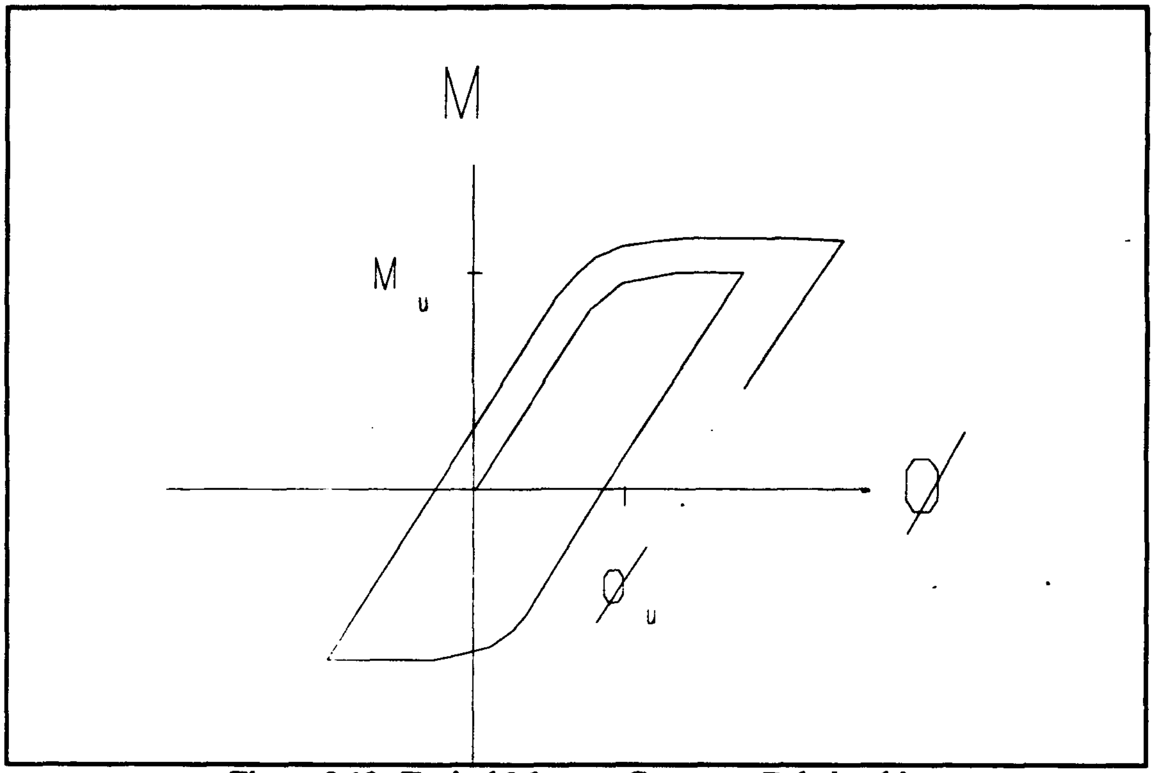

Figure 3.13 Typical Moment-Curvature Relationship

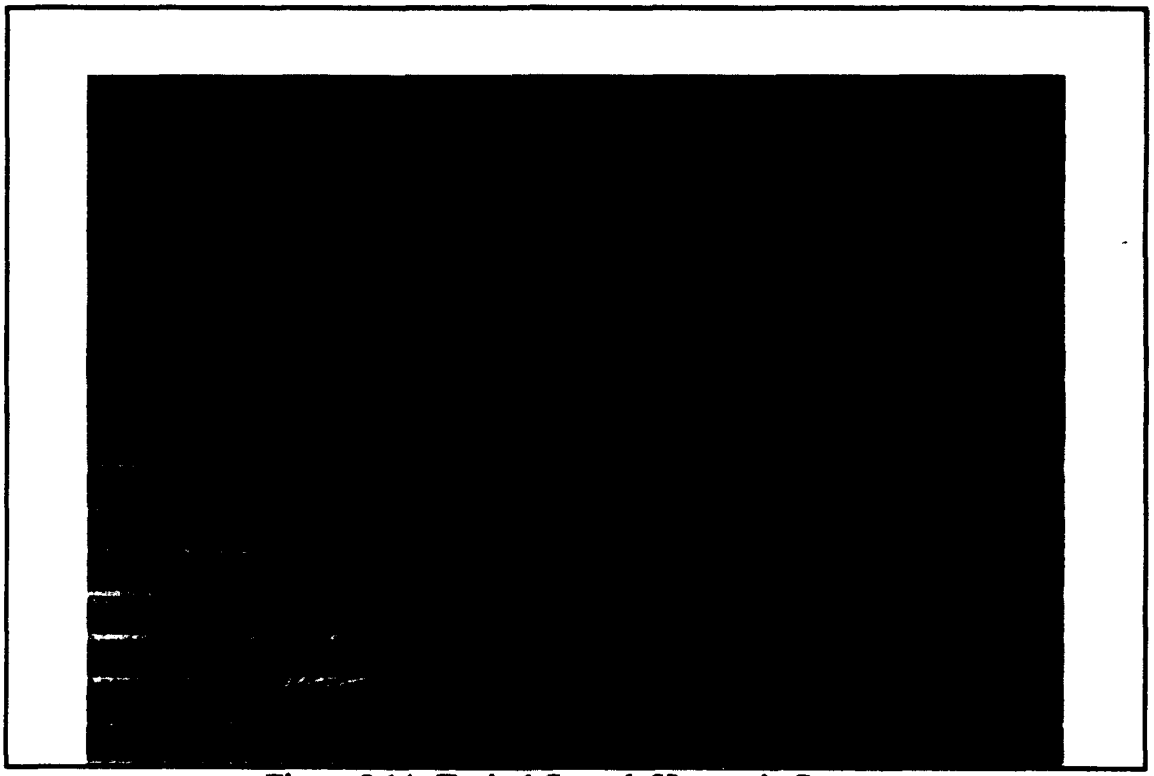

Figure 3.14 Typical Smooth Hysteretic System

3.5 Solution Technique

The approach chosen to solve these equations is the method of weighted residuals(Cunningham,1958). Following this methodology, a set of complete functions that satisfy the physical boundary conditions are chosen to approximate the response of the system. The displacement of the system is approximated by a finite sum of terms in the form

$$v(\xi,\tau) = \sum_{k=1}^{n_v} \alpha_k(\tau)\Psi_k(\xi) \tag{3.11}$$

where the complete set of functions Ψ_k are chosen to be the set of eigen-functions that satisfy the assumed end conditions. In a like manner the moment solution may be approximated as a series taking the form:

$$\mu(\xi,\tau) = \sum_{l=1}^{n_\mu} \beta_l(\tau)\Phi_l(\xi) \tag{3.12}$$

Substituting the assumed solutions of the associated linear systems into the differential equations results in a residual difference e. The residuals of equations 3.9 and 3.10 become:

$$\begin{aligned} e_{11} &= -\sum_{k=1} \Psi_k\alpha_{,\tau\tau} + \bar{q}(\xi,\tau) \\ &- (1 - A_0)\sum_{l=1}^{n_\mu} \Phi_{l,\xi\xi}\beta_l - A_0\sum_{k=1}^{n_v} \Psi_{k,\xi\xi\xi\xi}\alpha_k \end{aligned} \tag{3.13}$$

and

$$
\begin{aligned}
e_{12} = & -\sum_{l=1} \Phi_l \beta_{l,\tau} + \sum_{k=1} \Psi_{k,\xi\xi} \alpha_{k,\tau} \\
& - A_1 \left| \sum_{k=1}^{n_v} \Psi_{k,\xi\xi} \alpha_{k,\tau} \right| \left| \sum_{l=1}^{n_\mu} \Phi_l \beta_l \right|^{n-1} \left(\sum_{l=1}^{n_\mu} \Phi_l \beta_l \right) \\
& - A_2 \left(\sum_{k=1}^{n_v} \Psi_{k,\xi\xi} \alpha_{k,\tau} \right) \left| \sum_{l=1}^{n_\mu} \Phi_l \beta_l \right|^{n}
\end{aligned}
\tag{3.14}
$$

Introducing

$$
\alpha_{k,\tau} = \gamma_k \quad k=1,2,\ldots,n_v \tag{3.15}
$$

then substituting this variable into equations 3.13 and 3.14, results in three first order, partial differential equations. Following the weighted residual method, the error in equations 3.13 and 3.14 are orthogonalized with respect to a set of weighting functions with the equations taking the form

$$
\int_0^1 e_{11}(\xi,\tau)\Psi_k(\xi)d\xi = 0 \qquad k=1,2,\ldots,n_v \tag{3.16}
$$

$$
\int_0^1 e_{12}(\xi,\tau)\Phi_l(\xi)d\xi = 0 \qquad l=1,2,\ldots,n_\mu \tag{3.17}
$$

Where e_{11} and e_{12} denote the residual equations 3.13 and 3.14 above. The model solves equations 3.15, 3.16 and 3.17 simultaneously for the coefficients α, β and γ at specific times τ. The total number of equations to be solved is equal to twice the number of terms used in equation 3.11 plus the number of terms used in equation 3.12. The complete set of functions used as the approximate solution also represent the mode shapes of a linearly responding, simply supported beam. It is interesting that even with the nonlinearity of this problem significant "modal" response occurs when the detonation location is close to the wall. Once the coefficients are determined, the displacements, moments, shears and curvatures at any point along the beam and at any time during the response history, can be evaluated.

Input variables associated with the model are presented in table 3.3. Results of the model under a distributed unit, dynamic load were compared to a single degree of freedom (SDOF) and a finite element representations of the system. The SDOF analysis was run using a program entitled Biggs (Baker,1989). The finite element model consisted of 10 two-dimensional beam elements using the program ANSYS, (Swanson Analysis Systems, 1989) which represented half the beam recognizing symmetry. Deflection results at various points along the beam were compared. Figures 3.15-3.17 show a comparison of maximum deflections at three points. Maximum values were within 2% of each other for these locations.

The NONLIN model required seven alpha and beta terms to ensure convergence. The influence of the higher order terms is most evident in the response away from the midspan.

Model Variables

Variable Name	Description
n, A0, A1, A2	Hysteresis shape factors
N_μ and N_v	Number of moment (μ) and displacement (v) terms in the solution
TS/Iterations	Time step and iterations
Structure Variables	
f_s and f_c	Steel yield and concrete compressive strength
RHOS (ϱ_s)	Percentage of steel reinforcement
XL, d	Wall height and thickness
GAMC (γ_c)	Density of concrete
Delivery and Load Variables	
ZVAL, XVAL	Range and deflection distances from centerline of the ROI
WVAL	TNT equivalent throw weight of weapon

Table 3.3 NONLIN Input Variables

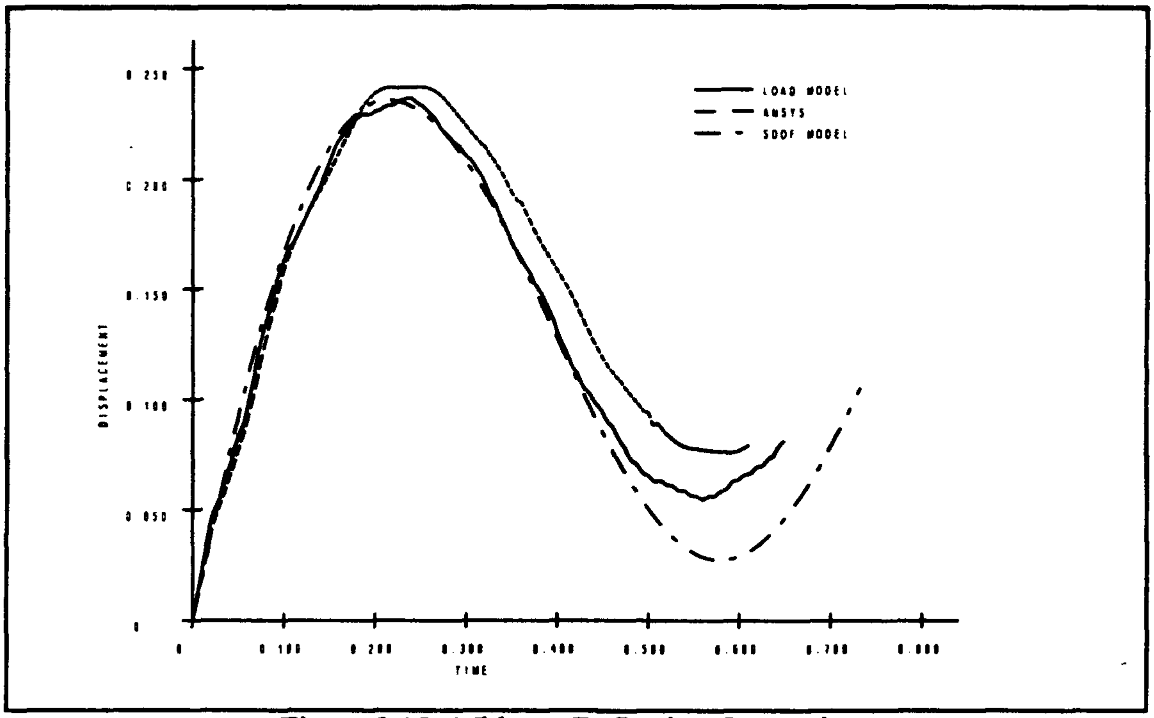

Figure 3.15 Midspan Deflection Comparison

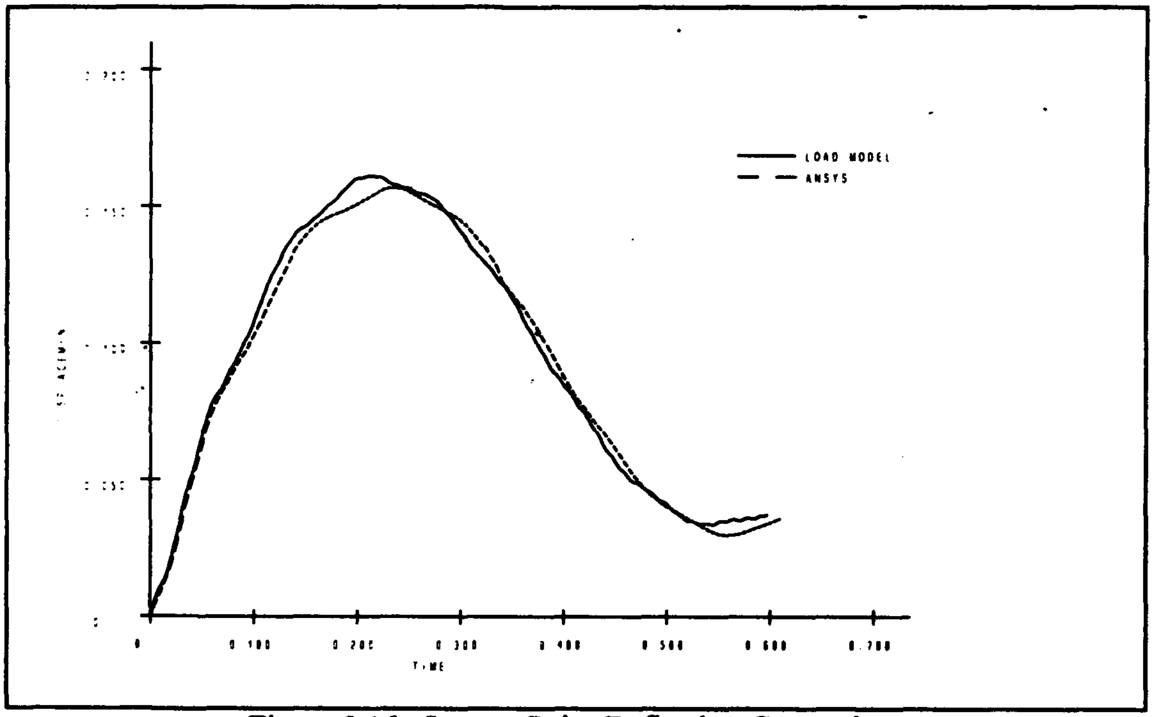

Figure 3.16 Quarter Point Deflection Comparison

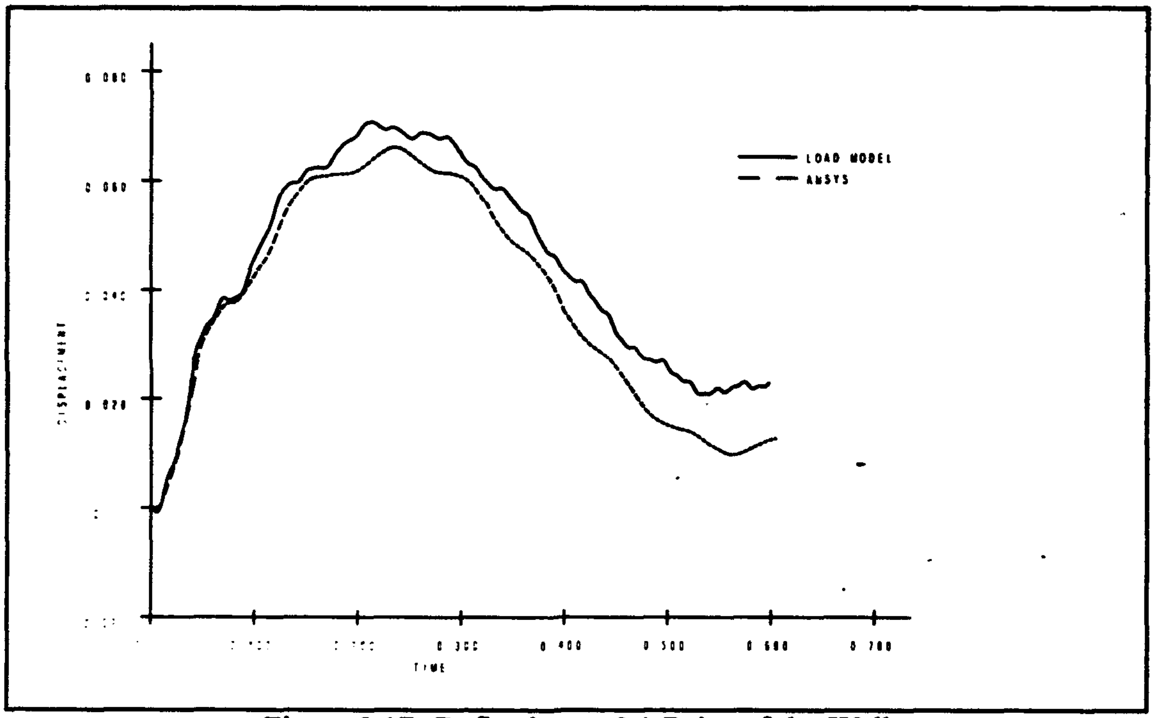

Figure 3.17 Deflection at 0.1 Point of the Wall

3.7 Effect of Varying the Number of Terms in the Solution

The effect of the number of terms N_μ and N_v, used in the solution was investigated for a typical loading scenario. Assuming the validity of the approximation increases with the number of terms used (Cunningham,1956), an attempt was made to find the point where the change in response became minimal with an increase of terms. Using the design of experiments (DOE) methodology and the program RS/Discover (BBN,1992A), an experiment was designed to show the effect of varying the number of

A0 = 0.05	A1 = 0.5
A2 = 0.5	n = 5
TS = 0.01	Iterations = 100
fc = 5000 psi	fs = 60,000 psi
ρs = 0.0025	γc = 150 pcf
XL = 120 inches	d = 30 inches
WVAL = 2000 lbs	ZVAL = 10 feet
XVAL = 0	

Table 3.4 NvNu Experiment Variable Settings

N_μ and N_v, terms on the response statistics generated by the NONLIN model. The parameters in Table 3.4 were used in the analysis. The DOE response surface methodology was chosen, with a Central Composite Face-Centered (CCF) design. The resulting relationship was modeled with a quadratic equation. The CCF design required 13 runs to characterize the response. The results showed that the deflection and curvature predictions were not nearly as sensitive to variations in the number of terms

NV	NU	Max Deflection (inches)	Max Shear (kips)
6	6	2.65	77.62
6	10	2.65	67.67
1	1	2.53	17.36
10	10	2.66	159.91
10	6	2.63	87.47
10	1	2.59	21.16
1	6	2.51	24.67
6	1	2.56	23.73
1	10	2.51	22.4

Table 3.5 RS/Discover Worksheet - Experiment NvNu

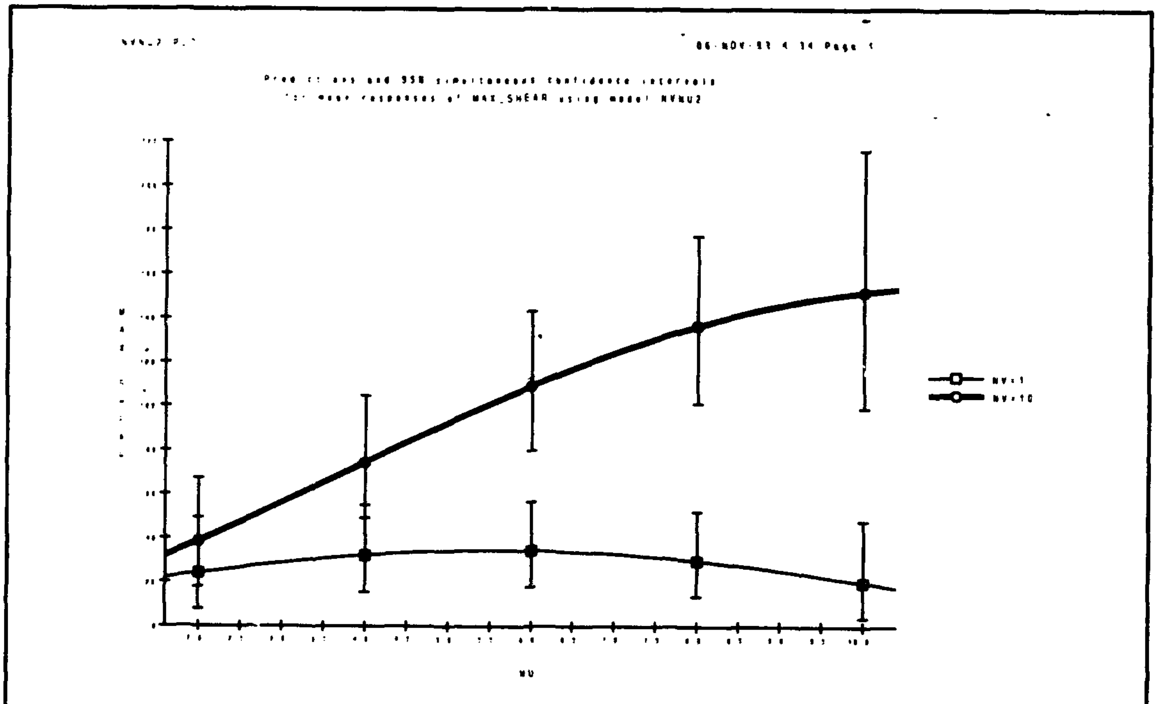

Figure 3.18 Plot of Shear for Combinations of Nv and Nu from RS/Discover

as the shear and moment predictions. The deflection and shear results are shown in Table 3.5. Figure 3.18 is a plot of the shear model developed by RS/Discover from the data of Table 3.5. The plot is of shear predictions for Nv equal to 1 and 10 versus a range of Nu. The 95% simultaneous confidence bounds shown have the property that, at most, 5% of the models predictions will have a single confidence interval that does not contain the true estimate for the prediction (BBN,1992B).

3.7 Comparison of Response Model to Test Results

The combined conventional weapon load model and semihardened structure model was evaluated by comparison of deflection results from the application of actual weapon loadings on structures for which test results are available in the literature. The tests series used for comparison are reported in Coltharp et al,1985, Wright et al,1987 and Hyde,1989. Table 3.6 gives the results of the model simulations. The standoffs referenced are incident values. Test displacements were recorded using active gages. The charge weight and standoff locations for the Hyde and Coltharp tests are not presented due to security classification. Although not fully validated, this comparison shows that the NONLIN code returns reasonable predictions for the input variable ranges of interest. The response statistics generator (NONLIN) returns a crude estimate of the total shear response that could be enhanced by inclusion of a Timoshenko beam element in the model. In a like manner, the inclusion of fragment effects may be included at the crude level of the current state of technology in this area. These two additions should add to the procedure's ability to predict shear kills explicitly. As stated in the background information there are numerous researchers working on the problem of the synergistic effects of blast and fragments on the response of the wall and the resultant synergistic shear and bending response. The hysteretic material model may also be modified to more

Charge Weight lb TNT	Stand off ft	Conc. Strength psi	Wall Height in	Wall Depth in	Test Mid-span Deflec. in	Calculated Deflect. in	Testing Ref
64	20	4700	94	12.6	.1	.35	Wright et al,87
64	5	4700	94	12.6	.64	.76	Wright et al,87
194	20	4700	94	12.6	.9	.85	Wright et al,87
-	-	5000	158	24.75	2.46	2.39	Hyde,89
-	-	4700	65	12	.94	.94	Coltharp et al,85
-	-	4700	65	12	.61	.37	Coltharp et al,85
-	-	4700	65	12	1.94	1.68	Hyde,89

Table 3.6 Response Model Comparison to Test Data

closely represent the response characteristics of reinforced concrete A major difficulty that must be resolved is generalizing the hysteresis (or failure model) to permit interaction between shear and flexure failure surfaces. This is not a trivial matter.

CHAPTER 4

Stochastic Analysis of A Hardened Facility

4.1 Introduction

This chapter takes the scenario discussed in Chapter 3 and presents a methodology to predict the probability of kill of a structural target following a conventional weapons attack. The load and structure models developed in Chapter 3 are used, where applicable, to predict the probability of kill of a section of the structure or region of interest (ROI) given an attack. The attack scenario of interest is an attack with tactical, non-precision weapons, delivered in a "Stick" pattern of four or eight bombs per stick. The target structure is considered killed if any portion of the outer shell, wall and/or roof, is compromised to the point that it allows the infiltration of airborne chemical or biological agents. The input statistics required to assess the probability of kill are given in Table 4.2. Limit state functions are developed for both weapon delivery accuracy as well as structural response using these input variables. The total probability of kill of the structure is the union of the probability of kill for each weapon. The probability of kill for each weapon is determined by evaluating each limit state function cited in Table 4.1. The probability of kill for each limit state, *i*, can be written as:

$$P_{k_i} = P_{R_ih} * P_{k_i/R_ih} \qquad (4.1)$$

Here the probability of kill, P_{ki}, is the product of two probabilities, the probability of structural kill ($P_{ki/Rih}$) given the weapon hits within that kill region and the probability that the weapon hits (P_{Rih}) within that region.

The structural kill limit state functions established for this work are listed and discussed briefly in Table 4.1, developed in detail in Sections 4.2 and 4.3 and presented explicitly in Section 4.5.1. Figure 4.1 shows the response regions cited in Table 4.1. A generic structural kill limit state function, $LSF(x)$, of a set of variables, x, may be further defined to have "load" ($LSF_{load}(x)$) and "resistance" ($LSF_{resist}(x)$) portions. With these definitions, the limit state function is in equilibrium if $LSF(x) = LSF_{load}(x) - LSF_{resist}(x) = 0$. If $LSF(x) \leq 0$ then the system has been killed. The $P_{k/Rh}$ is therefore the probability that $LSF(x) \leq 0$ given a weapon detonation in that kill region. The response and resistance function portions of the limit state functions of Table 4.1 are developed in Sections 4.2 and 4.3 respectively.

Section 4.4 presents the probability basis and methods of determining weapon delivery accuracy as it has been developed by the Joint Technical Coordinating Group/ Munitions Effectiveness (JTCG/ME) (JMEM,1990). The probability of a weapon hitting

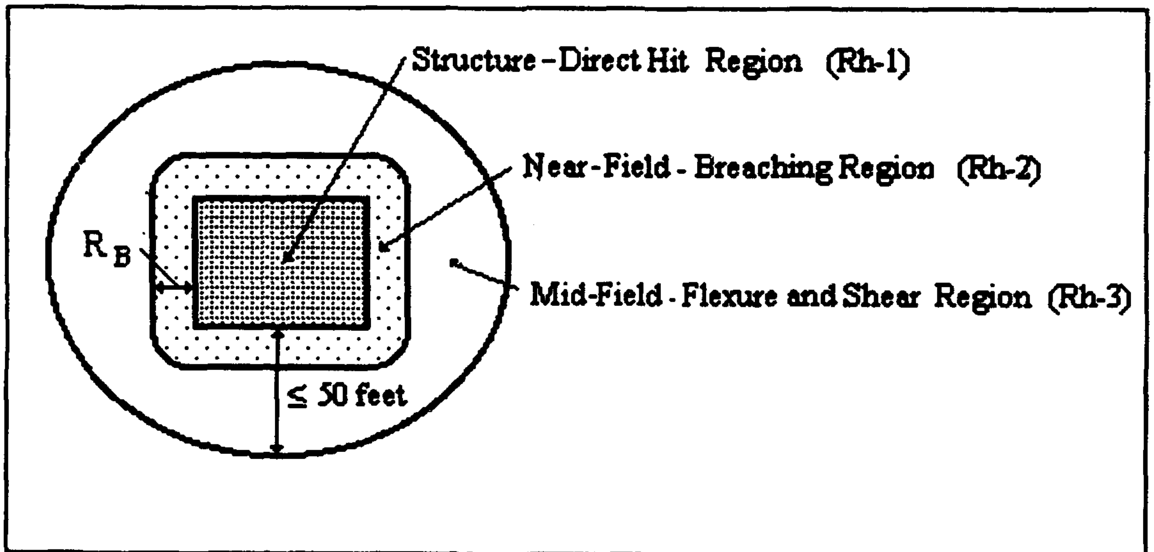

Figure 4.1 Structural Kill Regions

within a specific region (P_{Rh}) is based on these methods.

Limit State Functions (LSF)	Description
LSF-1 Structural hit, cratering and perforation of the roof.	The weapon hits the structure, detonates and creates a crater that may or may not perforate the structure.
LSF-2 Near-field detonation, breaching and severe damage of the near wall.	The models developed in Chapter 3 will not handle the severe environment and structural response modes present after the detonation of a conventional weapon close to the structure. The empirical relationship of equation 4.4 will be used to predict breaching and severe damage.
LSF-3 Mid-field detonation, excessive deflection of the near wall.	LSF-3 through LSF-5 Response surfaces are developed for the three response modes using the models presented in Chapter 3. The response surface equations are linked to maximum allowable response equations, which are functions of the same input variables.
LSF-4 Mid-field detonation, direct shear failure of the near wall.	
LSF-5 Mid-field detonation, diagonal shear failure of the near wall.	

Table 4.1 Limit State Function Definitions

Two Monte Carlo simulation procedures are developed in section 4.5.1 to assess the probability of kill of a hardened facility taking into account weapon delivery uncertainties as well as uncertainties in the physical characteristics of the structure. The procedures utilize the developed limit state functions to ascertain the probability of kill. The first procedure uses response surfaces developed to replace the nonlinear dynamic response code (NONLIN) of Chapter 3, to predict the response for three levels of weapon TNT equivalent throw weight, 500, 100 and 2000 pounds. The second procedure calls the NONLIN code directly and is not limited by weapon throw weight. A discussion of the Monte Carlo simulation results for several scenarios are presented in section 4.6 as well as a comparison between direct calculation and response surface substitution results.

A procedure is discussed in section 4.5.2 to accomplish a probability of kill analysis using reliability methods to evaluate the first and second moments of the random variables (Cornell,1969; Ang and Cornell,1974; Ang and Tang,1984) associated with equation 4.1.

4.2 Response Equation Development

Single response equations are required for regions Rh-1 and Rh-2 in Figure 4.1 while three response equations are required for Rh-3. These relationships are developed in the following three sections.

4.2.1 Direct Hit (Rh-1)

When a weapon lands within the footprint of the target, that structure is damaged

Model Variables		
Variable Name	Normal Range	Description
n	1-12	Hysteresis Shape Factor
A0	0.0-0.1	"
A1,A2	.25-1.0	"
N_μ and N_υ	1-10 each	Number of moment (μ) and displacement (υ) terms in solution.
TS/Iterations	100-200 etc	Time Steps and iterations
Structure Variables		
Fy	50,000-80,000 psi	Steel yield strength
Fc	3,000-7,000 psi	Concrete compressive strength
RHOS	.0025-.1	Percent of steel reinforcement
XL	96-156 inches	Wall height
Thickness	12-48 inches	Wall thickness
GAMC	100-200 pcf	Density of concrete
Delivery and Load Variables		
Zval	5-100	Range from centerline of ROI
Xval	0-50	Deflection from centerline of the ROI
Wval	500-2000	TNT throw weight of weapon

Table 4.2 Model, Structure, Delivery Conditions and Load Variables

based on the thickness of the roof and the throw weight of the weapon. Given, for example, the target as shown in Figure 4.1, with the dimensions of a typical NATO squadron operations facility, 60 feet on a side. The aim point will be at the center, therefore weapons landing within range and deflection offsets of 30 feet have hit the structure. The US Army Protective Construction Design Manual (TM5-855,1988) provides this relationship for crater depth:

$$\textit{Crater Depth} = D_p + (0.33)(W^{1/3}) \tag{4.2}$$

This equation provides prediction of the crater depth produced from the detonation of a conventional weapon impacting a finite thickness of concrete constructed above an air void, such as a ceiling or roof slab, versus a slab constructed on grade. The TNT throw weight, W, and the depth of penetration ,D_p , prior to detonation, and the overall depth (d) or thickness of the concrete layer, are the key parameters in this emperical relationship. Should this crater depth exceed 1/3 of the depth (d/3) of the concrete layer, that layer is perforated by the combined action of cratering of the front face of the concrete layer from impact and detonation and spalling of the back face of the concrete layer due to stress and crack propagation through the layer. In this study, only weapons that detonate on impact (nonpenetrating weapons with contact fuzes) are considered, therefore the term D_p of equation 4.2 will be equal to zero. These facts lead to the following definition of the limit state function for region one:

$$LSF\text{-}1 = \frac{d}{3} - (0.33) * W^{1/3} \tag{4.3}$$

4.2.2 Near-field Detonation (Rh-2)

The models developed in Chapter 3 provide an explicit computational method to predict the response of the structure in Figure 4.1. However, there are limitations in the loading and response portions of the model which preclude its use for very close-in, near-field detonations. A model which incorporates the following features is required to handle the dramatic loading and response environment which comes with near-field detonations: (1) explicit shear deformation, such as a Timoshenko beam model, (2) provisions for explicit fragment loading, (3) blast wave propagation through concrete, (4) failure surface interaction between shear and bending models. In lieu of such a model, which is difficult to construct at this time, the National Defense Research Committee, NDRC, (White,1946), equation, supplemented by more recent test data (McVay,1988), which was introduced in Chapter 2, will be used for this region. The equation

$$\frac{t}{w^{1/3}} = a\left(\frac{r}{w^{1/3}}\right)^{-b}\left(\frac{w}{w+C}\right)^{-c} \tag{4.4}$$

provides an empirical damage relationship between the standoff radius r, as shown in Figure 3.3, and a wall of thickness t given a cased weapon with TNT equivalent throw weight w, and case weight C. The parameters a, b *and* c vary according to degree of damage (see table 2.3) to be predicted. This equation provides a reasonable, albeit empirical measure of the response in this region. Taking the weapon case term, $w/(w+C)$, out of equation 4.4 provides a targeting conservative estimate of the wall response for these cases. In Bessete,1988, the equation

$$r = a * (\frac{w^{2/3}}{t}) - a*b*w^{1/3} \tag{4.5}$$

was used to predict the range *r*, at which breaching occurs. This equation is derived from equation 4.4 after removal of the weapon case term, *w/(w+C)*. The term *r* is defined as the breach range, r_B, when $a = 0.18$ and $b = 2.10$. When these parameter values are substituted into equation 4.5, the limit state function for region two is produced:

$$LSF\text{-}2 = r_{actual} - (0.18)(\frac{w^{2/3}}{t}) - (0.378)w^{1/3} \leq 0 \tag{4.6}$$

4.2.3 Mid-field Detonation (RH-3)

An experimental design or design of experiment (DOE) approach was used to develop response surfaces to replace the explicit use of the computer model NONLIN developed in Chapter 3. NONLIN was used to predict the deflection and shear response of a wall section or region of interest (ROI) as defined in section 3.4 and shown in Figure 3.4. The DOE approach aids in the selection of specific values and pairings of the input variables to the computer model. A modified central composite design (CCD) was used to represent each random input variable. The basic CCD for *k* variables consist of a 2^k factorial design, with each factor at two levels, the maximum and minimum, or -1 and +1 (Peterson,1985). Table 4.2 lists the significant variables associated with the NONLIN response model and the related loading model.

The model parameters listed in Table 4.2 will not be varied in the stochastic analysis. The values for the hysteretic variables were provided from Baber and Wen,1981, and are intended to represent a typical generic hysteretic material, such as reinforced concrete. Work by Sues et al,1983, extended the generic hysteretic model of Baber to represent reinforced concrete explicitly and could be incorporated to refine the model. A basic modeling uncertainty multiplier may be applied to the model representation as was suggested in Twisdale, et al,1988, but will not be included in this work. The effect of the number of terms, N_v and N_u, used in the solution was investigated in Section 3.3 for a typical loading scenario. As discussed in Section 3.3 the number of terms used effects the shear prediction more than the deflection prediction. For the purpose of response surface development five N_v and N_u terms are used. This number of terms maximizes the deflection predictions and returns shear predictions within 95% of their maximum. Table 4.3 shows the variables selected to map as random predictors in the CCD along with their associated data units and settings. This table is taken from the DOE software package RS/Discover (BBW,1993), used in this analysis. RS/Discover

Name	Abbrev	Data Units	Settings
INPUT			
Z_Range	Z	Feet	5 to 50
X_Deflection	X	Feet	0 to 50
Wall_Thickness	W_T	Inches	24 to 36
Wall_Strength	W_S	PSI	3000 to 7000
Wall_Height	W_H	Inches	108 to 168
OUTPUT			
Max_Deflection	M_D	Inches	
Direct_Shear	S_DIR	Kips	
Diagonal_Shear	S_DIAG	Kips	

Table 4.3 Response Surface Random Predictors

recommended 28 runs for the CCD including mid-points. Response surfaces were developed for three levels of weapon TNT weight, 500 and 1000 and 2000 pounds. The 500 and 1000 pound figures correspond to the TNT equivalent explosives found in two common US general purpose bombs (MK83 and MK84) whereas the 2000 pounds is a hypothetical, yet feasible, weapon weight. These levels were chosen purely to develop the methodology. The 28 runs were accomplished at each level using the NONLIN procedure. RS/Discover performed a least squares fit to the data.

The procedure used, in conjunction with RS/Discover, for fitting the response surfaces was as follows:

(1) Generate data and feed into the RS/Discover's multiple regression model generator, MULREG.

(2) Generate a model for the five input variables and their responses. Initially only quadratic terms were included, however it became apparent early that a few terms as high as fourth order would be required. The initial models therefore included the main effects, the main effect interactions and squares, cubics and quarters of the main effects.

(3) The MULREG routine walks one through a process of refining the models. A test of the regression models goodness of fit is based on an analysis of the sums of the squared residuals. The residual sum of squares for the response Y, using a least squares regression technique, is given as:

$$SS_{RESID} = \sum_i (Y_i - \bar{Y}_i)^2 \tag{4.7}$$

Here the $\bar{Y}_i$ is the real data point and Y_i is the model prediction.

The regression sum of squares for any model is defined as:

$$SS_{REGR} = b'[(X'X)^{-1*}]^{-1}b \tag{4.8}$$

Here b is the vector of estimated regression coefficients, without the constant term. The term X is the n x p matrix of predictor variables, where n is the number of responses and p is the number of terms in the model. The matrix $(X'X)^{-1*}$ is $(X'X)^{-1}$ with the row and column omitted for the constant term. The total sum of squares is defined as:

$$SS_{TOTAL} = SS_{REGR} + SS_{RESID} \tag{4.9}$$

The proportion of the variance or lack of fit of the model which can be attributed to the regression is called R squared or R^2 and is defined as:

$$R^2 = (SS_{TOTAL}\ SS_{RESID}) \ / \ SS_{TOTAL} \tag{4.10}$$

The amount of variance explained or adjusted for the number of degrees of freedom is:

$$\begin{aligned} R^2_{ADJ} &= (MS_{TOTAL} - MS_{RESID}) \ / \ MS_{TOTAL} \\ &= 1 - (1 - R^2)(n - c)/(n - p) \\ &\quad where \\ MS_{TOTAL} &= SS_{TOTAL}/(n-c) \\ MS_{RESID} &= SS_{RESID}/(n-p) \end{aligned} \tag{4.11}$$

This metric is affected by the number of terms in the model that don't contribute significantly to the fit of the model. When non-contributing terms are eliminated from the model this term increases towards the value of R^2. Here the c term is equal to 1 if there is a constant in the model and zero if not.

MULREG also recommends response transformation to increase the model fit. Response variables may be transformed by taking either their natural log, square root, inverse, or inverse square root. For a model to be accepted on the basis of goodness of fit, R^2 had to be greater than 0.85.

(4) A final check of the residuals was required for full acceptance of the model. Ideally all residuals would fall within 3 standard deviations of the fitted data. If this was not true the residuals were checked to be normally distributed by applying either a chi-square or Wilke-Shapiro test of normality. If the residuals had a normal distribution the model was accepted.

(5) If the models still did not pass the test the residuals were analyzed and additional runs accomplished until the criteria was met (Curry,1994).

Table 4.4 summarizes the nine models generated using RS/Discover. The models

Response	Regression Technique	Number of Terms
Max Deflection	Least Squares	
500#		14
1000#		14
2000#		15
Direct Shear	Least Squares	
500#		13
1000#		14
2000#		10
Diagonal Shear	Least Squares	
500#		15
1000#		14
2000#		11

Table 4.4 Response Surface Summary

are grouped by response with one model for each weapon load level (ie. 500, 1000 and 2000 pounds). Each model is elaborated on in Appendix C through a series of tables and graphs from RS/Discover. Presented for each model will be a summary of the model characteristics, a listing of the model terms and coefficients, a listing of the analysis of variation (ANOVA) table and a graph of the model residuals. As an example, Table 4.5 presents information on the 500 pound deflection model as it was provided by RS/Discover, with only slight format modifications. Figure 4.2 shows a RS/Discover plot of the residuals for the same model.

4.3 Resistance Equation Development

Deflection and shear design limit states are defined per the US Air Force's Protective Construction Design Manual (Drake,et al,1989). For the purpose of this study, reaching the upper design limits in this manual will be used to define the limit or failure state in these two response modes. From a lethality standpoint, the use of the maximum allowable design equations to define the limit state still results in a lethality or targeting nonconservative estimate.

4.3.1 Flexural Resistance Limit

Flexure limits are adopted based on testing of shallow buried, flat roofed structures (Kiger and Albritton,1980) subjected to conventional explosives. For beams with slenderness ratios (length over thickness, L/T) of five or more, the allowable deflection over length (v/L) is v/L = 0.10. For beams of L/T< 5, the allowable v/L = 0.06. These figures represent what was termed severe damage, which for the purpose of this work translate to a compromise of the wall as stated in Section 4.1.

500 Pound Deflection Model Summary

1 Model Name:	MR553
2 Response Transformation:	Untransformed
3 Method:	Least Squares
4 Weights:	None
5 Total Number of Cases:	29
6 Number of Predictors:	5
7 Number of Unexpanded Terms	14
8 Number of Excluded Cases	0
9 Error Degrees of Freedom	15
10 Standard Error of Respon	6.013722
11 Relative PRESS:	0.407118
12 Root Mean Squared Error:	2.984413

Least Squares Coefficients

Term	Coeff.	Std. Error	T-value	Signif.
1 1	-4.062295	17.936065	-0.23	0.8239
2 Z	0.652205	0.345298	1.89	0.0784
3 X	-0.426211	0.088692	-4.81	0.0002
4 W_T	-2.505735	0.583184	-4.30	0.0006
5 W_S	0.007857	0.002558	3.07	0.0078
6 W_H	0.181769	0.106889	1.70	0.1097
7 Z*W_T	-0.000047	0.000021	-2.22	0.0421
8 Z*W_H	-0.002520	0.001385	-1.82	0.0889
9 Z*W	0.005176	0.003065	1.69	0.1120
10 X*W	0.013339	0.003119	4.28	0.0007
11 W_T*W_H	-0.000041	0.000015	-2.68	0.0170
12 W_H*W_T	0.004851	0.002283	2.13	0.0506
13 Z**2	-0.003385	0.002456	-1.38	0.1883
14 W_T**2	0.022333	0.009945	2.25	0.0402

Least Squares Summary ANOVA

Source	df	Sum Sq	Mean Sq.	F-Ratio	Signif.
Total(Corr.)	28	1012.616			
Regression	200	891.071	44.554	2.93	0.0609
Linear	5	535.077	107.015	7.04	0.0083
Non-linear	15	355.995	23.733	1.56	0.2667
Residual	8	121.544	15.193		
Lack of fit	7	121.544	17.363		
Pure error	1	0.000	0.000		

Model obeys hierarchy. The sum of squares for linear terms is computed assuming nonlinear terms are first removed.

Table 4.5 Characteristics of the 500 Pound Response Surface Model

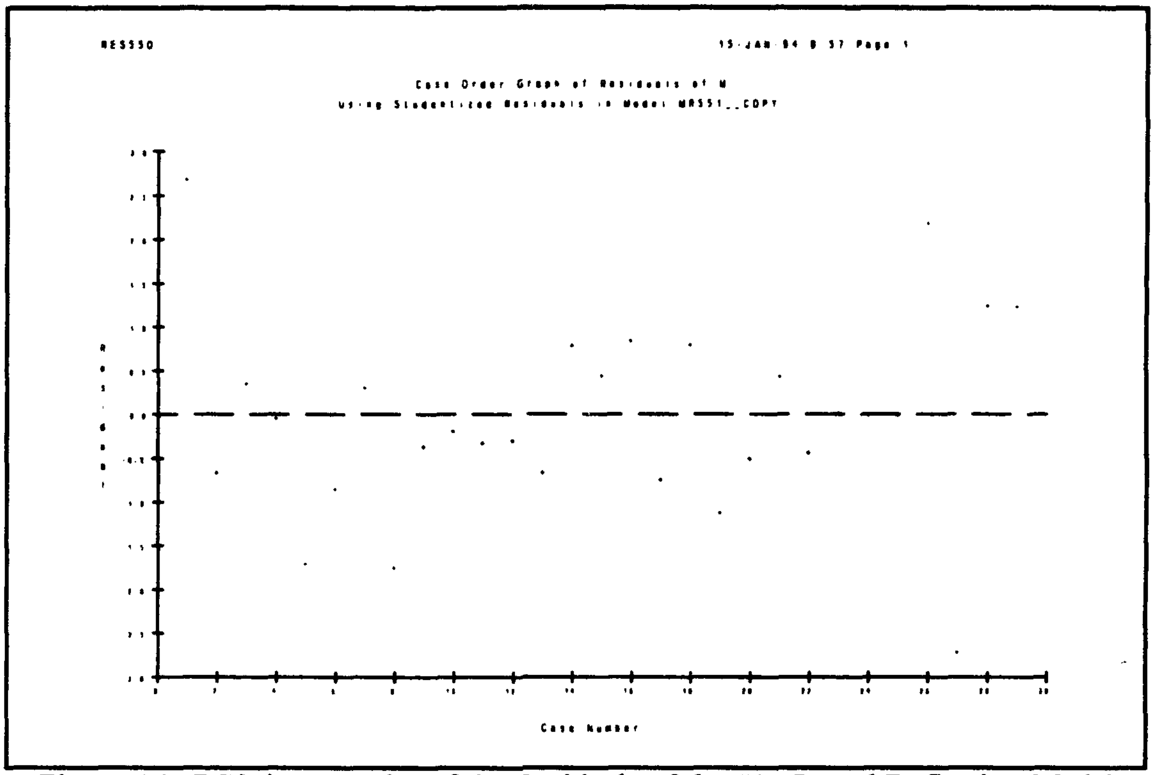

Figure 4.2 RS/Discover Plot of the Residuals of the 500 Pound Deflection Model

4.3.2 Shear Resistance Limits

Shear limit states are defined for two categories of failure, direct shear and support shear. Two components add to the shear capacity of a section, the shear capacity of the concrete and the shear strength provided by the presence of shear reinforcement. Span to depth ratios of ≤ 5 are considered deep beams and will be handled separately.

4.3.2.1 Support/Diagonal Shear Resistance Limits

4.3.2.1.1 Normal Depth Beams

The critical section for determining shear failure is at a distance equal to the effective depth of the member from the support or area of concentrated load (Drake,et al,1989). For members with span to depth ratios greater than 5 the shear capacity of the concrete is given as:

$$V_c = (1.9\sqrt{f_c'} + 2500\rho_w \frac{V'd}{M'})\ b_w d \le 3.5\sqrt{f_c'} b_{wd} \tag{4.12}$$

This is the nominal shear capacity per the American Concrete Institute (ACI) Code Requirements for Reinforced Concrete (ACI 318-89). The definition of ρ_w is

$$\rho_w = \frac{A_s}{b\ d} \tag{4.13}$$

where A_s is the area of flexural steel and b_w is the beam web width. V' and M' are the shear and moment at the critical section and d is the effective depth of the critical section.

The shear strength provided by shear reinforcement is given as:

$$V_s = \frac{A_v f_y d}{sb} (\sin\alpha + \cos\alpha) \le 8\sqrt{f_c'} bd \tag{4.14}$$

The term A_v refers to the cross sectional area of the shear reinforcement within a distance *s*. Combining the limits, the diagonal shear limit state for normal depth beams becomes:

$$V_n = V_c + V_s \le 11.5\ \sqrt{f_c'} bd \tag{4.15}$$

The total nominal shear strength (V_n) should be conservative as it assumes shear reinforcement which may not be present.

4.3.2.1.2 Deep Beams

The shear capacity of members with clear span-depth (L/d) ratios of less than 5 is further broken down into L/d < 2 and 2 ≤ L/d < 5. The normal shear strength values are multiplied by an increase factor to obtain the following limit state equations:

$$V_n \le 8\sqrt{f_c'}b_w d \qquad for\frac{L}{d} < 2 \tag{4.16}$$

$$V_n \le \frac{2}{3}(10+\frac{L}{d})\sqrt{f_c'}b_w d \qquad for\ 2 \le \frac{L}{D} < 5 \tag{4.17}$$

4.3.2.2 Direct Shear Resistance Limits

Direct shear failure usually occurs near construction joints or supports and are a result of high shear forces interacting with preexisting cracks. Under the dynamic loading resulting from conventional weapons detonations, cracking of sections is not uncommon. The direct shear failure occurs along cracks in the direction of the shear load versus inclined crack formations and failure planes. Static tests of monolithically cast construction joints, for typical protective construction sections, has shown an increase in shear capacity over the standard ACI equation (Karagozian and Case,1973) and has resulted in the proposed limit state:

$$V_n = 0.16f_c'b_w d + 1.4(P + A_v f_y) \le 0.51f_c'b_w d \tag{4.18}$$

4.4 Weapon Delivery Accuracy

Figure 4.3 shows a typical impact pattern for a stick of four weapons dropped from a single aircraft. The dispersal of the weapons relative to the center of the stick, which for this figure is also the aim point, is a function of the release conditions which will not be considered in this work. Two errors are associated with this stick impact pattern. They are the aiming error and the weapon ballistic error. Both are measured in terms of mils, or the deviation in feet per 1000 feet slant range from weapon release point to the aim point. For example, the ballistic error may be provided as a circular error probable (CEP) of 5 mils and the aim point error may be given as a CEP of 20 mils. The slant range would also be given, for example, as 6000 feet. From Chapter 2 recall the definition of the CEP as being the radius of a circle in which 50% of the bombs would land. The aim point error standard deviation in terms of the given CEP is defined as:

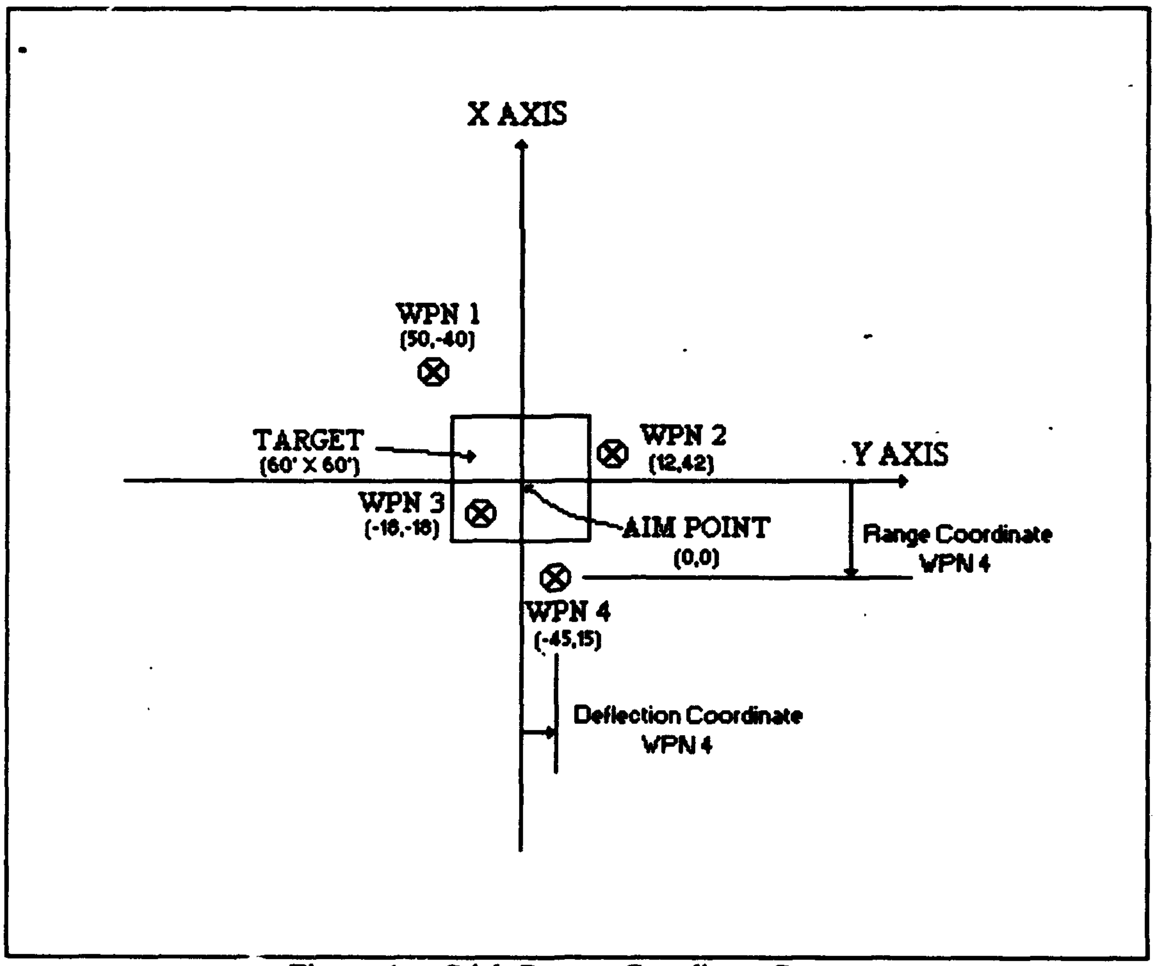

Figure 4.3 Stick Pattern Coordinate System

$$\sigma_{deflection} = \sigma_{range} = \frac{CEP(ft)}{1.1774} \tag{4.19}$$

As an example, the aim point of Figure 4.3 is shown as (0,0). If the slant range from the

MFC	mean concrete strength f_c'
SIGFC	standard deviation of the concrete strength
MXL	mean wall height or beam element length
SIGXL	standard deviation of the wall height
MD	mean depth of wall or thickness
SIGD	standard deviation of the wall thickness
MXB1	mean X coordinate of bomb one
MYB1	mean Y coordinate of bomb one
MXB2	mean X coordinate of bomb two
MYB2	mean Y coordinate of bomb two
MXB3	mean X coordinate of bomb three
MYB3	mean Y coordinate of bomb three
MXB4	mean X coordinate of bomb four
MYB4	mean Y coordinate of bomb four
SIGBOMB	standard deviation for each bomb based on standard ballistic error for that type of bomb
SIGRANGE	standard deviation of the aim point in the range, or X direction given the aim point is at 0,0
SIGDEFLECT	standard deviation of the aim point in the deflection, or Y direction given the aim point is at 0,0

Table 4.6 SIMTAC Input Variables

weapon release point to the aim point was 5000 feet and the CEP was 20 mils, the aim point standard deviation would be equal to:

$$\sigma_{range-aimpoint} = \sigma_{deflection-aimpoint} = \frac{(20*5)}{1.1774} = 84.93\ ft \tag{4.20}$$

The aim point error may also be provided in terms of range and deflection error probable (REP and DEP) terms, in feet.

Using weapon 1 impact point (WPN 1) on Figure 4.3 as an example, it's detonation location is normally distributed in the X and Y directions with a mean point of impact of (50,-40). The range to that impact point is 5000 feet and ballistic accuracy (CEP) is 5 mils. The ballistic error standard deviation for weapon one is therefore:

$$\sigma_{WPN-1} = \frac{(5*5)}{1.1774} = 21.23\ ft \tag{4.21}$$

For the purpose of this study, means and standard deviations for the stick center or aim point and the ballistic error of each weapon will be provided as straight input. Current automated JMEM tools provide the stick pattern as well as the probability statistics given the weapon, aircraft, aircraft load configuration, and the weapon drop sequence. An interface between these existing BASIC programs and this work would be easily accomplished. This was not done for the actual weapon delivery accuracy because portions of the actual data is classified SECRET or CONFIDENTIAL.

4.5 Probabilistic Analysis of Kill

The limit state functions defined in sections 4.1 through 4.3 are evaluated using a Monte Carlo simulation scheme to predict the probability of kill of a structure given mean and standard deviations of the input variables in Table 4.3. An alternative approach, not implemented herein, is to perform a first order - second moment (FOSM) analysis of the limit state functions. A discussion of this approach is provided in section 4.5.2

4.5.1 Monte Carlo Simulation

A FORTRAN program was written to perform the Monte Carlo simulation of an attack against a hardened facility. The source code for the program SIMTAC is provided in Appendix D. Two versions of SIMTAC were developed. The first version (SIMTAC1) uses the response surfaces developed in this chapter as replacements for the nonlinear dynamic analysis routine NONLIN, developed in Chapter 3. The second version (SIMTAC2) interfaces directly with the NONLIN program. The input parameters of the program are given in Table 4.6. The following is an overview of the procedure SIMTAC follows.

Each run evaluates the kill probability for the four weapons in the stick. Sampling for the concrete strength (FC), wall thickness (d) and wall height (XL) are accomplished initially and are valid for an entire stick sampling. That is, FC, d and XL are held constant for the analysis of four different weapons and their locations. Given the means and standard deviations of these values a uniform variate, random number generator is used with a Log-Trig transformation process to produce a sample of a normally distributed random variable on each call. All parameters are assumed to be normally distributed for this study, however the methodology is not restricted to this assumption and in reality many of these parameters will not be normally distributed. The individual weapon locations are determined by first sampling on the distribution of each weapon based on its ballistic error properties, which are input variables. This returns a location (RANGE1, DEFLECT1) relative to the stick center for that bomb. Subsequently, the aim point error is applied with the aim point standard deviations (sigrange and sigdeflect) and RANGE1,DEFLECT1 as the mean location coordinates. The RANGE,DEFLECT coordinate of the current weapon is then established. This step is accomplished four times within one run.

At this point the screening of the detonation locations begins to determine which limit state functions are required to be evaluated for that weapon. The RANGE,DEFLECT coordinate is first checked to see if it falls outside the structural damage zone identified in Figure 4.1. If it does a "no kill" is recorded and the next weapon evaluation begins. If it doesn't the analysis proceeds with the RANGE,DEFLECT coordinates being screened to see whether the weapon hits the structure or falls within the breach zone. As discussed in section 4.2.1, if the structure is hit, LSF-1

$$LSF\text{-}1 = \frac{d}{3} - (0.33)(W^{1/3}) \leq 0 \tag{4.22}$$

is evaluated. If perforation is achieved a "kill" is recorded and the next weapon evaluation begins.

If the weapon falls within the breach range as shown in Figure 4.1 and calculated by LSF-2,

$$\begin{aligned} LSF\text{-}2 &= R_{actual} - R_B \leq 0 \\ &= R_{actual} - (0.18)(\frac{W^{2/3}}{t}) - (0.378)W^{1/3} \leq 0 \end{aligned} \tag{4.23}$$

a "kill" is recorded.

If a weapon does not hit the structure or fall within the breach zone, the analysis continues by converting the RANGE,DEFLECT coordinates into local coordinates, ZVAL,XVAL. The ZVAL,XVAL coordinates are required as input to NONLIN in order to perform deflection and shear analysis. This procedure determines the closest point on the structure which would see the maximum loading from that weapon. The corners are considered unsusceptible to deflection or shear failures as they are calculated. Should a weapon fall outside a distance, in feet, (30 - 2.5*d) from the centerline of the structure, the ZVAL,XVAL coordinates are based on the distance from the detonation to the nearest face at a point 2.5 times the wall thickness or depth (d) from the corner. This estimate is conservative and is based on the fact that the corners are normally highly reinforced with steel extending a minimum of a wall thickness in to the adjacent wall.

Deflection, diagonal shear, and direct shear analysis are performed using the ZVAL,XVAL detonation locations determined above. Should any limit states be exceeded the procedure jumps ahead and sets the kill flag and goes on to the next weapon or begins a new run after recording the kill.

There are two limit state functions for the deflection based on the span (XL) to depth (d) ratio of the wall. If the deflection response surface equations developed in section 4.2.3 return predictions that exceed the limits stated in section 4.3.1 a "kill" is recorded. These limit state functions are given as:

$$LSF\text{-}3 = 0.10 - \frac{Deflection}{XL} \leq 0 \qquad XL/d \geq 5 \tag{4.24}$$

$$LSF\text{-}3 = 0.06 - \frac{Deflection}{XL} \leq 0 \qquad XL/d < 5 \tag{4.25}$$

There are three limit state functions for diagonal shear which are also based on the span to depth ratio. If the diagonal shear response surface returns (DiagShear) predictions which exceed the limits stated in section 4.3.2, a "kill" is recorded. These diagonal shear limit state functions are given as:

$$LSF\text{-}4 = 11.5\sqrt{f_c'}b_w d - DiagShear \leq 0 \qquad XL/d > 5 \tag{4.26}$$

$$LSF\text{-}4 = \frac{2}{3}(10+\frac{XL}{d})\sqrt{f_c'}b_w d - DiagShear \leq 0 \qquad 2 \leq \frac{XL}{d} < 5 \tag{4.27}$$

$$LSF\text{-}4 = 8\sqrt{f_c'}b_w d - DiagShear \leq 0 \qquad \frac{XL}{d} < 2 \tag{4.28}$$

The following single limit state function defines the criteria for a direct shear (DirShear) kill.

$$LSF\text{-}5 = 0.51\, f_c' bd \tag{4.29}$$

After all runs are completed the total number of kills is divided by the total number of weapons delivered to give the percent probability of kill for a single attack with the given input characteristics.

4.5.2 First Order - Second Moment Method Discussion

This section is broken down into two parts. The first part assesses the probability of kill for entire stick of weapons and the second part looks at the individual weapons probability of kill.

4.5.2.1 Probability of Kill For a Stick of Weapons

This section discusses a procedure for assessment of the probability of kill of a structural target and a given attack scenario using a first order second moment (FOSM) differential method. The total probability of kill from a stick of weapons is the union of the probability of kill of each individual weapon, as shown here.

$$\begin{aligned} P[K_1 \cup K_2 \cup K_3 \cup K_3 \cup K_4] = {} & P(K_1) + P(K_2) + P(K_3) + P(K_4) \\ & - P(K_1 \cap K_2) - P(K_1 \cap K_3) - P(K_1 \cap K_4) \\ & + P(K_1 \cap K_2 \cap K_3] + P(K_1 \cap K_2 \cap K_4] \\ & + P(K_1 \cap K_3 \cap K_4] + P(K_2 \cap K_3 \cap K_4] \\ & - P(K_1 \cap K_2 \cap K_3 \cap K_4] \end{aligned} \tag{4.30}$$

A weapon kill, K_i, of a stick of weapons is not an independent event due to the tie of each weapon to the aim-point error of the stick. The individual kill events are also not mutually exclusive. These facts lead to equation 4.30 as a definition of probability of kill for a stick of 4 weapons. Due to the correlation of the 4 kill events the probability of kill from one weapon is not independent of another weapon, but is given by:

$$P(K_1 \cap K_2) = P(K_1/K_2)\ P(K_2) \tag{4.31}$$

The co-variance matrix which describes the correlation between the individual bomb kills is unknown at this time.

4.5.2.2 Individual Weapon Probability of Kill

The probability of kill of an individual weapon is the union of the probability kill by way of each of the 5 limit state functions defined in Table 4.1. A single function which transitions over the three regions is required for evaluation of the probability of kill. The limit state functions developed need to be linked by appropriate transition functions. Development of a model which accommodates response of the structure explicitly beginning at the structure face would eliminate the transition problem. The fact that determination of the breach range is a function of the random input variables (equation 4.6) adds to the complexity. The correlations between the deflection and shear kill events are also not defined at this point but are required for complete evaluation. For these reasons accomplishment of a FOSM analysis for each weapon is inappropriate at this time.

4.6 Simulation Results

Initially, the Monte Carlo, response surface replacement program, SIMTAC, is compared to runs made with the Monte Carlo program, SIMTAC2, which calls the NONLIN program directly. Delivery conditions and distributions were held constant for

TNT Weight (pounds)	Response Surface 800 Runs	Response Surface 4800 Runs	Response Surface 8000 Runs	NONLIN Code 800 Runs
1000	7.6%	6.3%	5.8%	6.4%
500	2.3%	2.4%	2.3%	2.8%

Table 4.7 Response Surface Results versus Actual NONLIN Code Results

all simulations and represent typical accuracy for inventory weapons. Table 4.8 shows the delivery accuracy used. A comparison for 500 and 1000 lb TNT weapons is given in Table 4.7. This comparison reveals that as the number of simulations increases the ability of the response surface to replicate NONLIN results improve. These results appear reasonable in light of the simplified central composite design (CCD) method used to generate the response surfaces. It should be noted that the 8000 response surface model runs took approximately two and one half minutes, whereas the 800 NONLIN runs took approximately six hours to complete. This is a significant reduction in time with an

Aim Point			Bomb 1 (coord)	Bomb 2 (coord)	Bomb 3 (coord)	Bomb 4 (coord)	Bomb Error - Sigma (feet)
Mean	Sigma Range (feet)	Sigma Deflect (feet)					
0,0	70	70	15,40	-20,50	-20,-10	15,-60	5

Table 4.8 Simulation Delivery Conditions

acceptable reduction in accuracy. A more refined and robust response surface may be developed using a higher fractional factorial experimental design method, however such a model is not warranted for demonstration of the procedure put forth in this work. It should be noted that no shear kills were recorded for simulations run up to the 2000 lb. TNT weight level. Several factors may have contributed to this outcome. The following are a few possibilities:

a. A shear kill occurs primarily for detonations at close range to the target. The fact that the procedure established uses an empirically based breaching equation (section 4.2.1) to predict kills at most of these same ranges, precludes the calculation of a shear kill.

b. The NONLIN model calculates on bending shear response and as such may under calculate the total shear response.

c. For the kill criteria imposed, the beam sections under investigation, loaded by the weapons of interest, may not exceed the limit states.

In order to give insight into the relative effect of varying the characteristics of the random structural variables, a series of runs were accomplished as shown in Table 4.9 along with their results. A base case is shown in the first row of Table 4.9. Each random structural variables mean was set at one standard deviation from the maximum and minimum values while the other variables were maintained at their base case levels. A preliminary analysis of these results reveals that the probability of kill is most sensitive to the thickness of the wall and roof and least sensitive to the concrete strength. This type of analysis is required in order to extract the characteristics which positively effect the P_k so that greater effort is spent attempting to characterize that attribute from available intelligence resources.

This methodology will provide the military decision makers the probability of kill of a single sortie or aircraft dropping a stick of four weapons. The objective of the attack on a specific target will then be weighed against the number of aircraft that will fly a sortie against the facility. For example, if the objective is to kill a facility using the criteria established in this study, one sortie provides approximately a 15% probability of kill. If this is not acceptable a commander must make the decision to send more pilots and planes against that target to achieve the probability of success he desires.

Concrete Strength (psi)		Wall Section Height (inches)		Wall Section Thickness (inches)		Probability of Kill (P_k) (%)	
Mean (MFC)	Sigma (SFC)	Mean (MXL)	Sigma (SXL)	Mean (MD)	Sigma (SD)	1000 lbs	2000 lbs
5000	500	138	12	24	6	4.7	9.0
5000	500	138	12	18	6	9.0	18.0
5000	500	138	12	30	6	2.8	4.7
5000	500	120	12	24	6	4.0	8.0
5000	500	156	12	24	6	5.3	10.3
4000	500	138	12	24	6	5.0	9.6
6000	500	138	12	24	6	4.2	8.4

Table 4.9 Simulation Results

CHAPTER 5

Conclusions and Recomendations

5.1 Conclusions

A procedure was developed that returns a probability of kill of a hardened facility taking into account two types of uncertainties: weapon delivery accuracy and structural characteristics or intelligence uncertainties. The kill criteria are based on the structural response of the facility exceeding predetermined limits which represent the achievement of the attack objective. Perfect knowledge is rarely known about the structural characteristics of a target once a conflict is initiated. Analysts tasked to perform pre-attack weapons analysis and post-attack weapons effectiveness must be able to report to their superiors realistic probabilities of achieving the objective of an airborne strike on a target. Current methodologies do incorporate weapon delivery accuracy, however they overlook uncertainties in target structural characteristics which can make a dramatic difference in a probability of kill prediction.

The following specific items were accomplished under this effort.

a. A nonlinear, nondimensional, continuous hysteretic beam model was developed to represent a section of a hardened facility subjected to conventional weapons effects. The model returns response calculations across the height of the section as required to provide information for determining the kill state of a hardened target. The nondimensionalization allows for ease of parameter input and serves the stochastic analysis well where structural characteristics are continuously changed.

b. Existing empirical models which generate conventional weapon blast pressure time histories as a function of the TNT equivalent throw weight were modified to become a function of space as well as time. A new model was generated that returns the pressure at any point up a wall section as a function of time, space and angle of incidence. This type of load representation was required to feed the continuous beam model referenced above. The combination of the beam model and the load model was termed the NONLIN code.

c. Robust statistical models or response surfaces (RS) were derived from NONLIN code output calculated from typical combinations of weapon throw weight and range from the target, target wall height, depth and concrete compressive strength. The use of a design of experiments (DOE) or experimental design approach to the RS development ensured the RS closely replicated the input data across the parameter space of interest. The result was a multidimensional RS which returned the structural response given a set of the five parameters stated above. The RS replaced the full NONLIN code within the Monte Carlo simulation program which calculated the target probability of kill. Use of the RS replacement models allowed a simulation to be run in less than 1% of the time required to run the simulation with NONLIN. This time saving is crucial to the use of this tool in a dynamic wartime environment.

d. The two simulation programs developed (SIMTAC1 and SIMTAC2) are the first models which take into account structural characteristics as random input variables in addition to the traditional weapon delivery accuracy. SIMTAC1 uses the response surfaces which are good only for the range of the input parameters from which they were derived. Answers after 8400 simulations are returned in approximately two and one half minutes on a PC with an 80486 microprocessor running at 33 megahertz. Should real world circumstances take one out of the valid input ranges for the response surfaces, SIMTAC2, which calls the NONLIN code directly, may be used without input restrictions. The time to run 800 simulations with SIMTAC2 takes approximately six hours. It should be noted that response surfaces may be developed for any input parameters and their ranges using an experimental design approach. Use of other models and methods, such as the finite element method, may also be used.

It has been shown that uncertainties in the structural characteristics of a target may significantly effect its response to conventional weapons and the determination of the resulting probability of kill given an attack. The use of robust response surfaces to replace complex analytic procedures allows for timely calculation of probabilities of damage in spite of using a simulation technique such as Monte Carlo. In conjunction with a spatial-temporal load model, as presented herein, a total shear response procedure is required to predict shear failures at locations of high load concentrations away from the supports. A continuous beam model representation will allow response calculation against a myriad of potential kill criteria which need more than a single nodal response. An example, which would easily be accommodated, would be a kill criteria based on a maximum length of the wall section exceeding a limiting deflection. The methodology presented will accommodate studies to single out the most critical random structural variables and their critical ranges to allow the proper emphasis to be placed on variable significance in a targeting analysis and data gathering exercise.

5.2 Recommendations

The remaining sections of this chapter discuss recommendations for improvements, modifications and/or additions to the models and procedures presented.

5.2.1 Structural Model

The NONLIN program is sufficiently general in its nondimensional form to handle a variety of cross-sections and material properties which are found in the world-wide hardened facility community. As stated in Chapter 3, NONLIN returns a crude estimate of the total shear response that could be enhanced by inclusion of a Timoshenko beam element in the model. This fact is enhanced by the fact that the model never returned a shear kill as defined in Chapter 4. In a like manner, the inclusion of fragment effects may be included at the crude level of the current state of technology in this area. These two additions should add to the procedures ability to predict shear kills explicitly. As stated in the background information there are numerous researchers working on the problem of the synergistic effects of blast and fragments on the response of the wall and the resultant synergistic shear and bending response. The hysteretic material model may be modified to more closely represent the response characteristics of reinforced concrete as cited in section 4.2.3. A major difficulty that must be resolved is generalizing the hysteresis (or failure model) to permit interaction between shear and flexure failure surfaces. This is not a trivial matter. These areas warrant the further investigation that will add to the robustness of the current predictive techniques, however these facts do not detract from the significance of the methodology presented herein.

As discussed in section 4.6, the procedure presented may be used to highlight the critical structural uncertainties which most dramatically affect the probability of kill of a particular class of targets. In this light, a screening procedure may be used to recommend random variables which may be modeled by a more robust version of NONLIN or a higher fidelity predictive tool such as a nonlinear finite element code. Generation of the response surfaces using the revised random variables and a more robust predictive code, would greatly reduce the uncertainties inherent in the process and reduce the overall uncertainties of the analysis provided to air campaign decision makers.

5.2.2 Response Surface Replacement

One of the objectives of this work was to provide a procedure that returned probabilities of kill in as near real time as possible. This requirement comes from the need to be able to assess kill probabilities during a conflict such as DESERT STORM, in which there is not the time or the inclination to wait for such an assessment. In the same breath, the commander who wants an answer "now" also wants a high degree of confidence that the answer provided is accurate. The response surface replacement technique provides this flexibility and confidence. Better response surfaces may always be developed as discussed in Chapter 4, however the applicability of this method to the analysis performed herein was clearly shown.

5.2.3 Probabilistic Analysis Technique

The use of Monte Carlo Simulation, when used in conjunction with a response surface replacement models ran fairly quickly on a DOS based personal computer with a 80486 microprocessor running at 33 megahertz. Eighty-four hundred simulations would run in approximately two and one half minutes. In the absence of covariance matrices for delivery accuracy variables as well as the correlation between the shear and deflection response, an explicit integration, first order, second moment (FOSM) method, or other derivative method, can not be accomplished.

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Appendix A

Structural Model Nondimensionalization

Equations 3.9 and 3.10 of section 3.4 entitled, Structure Model, are nondimensionalized with respect to the ultimate bending moment, M_u, and the curvature, ϕ_i, where the initial tangent curve intercepts the horizontal ultimate moment curve. As shown in Figure 3.12, M_u is only the ultimate moment when $A_0 = 0$. For this model $A_0 = .05$. The ultimate curvature and nondimensional moment are defined as:

$$\phi_i = \frac{M_u}{EI} \qquad \mu = \frac{M}{M_u}$$

The ultimate moment is defined as:

$$M_u = (\rho - \rho')df_y(d - \frac{a}{2}) + \rho' df_y(d - d')$$

The nondimensional length and displacement are:

$$\xi = \frac{x}{L} \qquad \nu = \frac{v}{\phi_u L^2}$$

The nondimensional time is defined as:

$$\tau = \bar{\omega} t$$

where

$$\bar{\omega} = \sqrt{\frac{EI}{\rho A L^4}}$$

The nondimensional load and load per unit length are:

$$f = \frac{f_{ext} L}{M_u} \qquad \bar{q} = \frac{q_{ext} L^2}{M_u}$$

Incorporating these conversions into equations 3.7 and 3.8 results in equations 3.9 and 3.10 of the same section.

Appendix B

Nonlinear Load and Structural Response Model Code

```
PROGRAM RESPCOM3
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

C  This program will generate the one way slab or beam response of a
C  given reinforced concrete protective constructed facility subjected to
C  blast loading from a defined conventional weapon at an input location.
C  The loading environment is generated from a modified, empirical code
C  based on the code CONWEP provided by the US Army Waterways Experiment
C  Station (WES). The loading environment is fed into a hysteretic,
C  continuous beam model which solves for deflections, moments, shears
C  and curvatures using a weighted residual solution method.      Response
C  statistics may be generated at a user inputted number of points along
C  the beam element.
C  The main loading subroutine is entitled LOADCDC while the main con-
C   tinuous beam model subroutine is entitled NONLIN. NONLIN calls an
C  IMSL routine DGEAR which solves a set of three first order differential
C  equations at each time step.
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C  Variables
C
C  NV - The number of displacement terms to use in the solution
C  NU - The number of moment terms to use in the solution.
C  ITER - The number of iterations that the solution will be carried to.
C  XVAL - The coordinate left or right of the centerline of the region of
C          interest, which is "0" at the centerline where the detontation
C          is located.
C  YVAL - The vertical coordinate measured up the region of interest,
C          which is "0" at the ground elevation.
C  ZVAL - The distance perpendicular to the region of interest where the
C          detonation is located.
C  RJ - The coordinate up the region of interest where the response will
C       be calculated.
C  LOAD - The nondimensionalization factor which multiplies the load
C         terms.
C  TIME - The nondimensionalization factor which multiplies the time terms.
C  A0 - The post-yield to pre-yield moment-curvature ratio which controls
C       the degree of nonlinearity that the hysteretic model will exhibit.
C  A1, A2, P - Control the shape of the hysteretic curve.
C  NUM - Run reference number which is inserted into the name of the output
C       file (ie. NLC"num").
C  WVAL - The TNT throw weight of the charge.
C  XL - The height of the wall or length of the beam element.
C  TS - The time step at which DGEAR returns solutions.
C
```

```
$debug
      CHARACTER NUM*3
      INTEGER NV,NU,ITER
      REAL XVAL,YVAL,WVAL,RJ,LOAD,TIME
C
      COMMON /IN/ XVAL,ZVAL,WVAL,ITER,TS,RJ,NUM,II,k,D,FC,FY
      COMMON /CONV/ LOAD,TIME
      COMMON /PARAMS/ PRV(70),AV(70),TAV(70),T0V(70),XL,YDATA(70)
      COMMON /NONL/A0,A1,A2,P,NV,NU,PI,DCONV,SCONV
      EXTERNAL IVPAG
C
      kk=100
      call input(kk)
      OPEN(UNIT=17,FILE='PLOT'//num)
C      OPEN(UNIT=16,FILE='SUMM'//num)
C
      do 10 I=k,II
      CAll INPUT(I)
C
C
      CALL LOADCDC(XVAL,ZVAL,WVAL)
C
      CALL NONLIN(XL)
C
10       CONTINUE
      END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
    SUBROUTINE NONLIN(xl)
C
C
      INTEGER P,N,METH,INDEX,IWK(35),IER,XT,NV,NU,ITER,TOTE,Q,IRP
     / ,RES
       CHARACTER NUM*3,FLNM1*4,FLNM2*4
C
C
      REAL X1,X2,Y(35),WK(596),X,TOL,XEND,H,A1,A2,A0,TS,PI,DISP,MOM,
     / CURV,SH,RP,YPRIME(35),YM(10),RJ,tmaxs,smax,dmax,lmaxs,lmaxd,
     / dsx,XL
C       COMMON /PARAMS/ PRV(70),AV(70),TAV(70),T0V(70),XL,YDATA(70)
       COMMON /NONL/A0,A1,A2,P,NV,NU,PI,DCONV,SCONV
       COMMON /IN/ XVAL,ZVAL,WVAL,ITER,TS,RJ,NUM,II,K,D,FC,FY
      EXTERNAL FCN,FCNJ,DGEAR
c      oPEN(UNIT=12,FILE='CHECK'//CHAR(II+48)//CHAR(KK+48))
C
      PI = 3.14159
5     CONTINUE
C
       A0=.05
       A1=.5
       A2=.5
       P=5
```

```
C
c     WRITE(12,*) 'NV = ',NV
c     WRITE(12,*) 'NU = ',NU
c     WRITE(12,*)  'ITERATIONS: ', ITER
c     WRITE(12,*)  'TIME STEP: ', TS
c     WRITE(12,*)  ' A0,A1,A2: ',A0,A1,A2
c     WRITE(12,*)  'N - ',P
c     WRITE(12,*)  'XVAL,ZVAL,WVAL', XVAL,ZVAL,WVAL
c     WRITE(*,*)
C
    IT = ITER-1
    TOTE = 2*NV + NU
    Q = 2*NV
C
    DO 10 I=1,TOTE
      Y(I) = 0
10   CONTINUE
C
C  Y(1-NV) = GAMMA(K)
C  Y(NV-2NV) = ALPHA(K)
C  Y(2NV-2NV+NU) = BETA(L)
C
C      DO 15 I=1,NV,2
C        Y(I)=(2/((I*PI)*(X2-X1)))*(-COS(I*PI*X2) + COS(I*PI*X1))*XI
C15    CONTINUE
C
C
    N =TOTE
    METH=1
    MITER = 0
    X=0
    TOL=.001
    H =.00001
    INDEX = 1
    RP = TS*ITER
C
C   Diagonal shear calucalte at the effective depth (d-3) of the
C   concrete section (nondimensionalized) away from the support.
     PRINT*, D,XL
     DSX=(D-3)/(XL*12)
     Z=TS
     smax=0
     dsmax=0
     dmax=0
     tmaxs=0
     lmaxs=0
     tmaxd=0
     lmaxd=0
     DO 20 KKK= 1,ITER
        rj=0
      XEND=Z
```

```
      CALL DGEAR(N,FCN,FCNJ,X,H,Y,XEND,TOL,METH,MITER,INDEX,IWK,WK
     \ ,IER)
110  FORMAT(F12.5)
        DO 30 KKKK=1,11
         DISP=0
      MOM=0
      SH=0
        CURV=0
        diagsh1=0
        diagsh2=0
C
      DO 40 I=1,NV
         DISP=DISP+SIN(I*PI*RJ)*Y(NV+I)
         CURV=CURV-((I*PI)**2)*SIN(I*PI*RJ)*Y(NV+I)
40       CONTINUE
C
      DO 50 I=1,NU
         MOM=MOM+SIN(I*PI*RJ)*Y(Q+I)
         SH=SH+(I*PI)*COS(I*PI*RJ)*Y(Q+I)
50      CONTINUE
       if (disp .gt. dmax) then
        dmax=disp
        tmaxd=z
        lmaxd=rj
      ENDIF
      IF (ABS(MOM) .GT. .9999) THEN
        DO 55 I=1,NU
          print*, mom
          Y(Q+I)=(.9999/ABS(MOM))*Y(Q+I)
55       CONTINUE
      MOM=0
      SH=0
      DO 60 I=1,NU
              MOM=MOM+SIN(I*PI*RJ)*Y(Q+I)
              SH=SH+(I*PI)*COS(I*PI*RJ)*Y(Q+I)
60      CONTINUE

        PRINT*,'MOMENT AND SHEAR HAVE BEEN CORRECTED!',Kkk,mom
      ENDIF
C
        if (abs(sh).gt. abs(smax)) then
        smax=ABS(sh)
        tmaxs=z
        lmaxs=rj
       endif
c
      rj=rj+.1
30    continue
      do 65 i=1,NU
      Diagsh1=diagsh1+(i*pi)*cos(I*pi*dsx)*y(q+i)
      diagsh2=diagsh2+(i*pi)*cos(I*pi*(1-dsx))*y(q+I)
```

```
65      continue
        if (abs(diagsh1) .gt. abs(dsmax)) then
        dsmax= abs(diagsh1)
        endif
        if (abs(diaGsh2) .gt. abs(dsmax)) then
        dsmax= abs(diagsh2)
        endif
        Z=Z+TS
C
20       CONTINUE
        DMAX_C=DMAX*DCONV
        SMAX_C=(SMAX*SCONV)/1000
        dsmax_c=(dsmax*sconv)/1000
330   Format(I3,2x,F5.2,2x,F5.2,2X,F8.3,2X,F12.6,2X,F12.6,2X,F12.3,2X,
   /    F7.2,2X,F7.2,2X,F12.6,2X,F12.6)
C    write(16,330) KKK,ZVAL,XVAL,WVAL,D,FC,XL,DMAX,SMAX,DMAX_C,SMAX_C
400   FORMAT(8F8.2)
    xxl=xl*12
    WRITE(17,400) zval,xval,d,fc,xxl,DMAX_C,SMAX_c,DSmax_c
    RETURN
C
    END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
  SUBROUTINE FCN(N,X,Y,YPRIME)
CC  The following is an excerpt from the DGEAR comments concerning the sub-
CC  routine FCN.
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C               FCN    - NAME OF SUBROUTINE FOR EVALUATING
FUNCTIONS.    DGEA0180
C                      (INPUT)                            DGEA0190
C                      THE SUBROUTINE ITSELF MUST ALSO BE PROVIDED DGEA0200
C                        BY THE USER AND IT SHOULD BE OF THE       DGEA0210
C                        FOLLOWING FORM                        DGEA0220
C                          SUBROUTINE FCN (N,X,Y,YPRIME)          DGEA0230
C                          REAL X,Y(N),YPRIME(N)               DGEA0240
C                            .                              DGEA0250
C                            .                              DGEA0260
C                            .                              DGEA0270
C                      FCN SHOULD EVALUATE YPRIME(1),...,YPRIME(N) DGEA0280
C                        GIVEN N,X, AND Y(1),...,Y(N). YPRIME(I)   DGEA0290
C                        IS THE FIRST DERIVATIVE OF Y(I) WITH      DGEA0300
C                        RESPECT TO X.                       DGEA0310
C                      FCN MUST APPEAR IN AN EXTERNAL STATEMENT IN DGEA0320
C                        THE CALLING PROGRAM AND N,X,Y(1),...,Y(N) DGEA0330
C                        MUST NOT BE ALTERED BY FCN.            DGEA0340
CC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
    INTEGER N,P,NV,NU,W,XT,PT,XTG,Q,XTB,L
C
    REAL FUN1,FUN2,FUN3,A0,A1,A2,Y(N),YPRIME(N),H,CSG(100),CSB(100)
   /,CS(500),TOTAL1(21),TOTAL2(21),PART1(21),PART2(21),C,PI,TOT1(21),
```

```
   /TOT2(21),X,LOAD(10),F,TOTAL(69),SUM,FUN4,SUM1,SUM2
   / ,LOAD1,TIME
C
    COMMON /NONL/ A0,A1,A2,P,NV,NU,PI
    COMMON /CONV/ LOAD1,TIME
     COMMON / PARAMS/ PRV(70),AV(70),TAV(70),T0V(70),XL,YDATA(70)
C
     T1 = TIME*(TAV(69) + T0V(69))
    Q = 2 *NV
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C  The subroutine LIMITS takes the current form of the functions FUN1, FUN2
C  and FUN3 and finds their points of inflection across the beam and
    CALL LIMITS(Y,CSG,CSB,XTB,XTG)
    CALL SORT(CSG,CSB,XTG,XTB,CS,XT)
C
    DO 200 K=1,NV
     IF (X .GE. T1) THEN
       LOAD(K) = 0
     ELSE
C     WRITE(12,101) FUN4(K,I),F(I,X),K,I,X
     DO 210 I = 1,69
        TOTAL(I) = FUN4(K,I)*F(I,X)
210    CONTINUE
      SUM1 = 0
    SUM2 = 0
      DO 220 J=1,50
       IF ((J .EQ. 1) .OR. (J .EQ. 50)) THEN
            SUM1 = SUM1 + .5*TOTAL(J)
        ELSE
            SUM1 = SUM1 + TOTAL(J)
        ENDIF
220    CONTINUE
CCC  MULTIPLY BY THE INCREMENT "DELTA X" = .0102043
    SUM1 = SUM1*.0102043
C
    DO 230 J = 51,69
      IF ((J .EQ. 51) .OR. (J .EQ. 69)) THEN
            SUM2 = SUM2 + .5*TOTAL(J)
        ELSE
            SUM2 = SUM2 + TOTAL(J)
        ENDIF
230  CONTINUE
     SUM2 = SUM2*.0263158
C
    LOAD(K) = SUM1 + SUM2
C     WRITE(12,*) 'K,LOAD(K) = ', K,LOAD(K)
     ENDIF
200  CONTINUE
C
C
C
```

```
C
      IF (NV .GT. NU) THEN
        DO 10 K=1,NU
          YPRIME(K)=-A0*((K*PI)**4)*Y(NV+K)+(1-A0)*((K*PI)**2)*Y(Q+K)
     /  + 2*LOAD(K)
10      CONTINUE
        DO 15 K=NU+1,NV
          YPRIME(K)=-A0*((K*PI)**4)*Y(NV+K) + 2*LOAD(K)
15      CONTINUE
      ELSE
        DO 20 K=1,NV
          YPRIME(K)=-A0*((K*PI)**4)*Y(NV+K)+(1-A0)*((K*PI)**2)*Y(Q+K)
     /    + 2*LOAD(K)
20      CONTINUE
      ENDIF
C
C
      DO 30 K=1,NV
        L=NV+K
        YPRIME(L) = Y(K)
30    CONTINUE
C
C
      DO 40 K=1,NU
       DO 50 I=1,XT-1
         PT=0
         DO 60 C=CS(I),CS(I+1),.05
           PT=PT+1
           IF (P .GE. 2) THEN
             TOT1(PT)=FUN1(K,C)*ABS(FUN2(C,Y))*(ABS(FUN3(C,Y))**(P-1))*
     / FUN3(C,Y)
           ELSE
             TOT1(PT)=FUN1(K,C)*ABS(FUN2(C,Y))*FUN3(C,Y)
           ENDIF
           TOT2(PT)=FUN1(K,C)*FUN2(C,Y)*(ABS(FUN3(C,Y))**P)
60       CONTINUE
         PART1(I)=0
         PART2(I)=0
         DO 70 KI=1,PT-1
          IF ((KI.EQ.1) .OR. (KI.EQ.(PT-1))) THEN
            PART1(I)=PART1(I)+.5*TOT1(KI)
            PART2(I)=PART2(I)+.5*TOT2(KI)
          ELSE
            PART1(I)=PART1(I)+TOT1(KI)
            PART2(I)=PART2(I)+TOT2(KI)
          ENDIF
70       CONTINUE
         H = .05
         PART1(I) = H*PART1(I)
         PART2(I) = H*PART2(I)
50     CONTINUE
```

```
      TOTAL1(K)=0
      TOTAL2(K)=0
      DO 80 I=1,XT-1
        TOTAL1(K)=TOTAL1(K)+PART1(I)
        TOTAL2(K)=TOTAL2(K)+PART2(I)
80     CONTINUE
40    CONTINUE
C
C
    IF (NU .GT. NV) THEN
      DO 90 K=1,NV
        J=(2*NV)+K
     YPRIME(J)=-((K*PI)**2)*Y(K) -2*A1*TOTAL1(K)
   / - 2*A2*TOTAL2(K)
90     CONTINUE
      DO 100 K=NV+1,NU
        J=(2*NV)+K
        YPRIME(J)=-2*A1*TOTAL1(K)-2*A2*TOTAL2(K)
100    CONTINUE
    ELSE
      DO 110 K=1,NU
        J=(2*NV)+K
      YPRIME(J)=-((K*PI)**2)*Y(K) - 2*A1*TOTAL1(K)
   / - 2*A2*TOTAL2(K)
110    CONTINUE
    ENDIF
C
    RETURN
    END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
  REAL FUNCTION F(I,T)
C
C  This function takes the parameters computed in the subroutine
C  LOADCDC and returns the reflected blast pressure at a given point
C  for agiven time after blasrt arrival at the wall.  This function
C  represents a spatial Friedlander equation which returns the reflec-
C  ted pressure at point "I" and time "T" using the equation:
C
C       P(I,T) = PRV(I) * H[T - TAV(I)] * [1 - ((t - TAV(I))/TOV(I))]
C                * exp { -AV(I) * ((T - TAV(I)/TOV(I))
C
C  Where the term H[T - TAV(I)] represents a Heaviside function which
C  prevents the load from being applied prior to its arrival time.
C
C  The terms LOAD and TIME are nondimensionalization factors.
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCC
    REAL Y,T,P1,P2,P3,P4,WGHT,LOAD,TIME
    INTRINSIC EXP
C
```

```
      COMMON /PARAMS/ PRV(70),AV(70),TAV(70),T0V(70),XL,YDATA(70)
      COMMON /CONV/ LOAD,TIME
C
      P1 = PRV(I)*LOAD
      P2 = TAV(I)*TIME
      P3 = T0V(I)*TIME
      P4 = AV(I)
C
       P5 = P2 + P3
       IF (T .LT. P2 .OR. T .GT. P5) THEN
        F = 0
      ELSE
        F = P1 * (1-((T-P2)/P3))*EXP(-P4*((T-P2)/P3))
      ENDIF
C
C
      RETURN
      END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      SUBROUTINE LIMITS(Y,CSG,CSB,XTB,XTG)
C
C  This subroutine takes the fictions FUN2 and FUN3 and determines their
C  inflection points with the current set of coeficients "Y". It takes the
C  current set of "Y" coeficients, calculates the inflections points and
C  stores them in the array CSG for FUN2 and CSB for FUN3.  The number of
C  inflection points is recorded as integers XTG and XTB for FUN2 and FUN3
C  respectively.  These inflection points are used to define the limits
C  for the numerical integration of the equations which contain FUN2 and
C  FUN3 to preclude integration over a range which crosses the x axis.
C
C  Variables
C
C  XTG - Number of inflection points in the function FUN2.
C  XTB - Number of inflection points in the function FUN3.
C  CSG - Array of FUN2 inflection point locations.
C  CSB - Array of FUN3 inflection point locations.
C  L -  The length of the beam element
C  Z - Temporary array of terms in calculating current value of either
C       FUN2 or FUN3.
C  ZC - Term which determines the existance of an inflection point by
C        dividing the current function value by the previous.
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCC
      INTEGER XTB,XTG,NU,NV,Q,P,L
      REAL Y(35),A0,A1,A2,CSB(100),CSG(100),Z(11),ZC,PI
C
      COMMON /NONL/ A0,A1,A2,P,NV,NU,PI
      Q=2*NV
      XTG=0
      XTB=0
```

```
C
      DO 5 I=1,11
       Z(I)=0
5     CONTINUE
        L=0
      RJ=0
      DO 10 J=1,11
        L=L+1
         DO 20 I=1,NV
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CC  This is FUN2.
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
         Z(L)=Z(L)-((I*PI)**2)*SIN(I*PI*RJ)*Y(I)
20       CONTINUE
         RJ=RJ+.1
10    CONTINUE
C
      J=0
      DO 50 RJ=1,10
        J=J+1
       IF (ABS(Z(J)) .LT. .00001) GO TO 50
       ZC=Z(J)/Z(J+1)
       IF (ZC .LT. 0) THEN
         XTG=XTG+1
         CSG(XTG) = (RJ/10) - .05
       ENDIF
50    CONTINUE
      DO 55 I=1,11
       Z(I)=0
55    CONTINUE
       L=0
         RK=0
      DO 30 K = 1,11
         L=L+1
         DO 40 I=1,NU
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CC  This is FUN3.
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
         Z(L)=Z(L)+SIN(I*PI*RK)*Y(Q+I)
40       CONTINUE
         RK=RK+.1
30     CONTINUE
C
       K=0
       DO 60 RK=1,10
         K=K+1
        IF (ABS(Z(K)) .LT. .00001) GO TO 60
       ZC=Z(K)/Z(K+1)
       IF (ZC .LT. 0)THEN
         XTB=XTB+1
         CSB(XTB) =(RK/10)-.05
```

```
      ENDIF
60    CONTINUE
C
     RETURN
     END .
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
   SUBROUTINE SORT(CSG,CSB,XTG,XTB,CS,XT)
C
C   SORT takes the sets of inflection points generated in LIMITS and
C   integrates them into a single, sorted array CS of size XT.
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCC
     INTEGER XTG,XTB,XT,P,NV,NU,X,A
     REAL CSG(100),CSB(100),M,CS(200),A0,A1,A2
C
     XT=XTG+XTB+2
     CS(1)=0
     CS(XT)=1
     DO 10 I=1,XTG
       CS(I+1) = CSG(I)
10    CONTINUE
     DO 20 I=1,XTB
       CS(XTG+1+I)=CSB(I)
20    CONTINUE
     DO 70 I=1,XT-1
      DO 60 J=I+1,XT
       IF ((CS(I)-CS(J)) .LE. 0) GO TO 60
       M=CS(I)
       CS(I)=CS(J)
       CS(J)=M
60     CONTINUE
70    CONTINUE
C
     RETURN
     END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
   FUNCTION FUN1(K,C)
C
     INTEGER K,I
C
     REAL PI,C
C
     COMMON /NONL/ A0,A1,A2,P,NV,NU,PI
C
     FUN1 =SIN(K*PI*C)
     RETURN
     END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
  FUNCTION FUN2(C,Y)
C
```

```
      INTEGER NV
C
      REAL C,PI,Y(35)
C
      COMMON /NONL/ A0,A1,A2,P,NV,NU,PI
C
      FUN2=0
      DO 10 I=1,NV
         FUN2 = FUN2 - ((I*PI)**2)*SIN(I*PI*C)*Y(I)
10    CONTINUE
C
      RETURN
      END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
   FUNCTION FUN3(C,Y)
C
      INTEGER NU,NV,Q
C
      REAL PI,Y(35),C
C
      COMMON /NONL/ A0,A1,A2,P,NV,NU,PI
C
      FUN3 = 0
      Q = 2*NV
      DO 10 I=1,NU
        FUN3 = FUN3 + SIN(I*PI*C)*Y(Q+I)
10    CONTINUE
C
      RETURN
      END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
   FUNCTION FUN4(K,I)
C
      INTEGER K,I
      REAL PI,C
      COMMON /NONL/ A0,A1,A2,P,NV,NU,PI
      COMMON /PARAMS/ PRV(70),AV(70),TAV(70),T0V(70),XL,YDATA(70)
C
      C = YDATA(I)
      FUN4 = SIN(K*PI*C)
C
      RETURN
      END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
   SUBROUTINE FCNJ(N,X,Y,PD)
C
      INTEGER N
      REAL Y(N),PD(N,N),X
      RETURN
      END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
```

```
      SUBROUTINE LOADCDC(X,Z,TNT)
CCCCCCCCCCCCCCCCCCCCCCCCC 4 JANUARY 91
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C  This subroutine is a derivitive of source code taken from the program
C  CONWEP, which was developed by the Army Waterways Experiment Station
C  (WES) as described in the comments below taken from the CONWEP source
C  code.  The routines and functions marked are also used in this program.
C  The body of this routine comes from the CONWEP subroutine BLAST which is
C  described below, after CONWEP, in the original comments.      BLAST was
C  modified to meet the specific needs of this program.  It provides the
C  arrays of data required to specify the pressure time history at a point
C  using the Modifeid Friedlander Equation.  It provides these data arrays
C  to the function F(I,T) which returns the pressure at any point on the
C  region of interest and any time.
C  The subroutines and functions astericked are used in this program
C  as well.
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCC
C
C     PROGRAM ConWep
C
C  SOURCE: USAEWES / SS (Structures Division)
C         D. W. Hyde
C         (601) 634-2758
C
C  PURPOSE:  Calculate a variety of conventional weapons effects
C            according to TM5-855-1, "Fundamentals of Protective
C            Design for Conventional Weapons"
C
C  LAST UPDATED: April 13, 1989
C
C  REQUIRED SUBROUTINES:
C     ABOPTS   - Airblast options menu for PANDR, PANDW, & RANDW
C  *  BLAST    - Find impulse, time of arrival, duration, etc.
C     CASED    - Prompts user for weapon parameters for cased weapons
C     CRATER   - Calculate crater dimensions.
C  *  DECAY    - Find decay coefficient for Friedlander equation.
C     FRAG     - Calculate fragmentation effects.
C     INSIDE   - Calculate quasi-static pressure from an internal
C                explosion.
C     JHOOK    - Calculate path of a projectile through soil.
C     LOGO     - Write intodcutory screen.
C     MARRAY   - Multiply an array of values by a constant.  Used for
C                performing unit conversions prior to plotting.
C     NEWTNT   - Prompts user for explosive parameters.
C     NOSE     - Displays nose shape factors for common projectile shapes.
C     PANDR    - Given peak pressure & range, find charge weight.
C     PANDW    - Given peak pressure & charge weight, find range.
C     PAUSE    - Prompts user to press <CR> before continuing
```

```
C    PEN      - Calculate penetration of a projectile through
C               various target materials.
C    RANDW    - Given range and charge weight, find peak pressure.
C  * RCOEF    - Block data routine containing digitized values for
C               reflected pressure coefficients at different angles
C               of incidence.
C    REFLEC   - Finds pressure and impulse distributions on a wall.
C    SHAPE    - Find penetration of shaped charges into various mat'ls.
C    SHOCK    - Calculate pressure, displacement, acceleration due
C               to a buried charge detonation.
C    SMARMS   - Prompts user for small arms projectile parameters.
C    STDOUT   - Standard output routine for all routines that produce
C              X,Y arrays
C    STUNIT   - Prompt user for unit system to use; set conversion
C               factors.
C    SUBSUR   - Calculate airblast due to a shallow-buried explosion.
C    TNT      - Displays a list of common explosives and associated
C               constants.
C    TUNNEL   - Calculate airblast attenuation in a tunnel.
C    WEAPON   - Select a weapon for use in other subroutines.
C    WEAPS    - Block Data routine containing parameters for weapons
C              catalog.
C
C  REQUIRED FUNCTIONS:
C   * PINC     - Given a scaled range and burst configuration, returns
C              the peak incident pressure in psi.
C    PREF     - Returns the normally reflected pressure in psi.
C    PVEL     - Returns the shock front velocity in kfps.
C   * TARR     - Returns the scaled arrival time in msec / lb**1/3
C   * TDUR     - Returns the scaled positive phase duration in ms/lb**1/3
C    XIMPR    - Returns the scaled reflected impulse in psi*ms/lb**1/3
C   * XIMPS    - Returns the scaled incident impulse in psi*ms/lb**1/3
C    ZFROMP   - Given an incident pressure (psi) and burst configuration,
C              returns the scaled range in ft/lb**1/3.
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCC
C          SUBROUTINE BLAST(SURF)
C
C SOURCE: USAEWES / SS
C       D. W. Hyde
C       (601) 634-2758
C
C LAST UPDATED: 27 April 1988
C
C PURPOSE: Use the equations from BRL Technical Report
C       ARBRL-TR-02555 to find the incident and reflected
C       impulse, reflected pressure, time of arrival, duration,
C       and pressure-time history for a conventional
C       explosion.
C
```

```
C DESCRIPTION OF VARIABLES:
C   A       - Decay coefficient of incident pressure
C             vs. time history, where
C             P(t) = PSO*(1-T/TO)*exp(-A*T/TO)
C   B       - Decay coefficient of reflected pressure
C             vs. time history
C   IMPO    - Peak incident impulse, psi-msec
C   IMPR    - Peak reflected impulse, psi-msec
C   PSO     - Peak incident overpressure, psi
C   PI(1,i) - Incident pressure at time station i
C   PI(2,i) - Incident impulse at time station i
C   PR(1,i) - Reflected pressure at time station i
C   PR(2,i) - Reflected impulse at time station i
C   PRO     - Peak reflected pressure, psi
C   R       - Range, ft
C   SURF    - .TRUE. for surface burst, .FALSE. for air burst
C   T(1,i)  - Time at station i
C   T(2,i)  - Identical to T(1,i), kept for compatibility w/ plot
C             routine only
C   TA      - Arrival time, msec
C   TO      - Positive phase duration, msec
C   WTNT    - Equivalent weight of TNT, lb
C   Z       - Scaled range, ft/lb**1/3
C   ZLOG    - Logarithm of scaled range
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCC
      CHARACTER NUM*3
      REAL  MAXPI,IO,CONST,SSPOLY(10 ),STAT(10),LOGRS
     &       ,YINC1,YINC2
      REAL*8 DECAY
      INTRINSIC EXP
C
      common /in/ xval,zval,wval,iter,ts,rj,num,ii,k,d,fc,fy
      COMMON /PARAMS/ PRV(70),AV(70),TAV(70),TOV(70),XL,YDATA(70)
      COMMON /REFCO/RC(20,39),ATABLE(39),PTABLE(20)
      open(unit=20,file='load'//num)
C
C ====================================================================
C   BLOCK DATA REFLEC
C   THIS BLOCK DATA SUBPROGRAM CONTAINS REFLECTED PRESSURE COEFFICIENTS
C   FROM FIGURE 3-3 OF TM5-855. THESE DATA WERE DIGITIZED BY/FOR
C   PERSONNEL OF THE NAVAL CIVIL ENGINEERING LABORATORY FOR USE IN THE
C   MICRO PROGRAM SHOCK. THE ORIGINAL BLOCK DATA SUBPROGRAM CONTAINED
C   THE SINES OF THE INVERSE OF THE COEFFICIENTS; THIS VERSION HAS THE
C   ACTUAL COEFFICIENTS.
C     COMMON/REFCO/RC(20,39),ATABLE(39),PTABLE(20)
C 5000 PSI
      DATA (RC( 1,I),I=1,39) /12.25,12.00,11.65,11.20,10.65,10.05, 9.40,
     & 8.85, 8.55, 8.25, 7.95, 7.90, 7.85, 7.80, 7.60, 7.50, 7.35, 7.35,
     & 7.50, 9.00, 9.05, 9.05, 8.35, 7.20, 4.70, 2.45, 2.20, 2.05, 1.45,
```

```
     & 1.35, 1.30, 1.20, 1.15, 1.12, 1.02, 1.00, 1.00, 1.00, 1.00/
C 3000 PSI
      DATA (RC( 2,I),I=1,39) /10.80,10.70,10.55,10.30, 9.95, 9.40, 8.80,
     & 8.25, 8.00, 7.75, 7.50, 7.45, 7.40, 7.35, 7.30, 7.25, 7.40, 8.20,
     & 8.60, 8.65, 8.60, 8.50, 7.70, 6.40, 4.25, 2.45, 2.20, 2.05, 1.45,
     & 1.35, 1.30, 1.20, 1.15, 1.12, 1.02, 1.00, 1.00, 1.00, 1.00/
C 2000 PSI
      DATA (RC( 3,I),I=1,39) /10.00, 9.95, 9.80, 9.55, 9.20, 8.75, 8.20,
     & 7.75, 7.50, 7.25, 7.05, 7.00, 6.95, 6.90, 6.85, 6.85, 7.10, 8.00,
     & 8.20, 8.25, 8.15, 8.05, 7.35, 6.25, 4.30, 2.45, 2.20, 2.05, 1.45,
     & 1.35, 1.30, 1.20, 1.15, 1.12, 1.02, 1.00, 1.00, 1.00, 1.00/
C 1000 PSI
      DATA (RC( 4,I),I=1,39) / 8.60, 8.45, 8.25, 7.95, 7.65, 7.30, 6.90,
     & 6.60, 6.40, 6.25, 6.15, 6.10, 6.05, 6.05, 6.00, 6.15, 7.10, 7.60,
     & 7.55, 7.45, 7.35, 7.20, 6.55, 5.75, 3.90, 2.45, 2.20, 2.05, 1.45,
     & 1.35, 1.30, 1.20, 1.15, 1.12, 1.02, 1.00, 1.00, 1.00, 1.00/
C  500 PSI
      DATA (RC( 5,I),I=1,39) / 7.80, 7.65, 7.45, 7.25, 6.95, 6.70, 6.35,
     & 6.05, 5.85, 5.75, 5.70, 5.75, 5.80, 5.80, 6.05, 6.50, 7.10, 7.00,
     & 6.85, 6.75, 6.65, 6.55, 6.00, 5.25, 3.75, 2.45, 2.20, 2.05, 1.45,
     & 1.35, 1.30, 1.20, 1.15, 1.12, 1.02, 1.00, 1.00, 1.00, 1.00/
C  400 PSI
      DATA (RC( 6,I),I=1,39) / 7.00, 6.95, 6.85, 6.75, 6.55, 6.30, 6.00,
     & 5.75,5.6,5.5,5.5,5.6,5.7,5.8,6.05,6.35,6.6,6.5,
     & 6.4,6.3,6.2,6.1,5.6,4.9,3.6,2.45,2.2,2.05,1.45,
     & 1.35, 1.30, 1.20, 1.15, 1.12, 1.02, 1.00, 1.00, 1.00, 1.00/
C  300 PSI
      DATA (RC( 7,I),I=1,39) / 6.65, 6.60, 6.50, 6.35, 6.20, 5.90, 5.65,
     & 5.40, 5.30, 5.25, 5.40, 5.50, 5.60, 5.80, 6.00, 6.05, 5.95, 5.85,
     & 5.75, 5.70, 5.60, 5.55, 5.15, 4.60, 3.50, 2.45, 2.20, 2.05, 1.45,
     & 1.35, 1.30, 1.20, 1.15, 1.12, 1.02, 1.00, 1.00, 1.00, 1.00/
C  200 PSI
      DATA (RC( 8,I),I=1,39) / 6.00, 5.90, 5.85, 5.75, 5.65, 5.45, 5.20,
     & 4.95, 4.90, 4.95, 5.15, 5.30, 5.40, 5.50, 5.45, 5.40, 5.25, 5.10,
     & 5.05, 5.00, 4.95, 4.85, 4.55, 4.10, 3.30, 2.45, 2.35, 2.30, 1.90,
     & 1.85, 1.80, 1.60, 1.55, 1.50, 1.40, 1.35, 1.30, 1.15, 1.00/
C  150 PSI
      DATA (RC( 9,I),I=1,39) / 5.60, 5.50, 5.45, 5.35, 5.20, 5.05, 4.80,
     & 4.60, 4.60, 4.65, 4.90, 5.10, 5.15, 5.10, 5.05, 4.90, 4.75, 4.65,
     & 4.55, 4.45, 4.40, 4.35, 4.05, 3.70, 3.00, 2.20, 2.15, 2.10, 1.80,
     & 1.75, 1.70, 1.65, 1.60, 1.30, 1.25, 1.20, 1.15, 1.10, 1.00/
C  100 PSI
      DATA (RC(10,I),I=1,39) / 5.00, 4.95, 4.85, 4.80, 4.65, 4.55, 4.40,
     & 4.30, 4.25, 4.30, 4.65, 4.75, 4.70, 4.60, 4.40, 4.20, 3.95, 3.75,
     & 3.70, 3.60, 3.55, 3.45, 3.25, 2.95, 2.40, 2.00, 1.90, 1.85, 1.70,
     & 1.65, 1.60, 1.50, 1.45, 1.40, 1.30, 1.25, 1.22, 1.10, 1.00/
C   70 PSI
      DATA (RC(11,I),I=1,39) / 4.45, 4.40, 4.35, 4.25, 4.15, 4.10, 4.00,
     & 3.85, 3.85, 3.95, 4.30, 4.35, 4.25, 4.10, 3.85, 3.60, 3.35, 3.20,
     & 3.10, 3.05, 3.00, 2.90, 2.70, 2.45, 2.05, 1.80, 1.75, 1.70, 1.55,
     & 1.50, 1.45, 1.35, 1.30, 1.25, 1.22, 1.20, 1.20, 1.10, 1.00/
```

```
C  50 PSI
   DATA (RC(12,I),I=1,39) / 4.00, 3.90, 3.85, 3.80, 3.70, 3.65, 3.55,
  & 3.50, 3.50, 3.60, 4.10, 4.10, 4.00, 3.80, 3.50, 3.25, 2.95, 2.80,
  & 2.70, 2.65, 2.60, 2.55, 2.30, 2.05, 1.85, 1.55, 1.50, 1.45, 1.35,
  & 1.32, 1.30, 1.25, 1.22, 1.20, 1.15, 1.12, 1.10, 1.05, 1.00/
C  30 PSI
   DATA (RC(13,I),I=1,39) / 3.35, 3.30, 3.25, 3.20, 3.15, 3.10, 3.10,
  & 3.10, 3.15, 3.20, 3.50, 3.60, 3.55, 3.40, 3.20, 2.95, 2.75, 2.60,
  & 2.55, 2.50, 2.45, 2.40, 2.20, 2.00, 1.70, 1.55, 1.50, 1.45, 1.35,
  & 1.32, 1.30, 1.25, 1.22, 1.20, 1.15, 1.12, 1.10, 1.05, 1.00/
C  20 PSI
   DATA (RC(14,I),I=1,39) / 3.00, 3.00, 3.00, 2.95, 2.90, 2.85, 2.85,
  & 2.90, 2.90, 2.95, 3.05, 3.10, 3.20, 3.25, 3.40, 3.25, 3.00, 2.90,
  & 2.85, 2.75, 2.70, 2.65, 2.45, 2.20, 1.90, 1.70, 1.65, 1.60, 1.50,
  & 1.45, 1.40, 1.30, 1.27, 1.25, 1.22, 1.20, 1.20, 1.10, 1.00/
C  10 PSI
   DATA (RC(15,I),I=1,39) / 2.50, 2.50, 2.50, 2.50, 2.50, 2.50, 2.50,
  & 2.50, 2.50, 2.50, 2.50, 2.55, 2.60, 2.65, 2.70, 2.75, 3.00, 3.20,
  & 3.25, 3.25, 3.20, 3.15, 2.90, 2.60, 2.20, 1.90, 1.85, 1.80, 1.65,
  & 1.60, 1.55, 1.50, 1.45, 1.40, 1.30, 1.25, 1.20, 1.15, 1.00/
C   5 PSI
   DATA (RC(16,I),I=1,39) / 2.20, 2.20, 2.20, 2.20, 2.20, 2.20, 2.20,
  & 2.20, 2.20, 2.20, 2.20, 2.20, 2.20, 2.25, 2.30, 2.35, 2.35, 2.37,
  & 2.40, 2.45, 2.47, 2.52, 2.75, 3.25, 2.85, 2.45, 2.35, 2.30, 2.00,
  & 1.95, 1.90, 1.70, 1.65, 1.60, 1.40, 1.35, 1.30, 1.20, 1.00/
C   2 PSI
   DATA (RC(17,I),I=1,39) / 2.10, 2.10, 2.10, 2.10, 2.10, 2.10, 2.10,
  & 2.10, 2.10, 2.10, 2.10, 2.10, 2.10, 2.10, 2.10, 2.10, 2.10, 2.10,
  & 2.10, 2.10, 2.10, 2.10, 2.15, 2.20, 2.40, 3.10, 3.10, 3.05, 2.60,
  & 2.50, 2.40, 2.10, 2.00, 1.90, 1.60, 1.52, 1.47, 1.20, 1.00/
C   1 PSI
   DATA (RC(18,I),I=1,39) / 2.05, 2.05, 2.05, 2.05, 2.05, 2.05, 2.05,
  & 2.05, 2.05, 2.05, 2.05, 2.05, 2.05, 2.05, 2.05, 2.05, 2.05, 2.05,
  & 2.05, 2.05, 2.05, 2.05, 2.05, 2.05, 2.10, 2.25, 2.30, 2.35, 3.10,
  & 3.15, 3.10, 2.65, 2.50, 2.35, 1.90, 1.75, 1.65, 1.30, 1.00/
C   0.5 PSI
   DATA (RC(19,I),I=1,39) / 2.05, 2.05, 2.05, 2.05, 2.05, 2.05, 2.05,
  & 2.05, 2.05, 2.05, 2.05, 2.05, 2.05, 2.05, 2.05, 2.05, 2.05, 2.05,
  & 2.05, 2.05, 2.05, 2.05, 2.05, 2.05, 2.05, 2.05, 2.05, 2.10, 2.25,
  & 2.30, 2.40, 3.05, 3.10, 3.05, 2.30, 2.15, 2.00, 1.45, 1.00/
C   0.2 PSI
   DATA (RC(20,I),I=1,39) / 2.00, 2.00, 2.00, 2.00, 2.00, 2.00, 2.00,
  & 2.00, 2.00, 2.00, 2.00, 2.00, 2.00, 2.00, 2.00, 2.00, 2.00, 2.00,
  & 2.00, 2.00, 2.00, 2.00, 2.00, 2.00, 2.00, 2.00, 2.00, 2.00, 2.00,
  & 2.00, 2.05, 2.10, 2.15, 2.20, 3.05, 3.05, 2.95, 1.70, 1.00/
   DATA ATABLE/ 0.0, 5.0,10.0,15.0,20.0,25.0,30.0,34.0,36.0,38.0,
  &  40.0,40.5,41.0,41.5,42.5,43.5,45.0,46.0,46.5,47.0,47.5,48.0,
  &  50.0,52.5,57.0,62.0,63.0,64.0,68.0,69.0,70.0,73.0,74.0,75.0,
  &  79.0,80.0,81.0,85.0,90.0/
   DATA PTABLE/ 5000.,3000.,2000.,1000., 500., 400., 300., 200.,
  & 150., 100., 70., 50., 30., 20., 10., 5., 2., 1.,
```

```
    & 0.5,  0.2/
C
C
     YINC1 = XL/98
     YINC2 = XL/38
     YDATA(1) = 0
     DO 5 I = 2,69
        IF (I .LE. 50) THEN
           J = I-1
           YDATA(I) = YDATA(J) + YINC1
        ELSE
           J = I-1
           YDATA(I) = YDATA(J) + YINC2
        ENDIF
5    CONTINUE
C
C COMPUTE CUBE ROOT OF TNT
     W3 = TNT**(1./3.)
C
     DO 10 I=1,70
       RANG = SQRT(X*X + Z*Z + YDATA(I)*YDATA(I))
       RANGS = RANG/W3
C COMPUTE ANGLE OF INCIDENCE
       CO = AMIN1(1.,Z/RANG)
     RTOD = 45./ATAN(1.)
       ALPHA = ACOS(CO)*RTOD
C FIND INCIDENT PRESSURE AT THIS POINT, NEED THE LOG OF THE SCALED RANGE
       LOGRS = ALOG10(RANGS)
       MAXPI = PINC(LOGRS)
C
C  FIND PRESSURES FROM TABLE THAT BOUND PSO
        DO 200 KK = 1,20
         IF(MAXPI .GE. PTABLE(KK)) GOTO 201
200     CONTINUE
201      IP1 = MAX0(1,KK-1)
        IP2 = MIN0(20,KK)
C  FIND ANGLES FROM TABLE THAT BOUND ALPHA
        DO 205 KK = 1,39
         IF(ALPHA .LE. ATABLE(KK)) GOTO 206
205     CONTINUE
206      IA1 = MAX0(1,KK-1)
        IA2 = MIN0(39,KK)

        IF(IA1 .EQ. IA2) THEN
         FACTA = 0.0
        ELSE
         FACTA = (ALPHA - ATABLE(IA1)) / (ATABLE(IA2)-ATABLE(IA1))
        ENDIF
        C1 = RC(IP1,IA1) + ( RC(IP1,IA2) - RC(IP1,IA1) ) * FACTA
        C2 = RC(IP2,IA1) + ( RC(IP2,IA2) - RC(IP2,IA1) ) * FACTA
        IF(IP1 .EQ. IP2) THEN
```

```
         REF = C1
        ELSE
         REF = C1 + (C2-C1) * ( MAXPI - PTABLE(IP1) ) /
     &         ( PTABLE(IP2)-PTABLE(IP1) )
        ENDIF
C
        PRV(I) = MAXPI*REF
CCCCCCCCC
CCCCCCCCC    INSERT FUNCTIONS FROM CONWEP
CCCCCCCCC
      IO = XIMPS(LOGRS)*W3
      TAV(I) = TARR(LOGRS)*W3
      T0V(I) = TDUR(LOGRS)*W3
       TD = T0V(I)
      AV(I) = DECAY(MAXPI,IO,TD)
      write(20,22) i,prv(i),tav(i),t0v(i),td,av(i)
10    CONTINUE
22    FORMAT(I5,5F12.5)

      DO 15 J=1,69
       YDATA(J) = YDATA(J)/XL
15    CONTINUE
C
      RETURN
C
      END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      REAL FUNCTION PINC(ZLOG)
C
C
C PURPOSE: FIND THE INCIDENT PRESSURE DUE TO THE DETONATION
C        OF A 1 LB EQUIVALENT TNT CHARGE.  EQUATIONS ARE FROM BRL
C        TECHNICAL REPORT ARBRL-TR-02555.  PRESSURE IS RETURNED IN
C        UNITS OF PSI.
C
C  DESCRIPTION OF VARIABLES:
C    SURF    - .TRUE. FOR SURFACE BURST, .FALSE. FOR AIR BURST
C    ZLOG    - LOGARITHM OF SCALED RANGE
C
      PARAMETER (NS=11, NF=8)
      REAL CSURF(NS+1)
      DATA CSURF / 1.9422502013,    -1.6958988741,
     &          -0.154159376846,   0.514060730593,
     &           0.0988534365274, -0.293912623038,
     &          -0.0268112345019,  0.109097496421,
     &           0.00162846756311,-0.0214631030242,
     &           0.0001456723382,  0.00167847752266 /
C
      U   = -0.756579301809 + 1.35034249993*ZLOG
       PINC = CSURF(NS+1)
       DO 10 I = NS,1,-1
```

```
10      PINC = PINC*U + CSURF(I)
      PINC = 10.**PINC
      RETURN
      END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      DOUBLE PRECISION FUNCTION DECAY(P0,I0,TD)
      REAL*4 P0,I0,TD
      REAL*8 A,FA,FPA,PTOI
C
C  FIND RATE OF DECAY FOR PRESSURE ASSUMING:
C
C    P(T) = P0 * [ 1 - (T-TA)/TD] * EXP[-A*(T-TA)/TD]
C                                  (FRIEDLANDER'S EQUATION)
C
C  WHERE A IS A DECAY COEFFICIENT.  INTEGRATING THIS EQUATION
C  OVER TIME GIVES THE IMPULSE:
C
C    I0 = P0 * TD * [ A + EXP(-A) - 1 ] / A**2
C
C  FIND F(A) = A**2 - P0*TD/I0*[ A + EXP(-A) - 1] = 0
C  OR:
C            A**2 / [ A + EXP(-A) - 1] - P0*TD/I0 = 0
C
C  FOR LARGE A, EXP(-A) APPROACHES 0, AND
C  A**2 / (A - 1) APPROACHES A + 1
C
C   INITIAL GUESS A = P0*TD/I0 - 1
C
      PTOI = P0*TD/I0
C  INITIAL GUESS:
      A = PTOI - 1.
 1    FA  = A*A - PTOI*(A + EXP(-A) - 1.)
      FPA = 2*A - PTOI*(1. - EXP(-A))
      A = A - FA/FPA
      IF(ABS(FA) .GT. 1.D-6) GO TO 1
      DECAY = A
      RETURN
      END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      REAL FUNCTION TARR(ZLOG)
C
C PURPOSE: FIND THE SCALED TIME OF ARRIVAL FOR THE DETONATION OF A
C        1 LB EQUIVALENT TNT CHARGE.  EQUATIONS ARE FROM BRL
C        TECHNICAL REPORT ARBRL-TR-02555.  ARRIVAL TIME IS RETURNED
C        IN MSEC/LB**(1/3).
C
C  DESCRIPTION OF VARIABLES:
C   ZLOG     - LOGARITHM OF SCALED RANGE
C
      PARAMETER (NS=9)
      REAL CSURF(NS+1)
```

```
      DATA CSURF /-0.173607601251,   1.35706496258,
     &            0.052492798645,  -0.196563954086,
     &           -0.0601770052288,  0.0696360270891,
     &            0.0215297490092, -0.0161658930785,
     &           -0.00232531970294, 0.00147752067524 /
       U  = -0.755684472698 + 1.37784223635*ZLOG
       TARR = CSURF(NS+1)
       DO 10 I = NS,1,-1
 10     TARR = TARR*U + CSURF(I)
      TARR = 10.**TARR
      RETURN
      END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
    REAL FUNCTION TDUR(ZLOG)
C
C PURPOSE: FIND THE SCALED DURATION FOR THE DETONATION OF A 1 LB
C        EQUIVALENT TNT CHARGE.  EQUATIONS ARE FROM BRL TECHNICAL
C        REPORT ARBRL-TR-02555.  DURATION IS RETURNED IN
C        MSEC/LB**(1/3).
C
C  DESCRIPTION OF VARIABLES:
C   ZLOG    - LOGARITHM OF SCALED RANGE
C
      PARAMETER (NS1=5,NS2=8,NS3=5)
      REAL CSURF1(NS1+1), CSURF2(NS2+1), CSURF3(NS3+1)
      DATA CSURF1 / -0.728671776005,   0.130143717675,
     &              0.134872511954,   0.0391574276906,
     &             -0.00475933664702,-0.00428144598008 /
      DATA CSURF2 /  0.20096507334,   -0.0297944268976,
     &              0.030632954288,   0.0183405574086,
     &             -0.0173964666211, -0.00106321963633,
     &              0.00562060030977, 0.0001618217499,
     &             -0.0006860188944 /
       DATA CSURF3 /  0.572462469964,     0.0933035304009,
     &             -0.0005849420883, -0.00226884995013,
     &             -0.00295908591505, 0.00148029868929 /
       IF(ZLOG .LT. 0.4048337) THEN
         U  = -0.1790217052 + 5.25099193925*ZLOG
         TDUR = CSURF1(NS1+1)
         DO 11 I = NS1,1,-1
 11       TDUR = TDUR*U + CSURF1(I)
       ELSEIF(ZLOG .GE. 0.4048337 .AND.  ZLOG .LT. 0.845098) THEN
         U  = -5.85909812338 + 9.2996288611*ZLOG
         TDUR = CSURF2(NS2+1)
         DO 12 I = NS2,1,-1
 12       TDUR = TDUR*U + CSURF2(I)
       ELSE
         U  = -4.92699491141 + 3.46349745571*ZLOG
         TDUR = CSURF3(NS3+1)
         DO 13 I = NS3,1,-1
 13       TDUR = TDUR*U + CSURF3(I)
```

```
      ENDIF
     TDUR = 10.**TDUR
     RETURN
     END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
   REAL FUNCTION XIMPS(ZLOG)
C
C PURPOSE: FIND THE SCALED INCIDENT IMPULSE FOR THE DETONATION OF
C        A 1 LB EQUIVALENT TNT CHARGE.  EQUATIONS ARE FROM BRL
C        TECHNICAL REPORT ARBRL-TR-02555.  IMPULSE IS RETURNED IN
C        UNITS OF PSI*MSEC/LB**(1/3).
C
C  DESCRIPTION OF VARIABLES:
C   ZLOG    - LOGARITHM OF SCALED RANGE
C
     PARAMETER (NS1=4,NS2=7)
     REAL CSURF1(NS1+1),CSURF2(NS2+1)
     DATA CSURF1 / 1.57159240621, -0.502992763686,
    &            0.171335645235, 0.0450176963051,
    &           -0.0118964626402 /
     DATA CSURF2 / 0.719852655584,  -0.384519026965,
    &           -0.0280816706301,  0.00595798753822,
    &            0.014544526107,  -0.00663289334734,
    &           -0.00284189327204, 0.0013644816227 /
      IF(ZLOG .LT. 0.382017) THEN
        U = 0.832468843425 + 3.0760329666*ZLOG
        XIMPS = CSURF1(NS1+1)
        DO 11 I = NS1,1,-1
 11      XIMPS = XIMPS*U + CSURF1(I)
      ELSE
        U = -2.91358616806 + 2.40697745406*ZLOG
        XIMPS = CSURF2(NS2+1)
        DO 12 I = NS2,1,-1
 12      XIMPS = XIMPS*U + CSURF2(I)
      ENDIF
     XIMPS = 10.**XIMPS
     RETURN
     END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C  The remainder of the code contains the first order simultaneous
C  equation solver DGEAR and its associated subroutines.
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
```

Appendix C

Response Surface Model Information

500 lb Response Surface - NONLIN DATA

0	1 ZVAL	2 XVAL	3 W_T	4 W_S	5 W_H	6 M_D	7 SDIR	8 SDIAG
1	15	0	12	3000	168	19.20	7.01	5.81
2	15	0	12	3000	108	8.17	10.14	6.03
3	15	0	12	7000	168	15.74	8.45	7.00
4	55	0	36	7000	108	0.00	0.00	0.00
5	55	0	36	3000	168	0.22	19.30	6.94
6	5	55	36	3000	168	0.05	10.23	5.38
7	55	55	36	3000	108	0.00	0.00	0.00
8	5	0	24	7000	108	1.84	44.38	26.24
9	55	0	12	7000	168	3.40	4.61	3.96
10	5	55	12	7000	168	1.07	2.72	2.29
11	55	55	12	7000	108	0.00	0.00	0.00
12	5	0	36	7000	168	1.23	103.17	79.30
13	5	55	36	7000	108	0.00	0.00	0.00
14	55	55	36	7000	168	0.00	0.00	0.00
15	5	28	24	5000	144	0.40	15.53	6.17
16	55	28	24	5000	144	0.12	10.02	4.98
17	30	0	24	5000	144	1.73	33.26	4.07
18	30	55	24	5000	144	0.07	8.07	3.56
19	30	28	12	5000	144	3.68	3.29	2.58
20	30	28	36	5000	144	0.23	29.86	7.78
21	30	28	24	3000	144	0.89	16.79	6.41
22	30	28	24	7000	144	0.70	16.17	7.02
23	30	28	24	5000	108	0.21	18.29	7.77
24	30	28	24	5000	144	0.78	16.86	6.34
25	30	28	24	5000	144	0.78	16.86	6.34
26	5	0	12	7000	108	23.00	10.00	8.00
27	5	0	12	3000	168	8.00	7.00	5.00
28	5	0	36	7000	108	0.79	120.29	59.17
29	5	0	36	3000	168	1.49	65.75	41.05

1000 lb Response Surface - NONLIN DATA

0	1 ZVAL	2 XVAL	3 W_T	4 W_S	5 W_H	6 M_D	7 SDIR	8 SDIAG
1	5	0	12	3000	168	45.00	10.00	8.00
2	55	0	36	7000	108	0.00	0.00	0.00
3	55	0	36	3000	168	1.29	37.41	15.61
4	5	55	36	3000	168	0.24	17.90	5.89
5	55	55	36	3000	108	0.00	0.00	0.00
6	5	0	24	7000	108	6.07	105.92	9[illegible].44
7	55	0	12	7000	168	12.18	5.39	4.31
8	5	55	12	7000	168	2.90	3.31	2.61
9	55	55	12	7000	108	0.47	5.79	3.39
10	5	0	36	7000	168	3.99	176.59	164.29
11	5	55	36	7000	108	0.00	0.00	0.00
12	55	55	36	7000	168	0.00	13.47	4.21
13	5	28	24	5000	144	0.95	26.95	5.41
14	55	28	24	5000	144	1.18	19.20	4.05
15	30	0	24	5000	144	5.44	19.15	9.30
16	30	55	24	5000	144	0.47	13.08	4.50
17	30	28	12	5000	144	13.70	7.32	5.16
18	30	28	36	5000	144	1.22	43.96	24.79
19	30	28	24	3000	144	3.60	21.66	6.76
20	30	28	24	7000	144	2.91	41.70	8.03
21	30	28	24	5000	108	1.43	30.44	16.00
22	30	28	24	5000	144	3.18	23.86	7.52
23	30	28	24	5000	144	3.18	23.86	7.52
24	55	25	12	7000	108	2.96	5.41	3.28
25	15	0	12	3000	108	13.04	12.62	7.59
26	25	0	12	3000	108	13.77	11.17	6.70
27	25	0	12	3000	168	32.81	7.31	6.03
28	55	0	12	3000	108	5.88	5.58	3.79
29	5	55	12	3000	108	1.40	4.29	2.44
30	55	55	12	3000	168	7.21	3.44	2.71
31	5	0	12	7000	108	22.00	7.00	4.00

2000 lb Response Surface - NONLIN DATA

0	1 ZVAL	2 XVAL	3 W_T	4 W_S	5 W_H	6 M_D	7 SDIR	8 SDIAG
1	5	0	12	3000	168	35.50	8.00	6.00
2	55	0	12	3000	108	2.87	7.10	4.02
3	5	55	12	3000	108	0.78	3.62	2.70
4	55	55	12	3000	168	4.78	3.09	2.49
5	5	0	36	3000	108	1.73	122.03	71.97
6	55	55	12	3000	108	0.52	4.58	3.04
7	5	0	12	7000	108	12.00	15.00	9.00
8	55	0	12	7000	168	6.24	6.54	5.30
9	5	55	12	7000	168	1.71	3.75	3.19
10	55	55	12	7000	108	0.02	4.54	2.82
11	5	10	36	7000	168	0.35	66.75	27.87
12	55	0	36	7000	108	0.00	0.00	0.00
13	5	55	36	7000	108	0.00	0.00	0.00
14	55	55	36	7000	168	0.00	0.00	0.00
15	5	28	24	5000	144	0.66	20.05	6.02
16	55	28	24	5000	144	0.44	13.00	4.70
17	30	0	24	5000	144	3.25	40.52	7.94
18	30	55	24	5000	144	0.21	9.70	4.50
19	30	28	12	5000	144	6.85	9.44	6.82
20	30	28	36	5000	144	0.53	40.42	15.61
21	30	28	24	3000	144	1.75	24.74	4.13
22	30	28	24	7000	144	1.41	20.50	6.52
23	30	28	24	5000	108	0.59	25.14	8.34
24	30	28	24	5000	144	1.54	25.31	5.13
25	30	28	24	5000	144	1.54	25.31	5.13

500 lb Response Surface Model Information

!MOD55D 12R x 1C 15-JAN-94 8:56
Page 1

Accepted model for response M_D

0	1
1 Model Name:	MR553
2 Response Transformation:	Untransformed
3 Method:	Least Squares
4 Weights:	None
5 Total Number of Cases:	29
6 Number of Predictors:	5
7 Number of Unexpanded Ter	14
8 Number of Excluded Cases	0
9 Error Degrees of Freedom	15
10 Standard Error of Respon	6.013722
11 Relative PRESS:	0.407118
12 Root Mean Squared Error:	2.984413

!COEF55D 14R x 4C 15-JAN-94 8:56
Page 1

Least Squares Coefficients, Response M, Model MR551__COPY

0 Term	1 Coeff.	2 Std. Error	3 T-value	4 Signif.
1 1	-4.062295	17.936065	-0.23	0.8239
2 Z	0.652205	0.345298	1.89	0.0784
3 X	-0.426211	0.088692	-4.81	0.0002
4 W	-2.505735	0.583184	-4.30	0.0006
5 W_	0.007857	0.002558	3.07	0.0078
6 W_H	0.181769	0.106889	1.70	0.1097
7 Z*W_	-0.000047	0.000021	-2.22	0.0421
8 Z*W_H	-0.002520	0.001385	-1.82	0.0889
9 Z*W_	0.005176	0.003065	1.69	0.1120
10 X*W	0.013339	0.003119	4.28	0.0007
11 W_*W_H	-0.000041	0.000015	-2.68	0.0170
12 W_H*W	0.004851	0.002283	2.13	0.0506
13 Z**2	-0.003385	0.002456	-1.38	0.1883
14 W**2	0.022333	0.009945	2.25	0.0402

No. cases = 29 R-sq. = 0.8681 RMS Error = 2.984
Resid. df = 15 R-sq-adj. = 0.7537 Cond. No. = 175.6

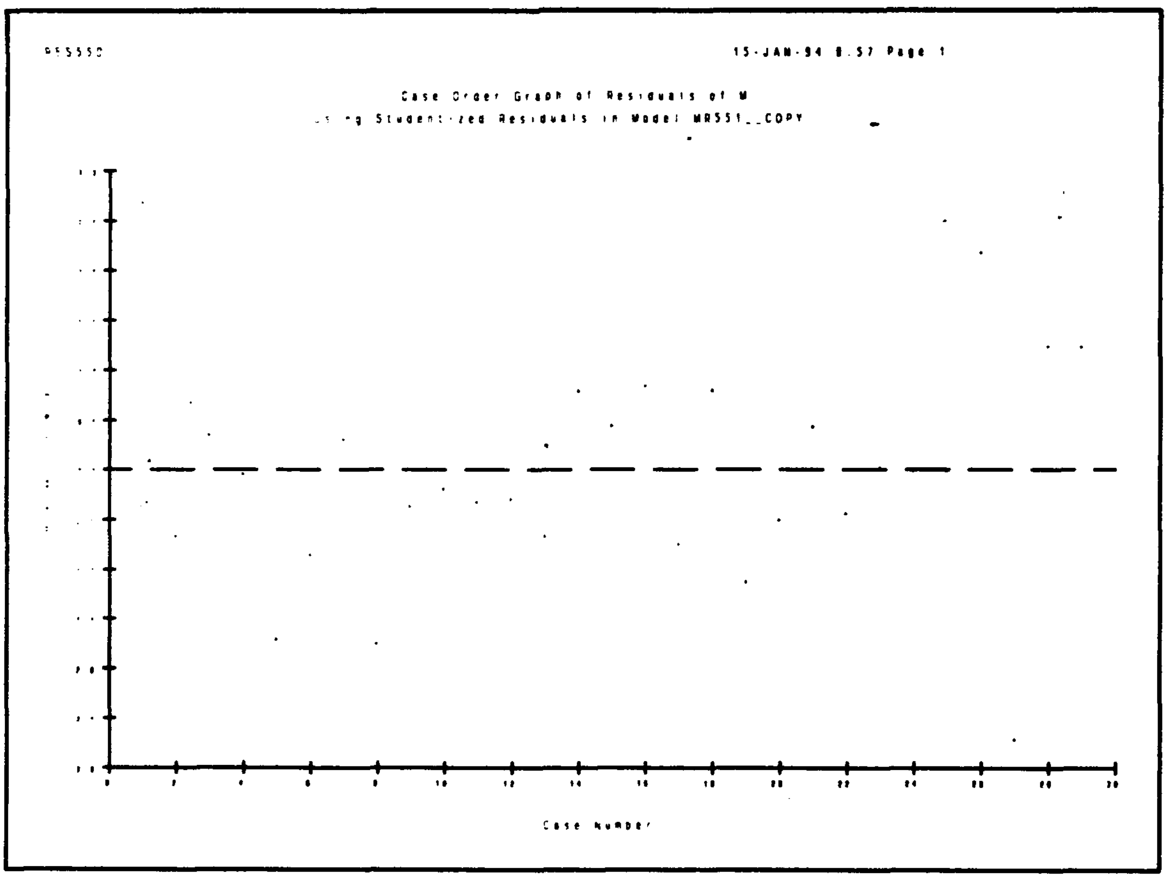
!ANOV55D 7R x 5C 15-JAN-94 8:51
Page 1

Least Squares Summary ANOVA, Response M Model MR551

0 Source	1 df	2 Sum Sq.	3 Mean Sq.	4 F-Ratio	5 Signif.
1 Total (Corr.)	28	1012.616			
2 Regression	20	891.071	44.554	2.93	0.0609
3 Linear	5	535.077	107.015	7.04	0.0083
4 Non-linear	15	355.995	23.733	1.56	0.2667
5 Residual	8	121.544	15.193		
6 Lack of fit	7	121.544	17.363		
7 Pure error	1	0.000	0.000		

R-sq. = 0.8800
R-sq-adj. = 0.5799

Model obeys hierarchy. The sum of squares for linear terms is computed assuming nonlinear terms are first removed.



!MOD55S 12R x 1C 15-JAN-94 8:56
Page 1

Accepted model for response SDIR

0	1
1 Model Name:	MR554
2 Response Transformation:	Untransformed
3 Method:	Least Squares
4 Weights:	None
5 Total Number of Cases:	29
6 Number of Predictors:	5
7 Number of Unexpanded Ter	13
8 Number of Excluded Cases	0
9 Error Degrees of Freedom	16
10 Standard Error of Respon	29.162779
11 Relative PRESS:	0.77632
12 Root Mean Squared Error:	7.503846

!COEF55S 13R x 4C 15-JAN-94 8:57
Page 1

Least Squares Coefficients, Response S, Model MR554

0 Term	1 Coeff.	2 Std. Error	3 T-value	4 Signif.
1 1	-52.895570	40.769655		
2 Z	1.942077	0.466188		
3 X	-2.154419	0.523765		
4 W	6.267415	0.977596		
5 W_	-0.005148	0.005973		
6 W_H	-0.076856	0.263059		
7 Z*X	0.025219	0.003388	7.44	0.0001
8 Z*W_	-0.000208	0.000052	-3.99	0.0011
9 Z*W	-0.071017	0.009085	-7.82	0.0001
10 X*W_H	0.012470	0.003068	4.06	0.0009
11 X*W	-0.035524	0.006581	-5.40	0.0001
12 W_*W_H	0.000069	0.000037	1.86	0.0819
13 W_H*W	-0.016012	0.006058	-2.64	0.0177

No. cases = 29 R-sq. = 0.9622 RMS Error = 7.504
Resid. df = 16 R-sq-adj. = 0.9338 Cond. No. = 156.7

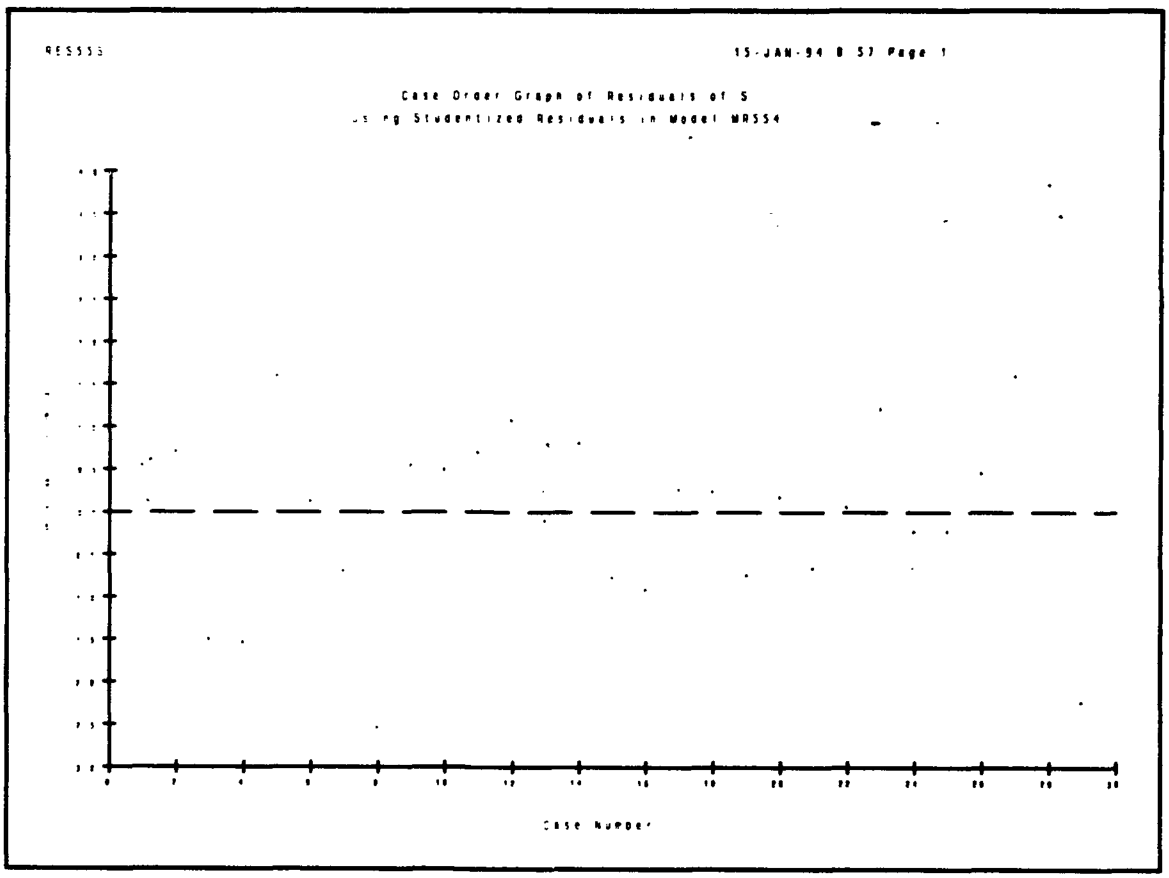
!ANOV55S 7R x 5C 15-JAN-94 8:55
Page 1

Least Squares Summary ANOVA, Response S Model MR554

0 Source	1 df	2 Sum Sq.	3 Mean Sq.	4 F-Ratio	5 Signif.
1 Total (Corr.)	28	23813.09			
2 Regression	12	22912.17	1909.35	33.91	0.0000
3 Linear	5	14107.21	2821.44	50.11	0.0000
4 Non-linear	7	8804.96	1257.85	22.34	0.0000
5 Residual	16	900.92	56.31		
6 Lack of fit	15	900.92	60.06		
7 Pure error	1	0.00	0.00		

R-sq. = 0.9622
R-sq-adj. = 0.9338

Model obeys hierarchy. The sum of squares for linear terms is computed assuming nonlinear terms are first removed.



!MOD55SD 12R x 1C 15-JAN-94 8:56
Page 1

Accepted model for response SDIAG

0	1
1 Model Name:	MR555
2 Response Transformation:	Untransformed
3 Method:	Least Squares
4 Weights:	None
5 Total Number of Cases:	29
6 Number of Predictors:	5
7 Number of Unexpanded Ter	15
8 Number of Excluded Cases	0
9 Error Degrees of Freedom	14
10 Standard Error of Respon	18.270403
11 Relative PRESS:	0.791464
12 Root Mean Squared Error:	3.622131

!COEF55SD 15R x 4C 15-JAN-94 8:57
Page 1

Least Squares Coefficients, Response SD, Model MR555

0 Term	1 Coeff.	2 Std. Error	3 T-value	4 Signif.
1 1	214.375478	41.805261		
2 Z	0.967757	0.217279		
3 X	0.780201	0.194868		
4 W	-0.386121	0.628712		
5 W_	-0.009305	0.002934		
6 W_H	-3.129392	0.549253		
7 Z*X	0.011766	0.001568	7.50	0.0001
8 Z*W_	-0.000126	0.000026	-4.94	0.0002
9 Z*W_	-0.033258	0.003835	-8.67	0.0001
10 X*W_	-0.000109	0.000023	-4.78	0.0003
11 X*W_	-0.030166	0.003404	-8.86	0.0001
12 W_*W_H	0.000056	0.000018	3.06	0.0085
13 W_*W_	0.000298	0.000054	5.56	0.0001
14 W_H*W	0.006501	0.002973	2.19	0.0462
15 W_H**2	0.010443	0.001918	5.45	0.0001

No. cases = 29 R-sq. = 0.9803 RMS Error = 3.622
Resid. df = 14 R-sq-adj. = 0.9607 Cond. No. = 494.4

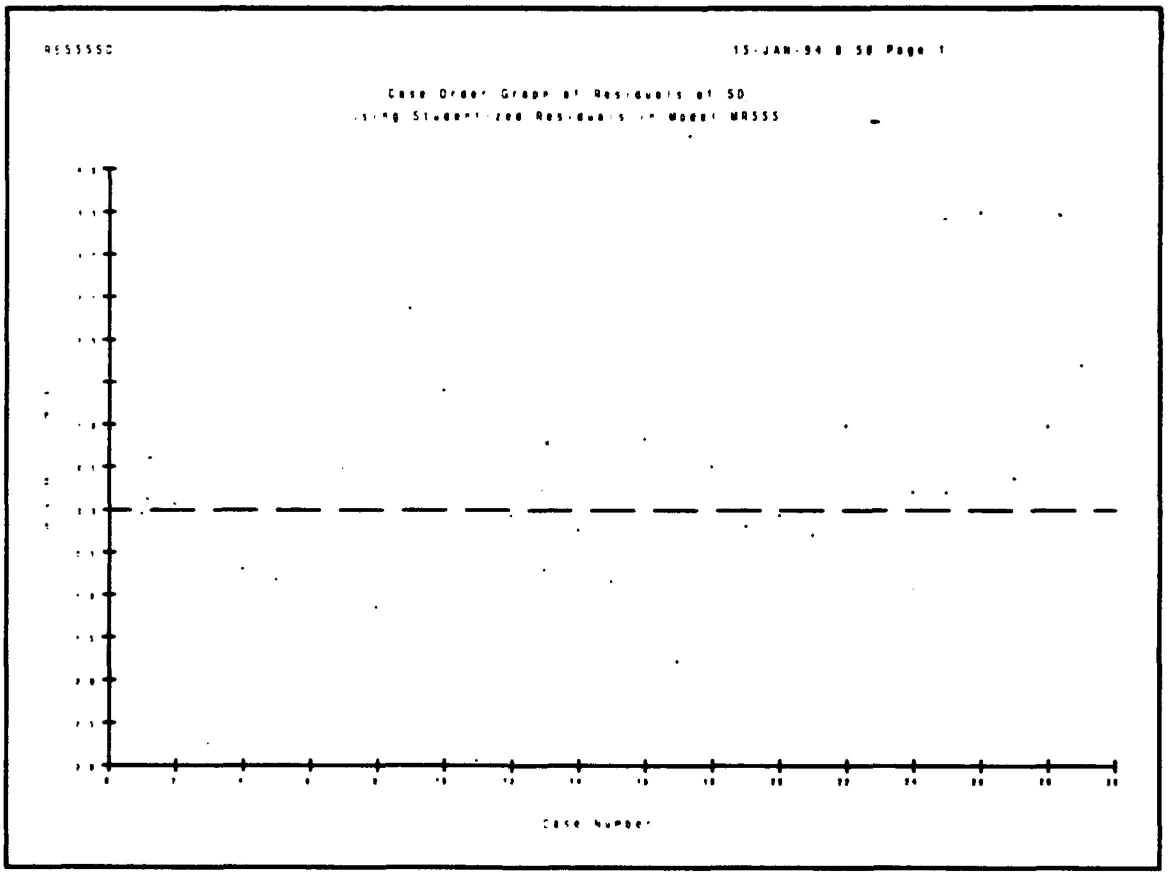
!ANOV55SD 7R x 5C 15-JAN-94 8:55
Page 1

Least Squares Summary ANOVA, Response SD Model MR555

0 Source	1 df	2 Sum Sq.	3 Mean Sq.	4 F-Ratio	5 Signif.
1 Total(Corr.)	28	9346.614			
2 Regression	14	9162.936	654.495	49.89	0.0000
3 Linear	5	5307.318	1061.464	80.91	0.0000
4 Non-linear	9	3855.618	428.402	32.65	0.0000
5 Residual	14	183.678	13.120		
6 Lack of fit	13	183.678	14.129		
7 Pure error	1	0.000	0.000		

R-sq. = 0.9803
R-sq-adj. = 0.9607

el obeys hierarchy. The sum of squares for linear terms
computed assuming nonlinear terms are first removed.



1000 lb Response Surface Model Information

!MOD2 12R x 1C 07-JAN-94
11:24 Page 1

Accepted model for response M_D

0	1
1 Model Name:	PLOT2002
2 Response Transformation:	Untransformed
3 Method:	Least Squares
4 Weights:	None
5 Total Number of Cases:	25
6 Number of Predictors:	5
7 Number of Unexpanded Ter	14
8 Number of Excluded Cases	0
9 Error Degrees of Freedom	11
10 Standard Error of Respon	7.242622
11 Relative PRESS:	0.208364
12 Root Mean Squared Error:	1.690644

!COEF2 14R x 4C 07-JAN-94
11:25 Page 1

Least Squares Coefficients, Response M, Model PLOT2002

0 Term	1 Coeff.	2 Std. Error	3 T-value	4 Signif.
1 1	-5.969702	7.072281		
2 Z	-0.187083	0.108461		
3 X	-0.186465	0.102248		
4 W	-0.525068	0.327016		
5 W_	-0.001926	0.000538		
6 W_H	0.437493	0.045519		
7 Z*X	0.006853	0.000781	8.78	0.0001
8 Z*W	0.011265	0.001819	6.19	0.0001
9 Z*W_H	-0.002346	0.000720	-3.26	0.0076
10 X*W_	0.011900	0.001793	6.64	0.0001
11 X*W_H	-0.002847	0.000658	-4.33	0.0012
12 W*W_	0.000056	0.000028	2.02	0.0686
13 W*W_H	-0.011774	0.001523	-7.73	0.0001
14 W**2	0.019214	0.005685	3.38	0.0061

No. cases = 25 R-sq. = 0.9750 RMS Error = 1.691
Resid. df = 11 R-sq-adj. = 0.9455 Cond. No. = 115.9

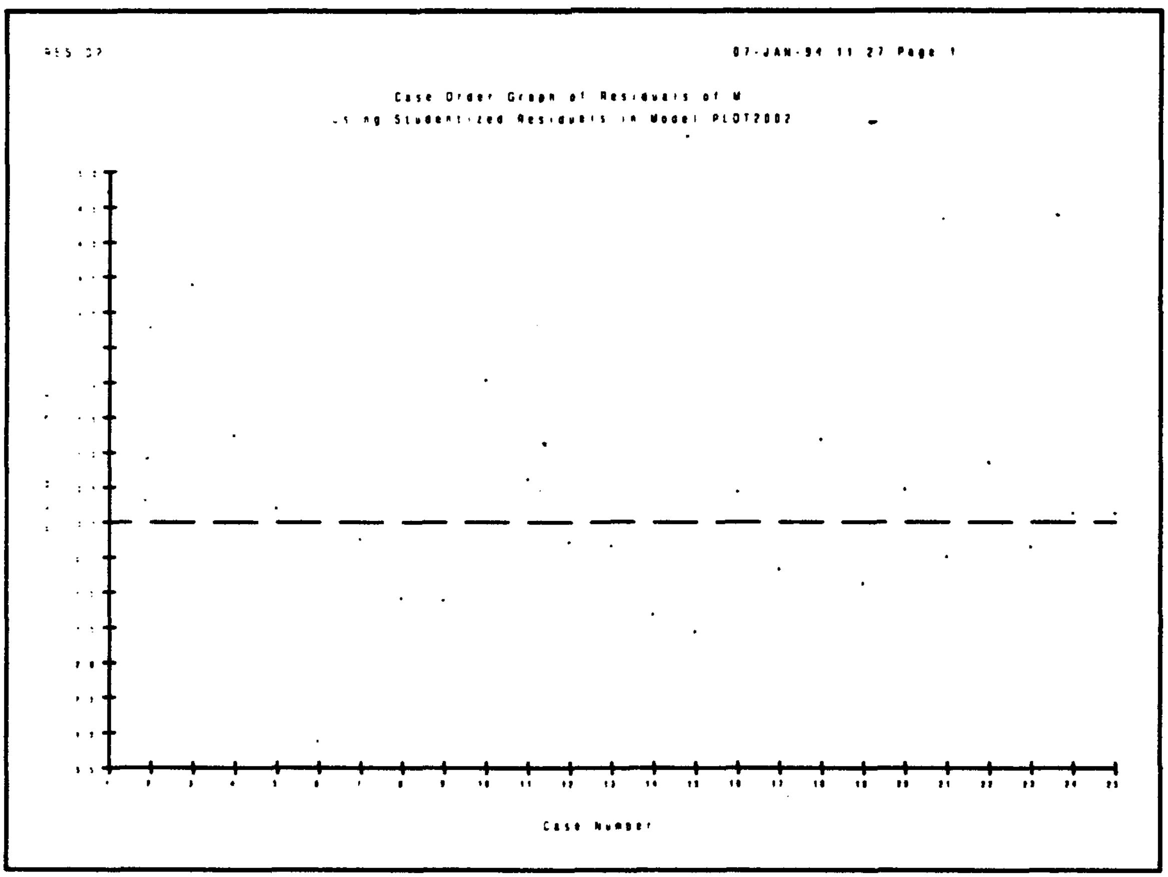
!ANOVA2 7R x 5C 07-JAN-94
11:24 Page 1

Least Squares Summary ANOVA, Response M Model PLOT2002

0 Source	1 df	2 Sum Sq.	3 Mean Sq.	4 F-Ratio	5 Signif.
1 Total (Corr.)	24	1258.934			
2 Regression	13	1227.493	94.423	33.03	0.0000
3 Linear	5	656.755	131.351	45.95	0.0000
4 Non-linear	8	570.738	71.342	24.96	0.0000
5 Residual	11	31.441	2.858		
6 Lack of fit	10	31.441	3.144		
7 Pure error	1	0.000	0.000		

R-sq. = 0.9750
R-sq-adj. = 0.9455

Model obeys hierarchy. The sum of squares for linear terms is computed assuming nonlinear terms are first removed.



MOD3 12R x 1C
Page 1

07-JAN-94 11:25

Accepted model for response SDIR

0	1
1 Model Name:	PLOT2003
2 Response Transformation:	Untransformed
3 Method:	Least Squares
4 Weights:	None
5 Total Number of Cases:	25
6 Number of Predictors:	5
7 Number of Unexpanded Ter	14
8 Number of Excluded Cases	0
9 Error Degrees of Freedom	11
10 Standard Error of Respon	26.471305
11 Relative PRESS:	0.880064
12 Root Mean Squared Error:	3.393651

!COEF3 14R x 4C
11:26 Page 1

07-JAN-94

Least Squares Coefficients, Response S, Model PLOT2003

0 Term	1 Coeff.	2 Std. Error	3 T-value	4 Signif.
1 1	118.627133	20.455120		
2 Z	-0.640760	0.255962		
3 X	-0.560721	0.120671		
4 W	4.347709	0.345749		
5 W_	-0.020032	0.002916		
6 W_H	-1.021689	0.113097		
7 Z*X	0.014785	0.001509	9.80	0.0001
8 Z*W	-0.029421	0.003347	-8.79	0.0001
9 Z*W_H	0.008676	0.001782	4.87	0.0005
10 X*W	-0.043227	0.004627	-9.34	0.0001
11 X*W_	0.000106	0.000025	4.31	0.0012
12 W*W	-0.000246	0.000064	-3.82	0.0028
13 W_*W_H	0.000151	0.000017	8.97	0.0001
14 Z**2	-0.010774	0.002796	-3.85	0.0027

No. cases = 25 R-sq. = 0.9925 RMS Error = 3.394
Resid. df = 11 R-sq-adj. = 0.9836 Cond. No. = 160.5

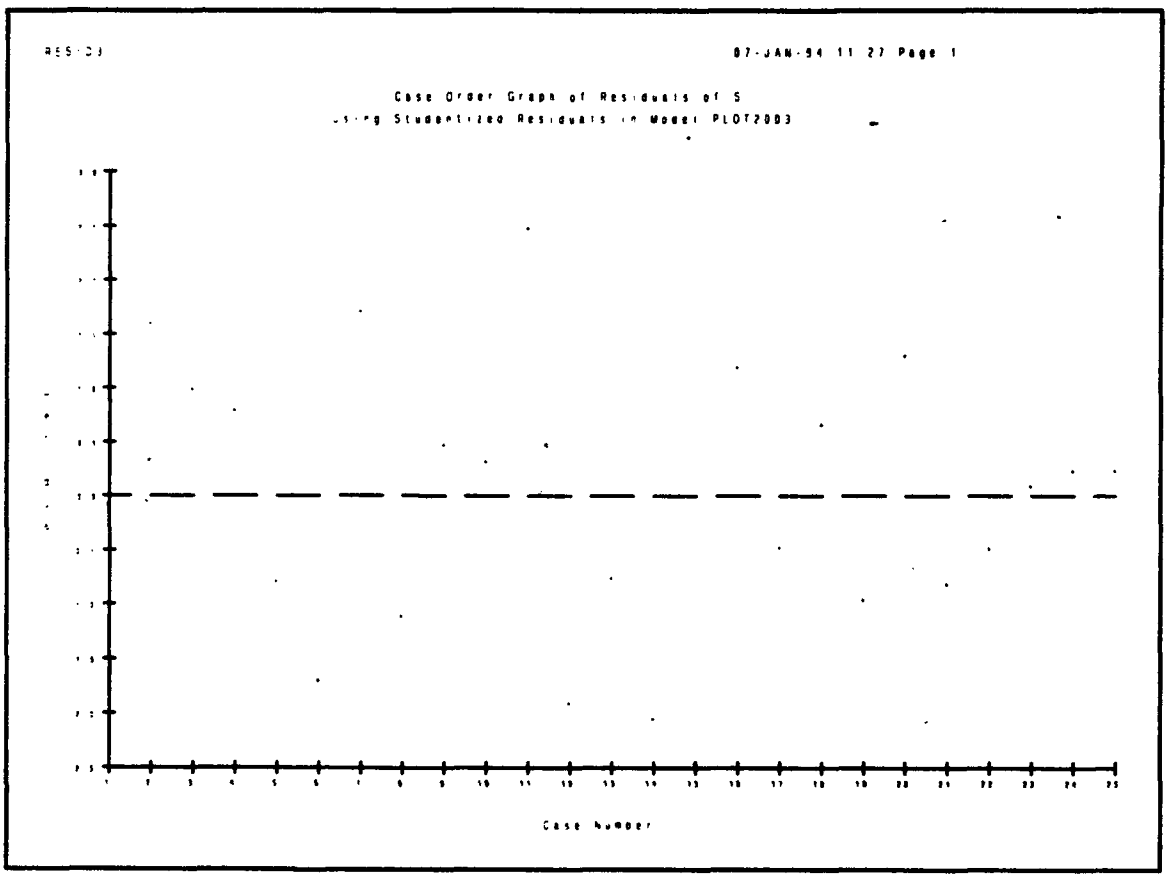
!ANOVA3 7R x 5C 07-JAN-94
11:26 Page 1

Least Squares Summary ANOVA, Response S Model PLOT2003

0 Source	1 df	2 Sum Sq.	3 Mean Sq.	4 F-Ratio	5 Signif.
1 Total (Corr.)	24	16817.52			
2 Regression	13	16690.83	1283.91	111.50	0.0000
3 Linear	5	9335.91	1867.18	162.10	0.0000
4 Non-linear	8	7354.92	919.37	79.83	0.0000
5 Residual	11	126.69	11.52		
6 Lack of fit	10	126.69	12.67		
7 Pure error	1	0.00	0.00		

R-sq. = 0.9925
R-sq-adj. = 0.9836

Model obeys hierarchy. The sum of squares for linear terms is computed assuming nonlinear terms are first removed.



!MOD4 12R x 1C 07-JAN-94
11:26 Page 1

Accepted model for response SDIAG

0	1
1 Model Name:	PLOT2004
2 Response Transformation:	Untransformed
3 Method:	Least Squares
4 Weights:	None
5 Total Number of Cases:	25
6 Number of Predictors:	5
7 Number of Unexpanded Ter	14
8 Number of Excluded Cases	0
9 Error Degrees of Freedom	11
10 Standard Error of Respon	14.366108
11 Relative PRESS:	0.481828
12 Root Mean Squared Error:	4.099204

!COEF4 14R x 4C 07-JAN-94
11:26 Page 1

Least Squares Coefficients, Response SD, Model PLOT2004

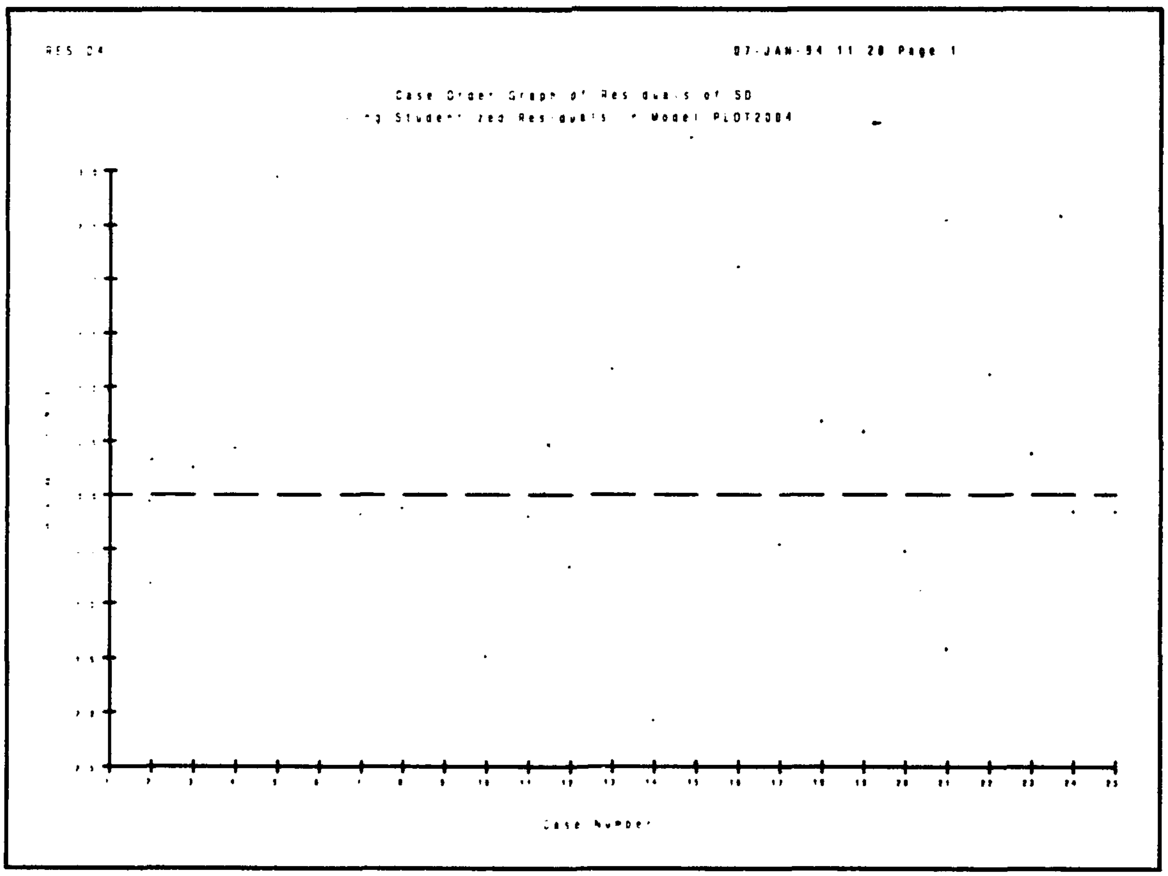
0 Term	1 Coeff.	2 Std. Error	3 T-value	4 Signif.
1 1	81.481744	22.482048		
2 Z	-0.311996	0.156940		
3 X	-0.896116	0.300395		
4 W	0.981792	0.626264		
5 W_	-0.009560	0.003540		
6 W_H	-0.557030	0.130852		
7 Z*X	0.007351	0.001821	4.04	0.0020
8 Z*W	-0.025476	0.006004	-4.24	0.0014
9 Z*W_	0.000083	0.000034	2.46	0.0319
10 X*W_	-0.009849	0.003876	-2.54	0.0274
11 X*W_H	0.005363	0.002045	2.62	0.0237
12 W*W_	-0.000220	0.000075	-2.92	0.0140
13 W_*W_H	0.000075	0.000020	3.70	0.0035
14 W_**2	0.035083	0.014657	2.39	0.0356

No. cases = 25 R-sq. = 0.9627 RMS Error = 4.099
Resid. df = 11 R-sq-adj. = 0.9186 Cond. No. = 151.2

Least Squares Summary ANOVA, Response SD Model PLOT2004

0 Source	1 df	2 Sum Sq.	3 Mean Sq.	4 F-Ratio	5 Signif.
1 Total (Corr.)	24	4953.242			
2 Regression	13	4768.403	366.800	21.83	0.0000
3 Linear	5	2193.701	438.740	26.11	0.0000
4 Non-linear	8	2574.703	321.838	19.15	0.0000
5 Residual	11	184.838	16.803		
6 Lack of fit	10	184.838	18.484		
7 Pure error	1	0.000	0.000		

R-sq. = 0.9627
R-sq-adj. = 0.9186
Model obeys hierarchy. The sum of squares for linear terms
is computed assuming nonlinear terms are first removed.



2000 lb Response Surface Model Information

!MOD22 12R x 1C 17-JAN-94
20:40 Page 1

Accepted model for response M_D

0	1
1 Model Name:	PLOT3502
2 Response Transformation:	Untransformed
3 Method:	Least Squares
4 Weights:	None
5 Total Number of Cases:	31
6 Number of Predictors:	5
7 Number of Unexpanded Ter	15
8 Number of Excluded Cases	0
9 Error Degrees of Freedom	16
10 Standard Error of Respon	10.193068
11 Relative PRESS:	0.889395
12 Root Mean Squared Error:	1.967447

!COEF22 15R x 4C 07-JAN-94
21:14 Page 1

Least Squares Coefficients, Response M, Model PLOT3502

0 Term	1 Coeff.	2 Std. Error	3 T-value	4 Signif.
1 1	-24.193203	7.342000		
2 Z	-0.160725	0.096374		
3 X	-0.193163	0.088468		
4 W	-2.285052	0.348288		
5 W_	0.006236	0.001121		
6 W_H	0.651004	0.051447		
7 Z*X	0.003661	0.000760	4.82	0.0002
8 Z*W	0.011528	0.001862	6.19	0.0001
9 Z*W_H	-0.002129	0.000668	-3.19	0.0057
10 X*W_	0.014530	0.001632	8.90	0.0001
11 X*W_H	-0.002875	0.000590	-4.87	0.0002
12 W*W_	0.000091	0.000023	4.03	0.0010
13 W*W_H	-0.003531	0.001506	-2.34	0.0323
14 W_*W_H	-0.000062	0.000008	-7.57	0.0001
15 W**2	0.022051	0.005694	3.87	0.0013

No. cases = 31 R-sq. = 0.9801 RMS Error = 1.967
Resid. df = 16 R-sq-adj. = 0.9627 Cond. No. = 116.9

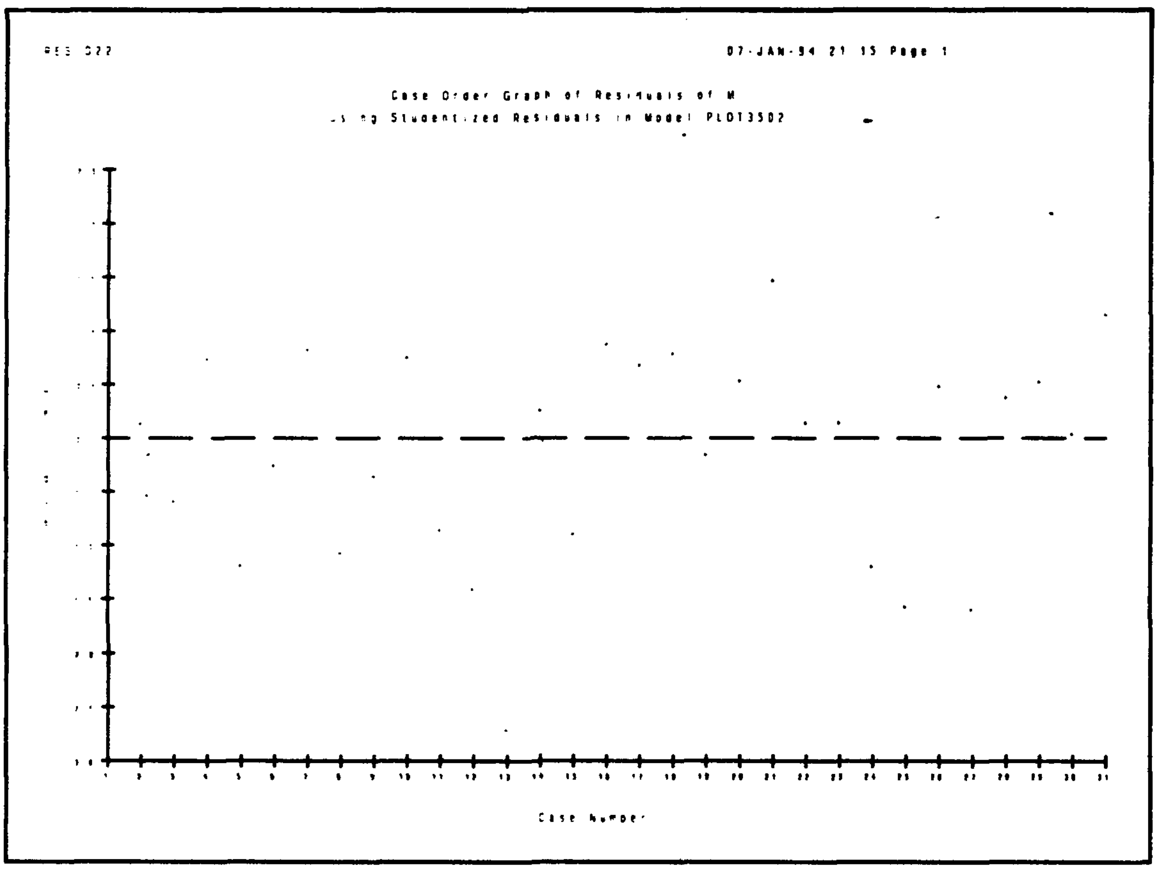
!ANOVA22 7R x 5C 07-JAN-94
21:13 Page 1

Least Squares Summary ANOVA, Response M Model PLOT3502

0 Source	1 df	2 Sum Sq.	3 Mean Sq.	4 F-Ratio	5 Signif.
1 Total (Corr.)	30	3116.959			
2 Regression	14	3055.026	218.216	56.37	0.0000
3 Linear	5	1926.404	385.281	99.53	0.0000
4 Non-linear	9	1128.621	125.402	32.40	0.0000
5 Residual	16	61.934	3.871		
6 Lack of fit	15	61.934	4.129		
7 Pure error	1	0.000	0.000		

R-sq. = 0.9801
R-sq-adj. = 0.9627

Model obeys hierarchy. The sum of squares for linear terms is computed assuming nonlinear terms are first removed.



!MOD33 12R x 1C 17-JAN-94
20:40 Page 1

Accepted model for response SDIR

0	1
1 Model Name:	PLOT3503
2 Response Transformation:	Untransformed
3 Method:	Least Squares
4 Weights:	None
5 Total Number of Cases:	31
6 Number of Predictors:	5
7 Number of Unexpanded Ter	10
8 Number of Excluded Cases	0
9 Error Degrees of Freedom	21
10 Standard Error of Respon	35.056863
11 Relative PRESS:	0.694524
12 Root Mean Squared Error:	14.629961

!COEF33 10R x 4C 07-JAN-94
21:14 Page 1

Least Squares Coefficients, Response S, Model PLOT3503

0 Term	1 Coeff.	2 Std. Error	3 T-value	4 Signif.
1 1	92.986651	42.109917		
2 Z	0.047889	0.331640		
3 X	-0.125998	0.302151		
4 W	5.550065	0.631001		
5 W_	-0.029305	0.007962		
6 W_H	-0.993305	0.304785		
7 Z*X	0.029550	0.005391	5.48	0.0001
8 Z*W	-0.066073	0.012802	-5.16	0.0001
9 X*W	-0.063864	0.011397	-5.60	0.0001
10 W_*W_H	0.000221	0.000056	3.92	0.0008

No. cases = 31 R-sq. = 0.8781 RMS Error = 14.63
Resid. df = 21 R-sq-adj. = 0.8258 Cond. No. = 87.33

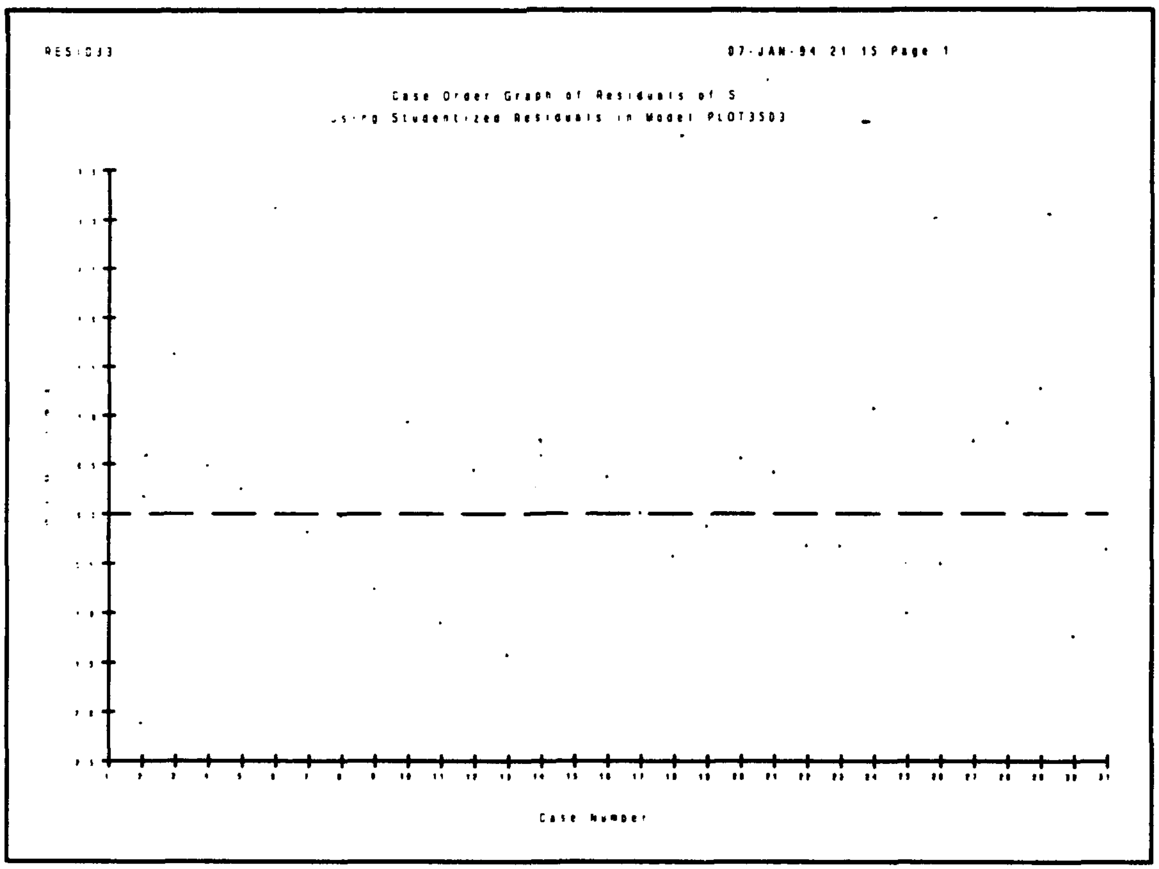
!ANOVA33 7R x 5C 07-JAN-94
21:13 Page 1

Least Squares Summary ANOVA, Response S Model PLOT3503

0 Source	1 df	2 Sum Sq.	3 Mean Sq.	4 F-Ratio	5 Signif.
1 Total (Corr.)	30	36869.51			
2 Regression	9	32374.76	3597.20	16.81	0.0000
3 Linear	5	16442.47	3288.49	15.36	0.0000
4 Non-linear	4	15932.29	3983.07	18.61	0.0000
5 Residual	21	4494.75	214.04		
6 Lack of fit	20	4494.75	224.74		
7 Pure error	1	0.00	0.00		

R-sq. = 0.8781
R-sq-adj. = 0.8258

Model obeys hierarchy. The sum of squares for linear terms is computed assuming nonlinear terms are first removed.



Accepted model for response SDIAG

0	1
1 Model Name:	PLOT3504
2 Response Transformation:	Untransformed
3 Method:	Least Squares
4 Weights:	None
5 Total Number of Cases:	31
6 Number of Predictors:	5
7 Number of Unexpanded Ter	11
8 Number of Excluded Cases	0
9 Error Degrees of Freedom	20
10 Standard Error of Respon	32.609024
11 Relative PRESS:	0.705662
12 Root Mean Squared Error:	13.499653

!COEF44 11R x 4C 07-JAN-94
21:15 Page 1

Least Squares Coefficients, Response SD, Model PLOT3504

0 Term	1 Coeff.	2 Std. Error	3 T-value	4 Signif.
1 1	436.520515	120.302831		
2 Z	0.079125	0.306166		
3 X	-0.106779	0.280290		
4 W	5.149210	0.587511		
5 W_	-0.028980	0.007374		
6 W_H	-6.187558	1.745447		
7 Z*X	0.028887	0.004975	5.81	0.0001
8 Z*W	-0.065194	0.011828	-5.51	0.0001
9 X*W	-0.060722	0.010574	-5.74	0.0001
10 W_*W_H	0.000220	0.000052	4.21	0.0004
11 W_H**2	0.018801	0.006223	3.02	0.0067

No. cases = 31 R-sq. = 0.8857 RMS Error = 13.5
Resid. df = 20 R-sq-adj. = 0.8286 Cond. No. = 364.6
!MOD44 12R x 1C 07-JAN-94
21:13 Page 1

!ANOVA44 7R x 5C 07-JAN-94
21:13 Page 1

Least Squares Summary ANOVA, Response SD Model PLOT3504

0 Source	1 df	2 Sum Sq.	3 Mean Sq.	4 F-Ratio	5 Signif.
1 Total (Corr.)	30	31900.45			
2 Regression	10	28255.64	2825.56	15.50	0.0000
3 Linear	5	12471.85	2494.37	13.69	0.0000
4 Non-linear	5	15783.79	3156.76	17.32	0.0000
5 Residual	20	3644.81	182.24		
6 Lack of fit	19	3644.81	191.83		
7 Pure error	1	0.00	0.00		

R-sq. = 0.8857
R-sq-adj. = 0.8286

Model obeys hierarchy. The sum of squares for linear terms is computed assuming nonlinear terms are first removed.

Appendix D

Monte Carlo Simulation Program - SIMTAC

```
      PROGRAM MONTE2
CC  THIS PROGRAM RUNS A MONTE CARLO SIMULATION OF AN ATTACK OF A
CC   HARDENED FACILITY WITH A STICK OF CONVENTIONAL WEAPONS.
CC
CC  The input variables for each attack are as follows:
CC  MFC - mean concrete strength fc'
CC  SIGFC -  standard deviation of the concrete strength
CC  MXL - mean wall height or beam element length
CC  SIGXL - standard deviation of the wall height
CC  MD - mean depth of wall or thickness
CC  SIGD -     standard deviation of the wall thickness
CC  MXB1 - mean X coordinate of bomb one
CC  MYB1 - mean Y coordinate of bomb one
CC  MXB2 - mean X coordinate of bomb two
CC  MYB2 - mean Y coordinate of bomb two
CC  MXB3 - mean X coordinate of bomb three
CC  MYB3 - mean Y coordinate of bomb three
CC  MXB4 - mean X coordinate of bomb four
CC  MYB4 - mean Y coordinate of bomb four
CC  SIGBOMB - standard deviation for each bomb based on standard
ballistic for
CC     that type of bomb
CC  SIGRANGE - standard deviation of the aimpoint in the range, or X
direction
CC      given the aim point is at 0,0
CC  SIGDEFLECT - standard deviation of the aimpoint in the deflection,
or Y
CC      direction given the aim point is at 0,0
CC  FC - current value of concrete strength
CC  D - current value for the depth or thickness of the wall
CC  XL - current value for the height of the wall
CC  RANGE1 - current value of the range for the ith bomb after sampling
for
CC    the ballistic error
CC  RANGE - current value for the range for the ith bomb after sampling
for
CC      aim point error
CC  KILL - flag variable, if KILL = 1 structure is killed, if KILL = 0
structure
CC   is not killed
CC  ZVAL,XVAL - tranformed coordinates for deflection and shear analysis
CCC
      REAL MFC,MXL,MD,SIGFC,SIGXL,SIGD,XB1,YB1,XB2,YB2,XB3,YB3,
     &
SIGB,RANGE,DEFLECT,RANGE1,DEFLECT1,SIGRANGE,SIGDEFLECT,XVAL,
     &       CHECK1,SCHECK1,SCHECK2,SCHECK3,PENETRATE,DIAGSHEAR,
     &       DEFLECTION,WVAL,B,D,XB4,YB4,ZVAL,DFT,DIRECTSHEAR
```

```
CC
      INTEGER IRUNS,KHIT,KBREACH,KDEFLECT,KSHDIR,KSHDIAG,PK,KILL
CC
     CHARACTER NUM*3
     KBREACH=0
     KHIT=0
     KDEFLECT=0
     KSHDIR=0
     KSHDIAG=0
     B=12
C
CC
990   FORMAT(I5,17F7.2)
      OPEN (UNIT=12,FILE='MONTEIN')
      READ(12,'(A)') NUM
      READ(12,*) IRUNS,MFC,SIGFC,MXL,SIGXL,MD,SIGD,XB1,YB1,XB2,YB2
     &     ,XB3,YB3,XB4,YB4,SIGB,SIGRANGE,SIGDEFLECT,WVAL
CC
     OPEN (UNIT=13,FILE='MONT'//NUM)
     OPEN (UNIT=14,FILE='SUMM'//NUM)
     RUN=0
     KILL=0
     WRITE(13,*) WVAL
     DO 100 I=1,IRUNS
CC
CC  Each run will evaluate the kill probility for the four weapons in
the stick.
CC  Sampling for the concrete strength (FC), wall thickness (D) and wall
height (XL)
CC  are accomplished initially and are valid for an entire stick
sampling. That is,
CC  FC,D and XL are held constant for the analysis of four different
weapon
CC  locations.
CC
CC  Sanity checks are placed on the values of FC,D,XL. Also, the
response
CC  surfaces are only valid over a specific range.
CC
      FC = RANNORM(MFC,SIGFC)
      IF (FC .LT. 2500) FC=2500
      XL = RANNORM(MXL,SIGXL)
      IF (XL .GT. 168) XL=168
      IF (XL .LT. 96) XL=96
      D = RANNORM(MD,SIGD)
      IF (D .GT. 36) D=36
      IF (D .LT. 12) D=12
CC  The individual weapon locations are determined by first sampling on  the
CC  distribution of each weapon based on its ballistic error properties.
CC  This returns a location (RANGE1, DEFLECT1) relative to the stick center for
CC  that bomb. Subsequently,  the aim point error is applied with the
```

```
CC  aim point standard deviations (sigrange and sigdeflect) with  RANGE1,DEFLECT1
CC  as the mean location coordinates.  The RANGE,DEFLECTION coordiante   of the
CC  current weapon is then establised.  This step is accomplished four
times
CC  with in one run.
CC
      DO 25 J=1,4
     IF (J .EQ. 1) THEN
        RANGE1=RANNORM(XB1,SIGB)
        RANGE=RANNORM(RANGE1,SIGRANGE)
        DEFLECT1=RANNORM(YB1,SIGB)
        DEFLECT=RANNORM(DEFLECT1,SIGDEFLECT)
     ELSEIF (J .EQ. 2) THEN
        RANGE1=RANNORM(XB2,SIGB)
        RANGE=RANNORM(RANGE1,SIGRANGE)
        DEFLECT1=RANNORM(YB2,SIGB)
        DEFLECT=RANNORM(DEFLECT1,SIGDEFLECT)
     ELSEIF (J .EQ. 3) THEN
        RANGE1=RANNORM(XB3,SIGB)
        RANGE=RANNORM(RANGE1,SIGRANGE)
        DEFLECT1=RANNORM(YB3,SIGB)
        DEFLECT=RANNORM(DEFLECT1,SIGDEFLECT)
     ELSE
        RANGE1=RANNORM(XB4,SIGB)
        RANGE=RANNORM(RANGE1,SIGRANGE)
        DEFLECT1=RANNORM(YB4,SIGB)
        DEFLECT=RANNORM(DEFLECT1,SIGDEFLECT)
     ENDIF
CC
5    WRITE(13,*) RUN,KILL,RANGE,DEFLECT,FC,D,XL
CC
CC  The RANGE,DEFLECT is initially check to see if it is outside the
CC  effective range of the weapon,here assumed to be 80 feet.
CC  The   analysis proceeds with the RANGE,DEFLECT coordiantes being
screened to
CC  see whether they hit the structure or fall within the breach zone.
CC
      IF ((ABS(RANGE) .GT. 80) .OR. (ABS(DEFLECT) .GT. 80)) GO TO 15
CC
      IF ((ABS(RANGE) .LT. 30) .AND.
     &    (ABS(DEFLECT) .LT. 30)) THEN
     PENETRATE = (0.33)*(WVAL**(.333)) - (D*(0.333))
     IF (PENETRATE .GE. 0) THEN
     KHIT=KHIT+1
     GO TO 10
     ENDIF
     GO TO 15
      ENDIF
CC
      DFT=D/12
      XA=0.18
```

```
      AB=0.378
      RB=XA*((WVAL**(.667))/DFT) - AB*(WVAL**(.333))
      CHECKRB = RB+30
      WRITE(13,*) RANGE,DEFLECT,RB,CHECKRB
      IF ((ABS(DEFLECT) .GE. 30) .AND. (ABS(DEFLECT) .LE. CHECKRB).AND.
     &    (ABS(RANGE) .LE. CHECKRB)) THEN
     KBREACH=KBREACH+1
     GO TO 10
      ENDIF
      IF ((ABS(RANGE) .GE. 30) .AND. (ABS(RANGE) .LE. CHECKRB) .AND.
     &    (ABS(DEFLECT) .LE. CHECKRB)) THEN
     KBREACH=KBREACH+1
     GO TO 10
       ENDIF
CC
CC
CC  If a weapon does not hit the structure or fall within the breach  zone, its
CC  RANGE,DEFLECT coordinates are transformed into local coordinates ZVAL,XVAL
CC  in order to perform deflection and shear analysis. This procedure determines
CC  the closest point on the structure which would see the maximum  loading from
CC  that weapon.  The corners are considered unsucceptable to deflection  or shear
CC  failures as they are calculated.  As shown in Figure 4.1, should a  weapon fall
CC  outside a distance 30 - 2.5*D from the centerline of the structure,  the
CC  ZVAL,XVAL coordinates are based on the distance from the detonation to the
CC  nearest face at a point 2.5 times the wall thickness (D).  This  estimate is
CC  conservative and is based in the fact that the corners are normally
CC  highly reinforced with steel extending a minimum of a wall thickness in to the
CC  adjacent wall.  The subroutine LOCATE performs the determination of  the
CC  ZVAL,XVAL coordinates for each weapon.
CC
      CALL LOCATE(D,RANGE,DEFLECT,ZVAL,XVAL)
CC
      WRITE(13,*) RANGE,DEFLECT,ZVAL,XVAL
CC
CC  Deflection, diagonal shear, and direct shear analysis are performed
using the
CC  ZVAL,XVAL detonation locations determined above.  Should any limit
states
CC  be exceeded the procedure jumps ahead and sets the kill flag and
goes on to the
CC  next weapon or begins a new run after recording the kill.
CC
      IF (WVAL .LE. 1000) THEN
     DEFLECTION = DEFLEC(ZVAL,XVAL,D,FC,XL)
      ELSE
     DEFLECTION = DEFLEC2(ZVAL,XVAL,D,FC,XL)
      ENDIF
      CHECK1=XL/D
      DCHECK=DEFLECTION/XL
      WRITE(13,*) DEFLECTION,CHECK1,DCHECK
      IF ((CHECK1 .GE. 5) .AND. (DCHECK .GE. (0.10))) THEN
```

```
      KDEFLECT=KDEFLECT+1
      GO TO 10
       ENDIF
       IF ((CHECK1 .LT. 5) .AND. (DCHECK .GE. (0.06))) THEN
      KDEFLECT=KDEFLECT+1
      GO TO 10
       ENDIF
CC
CC
CC
CC   CHECK DIAGONAL SHEAR
CC
       IF (WVAL .LE. 500) THEN
      DIAGSHEAR=SDIAG(ZVAL,XVAL,D,FC,XL)
       ELSE
      DIAGSHEAR=SDIAG2(ZVAL,XVAL,D,FC,XL)
       ENDIF
CC  SCHECK1=NORMAL DEPTH TO SPAN RATIO OR XL/D > 5
       SCHECK1=((11.5)*SQRT(FC)*B*D)/1000
CC  SCHECK2= XL/D <= 5 AND XL/D >= 2
       SCHECK2=((.667)*(10 + (XL/D))*SQRT(FC)*B*D)/1000
CC  SCHECK3 =  XL/D < 2
       SCHECK3=(8*SQRT(FC)*B*D)/1000
CC
       WRITE(13,*) DIAGSHEAR,SCHECK1,SCHECK2,SCHECK3
       IF ((CHECK1 .GT. 5) .AND. (DIAGSHEAR .GT. SCHECK1)) THEN
      KSHDIAG=KSHDIAG+1
      GO TO 10
       ENDIF
       IF ((CHECK1 .LE. 5) .AND. (CHECK1 .GE. 2) .AND.
      &     (DIAGSHEAR .GT. SCHECK2)) THEN
      KSHDIAG=KSHDIAG+1
      GO TO 10
       ENDIF
       IF ((CHECK1 .LT. 2) .AND. (DIAGSHEAR .GT. SCHECK3)) THEN
      KSHDIAG = KSHDIAG+1
      GO TO 10
       ENDIF
CC
CC    CHECK DIRECT SHEAR
CC
       IF (WVAL .LE. 500) THEN
      DIRECTSHEAR=SDIR(ZVAL,XVAL,D,FC,XL)
       ELSE
      DIRECTSHEAR=SDIR2(ZVAL,XVAL,D,FC,XL)
       ENDIF
C
       SCHECK4=((0.51)*FC*B*D)/1000
       WRITE(13,*) DIRECTSHEAR,SCHECK4
       IF (DIRECTSHEAR .GT. SCHECK4) THEN
      KSHDIR=KSHDIR+1
```

```
    GO TO 10
     ENDIF
CC
     GO TO 15
CC
CC  COLLECT THE NUMBER OF KILLS
CC
10   CONTINUE
     KILL = KILL + 1
CC
CC  After all runs are complete the total number of kills is divided by
the total
CC  number of runs times four for the four weapons analyzed per run, to
give the
CC  percent probability of kill for a single attack with the input
characteristics.
CC
15    CONTINUE
      RUN = RUN + 1
CC
25    CONTINUE
CC
100   CONTINUE
    KILL=KILL*100
CC
      PK = (KILL/RUN)
      WRITE(14,*) 'Probability of Kill (Pk) =',PK,' %'
      WRITE(14,*)
CC
      WRITE(14,*) 'KHIT =     ',KHIT,'        KBREACH =',KBREACH
      WRITE(14,*)
      WRITE(14,*) 'KDEFLECT =',KDEFLECT,'        KSHDIAG =',KSHDIAG
      WRITE(14,*)
      WRITE(14,*) 'KSHDIR =  ',KSHDIR
      END
CC
CC
CC
     FUNCTION RANNORM(MU,SIG)
     REAL MU,SIG
     CALL SEED(SEEDVAL)
     IDUM=SEEDVAL
     RANNORM = SIG*GASDEV(IDUM) + MU
     END
C
     FUNCTION GASDEV(IDUM)
     DATA ISET/0/
     IF (ISET.EQ.0) THEN
1      V1=2.*RAN1(IDUM)-1.
      V2=2.*RAN1(IDUM)-1.
      R=V1**2+V2**2
```

```
      IF(R.GE.1.)GO TO 1
      FAC=SQRT(-2.*LOG(R)/R)
      GSET=V1*FAC
      GASDEV=V2*FAC
      ISET=1
    ELSE
      GASDEV=GSET
      ISET=0
    ENDIF
    RETURN
    END
C
    FUNCTION RAN1(IDUM)
    DIMENSION R(97)
    PARAMETER (M1=259200,IA1=7141,IC1=54773,RM1=3.8580247E-6)
    PARAMETER (M2=134456,IA2=8121,IC2=28411,RM2=7.4373773E-6)
    PARAMETER (M3=243000,IA3=4561,IC3=51349)
    DATA IFF /0/
    IF (IDUM.LT.0.OR.IFF.EQ.0) THEN
      IFF=1
      IX1=MOD(IC1-IDUM,M1)
      IX1=MOD(IA1*IX1+IC1,M1)
      IX2=MOD(IX1,M2)
      IX1=MOD(IA1*IX1+IC1,M1)
      IX3=MOD(IX1,M3)
      DO 11 J=1,97
        IX1=MOD(IA1*IX1+IC1,M1)
        IX2=MOD(IA2*IX2+IC2,M2)
        R(J)=(FLOAT(IX1)+FLOAT(IX2)*RM2)*RM1
11      CONTINUE
      IDUM=1
    ENDIF
    IX1=MOD(IA1*IX1+IC1,M1)
    IX2=MOD(IA2*IX2+IC2,M2)
    IX3=MOD(IA3*IX3+IC3,M3)
    J=1+(97*IX3)/M3
    IF(J.GT.97.OR.J.LT.1)PAUSE
    RAN1=R(J)
    R(J)=(FLOAT(IX1)+FLOAT(IX2)*RM2)*RM1
    RETURN
    END
CC
CC
CC
    SUBROUTINE LOCATE(D,RANGE,DEFLECT,ZVAL,XVAL)
    DCHECK = D*2.5/12
    IF (ABS(RANGE) .GT. ABS(DEFLECT)) THEN
   IF ( ABS(DEFLECT) .LT. (30 - DCHECK)) THEN
      ZVAL = ABS(RANGE) - 30
      XVAL = 0
   ELSE
```

```
      ZVAL = ABS(RANGE) - 30
      XVAL = ABS(DEFLECT) - (30 - DCHECK)
   ENDIF
    ELSE
   IF (ABS(RANGE) .LT. (30 - DCHECK)) THEN
      ZVAL = ABS(DEFLECT) - 30
      XVAL = 0
   ELSE
      ZVAL = ABS(DEFLECT) - 30
      XVAL = ABS(RANGE) - (30 - DCHECK)
   ENDIF
    ENDIF
    RETURN
    END
CC
CC
CC
    FUNCTION DEFLEC(Z,X,T,FCC,XLL)
    REAL COEF(14),ZVAL,XVAL,FC,XL,D
    DATA COEF  /-5.969702,  -0.187083,
   &         -0.186465,   -0.525068,
   &         -0.001926,    0.437493,
   &          0.006853,    0.011265,
   &         -0.002346,    0.011900,
   &         -0.002847,    0.000056,
   &         -0.011774,    0.019214/
C
    ZVAL = Z
    XVAL = X
    FC = FCC
    XL = XLL
    D =  T
    DEFLEC   =  COEF(1) + COEF(2)*ZVAL + COEF(3)*XVAL + COEF(4)*D
   &         + COEF(5)*FC + COEF(6)*XL + COEF(7)*ZVAL*XVAL
   &         + COEF(8)*ZVAL*D + COEF(9)*ZVAL*XL+ COEF(10)*XVAL*D
   &         + COEF(11)*XVAL*XL + COEF(12)*D*FC + COEF(13)*D*XL
   &         + COEF(14)*(D**2)
C
    PRINT*, ZVAL,XVAL,FC,XL,D,DEFLEC
    RETURN
    END
CC
CC
CC
    FUNCTION SDIR(Z,X,T,FCC,XLL)
    REAL COEF(14),ZVAL,XVAL,FC,XL,D
    DATA COEF  /118.627133, -0.640760,
   &         -0.560721,    4.347709,
   &         -0.020032,   -1.021689,
   &          0.014785,   -0.029421,
   &          0.008676,   -0.043227,
```

```
     &          0.000106,    -0.000246,
     &          0.000151,    -0.010774/
C
      ZVAL = Z
      XVAL = X
      FC = FCC
      XL = XLL
      D =  T
      SDIR    =   COEF(1) + COEF(2)*ZVAL + COEF(3)*XVAL + COEF(4)*D
     &         + COEF(5)*FC + COEF(6)*XL + COEF(7)*ZVAL*XVAL
     &         + COEF(8)*ZVAL*D + COEF(9)*ZVAL*XL + COEF(10)*XVAL*D
     &         + COEF(11)*XVAL*FC + COEF(12)*D*FC +COEF(13)*FC*XL
     &         + COEF(14)*(ZVAL**2)
C
      PRINT*, ZVAL,XVAL,FC,XL,D,SDIR
      RETURN
      END
CC
CC
      FUNCTION SDIAG(Z,X,T,FCC,XLL)
      REAL COEF(14),ZVAL,XVAL,FC,XL,D
      DATA COEF  /81.481744,  -0.311996,
     &         -0.896116,     0.981792,
     &         -0.009560,    -0.557030,
     &          0.007351,    -0.025476,
     &          0.000083,    -0.009849,
     &          0.005363,    -0.000220,
     &          0.000075,     0.035083/
C
      ZVAL = Z
      XVAL = X
      FC = FCC
      XL = XLL
      D =  T
      SDIAG =  COEF(1) + COEF(2)*ZVAL + COEF(3)*XVAL + COEF(4)*D
     &         + COEF(5)*FC + COEF(6)*XL + COEF(7)*ZVAL*XVAL
     &         + COEF(8)*ZVAL*D + COEF(9)*ZVAL*FC + COEF(10)*XVAL*D
     &         + COEF(11)*XVAL*XL + COEF(12)*D*FC + COEF(13)*FC*XL
     &         + COEF(14)*(D**2)

C
      PRINT*, ZVAL,XVAL,FC,XL,D,SDIAG
      RETURN
      END
CC
      FUNCTION DEFLEC2(Z,X,T,FCC,XLL)
      REAL COEF(15),ZVAL,XVAL,FC,XL,D
      DATA COEF  /-24.193203, -0.160725,
     &         -0.193163,    -2.285052,
     &          0.006236,     0.651004,
     &          0.003661,     0.011528,
```

```
     &        -0.002129,     0.014530,
     &        -0.002875,     0.000091,
     &        -0.003531,    -0.000062,
     &         0.022051/
C
      ZVAL = Z
      XVAL = X
      FC = FCC
      XL = XLL
      D =  T
      DEFLEC2 = COEF(1) + COEF(2)*ZVAL + COEF(3)*XVAL + COEF(4)*D
     &        + COEF(5)*FC + COEF(6)*XL + COEF(7)*ZVAL*XVAL
     &        + COEF(8)*ZVAL*D + COEF(9)*ZVAL*XL + COEF(10)*XVAL*D
     &        + COEF(11)*XVAL*XL + COEF(12)*D*FC + COEF(13)*D*XL
     &        + COEF(14)*FC*XL +COEF(15)*(D**2)
C
      PRINT*, ZVAL,XVAL,FC,XL,D,DEFLEC2
      RETURN
      END
CC
      FUNCTION SDIR2(Z,X,T,FCC,XLL)
      REAL COEF(10),ZVAL,XVAL,FC,XL,D
      DATA COEF  /92.986651,  0.047889,
     &        -0.125998,     5.550065,
     &        -0.029305,    -0.993305,
     &         0.029550,    -0.066073,
     &        -0.063864,     0.000221/
C
      ZVAL = Z
      XVAL = X
      FC = FCC
      XL = XLL
      D =  T
      SDIR2 = COEF(1) + COEF(2)*ZVAL + COEF(3)*XVAL + COEF(4)*D
     &        + COEF(5)*FC + COEF(6)*XL + COEF(7)*ZVAL*XVAL
     &        + COEF(8)*ZVAL*D + COEF(9)*XVAL*D + COEF(10)*FC*XL
C
      PRINT*, ZVAL,XVAL,FC,XL,D,SDIR2
      RETURN
      END
CC
      FUNCTION SDIAG2(Z,X,T,FCC,XLL)
      REAL COEF(11),ZVAL,XVAL,FC,XL,D
      DATA COEF  /436.520515,  0.079125,
     &        -0.106779,     5.149210,
     &        -0.028980,    -6.187558,
     &         0.028887,    -0.065194,
     &        -0.060722,     0.000220,
     &         0.018801/
C
      ZVAL = Z
```

```
      XVAL = X
      FC = FCC
      XL = XLL
      D =  T
      SDIAG2 = COEF(1) + COEF(2)*ZVAL + COEF(3)*XVAL + COEF(4)*D
     &        + COEF(5)*FC + COEF(6)*XL +  COEF(7)*ZVAL*XVAL
     &        + COEF(8)*ZVAL*D + COEF(9)*XVAL*D + COEF(10)*FC*XL
     &        + COEF(11)*(XL**2)
C
      PRINT*, ZVAL,XVAL,FC,XL,D,SDIAG2
      RETURN
      END
```