Incorporation of BICADS Injury Prediction Methodology into VAPO

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Abstract

The VAPO (Vulnerability Assessment and Protection Option) V2.0 program developed for the Defense Threat Reduction Agency (DTRA) calculates injuries to building occupants from an exterior explosion using the methodology in the BICADS (Building Injury Calculator And DatabaseS) computer program. This methodology estimates the percentages of exposed building occupants with four injury levels caused by failed nearby structural and non-structural components based on correlations to applicable injury data and engineering judgment. BICADS has been developed under funding from the Office of Special Technology, Technical Support Working Group (TSWG), DTRA, and the U.S. Army Corps of Engineers Protective Design Center (PDC). Currently, BICADS V2.0 is distributed by the PDC.

Several significant improvements were made to BICADS V1.0 prior to its inclusion in VAPO. These include the use of the CEDAW (Component Explosive Damage Assessment Workbook) methodology to predict component blast damage levels and new pressure-impulse (P-i) diagrams to calculate injuries from failed building components. The new Injury P-i diagrams have P-i curves defining each injury level that are defined relative to the CEDAW P-i curve corresponding to component failure by delta pressure and impulse offset values determined from correlations to injury data. BICADS also calculates injuries from windows and interior non-structural components based on empirical P-i diagrams developed from large injury databases. The injury calculations in VAPO are performed on a per-room basis in order to allow for injury predictions of arbitrary-shaped buildings with non-uniform construction. A non-linear summation is used to get the total injuries predicted with the BICADS methodology from each injury source and each room. In addition to the BICADS methodology, VAPO has methods to calculate glass hazards based on the HazL single-degree-of-freedom glazing response model, injuries from blunt trauma of both filmed and unfilmed glass based on a K&C developed model, and injuries from glass penetration based on an ARA developed model.

Introduction

Occupant injuries are typically the primary concern of blast vulnerability studies. Therefore, injury information is of interest in addition the blast loads and building damage information. Injury data for occupants of blast-loaded buildings has been gathered since World War II, including extensive data collected after the Oklahoma City and Khobar Towers terrorist bombings, but it has not been available in a form that is very useful for typical blast vulnerability studies. The BICADS computer program was

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developed at Baker Engineering and Risk Consultants (BakerRisk) by gathering available injury information for occupants of blast-loaded buildings and using this data to develop correlations between building damage, blast loads, and the corresponding building occupant injuries from different types of failed building components.

The BICADS methodology calculates blast loads on structural and non-structural components of a given building, determines any building component failures, and then determines any building occupant injuries from the failed components. Only the latter two steps from this methodology are incorporated into VAPO, since VAPO has been programmed previously to calculate all the blast loads with the TNT standard methodology. BICADS calculates damage to structural components using the scaled pressure-impulse (P-i) curves in the CEDAW (Component Explosive Damage Assessment Workbook) distributed by the PDC. If the component fails according to the relevant CEDAW P-i curves, the portion of the blast load above that which just causes failure (i.e. the "delta blast load") is assumed to propel the components into the building and cause injuries. Correlations between each of four injury levels and the delta blast load are used to determine injuries to building occupants in the room area adjacent to each failed component. Separate correlations are used for three different component groups with differing basic mass and stiffness properties. Injuries are also calculated separately from non-structural components, including windows and interior components. After all injuries are calculated independently from each failed component, injuries are summed through the building with a non-linear summation process that approximately accounts for the fact that occupants are, in general, simultaneously subjected to injuries from multiple nearby failed components. This is summarized in Figure 1.

This methodology is discussed in detail in the BICADS V2.0 methodology report (Oswald, 2007) that is hot-linked to the program, along with several large injury databases and several comparisons between observed injuries to occupants of blast load building and injuries predicted with BICADS. This paper summarizes many of the main parts of the injury prediction methodology in BICADS that have been incorporated into VAPO and one comparison to data. Several other case studies that are sufficiently well defined are compared to BICADS in a separate document hot-linked to the program.

VAPO Components Analyzed by BICADS

BICADS calculates injuries to building occupants for input scenarios defined by building components, a blast source, and occupant location information. Building components must be prescribed types shown in Table 1 and Table 2. Varying degrees of detailed input are allowed in VAPO to define the component types in Table 1. VAPO also allows users to accept default components that are "designed" by the program based on a set of common design requirements. The user should always keep in mind that the BICADS methodology defines injuries in terms of relatively broad injury levels, so that a number of assumptions in the building component input are acceptable.

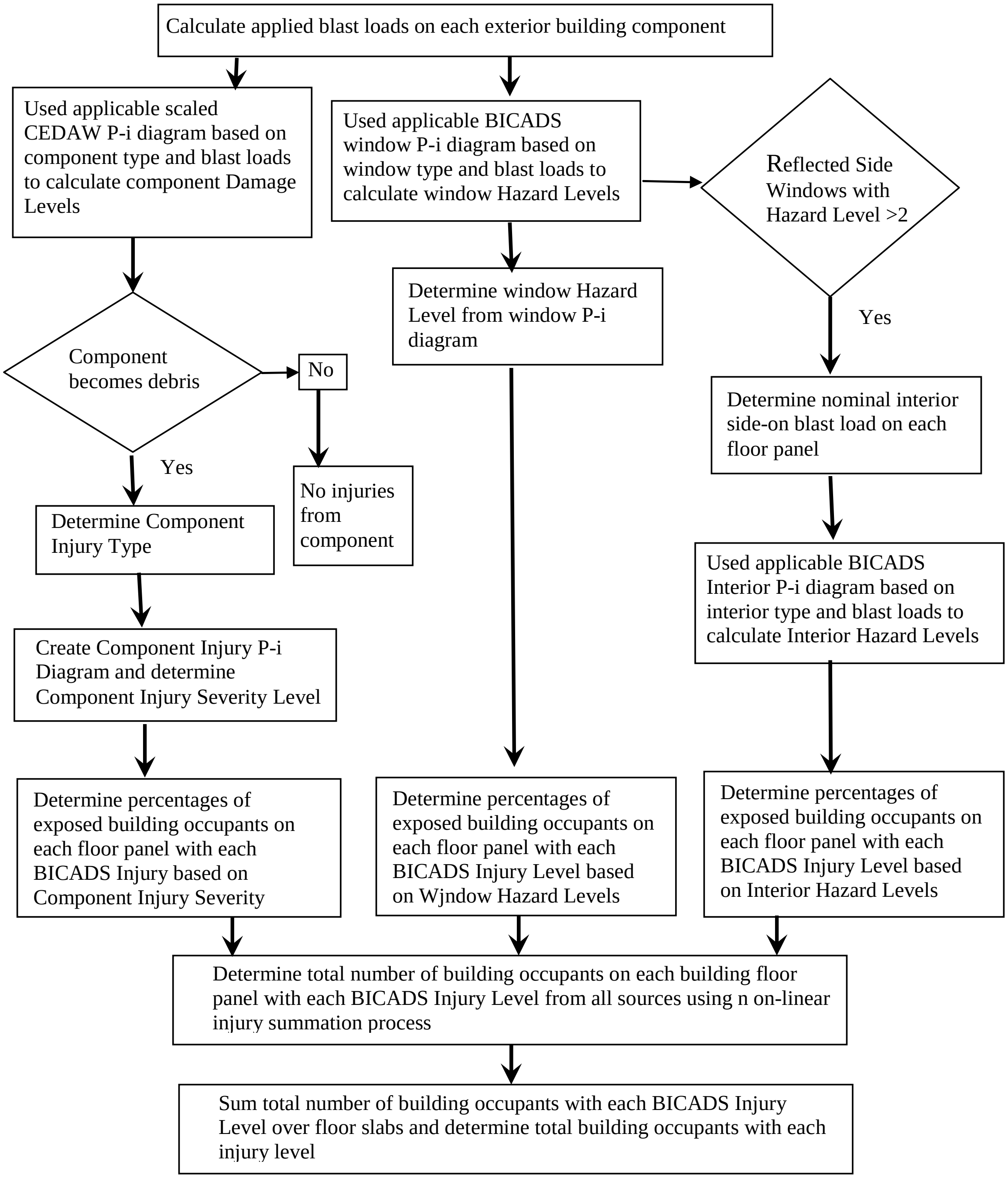

Figure 1. Flowchart of BICADS Injury Prediction Methodology

Table 1. Exterior Building Components

Building Surface	Component Types	Comment
Wall	One-Way Unreinforced Masonry Wall	Brick, CMU, or European block. User inputs geometric and arching information.
	Two-Way Unreinforced Masonry Wall	Brick, CMU, or European block. User inputs geometric information.
	One-Way Reinforced Masonry Wall	Brick, CMU, or European block. User inputs geometric and steel reinforcing information.
	One-Way Reinforced Concrete Panel	User inputs geometric and steel reinforcing information.
	Metal/Wood Stud Wall	User specifies span, 4” (100 mm) or 6” (150 mm) studs at 16” (400 mm), and cladding information. Program assumes similar injuries from wood and metal studs of similar depth and all calculations are based on wood studs. Injuries higher depending on cladding weight (i.e. highest for brick veneer).
	Steel Beam	User specifies corrugated or insulated metal panel or cement-based panel and wall girt size, loaded axis, yield strength and span.
	Non-Failing Wall*	This will not cause any calculated injuries from wall debris or collapse of load-bearing walls
Roof	Steel Beam	User inputs typical roof beam size, yield strength, loaded axis, span, and supported roof weight. Injuries higher if beam with roof weight > 30 psf (625 kPa) fails.
	Reinforced Concrete Beam or Critical Panel	User inputs geometric and reinforcing information for critical roof slab or beam. Typically, the beam will be more critical.
	Open Web Steel Joists	User inputs joist load capacity and self weight information from manufacturers’ literature and supported roof weight. Injuries higher if beam with roof weight > 30 psf (625 kPa) fails.
	Wood Roof System	User specifies span and 4” (100 mm) or 6” (150 mm) wood joists at 16” (400 mm) and roof cladding information.
	Non-Failing Roof*	This will not cause any calculated injuries from roof debris
Column	Ground Floor Steel Column	User inputs column size, yield strength, loaded axis, span, number and diameter of anchor bolts, and information on whether column is continuous into basement or has its baseplate buried in slab. If neither of the latter two factors are true, the column blast capacity is based on shear failure of anchor bolts. Otherwise, flexural response is assumed. Column spacing is also input.
	Ground Floor Concrete Column	User inputs column cross sectional area and concrete compression strength and whether building is in seismic zone. Column blast capacity is based on shear capacity, including assumed strength from column ties if in seismic zone. Column spacing is also input.
	Non-Failing Column*	This will component will not cause any calculated injuries from progressive collapse due to column failure.
Window	3/16" Annealed Pane	Large pane (5’x4’ or 1525mm x 1220 mm) or Small pane (4’x2’ or 1220mm x 610mm) available
	1/4" Annealed Pane	
	1/4" Annealed Pane w/ 4 mil Daylight Film	
	1/4" Tempered Pane	
	1/4" Laminated Pane	
	1/4" Annealed IGU	
	1/4" Annealed –1/4" Laminated IGU	
	No windows	

* These components can be used to calculate the reduced injuries from an upgrade that prevents a component from failing or when a component is known to resist the applied blast loads based on test data or more detailed structural calculations.

Table 2. Interior Building Components

Building Surface	Component Types	Comment
Floor System	Office/Residential Floor System	Typical office/residential floor system with approximate design live load of 50 psf.
	Industrial Building Floor System	Industrial floor system with approximate design live load of 100 psf or higher.
	Non-Failing Floor*	This component will not cause any calculated injuries from floor system collapse.
Interior Construction	Residential/Dormitory Interior	Few overhead items, similar to residence or dorm.
	Office Interior	Overhead fluorescent lights, lightweight overhead ducting, and lightweight drop ceiling material.
	Warehouse/Industrial Interior	Interior unreinforced masonry walls, heavy overhead piping and heating equipment, high shelving with heavy items, or other interiors with heavy items that can fall on occupants.
	No Injuries from Interior Components*	This component will not cause any calculated injuries from interior components.
* See note at bottom of Table 1		

Building Occupant Location Input

The user must input the percentage of building occupants in “interior” space that are more than one room, or 15 ft from the exterior walls. The user can do this in VAPO on an overall building basis or on a floor-by-floor basis assuming uniform distribution of the occupants within identified areas. All other occupants are assumed to be in perimeter space, where they are subject to injury by failed windows and wall components. All occupants, including interior occupants, are subject to injury from floor failure including progressive collapse and roof component failure (top floor only). Interior occupants and perimeter occupants in rooms without windows are subject to injuries from non-structural interior components. Injuries from windows are assumed to be much worse than those from non-structural components in exterior rooms with windows.

Blast Load Calculations

The basic procedures used to calculate blast loads in VAPO V2.0 is summarized in Table 3. VAPO uses the TNT Standard method to calculate blast loads from an explosion in free-air and non-linear shock pulse addition laws to add together blast load pulses at the point of interest from reflecting surfaces including the ground (Jerrett, et al, 2006). For components that receive full or partial reflected blast loads, the load is calculated at nine points on each component and averaged to get the overall blast load used to determine damage to building component and any subsequent injuries to building occupants. For incident surfaces, VAPO uses a single point to compute overall blast load to the component. Interior blast loads on building components are calculated with a model developed from fits to SHAMRC hydrocode calculations through wall openings. The input parameter space includes opening height, opening width, ceiling height, angle of incidence to the opening, and angle of egress from the opening to the target point. An exception to this is that a simplified nominal interior blast load is calculated for purposes of calculating injuries to interior building occupants from non-structural components. This blast load is calculated in the same manner as in the BICADS computer program because the BICADS methodology determines injuries to interior building occupants based on an empirical correlation to simplified nominal interior blast loads. This is explained more elsewhere (Oswald, 2006).

Table 3. Component Blast Load Calculation Methods in VAPO for BICADS

Component	Blast Load Calculation Method[1,2]
Exterior Walls and Sloped Roof Facing Blast Source	Reflected blast loads are calculated accounting for angle of incidence. There is no accounting for clearing effects.
Exterior Walls and Roof Not Facing Blast Source	Side-on blast loads are calculated where standoff distance accounts for distance around closest building corner or combination of (i.e. along shortest string-distance path)
Interior Floors	Blast loads to above and below floors are calculated based on fits to SHAMRC hydrocode calculations through wall openings
Interior Components (for injury calculations only)	Simplified blast loads are calculated at each floor level based on side-on pressure at building exterior and leakage pressures through failed windows on reflected face of building
Note 1: All blast loads calculated using TNT Standard method Note 2: Blast loads for components on building surfaces are calculated at 9 points on component that are averaged using a Gaussian integration scheme to get overall component blast load.	

Structural Component Damage Calculations

Scaled pressure-impulse (P-i) curves from the CEDAW (Component Explosive Damage Assessment Workbook) methodology (Oswald and Nebuda, 2006) are used in VAPO V2.0 to predict component damage levels based on the average calculated blast load on the component. The geometry and material properties of each structural component and applied blast loads are used to calculate scaled Pbar and Ibar terms that describe the building blast capacity relative to the blast loads and this information is compared to curves that graphically divide Pbar-Ibar space into areas associated with each component damage level based on scaled blast test data. This is illustrated for reinforced concrete components in Figure 2, where the levels of protection (LOP) are described in Table 4. Equation 1 shows the Pbar and Ibar terms for this case. The CEDAW methodology includes component-type specific scaled P-i curves for eleven common structural building component types. VAPO determines the CEDAW component damage levels, which are directly converted to DoD and BICADS damage levels as shown in Table 4. The BICADS Damage Levels shown in Table 4 are used as part of the methodology to calculate injuries. The CEDAW methodology is described in more detail elsewhere (Oswald and Nebuda, 2006).

BICADS Injury Levels

Injuries are predicted in the BICADS program in terms of the injury levels shown in Table 5. The ranges of Injury Severity Scores (ISS) (Baker et al, 1974) associated with each qualitative injury level in Table 5 were selected to be generally consistent with the injury level descriptions. The example injuries in Table 5 are the most prevalent among building occupants with each BICADS injury level from the Oklahoma City and Khobar Towers bombings (Oswald, 2006).

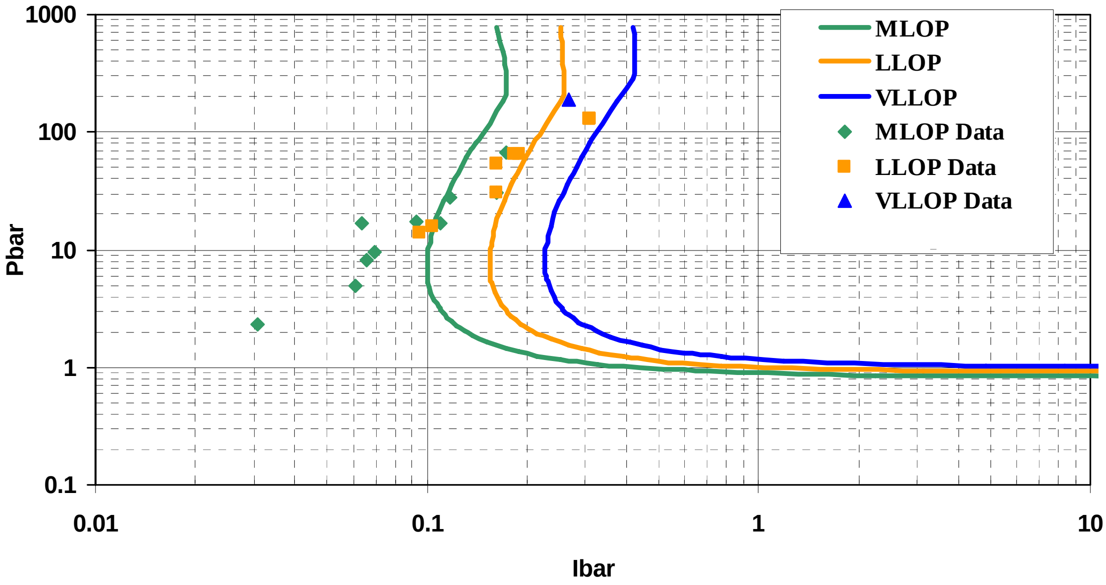

Figure 2. CEDAW Scaled P-i Curves vs. Scaled Data for Reinforced Concrete Slabs

$$Pbar = \frac{P}{R_u} \qquad Ibar = i\sqrt{\frac{1}{K_{LM}\,mR_u L}}$$

Equation 1

where: P = peak pressure

i = applied positive phase impulse

m = mass of equivalent SDOF system for component

K_{LM} = load-mass factor of equivalent SDOF system for component

R_u = ultimate flexural resistance of equivalent SDOF system for component at yield

K = flexural stiffness of equivalent SDOF system for component

L = component span length

Table 4. BICADS Component Structural Damage Level Descriptions

CEDAW Component Damage Level Note 1	**Component Damage Description**	**BICADS Damage Level** Note 2	**DoD Component Damage Level** Note 3
N/A	No net blast load on component or non-failing component input by user. No component damage causing injuries.	0	N/A
High LOP Medium LOP	The component may have some permanent deflection. If it has permanent deflection, it is generally repairable, if necessary, although replacement may be more economical and aesthetic. The component is expected to withstand the same blast load again without failing.	1	Low and Medium Damage
Low LOP	The component has not failed, but it has significant permanent deflections causing it to be unrepairable. The component is not expected to withstand the same blast load again without failing.	2	Heavy Damage
Very Low LOP	At least a portion of the component has failed. Debris velocities vary depending on the extent of failure.	3	Hazardous
Blowout	The component is overwhelmed by the blast load causing failure and debris with significant velocities	4	Blowout

Note 1: LOP = Level of Protection
Note 2: Floor panel components only have Damage Levels 1 or 4. Column components only have Damage Levels 1 or 3. In both cases these imply either failure or no failure.
Note 3: See PDC-TR 06-08 for more details.

Injury Predictions

The approach for predicting injuries from wall and roof components in BICADS is based on three Injury Component Types; 1) non-deformable components (i.e. masonry and concrete), 2) deformable components (i.e. wood, cold-formed steel materials), and 3) deformable components supported by hot-rolled beams. Each Injury Component Type has a separate Injury P-i Diagram that graphically determines the Injury Severity Level. The Injury Severity Levels are associated with given percentages of each BICADS Injury Level for exposed building occupants. The Injury P-i Diagrams and Injury Levels associated with each Injury Severity Level are based on correlations to available injury data and engineering judgment. Non-structural components (i.e., windows and interior components) have a completely separate injury prediction method as described later in this paper.

Table 5. Injury Level Descriptions

BICADS Injury Level	Description	Range of ISS[1] Scores	Example of Injuries	Typical Worst AIS[2] Score
No Calculated Injury	Typically no medical treatment required	0	No injury Minor bruises Minor cuts Small foreign object in eyes Hearing loss	0
Minor to Moderate Injury (Level 1)	Injuries can be treated with medical aid, hospitalization not required	1 to 4	Lacerations to face and body from glass fragments Cuts or abrasions to eye Contusions and abrasions	1
Serious Non-Life Threatening Injury (Level 2)	Injuries require greater degree of medical aid and hospitalization, but not immediately life-threatening	5 to 10	Bone fractures Large numbers of lacerations Artery or tendon lacerations Concussions	2
Serious Life Threatening Injury (Level 3)	Severe injuries, immediate medical attention required, high likelihood of survival with prompt medical treatment	11 to 24	Very severe lacerations with significant blood loss Severe open bone fractures Crush injuries Skull fractures	3 to 4
Fatal/Severe Injury (Level 4)	Very severe injury, likelihood of fatality	≥ 25	Multiple very serious injuries Primarily fatalities	5 to 6

Note 1: ISS (Injury Severity Score) scores are a composite injury score based on worst AIS scores assigned to the three most severely injured body regions, out of six body regions, ranging from 1 to 75.

Note 2: AIS (Abbreviated Injury Scale) scores are individual injury scores ranging from 1 to 6, where 1 is minor, 2 is moderate, 3 is serious, 4 is severe, 5 is critical, and 6 is fatal.

Injury Component Types

Table 6 shows component types and associated component category used for injury calculations in BICADS, including non-structural components. Injuries from failed wall and roof components are assumed to be primarily related to blunt trauma. This approach is based on the assumption that debris from components in each category cause injuries in a fundamentally different manner. Non-deformable components cause the worst-case injuries for a given impact velocity and mass based on their greater mass density, rigidity, and stiffness. Deformable components, which are less dense and more crushable, cause much less severe injury for the same applied impact velocity and mass. These components deform upon impact with people, reducing the local accelerations and damage caused to impacted body parts. Deformable components supported by hot-rolled beams (i.e., light roof supported by open web steel joists) fall partially into both categories, where the failed beams are non-deformable components that affect a limited percentage of the exposed building occupants because they are only present over a limited area on the wall or roof, and the cladding is a deformable component that causes less severe injuries to the remainder of the exposed occupants.

The different injurious affects of deformable and non-deformable components can be understood in a general sense by looking at selected results from a series of 70 simple drop tests on a 50th percentile male Hybrid III Anthropomorphic Test Device (ATD) conducted by Biodynamics Research Corporation (BRC) under subcontract to Wilfred Baker Engineering, Inc. (Oswald, 2003). The tests were intended to simulate blunt trauma injuries to building occupants by blast-induced translation or impact by non-structural interior components in a simplified manner. Tests were conducted by dropping the ATD onto various ground surfaces and interior walls, simulating injury from sudden deceleration after blast-induced translation, and by dropping building materials and interior components onto the ATD, simulating injury from impact by flying debris. Table 7 summarizes representative tests where CMU (concrete masonry units) block sections, 4 ft long, ceiling-mounted, fluorescent light fixtures, wood panels and cracked and uncracked laminated glass panes were all dropped from varying distances onto the ATD's head and/or chest.

Table 6. Component Category for Injury Predictions for Each Component Type

Component Type	Component Category for Injury Calculations	Comment
Reinforced and Unreinforced Masonry Wall Components	Non-deformable component	
Reinforced Concrete Wall and Roof Panels		
Light Metal Panel/Beam System	Deformable component	
Steel Roof Beam (Cold-Formed)		
Metal/Wood Stud Wall		
Wood Roof System[1]		
Steel Roof Beam (Hot-Rolled)[1]	Deformable component supported by Hot-Rolled Beam	This includes deformable components supported by steel beams.
Open Web Steel Joists [1]		
Ground Floor Steel Column	Overhead floor slab collapse if column fails and progressive collapse criteria are met	Overhead floor slab causes 100% Level 4 injuries if it fails, otherwise no injuries.
Ground Floor Concrete Column		
Floor slabs (above ground floor)	Overhead floor slab	
Windows	Annealed/tempered windows and laminated/filmed windows	Injuries are based on window injury P-i diagrams that directly correlate injuries to the blast load applied to window.
Interior Components	Office/residential interior component Industrial interior component	Injuries are based on interior component P-i diagrams that directly correlate injuries to nominal free-field blast load in room through any failed windows or walls that fail quickly compared to blast load duration.
Note 1: Non-deformable component if supported roof > 30 psf		

The information in Table 7 shows that deformable objects of equal or greater weight dropped from equal or greater heights cause less injury than the non-deformable CMU block. This is consistent with the approach in BICADS to create separate empirical relationships between the "delta" blast load above the failure blast load and corresponding injury to exposed building occupants for deformable and non-deformable debris from failed building components.

Table 7. Probability of Injury to ATD from Deformable and Non-Deformable Dropped Objects

Dropped Object	Weight (lb)	Drop Height (in)	Calculated Velocity (ft/sec)	ATD Orientation	Impact Condition	Probability MAIS >= 1 (%)[1,2]	Probability MAIS >= 4 (%)[1,2]	Probability Fatality (%)
1 CMU block (non-deformable)	24.2	72	19.7	ATD facing up, suspended by magnet	Strike to ATD's head	100	84	16
1 CMU block (non-deformable)	25	72	19.7	ATD facing up, suspended by magnet	Strike to ATD's chest	52	16	N/A
4 ft Light fixture (deformable)	31.25	76	20.2	ATD sitting down in rigid chair w/o back, neck fully extended	Impact top of ATD's head by edge of light fixture	0	0	0
4 ft Light fixture (deformable)	31.25	76	20.2	ATD sitting down in rigid chair w/o back, neck fully extended	Impact top of ATD's head by center of light fixture	0	0	0
53”x48”x3/4” Plywood (Deformable)	37	209		ATD facing up, suspended by magnet, no nose on face skin	Strike to ATD's head and chest, forehead above chest	40	1	0
65”x47”x0.3” laminated cracked glass (Deformable)	~67	209		ATD facing up, suspended by magnet	Strike to ATD's head and chest, forehead above chest	0	0	0

Note 1: MAIS = Maximum Abbreviated Injury Score (AIS) to ATD
Note 2: MAIS = 0 corresponds to no injury, MAIS = 4 corresponds to severe, life-threatening injury

Injury P-i Diagrams for Wall and Roof Components

Injury P-i Diagrams relate the applied blast load to the resulting injuries to exposed building occupants. The P-i Diagrams have P-i curves dividing the graph into four Injury Severity Level regions. Figure 3 shows an Injury P-i Diagram for a lightly reinforced concrete wall. Table 8 summarizes an explanation of the three P-i curves on the Injury P-i Diagram and their use for injury prediction. The CEDAW failure curve is determined by solving the Pbar and Ibar equations for corresponding peak pressure and impulse values for each point on the LLOP curve in Figure 2 based on the known parameters for the wall defined in Equation 1.

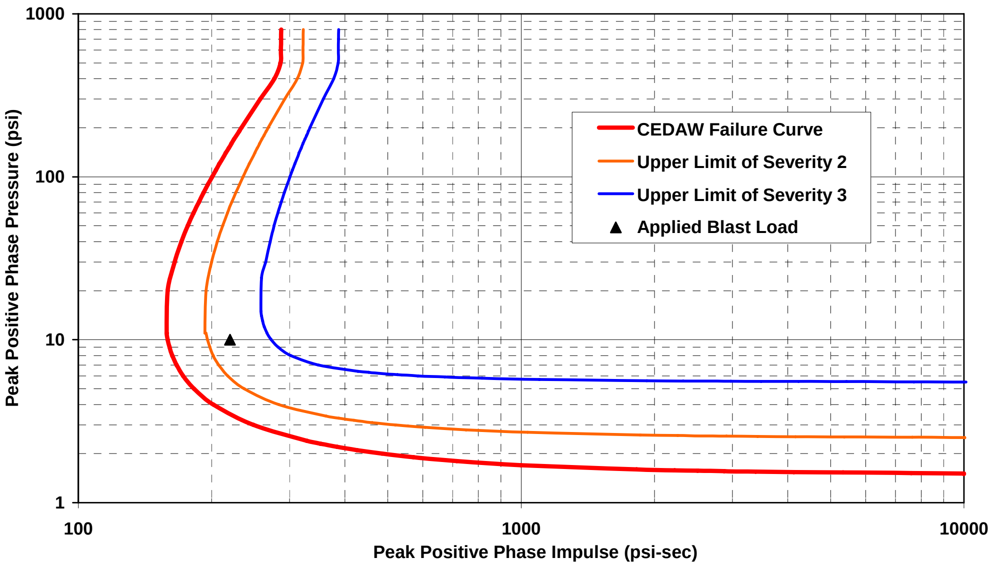

Figure 3. Injury P-i Diagram for Lightly Reinforced Concrete Wall

Table 8. Explanation of BICADS Injury P-i Diagrams for Given Component

Curve No.	Curve Description	Calculation of Values for P-i Curve	Injuries[1]
1	Upper Bound of Injury Severity Level 1	Unscaled CEDAW P-i curve for the onset of component debris (i.e. total component failure) for input component	No injuries for Injury Severity Category 1
2	Upper Bound Curve for Injury Severity Level 2	Offset from Curve No. 1 by delta impulse and peak pressure offsets based on Injury Component Type[1]	Very limited fatalities
3	Upper Bound Curve for Injury Severity Level 3	Offset from Curve No. 1 by delta impulse and peak pressure offsets based on Injury Component Type[1]	Significant fatalities
N/A	P-i Diagram Area above Curve No. 3 is Injury Severity Level 4	N/A	100% BICADS Level 4 injuries (typically all fatalities)
Note 1: See Table 9 for specific percentages for each BICADS Injury Level for Injury Severity Levels and delta peak pressure and impulse values for each Component Injury Type .			

The next two curves are at delta impulse and pressure offset values from the first curve, where the offset values differ based on the Component Injury Type. The offsets are shown in Table 9. Since the reinforced concrete component in Figure 3 is a non-deformable component, the delta impulse values for upper bound curves for Injury Severity Levels 2 and 3 are 35 psi-ms and 100 psi-ms respectively. These delta values apply in the impulse sensitive region of the curves where they are roughly parallel to the pressure asymptote. The delta pressure values for upper bound curves for Injury Severity Levels 2 and 3 are 1 psi and 3 psi respectively. These delta values apply in the pressure sensitive region of the curves where they are roughly parallel to the pressure asymptote. Both delta values are applied in the dynamic region between the pressure and impulse sensitive regions.

A blast load on this reinforced concrete wall defined by the blast load point in Figure 3 will cause Injury Severity Level 3 to building occupants directly behind the wall. BICADS also interpolates using an approximate method within Injury Severity Levels 2 and 3 based on the exact location of the blast load point between the upper bound curves for these levels in the Injury P-i Diagram. For example, the blast load point in Figure 3 has an interpolation factor of 30% within Level 3.

Table 9. Delta Blast Load Values for Injury P-i Diagrams

Injury Component Type	Injury Severity Category	Δi [1] (psi-ms)	Δp [1] (psi)	Percentages of Each BICADS Injury Level [2]			
				1	2	3	4
Deformable Components [3]	Upper Bound of 1	Δi = 0	Δp = 0	0	0	0	0
	Upper Bound of 2	Δi = 150	Δp = 10	60	25	5	10
	Upper Bound of 3	Δi = 310	Δp = 40	0	0	0	100
	4	Δi > 310	Δp > 40	0	0	0	100
Nondeformable Components [3]	Upper Bound of 1	Δi = 0	Δp = 0	0	0	0	0
	Upper Bound of 2	Δi = 35	Δp = 1	40	20	5	15
	Upper Bound of 3	Δi = 100	Δp = 3	0	0	0	100
	4	Δi > 100	Δp > 3	0	0	0	100
Deformable Components Supported by Hot-Rolled Beams [4]	Upper Bound of 1	Δi = 0	Δp = 0	0	0	0	0
	Upper Bound of 2	Δi = 35	Δp = 2	30	10	2	10
	Upper Bound of 3	Δi = 280	Δp = 40	0	0	0	100
	4	Δi > 280	Δp > 40	0	0	0	100

Note 1: Delta values for impulse and pressure asymptotes for P-i curves defining Injury Severity Categories on Component Injury P-i Diagram.

Note 2: Actual percentages interpolated between upper bound values based on interpolation factor of blast load point on Injury P-i diagram. See Table 5 for Injury Level definitions.

Note 3: Δi and Δp values relative to BICADS Damage Level 3 from component CEDAW P-i diagram

Note 4: Δi and Δp values relative to BICADS Damage Level 4 from component CEDAW P-i diagram

In general, deformable components have the largest delta pressure and delta impulse values for Curves 2 and 3 relative to Curve 1 in Figure 3, and non-deformable components have smaller values. This reflects the fact that higher delta blast loads above the component failure blast load must be applied to deformable components to cause the same injury levels as non-deformable components. Figure 3 is representative for a non-deformable component type, which has closer spacing between Injury Severity Curves. As implied by Table 9, the exact percentages of each BICADS Injury Level predicted for the exposed occupants near a blast-loaded building component are based on the Injury Component Type, Injury Severity Category, and the interpolation factor. The interpolation factor is used to interpolate between the upper bound percentages of each Injury Level shown in Table 9 for Injury Severity Levels 2 and 3.

These percentages of each Injury Level and the delta blast load values in Table 9 are derived from available data and engineering judgment for each Injury Component Type. The development of the Injury P-i diagrams was based on separate consideration of the pressure dependent and impulse dependent sections of the P-i diagram, where the pressure dependent region is parallel to the impulse axis and the impulse dependent region is roughly parallel to the pressure axis. The impulse region represents cases where the blast load duration is short compared to the natural period of the component and primarily the impulse of the blast load affects injuries. The pressure region represents cases where the blast load duration is very long compared to the natural period of the component and primarily the peak pressure of the blast load affects injuries. The dynamic region is between these two extremes, where both peak pressure and impulse of the blast load affect injuries.

The available data for injuries from deformable and non-deformable components is very limited. The injury data used to determine information in Table 9 for deformable components includes blast-related injuries to occupants of wood frame houses from the WWII nuclear bombing of Japan and injuries to ATDs behind wood stud walls that were failed in explosive tests in the Devine Buffalo and BAITS test series (Bogosian, 2004) (Marchand, 2002) test series. The injury data used to determine information in Table 9 for non-deformable components includes a relatively large database from the London Blitz for injuries to occupants of typical London brick houses during World War II (HSE, 1998) (Hadjipavlou and Carr-Hill 1986) (Zuckerman, 1940) and limited data from the 1995 Oklahoma City Bombing (OSDH, 1996). Only injury data that included information on the applied blast load, relatively detailed information on the building structural components, and extent of injuries to building occupants in the immediate vicinity of the failed component was used to help determine the information in Table 9.

The available data was analyzed by calculating the failure P-i curve for the failed component based on the CEDAW methodology, determining the delta impulse or delta pressure values based on whether the component damage and failure was primarily dependent on the impulse or peak pressure of the blast load, and determining the equivalent Injury Levels from Table 5 for the building occupants injured by the failed component. The final values in Table 9 were averages from the available data. Considerable engineering judgment was required in this process, which was done separately for deformable and non-deformable components. There was almost no data for Non-deformable components supported by hot-rolled steel members. Therefore, the information in Table 9 for this Injury Component Type was based on an assumption that approximately 20% of the exposed building occupants would be subject to the more severe debris from hot rolled beams and the remainder would be subject to the less severe debris from the deformable wall cladding.

Much more detail on the determination of the information in Table 9 is provided in the BICADS Methodology Report prepared for VAPO V2.0 (Oswald, 2006) and the BICADS V2.0 Methodology Report distributed with BICADS V2.0 (Oswald, 2007).

Prediction of Injuries from Non-Structural Components

Injuries from failed window components are predicted in BICADS for occupants in perimeter rooms with windows based on P-i diagrams similar to Figure 4. The lowest two P-i curves in Figure 4 are based on the P-i curves for Low and High hazard levels in WinDAS (2004) for the applicable window type and size (i.e., large or small pane). Figure 5 shows the P-i diagram used to determine injuries from non-structural components of residential and office buildings. This generally includes injuries from items such as failed overhead lights, interior walls, and occupant impact with interior objects or the floor due to translation by the blast load. Table 10 shows the Injury Levels associated with Hazard Region on these P-i diagrams.

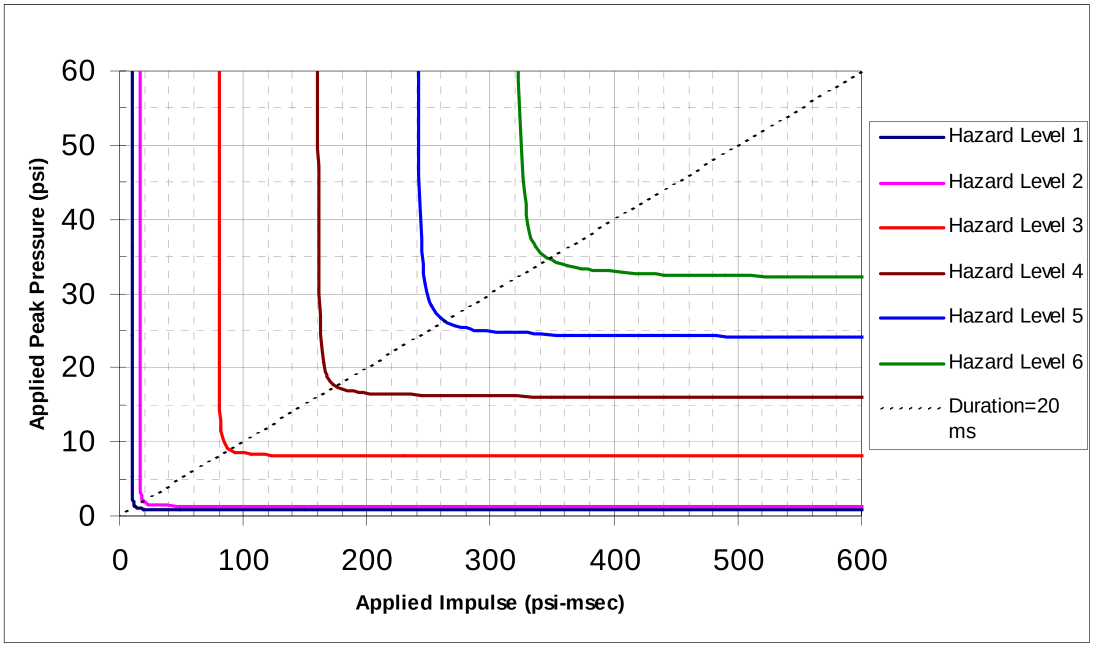

Figure 4. P-i Diagram Showing Window Hazard Levels for Large Annealed Glass Windows (All Annealed Window Types Similar for Levels 3 to 6)

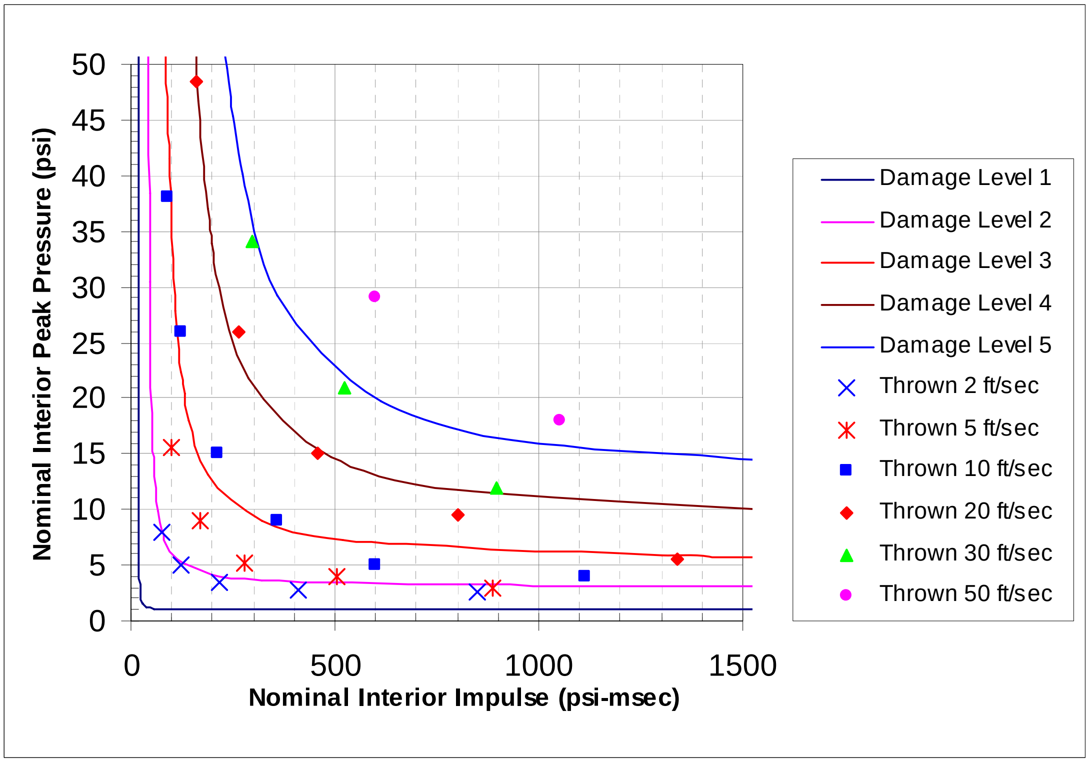

Figure 5. P-i Diagram for Interior Occupant Hazard Levels in Office and Residential Buildings Showing Nominal Throw Velocity Levels

Table 10. Percentage Injuries to Exposed Population at Column, Floor Slab, Interior, and Window Component Damage Levels

Component Type[1]	Hazard Level 1	Hazard Level 2				Hazard Level 3				Hazard Level 4				Hazard Level 5				Hazard Level 6				Hazard Level 7	
	Injury Level[2]	Injury Level				Injury Level				Injury Level				Injury Level				Injury Level				Injury Level	
	All	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1-3**	**4**
Residential/ Dormitory Interior	0	50	0	0	0	75	5	2	3	37	20	7	22	12	10	3	62	0	0	0	100		
Office Interior	0	50	0	0	0	75	5	2	3	37	20	7	22	12	10	3	62	0	0	0	100		
Warehouse/ Industrial Interior	0	50	0	0	0	15	15	10	60	0	0	0	100										
All Windows	0	35	0	0	0	69	3	0	0	58	21	6	2	35	20	20	20	18	8	8	62	0	100

Note: 1 Constant injury levels for any case within each hazard level (i.e. no interpolation within hazard level) for all component types in this table. Hazard levels are determined based on applied blast load and applicable P-i diagram.

Note 2: Percentages of each BICADS Injury Level from Table 5.

All injury predictions for non-structural components are empirical. The P-i diagrams and injury levels are based primarily on a large database of injuries to occupants of buildings damaged by blast loads from the Oklahoma City and Khobar Towers bombings in building areas without floor slab or wall collapse. The occupant locations relative to windows, applicable blast loads, and injuries of building occupants were known based on a large database of injury information collected by the Oklahoma State Department of Health. Summarized versions of the databases are distributed with the BICADS V2.0 program. Figure 5 is based on nominal side-on blast loads considering the charge weight, line-of-sight standoff to the center of rooms without windows, and percentage of predicted broken windows on the reflected side(s) of the buildings. Details on injury prediction methodologies for non-structural components and their development are described elsewhere (Oswald, 2006).

Injury Summations

Building occupants are assumed uniformly distributed in each room in VAPO based on user input information. All perimeter rooms are assumed to be perimeter space and all other rooms are assumed to be interior space. This defines the types of failed components that can cause injuries in each type of space, as described previously. The percentages of building occupants on each floor panel with each injury level from each applicable damaged component adjacent to the floor panel are calculated using previously discussed correlations between injury percentages and component damage and blast load.

After the percentages of occupants with each injury level from each applicable damaged component, or injury source are calculated independently of each other, the BICADS program determines summed or overall injuries to the occupants of each room from all injury sources assuming injuries from each injury source are independent of injuries from all other injury sources. Therefore, Equation 2 applies (Kurtz, 1991). The basic summation approach in Equation 2 is used within the overall injury summation approach in the BICADS program as shown Equation 3, which also includes the $CF_n(i)$ and K_i factors. The K_i factor causes the percentage of the floor panel population exposed to a given injury level to equal the remaining population not injured at higher injury levels. This ensures that no more than 100% of an exposed population will be injured considering all injury levels. It also requires that the percentages of occupants with each injury level from all injury sources are calculated in order of decreasing injury level in the BICADS program. The highest injury levels are calculated considering all injury sources and the percentages of lower injury levels are assumed to apply only to the remaining room occupants that do not have the higher injury levels.

$$P_{tot} = 100\left[1-\left(1-\frac{P_1}{100}\right)\left(1-\frac{P_2}{100}\right)...\left(1-\frac{P_N}{100}\right)\right]$$

Equation 2

$$SI(i) = 100\left[1-\left(1-\frac{I_1(k(1),i)}{100}CF_1(i)\right)\left(1-\frac{I_2(k(2),i)}{100}CF_2(i)\right)....\left(1-\frac{I_n(k(n),i)}{100}CF_n(i)\right)\right]K_i$$

$$CF_n(i) = \frac{1}{\left(1-\sum_{i+1}^{4}\frac{I_n(k(n),j)}{100}\right)}$$

$$K_i = 1-\sum_{j=i+1}^{4}\frac{SI(j)}{100}$$

$$Note:\quad \sum_{1}^{4}S(i) \leq 100$$

Equation 3

SI(i) = summed injury percentage at ith injury level (i =1 to 4) from all n sources
$I_n(k(n),i)$ = “baseline” percentage of exposed occupants with ith injury level from BICADS correlation between Damage Level k for the nth injury source, k(n), and the ith injury level
$CF_n(i)$ = factor that converts $I_n(i)$ to apply to remaining percentage of floor panel occupants not injured at higher injury levels

Comparisons of BICADS Injury Levels to Injury Databases

Table 11shows a comparison of injuries calculated with the BICADS computer program and injuries to building occupants near the Oklahoma City bombing based on the OSDH database. BICADS injury levels were assigned to all building occupants in the database using Injury Severity Scores (ISS) determined by OSDH and the relationship between ISS and the BICADS injury levels in Table 5. Figure 6 shows the buildings in Table 11 relative to the bomb location. The BICADS input for the building construction and occupant location in perimeter and interior space was determined as best as possible for each building. Detailed information to determine these variables was available for the Murrah, Journal Record, and Water Resources Buildings. Only estimated building census information and limited building construction information were available for the other buildings. A 4000 lb ANFO surface burst explosion was assumed. All BICADS input information related to Table 11 is in an input file distributed with the BICADS computer program.

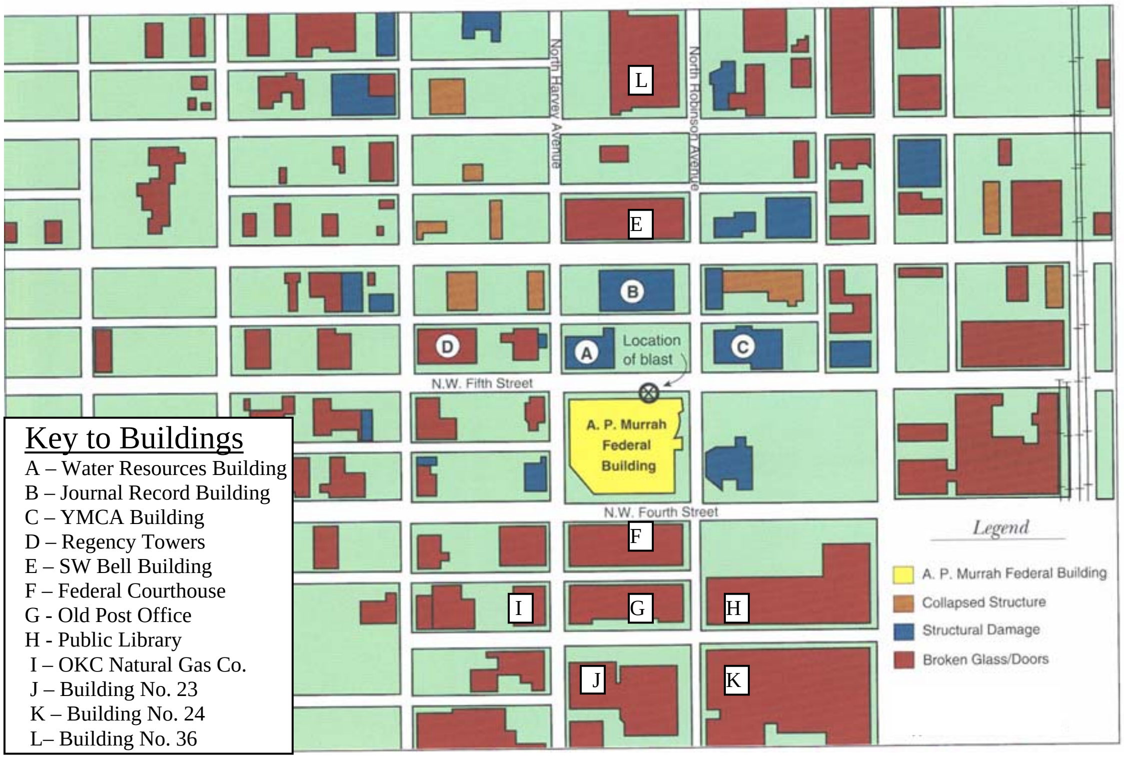

Figure 6. Layout of Buildings Near Oklahoma City Bombing

The comparisons in Table 11 show that most of the predicted injury percentages are within 5 to 10 percentage points of observed values except at the larger standoff distances, where the values calculated with BICADS are conservative. However, the observed data at the larger standoffs is sketchy since the building censuses used to determine the percentages of injured occupants was estimated and there were very few reported injuries in the database considering the observed number of broken windows. More complete information is only known for the first four buildings in Table 11. Generally, damage to buildings in Table 11 was limited to windows and non-structural components except as noted in the table. More comparisons that show a similar level of agreement between calculated and reported injuries and between calculated and measured blast loads are hot-linked to the BICADS V2.0 computer program (Oswald, 2007).

Table 11. Comparison of Predicted and Observed Injuries in Buildings Near Oklahoma City Bombing

Building[1]	Closest Face to Explosion (ft)	P (psi)	i (psi-ms)	Census	Predicted vs. (Observed) Injuries[2] (%)					Comments
					Level 4	Level 3	Level 2	Level 1	No Injury	
Murrah Building	15	11000	7000	361	47 (48)	3 (6)	5 (8)	28 (34)	17 (5.5)	Column, floor panel collapse
Journal Record	230	10	182	297	0 (0.3)	0 (1.4)	2 (4)	48 (52)	50 (42)	
Water Resources	220	13	150	65	1 (3.1)	1 (1.5)	4 (11)	57 (61)	40 (23)	1 shielded wall,limited wall failure
YMCA	246	9.1	157	165	3 (0)	1 (0)	6 (6)	56 (44)	34 (50)	
Federal Courthouse	430	3.8	86	161	0 (0)	0 (0)	2 (0)	27 (9)	71 (91)	
SW Bell	451	3.6	82	90	0 (0)	0 (0)	2 (0)	28 (8)	70 (92)	
Old Post Office	615	2.3	59	161	0 (0)	0 (0)	1 (0)	21 (1)	78 (99)	
OKC Building #23	861	1.5	41	150	0 (0)	0 (0)	2 (0)	14 (1)	84 (99)	
Building #24	943	1.3	38	600	0 (0)	0 (0)	1 (0)	22 (0)	77 (100)	
Building #36	841	1.6	42	120	0 (0)	0 (0)	1 (0)	8 (2)	91 (98)	
OKC Natural Gas Co.	697	2.0	52	150	1 (0)	1 (0)	3 (0)	25 (1)	70 (99)	
Public Library	666	2.1	54	58	0 (0)	0 (0)	1 (0)	21 (7)	78 (93)	

Note 1: See Figure 6 for layout of buildings around explosion.
Note 2: Observed injury percentages are in parentheses below percentages predicted with BICADS program.

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