

A Computer Program for Explosive Damage Assessment of Conventional Buildings

by

Charles J. Oswald, Southwest Research Institute
Edward J. Conrath, U.S. Army Corps of Engineers, Omaha District

ABSTRACT

This paper describes the recently developed FACEDAP (Facility and Component Explosive Damage Assessment Program) computer program, which provides a quick estimate of blast damage to conventional buildings from external detonations. It uses a blast damage assessment procedure which is based on dynamic structural analysis theory and is validated against available data from explosive tests on structural components. The code assesses blast damage to each structural component in a conventional building and then calculates the composite building damage based on the summed component damage. It is intended to predict the actual amount of building damage, without the conservatism that is often built into such analyses, within the accuracy permitted by simplifying assumptions that have been incorporated to maintain efficiency. This paper describes the building damage assessment procedure, shows comparisons between predicted component damage and data from explosive tests, and discusses limitations of the code caused by simplifying assumptions that have been incorporated.

Introduction

When conventional buildings are sited near potential accidental explosive sources or potential terrorist threats, it is important to estimate the damage to the buildings from external explosive loading. Such siting requires limiting building blast damage and fragments hazards and resisting other blast effects. Currently, blast damage can be determined based on either very approximate criteria such as a simple relationship between building damage and scaled standoff, or it can be calculated closely using time-consuming dynamic structural analyses. Quick, easy-to-use blast damage assessment tools are needed to provide a more reliable estimate of building damage than current approximate criteria without requiring a significant amount of time or structural engineering input.

The recently developed FACEDAP (Facility and Component Explosive Damage Assessment Program) computer program is a tool that provides a quick estimate of blast damage using a procedure that is based on dynamic structural analysis theory and is validated against available data from explosive tests on structural components. The code assesses blast damage to each structural component in a conventional building and then calculates the composite building damage based on the summed component damage. Information on building components is input in an efficient, user-friendly manner, and the program calculates the response of each component to the applied blast loads in terms of a damage level based on the

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input charge weight and location and on building geometry and material property information. The damage level (0, 30, 60, or 100 percent damage) of each building component is calculated using pressure-impulse (P-i) diagrams, which are based on results from single-degree-of-freedom (SDOF) analyses that are collapsed into simple nondimensionalized curves incorporated into the computer program. Only structural building components are considered in the code, excluding windows and doors. Windows and doors can be considered using other procedures.

The greatest advantage of the FACEDAP program over other programs used to estimate building vulnerability to blast loading is that the response of each structural component is evaluated separately and then overall building damage is evaluated as a composite of calculated component damage levels. This approach is consistent with the actual manner in which buildings respond to blast load. Most other approximate procedures determine building vulnerability with correlations based only on the peak pressure and/or impulse at the center of a building and the general type of building construction.

The preprocessor for the FACEDAP program has 13 resident building input files. The program can be run to quickly determine approximate damage using one of the 13 existing input decks for a building with similar construction. The program can also be used to calculate damage, considering any unique characteristics of a building, by simply modifying one of the 13 existing input decks as necessary before calculating blast damage. It can be used to re-analyze a building after modifying the structural input parameters for the most vulnerable components to reflect simple strengthening measures. The pre-processor is also set up to allow efficient input of an entirely new building and to analyze the response of a single building component. The theory¹, user's², and programmer's³ manuals have been written for the program.

Overview and Background

The program consists of a reprocessor, an analysis module, and a postprocessor. This paper is concerned primarily with the two-step procedure used in the analysis module to determine building damage. This procedure is intended to predict the actual amount of building damage, without the conservatism that is often built into such analyses, within the accuracy permitted by simplifying assumptions that have been incorporated to maintain efficiency. This section provides an overview of the procedure, and the following sections provide a more detailed description of the procedure followed by comparisons between predicted component damage and data from explosive tests. Also, simplifying assumptions used in the program, and limitations due to these assumptions, are discussed.

In the first step of the building damage assessment procedure, damage to each structural component in the building (i.e., beams, columns, wall panels) is calculated using equations fit through damage curves on P-i diagrams which define four different blast induced damage levels (0, 30, 60, and 100 percent damage). Theoretical P-i diagrams are graphs which predict maximum component response based on two nondimensional parameters which include all relevant structural and blast loading parameters. The diagrams are compiled from SDOF

analyses assuming a given pressure history shape and spatial distribution for the blast load. The P-i diagrams in the FACEDAP program predict general damage levels instead of specific response levels. These diagrams were developed from theoretical P-i diagrams by defining maximum and minimum response levels for each damage level.

In the second step of the damage assessment procedure, parameters which measure different types of overall building damage are calculated based on the amount of component damage. The calculated component damage is weighted by a user-defined multiplication factor (the weighting factor) before overall building damage is determined so that damage to more important structural components, such as columns, can affect the overall building damage more than equal damage to secondary structural components, such as cladding. Cascading failure, where failure of a supporting component causes failure of all supported components, is also considered.

Considerable effort has been expended to implement the building damage assessment procedure into a user-friendly program. The FACEDAP preprocessor has been designed to simplify the detailed input that is required for the analysis of all the components of a building. It takes advantage of the fact that most buildings are comprised of a relatively small number of "unique" building components which are used repetitively throughout the building construction. It also checks for apparent errors during input and it makes extensive use of user-friendly form-type and spreadsheet-type input screens. These screens include on-screen help messages for each input item and the capability to calculate a number of input items for the user based on default equations. Finally, the preprocessor includes a validation program that checks the completed input prior to analysis and provides a specific explanation of each error that is found. The postprocessor displays the overall building damage parameters mentioned previously, as well as the most damaged building components and the blast load and damage to each input building component.

The FACEDAP program was developed under sponsorship by the U.S. Army Corps of Engineers (COE), Omaha District. It is an extension of work performed by Southwest Research Institute for the Naval Civil Engineering Laboratory NCEL) in Port Hueneme, California⁴ and the COE⁵ over an 8-year period. The work initially consisted of developing a building damage assessment procedure based on component damage predicted with P-i diagrams. More recently the work has focused on implementing this procedure into a user-friendly PC-based program and improving the component damage prediction procedure as more data becomes available. The most recent version of the code (Version 1.2) includes the capability to calculate blast damage to a single component as well as the damage to the overall building.

Prediction of Blast Loads

The building damage assessment procedure begins with the calculation of blast loads on each building component. The load on each component is calculated based on the input weight and location of an equivalent TNT charge, the angle of incidence for the blast load on the component, and the assumption of an external surface burst explosion. Curve-fit equations

from Reference 6, which also appear in the recently updated version of TM 5-13007, are used to calculate the blast load at the center of the component in terms of the peak pressure and the positive phase impulse. A fully reflected blast load is calculated if the angle of incidence between the direction of blast wave propagation and the outward normal from the component surface is less than 45 degrees. Otherwise, a free-field blast load is calculated. Also, the spatial distribution of the blast load on each component is assumed to be uniform and the pressure history is assumed to have the shape of a right triangle. In order to further simplify the blast pressure calculation procedure, the drag pressures from "dynamic" blast pressures, gradual loading of long components parallel to the direction of shock wave propagation, and the effect of negative phase blast pressures are not considered.

The blast load on primary members (e.g., frame members) is equal to the calculated pressure typically selected based on the full tributary area of the supported members. This implies that the supported components respond very quickly to the blast load compared to the primary members (i.e., uncoupled response) and that they have enough strength to transfer the full applied blast load without yielding. This conservatism can be reduced somewhat by inputting a reduced loaded width, but the load transfer between secondary and primary building components cannot be accounted for in a direct manner.

Component Damage Prediction

The calculated blast pressures are used to determine the damage to each building component. The component damage assessment procedure in the FACEDAP program is based on an idealization of the building components as independent, SDOF systems responding in flexure or buckling to a uniformly distributed load pulse with a right triangular shape. These assumptions were used to construct theoretical P-i diagrams, which correlate component response to loading and structural parameters. After theoretical P-i diagrams were constructed, the diagrams were modified to predict general damage levels rather than specific response levels and available explosive testing data was used to validate or modify the damage regions on the P-i diagrams.

P-i diagrams can be formulated by performing an array of SDOF analyses which use a full spectrum of possible pressure histories to cause a single targeted maximum response level (usually either a strain, ductility ratio, or support rotation). The pressure histories, or load cases must vary from purely impulsive loading (a load duration less than approximately 20 percent of the natural period) to quasistatic loading (a load duration greater than approximately five times the natural period) for the structural component that is analyzed. The impulse and peak pressure in each load case are normalized separately against relevant flexural response properties of the structural component creating two parameters, usually referred to as the pbar term (which relates the peak pressure to structural parameters) and the ibar term (which relates the impulse to structural parameters). These parameters can be derived using an energy balance for SDOF response to purely quasistatic and impulsive loading⁸, respectively. Usually pbar, ibar, and the response term are nondimensional parameters. A P-i diagram is constructed by plotting pbar vs. ibar for all load cases causing the desired maximum response level. The line through these points is a response curve

which defines all $pbar$ and $ibar$, and therefore all blast load and structure conditions, causing the target response level. A simplified approximate procedure for constructing P-i diagrams is discussed in Reference 1.

This process is repeated for different target maximum response levels to construct a number of response curves on a given P-i diagram. The curves in Figure 1, where the two asymptotes correspond to the extreme cases of quasistatic and impulsive blast loading. The P-i diagram can then be used to determine the maximum response level for any SDOF system by calculating the $pbar$ and $ibar$ terms, plotting the corresponding point on the P-i diagram, and determining the maximum response based on the response level curve nearest the point. The response curves on the P-i diagram in figure1 show the maximum elastic strain for a beam responding in flexure to a blast load.

In the FACEDAP program theoretical P-i diagrams which predict maximum response levels, such as that in Figure 1, are simplified into diagrams that predict qualitative "damage levels," such as that shown in Figure 2, by selecting specific response levels to represent upper and lower bounds on each damage level. Qualitative damage levels are used, rather than quantitative response levels, because simplifying assumptions in load and structural response calculation procedures give rise to uncertainties that preclude accurate calculation of a specific response level. The four qualitative damage levels used in the program are described in Table 1. They were selected based mainly on the qualitative damage descriptions found in available test data 4 & 5.

Table 1. Description of Damage Levels

<u>Damage Level</u>	<u>Component Condition</u>
0% Damage	No appreciable damage; the component is reusable without repair.
30% Damage	Moderate damage; the component is probably repairable and it has provided a medium; or generally adequate level of protection to personnel and equipment from the effects of the explosion.
60% Damage	Several damage; the component is not worth repairing, but it has not failed and it has provided at least some protection to personnel and equipment from the effects of the explosion.
100% Damage	The component is definately beyond repair but it has not necessarily completely collapsed. It has undergone a deformation such that it cannot be counted on with high certainty to protecy personnel and equipment from the effects of the explosion.

The specific response levels representing upper and lower bounds on each damage level

were selected for each of the structural components considered by the program and separate P-i diagrams were constructed. The selected response levels were based on a review of data from explosive tests, on design criteria for different protection levels in References 7 and 9, and on engineering judgement. These upper and lower bounds are shown in Table 2 in terms of ductility ratio (μ) and maximum yield deflection to length ratio (w/l). The table also shows the different types of components and component response that can be considered by the program. The P-i diagrams used in the FACEDAP program only correlate the input blast load and structural parameters to the ductility ratio of the component assuming flexural or buckling response. Therefore, the limits defining damage levels can only be directly expressed quantitatively in terms of corresponding ductility ratios. The w/l values in Table 2 were derived from the corresponding ductility ratios for each component damage level using an assumed "typical" yield deflection value as a function of span for each component type (i.e., $w/l = \mu(W)$, where $W = (\text{yield deflection}/l)$). For components with arching, w/l values were determined directly from data.

Table 2. Quantitive Criteria Defining Damage Levels for Each Component Type

<u>Component Type</u>	<u>Damage Criteria</u>						<u>Notes</u>
	Lower Limit of 30% Damage		Lower Limit of 60% Damage		Lower Limit of 100% Damage		(See text for more discussion and see general notes below)
	<u>μ</u>	<u>w/l</u>	<u>μ</u>	<u>w/l</u>	<u>μ</u>	<u>w/l</u>	
	1	.005	5	.022	20	.09	
Reinforced Concrete (R/C) Beam							Ductility values assumed same as one-way R/C slab
R/C One-Way Slabs	1	.007	5	.034.	20	.135	Ductility values validated w/data
R/C Two-Way Slabs without Archning	1	.015	5	.08	20	.31	Ductility values assumed same as one-way R/C slab
R/C Two-Way Slabs with Arching	1	.005	5	.013	20	.20	Ductility criteria based on approxtheoretical approach, w/l values based on data
R/C Exterior Columns (bending)	1	.003	5	.014	20	.054	Ductility values assumed same as one-way R/C slab
R/C Interior Column (buckling)	--	--	--	--	1	.002	Criteria apply only to impulsive response and are assumed
R/C Frames	1.3	.014	6	.066	12	.133	Ductility values validated w/some data, w/l values are ration of max. frame sway to column height
Prestressed Beams	.5	.005	1	.01	2	.02	Ductility values are assumed
Steel Beams (Note 3) (bending)	2	.012	7	.04	15	.009	Ductility values are based on some data
Metal Stud Walls	2	.02	7	.07	15	.15	Ductility values are assumed same as steel beams
Open Web Steel Joists (based on flexural tensile stress in bottom chord)	1	.01	3.5	.035	6	.06	Ductiltiy values are assumed
Corrugated Metal Deck	2	.012	7	.042	15	.09	Ductiltiy values validated w/some data
Steel Exterior Columns (bending) (Note 3)	2	.009	7	.032	15	.068	Ductility values are assumed same as steel beams
Steel Interior Columns (buckling)	--	--	--	--	1	.0045	Ductility values apply only to impulsive response and are assumed
Steel Frames	1.3	.021	6	.10	12	.20	Ductility values validated w/some data, w/l values are ratio of max. frame sway to column height
One-Way Unreinforced Masonry (unarched)	--	--	--	--	1	.0005	Ductility values are assumed

**Table 2. Quantitive Criteria Defining Damage Levels for Each Component Type
(Continued)**

<u>Component Type</u>	<u>Damage Criteria</u>						<u>Notes</u> (See text for more discussion and see general notes below)
	Lower Limit of 30% Damage		Lower Limit of 60% Damage		Lower Limit of 100% Damage		
	μ	w/l	μ	w/l	μ	w/l	
One-Way Unreinforced Masonry (arched)	.25	.005	.5	.02	1.0	.04	Ductility values based on approx. theoretical approach, w/l values based on data
Two-Way Unreinforced Masonry (fully arched)	.1	.005	.15	.02	.25	.04	Ductility values based on approx. theoretical approach, w/l values based on data
One-Way Reinforced Masonry	1	.0016	5	.008	20	.032	Ductility values assumed same as one-way R/C slab
Two-Way Reinforced Masonry	1	.0016	5	.008	20	.032	Ductility values assumed same as two-way R/C slab
Masonry Pilasters	1	.0006	5	.021	20	.012	Ductility values assumed same as R/C beams
Wood Stud Walls	.5	.01	1	.021	2	.043	Ductility values based on data
Wood Roofs	.5	.01	1	.016	2	.043	Ductility values based on data
Wood Beams	.5	.008	1	.021	2	.032	Ductility values assumed same as wood walls/roof
Wood Exterior Columns (bending)	.5	.01	1	.021	2	.043	Ductility values assumed same s wood walls/roof
Wood Interior Columns (buckling)	--	--	--	--	1	0.21	Ductility values apply only to impulsive response and are assumed

General Notes

1. All w/l values are derived from ductility values using an assumed ratio of yield capacity and stiffness for a "typical" component.
2. All values in this table are intended to correlate as well as possible to damage observed in test data and therefore will not always correlate with design criteria
3. P-i diagrams for tension membrane response cannot be correlated with ductility ratios for flexural response.

Validation of Component Damage Prediction Procedures With Available Data

Considerable effort has been expended in gathering data from tests where structural components have been subjected to well-characterized blast loading and the response and structural characteristics were measured and reported. The available data was used to calculate the two nondimensional parameters ($pbar$ and $ibar$) on the component P-i diagrams, and then the corresponding point was plotted on the diagram (these points are termed "data points") so that the actual response or damage could be compared to the damage level indicated on the P-i diagram. In some cases, the data "validated" the diagrams in the sense that assumed damage regions on the P-i diagrams predicted damage which matched that observed in the test. In other cases, the ductility ratios defining the upper and lower bounds of the damage curves were modified to cause the damage regions on the P-i diagrams to match the data more closely.

The available test data included a significant number of cases where nonflexural (i.e., tensile membrane and arching) response occurred. Since these types of responses are important for many types of building components that can be subjected to blast loads, approximate procedures were used to modify the P-i diagrams to account for these types of nonflexural response. In the case of beams with tensile membrane response, the damage curves corresponding to flexural response were just "shifted" to match the data as well as possible. This shift can be interpreted as an approximate attempt to account for the increased resistance of these nonflexural response modes. In cases of concrete and masonry components responding in compression membrane response, or arching, theoretical P-i diagrams were constructed using SDOF analyses which considered additional resistance from compression membrane response. However, the $pbar$ and $ibar$ parameters on these P-i diagrams were not modified to include applicable compression membrane response terms, and therefore the results from the SDOF analyses are not properly normalized by these terms and the P-i diagrams are not applicable in a fully general sense.

Figures 3 through 10 show data points plotted on P-i diagrams used in the FACEDAP program to predict damage for a number of components. The data points are labeled with the observed damage level so that they can be compared with that predicted by the P-i diagrams. In most cases, the observed damage levels were directly reported by the experimenters. However, in some cases, the maximum observed deflection was reported. In these cases, the observed damage levels were determined by calculating the ductility ratio from the reported component deflection and geometry and assigning the observed damage level based on the criteria in Table 2. Therefore, they do not validate the damage level predictions themselves, but they do show how well the P-i diagrams predict measured response levels. The comparison between the P-i diagrams and data from explosive tests on structural components is discussed in more detail in Reference 1. For those components where explosive test data was not available, P-i diagrams were determined using engineering judgment and criteria in References 7 and 9 to establish the ductility levels of the response curves bounding each damage level.

Consideration of Cascading Damage to Components

After all component damage has been determined on a component-by-component basis using the P-i diagrams, the FACEDAP program considers cascading or secondary component damage based on component "dependencies." The dependencies of each component are the list of other components which support the given component. The user can input this list for each component or use default "rules" coded into the program to automatically generate the dependency lists¹. After automatic generation, default dependencies can be modified as necessary by the user. Some components, such as columns, are only supporting components and therefore have no dependencies. The damage level of all supported components is set to 100 percent damage by the program if a supporting component in the dependency list is damaged at the 100 percent damage level by the applied blast. This is based on the simple reasoning that 100 percent damage to a supporting component prevents it from providing the assumed support and this causes the supported component damage to also sustain 100 percent damage.

Building Damage Calculation

After all component damage has been calculated, including that occurring during cascading failure, the overall building damage is calculated with a summation procedure which takes into account the damage calculated for each building component. Different types of overall building damage are calculated in the FACEDAP program with four parameters: the percentage of building damage, the building component replacement factor, the building reusability factor, and the building level of protection.

The percentage of building damage is a weighted average of the damage to the building components. In the first step of the calculation process, the damage level of each component in the decimal form (e.g., the 30 percent damage level is considered as 0.3) is multiplied by a user-defined component weighting factor. This product is the weighted component damage level. A weighting factor is assigned to each building component by the user in order to cause blast damage occurring in major building components to influence the calculated building damage parameters more than an equal level of damage to minor components. For example, a scheme which is commonly used assigns a weighting factor of 1.0 to cladding components; a factor of 2.0 to stringers, girts, and other secondary beams which support cladding components; a factor of 3.0 to primary beams and girders; and a factor of 4.0 to columns. In the second step of the procedure, the weighted damage levels of all the building components are summed and this sum is divided by the weighted number of components (each component is multiplied by its weighting factor and summed) to get an average component damage level. This ratio is multiplied by 100 to obtain the percentage of building damage.

The building component replacement factor is calculated in a similar manner except that a component replacement factor, equal to either 0.0 (no replacement required) or 1.0 (replacement required), is used in the component summation rather than the component damage level. The component replacement factor is based on the component damage level

and the component type so that a lightweight component, such as metal panel, may have a replacement factor of 1.0 at 30 percent damage and above, while a heavier component, such as a steel column, may have a replacement factor of 1.0 only at 60 percent damage and above. The building reusability factor is an approximate value intended to provide information on the amount of reusable floor space in a wartime or extreme situation. It is simply the unweighted percentage of building components with less than 100 percent damage. Finally, the building level of protection (LOP) is a factor based on a correlation between U.S. Army COE level of protection criteria and the four component damage levels⁵. The building LOP is equal to the lowest calculated component LOP based on the assumption that the building only provides a level of protection equal to that of its most vulnerable component.

Limitations of FACEDAP Program

The response of an entire building to blast loading is a complex process that can only be determined quickly if it is based on a number of simplifying assumptions. Because it incorporates such simplifying assumptions, the FACEDAP program is a preliminary assessment tool which is not intended for use during final design or analysis. This section discusses limitations introduced by assumptions in the FACEDAP code so that engineers can interpret or understand FACEDAP results in a fuller sense and they can understand modifications to the program that will be required to obtain a more accurate procedure.

1. The P-i diagrams in the FACEDAP procedure analyze each component as a separate, independent, SDOF dynamic system. Therefore, the dynamic interaction which can occur between primary structural members and the secondary members they support is not explicitly accounted for. Also blast loads on primary members must be simplistically represented in terms of the directly applied blast load multiplied by a user-input loaded width. In reality, the maximum blast load on primary members is heavily influenced by the dynamic response characteristics of supported members (particularly the yield load of the supported component). It is almost always much less severe than that calculated based on the typical assumption of a loaded width based on the full supported tributary area. Some usage of the program has shown that this is probably the most significant limitation of the program in that it can cause over-conservative calculation of damage to primary structural components¹⁰. It is probable that further research can identify simple procedures which define more representative loading on primary members using the structural information already input into the code for secondary building members.

2. The reduced damage which occurs when a component responds in tension membrane or compression membrane response is accounted for in several P-i diagrams. These diagrams are identical to those used to predict flexural response except that the damage curve locations have been modified to account for the additional energy absorbed in tension or compression membrane response. However, the $pbar$ and $ibar$ terms, which are a basic part of P-i diagrams, have not been re-derived to include structural response parameters which account for the additional resistance from tension or compression membrane response. Therefore, these "modified" P-i diagrams are not generally applicable for predicting damage to components undergoing tension or compression membrane response with sectional properties

significantly different than those used to develop these P-i programs. In the case of tension membrane response of steel members, the P-i diagrams were shifted to match data from light cold-formed girts and purlins. In the case of compression membrane response of concrete and masonry members, the P-i diagrams were formulated using thin panels with span/thickness ratios of 33 (concrete) and 10 to 20 (masonry).

3. The blast pressure and impulse are calculated in a simplified manner which idealizes the applied blast load as either fully reflected or free-field. This is generally conservative except for components which are subjected to reflected blast pressures at angles of incidence between 45 degrees and 70 degrees. In this case, the nonconservatism in the simplified FACEDAP blast load calculation procedure is a factor between 2 and 5 for the peak pressure, and a factor between 1.5 and 2.5 for the impulse compared to more accurate methods in Reference 7. The peak blast pressure can be overconservatively calculated (conservative by a factor between 2 and 4) on components in sidewalls and roofs with spans parallel to the direction of shock wave propagation because the simplified procedure does not consider the reduction in effective peak pressure that occurs when the shock wavelength is less than the span length. The amount of nonconservatism caused by ignoring the effect of the negative phase blast pressure on the damage of light building components (building components with an ultimate resistance less than 2 psi) when it is in-phase with the component response is unknown.

4. Damage caused by flexural shear response, torsional response, and localized breaching or spalling is not predicted by the FACEDAP program. The recommended minimum scaled standoff of $3.0 \text{ ft/lb}^{1/3}$ between the explosive charge and the closest building component is intended to prevent the use of the program in situations where localized damage and highly nonuniform blast pressure distributions can occur on the building components. Also, no combined beam-column response is considered in the FACEDAP methodology and damage to windows and doors is not considered.

5. The building damage assessment procedure in the FACEDAP program has not been compared against overall blast damage to buildings except for one case¹¹ where very little information was available about the buildings damaged by blast. Therefore, the cascading failure procedure and building damage summation procedures have not been well validated against data. Also, the P-i diagrams which predict component blast damage for a number of component types have not been compared against measured blast damage.

Summary and Conclusions

The FACEDAP program is a flexible, well-documented, easy-to-use program for determining structural blast damage to buildings. The program is based on a component-by-component analysis of the building which allows the user to view the damage to each component, as well as the overall building damage, and thus develop an overall understanding of the building response. The program can be used to analyze buildings very quickly by using existing default input decks which describe an applicable generic building, or these default input decks can be modified to reflect any significant differences from the generic building. New

buildings can also be input, analyzed, and stored in input decks using user-friendly features of the preprocessor. Finally, single component blast damage (i.e., damage to a single, important component in a building) can also be calculated quickly using this option in the program.

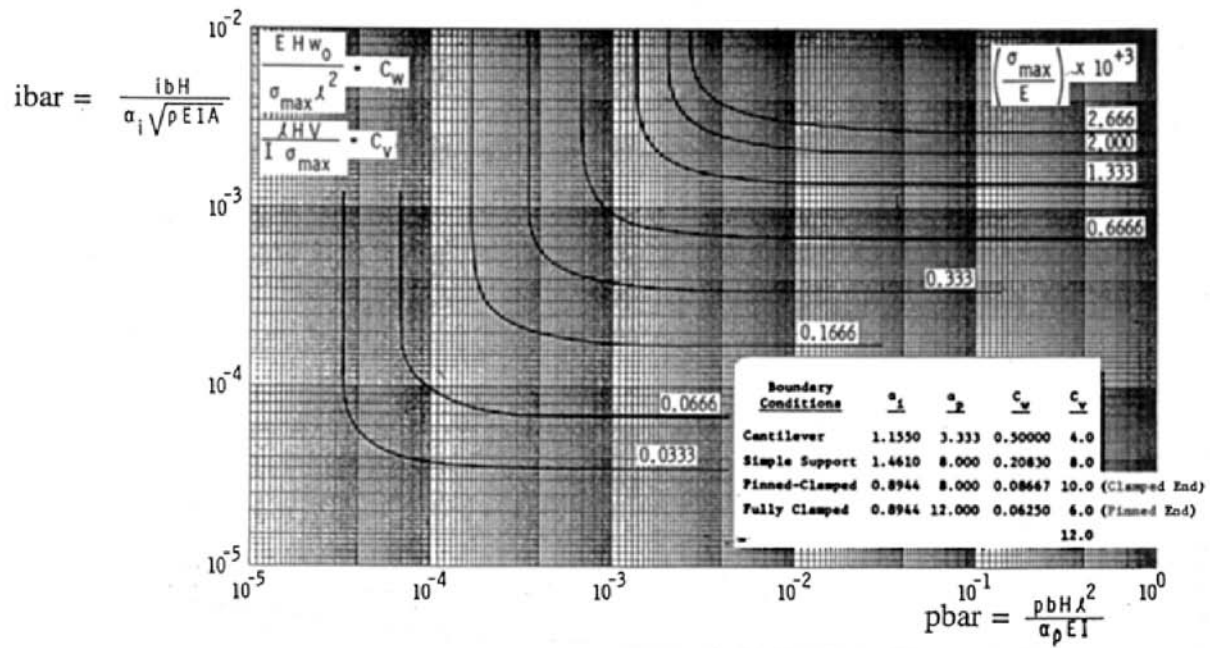
The general procedure used to calculate building damage is discussed in this paper along with comparisons between this procedure and measured building component damage. Also, simplifying assumptions used in the program, and limitations due to these assumptions, are discussed. An assessment of the overall accuracy of the program is limited by the lack of well characterized data on the response of buildings to blast pressures. The simplifying assumptions used in the program are generally consistent with the goal of the program, which is to provide an approximate analysis procedure which can quickly estimate the overall building blast damage. However, additional work could be very effective at improving the accuracy of the procedure, particularly the manner in which loads on primary frame members are calculated.

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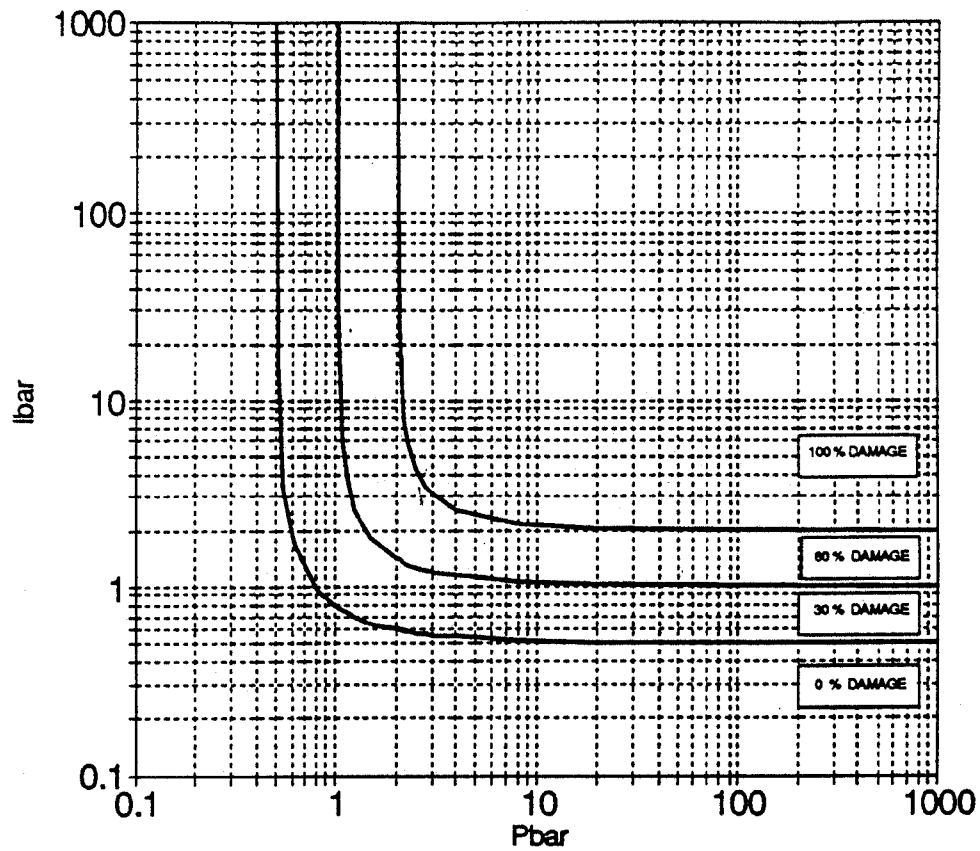
Figure 1. P-i Diagram Showing Maximum Elastic Strain for a Beam Responding in Flexure



H = Beam depth
 I = Span length
 b = Loaded width
 E = Modulus of elasticity
 I = Moment of inertia
 $\sigma_{\max}$ = Maximum stress
 p = Peak blast pressure
 i = Positive phase blast impulse
 A = Cross sectional area
 ρ = Mass density
 V = Maximum shear
 w_0 = Maximum deflection

Figure 1. P-i Diagram Showing Maximum Elastic Strain for a Beam Responding in Flexure

Figure 2. P-i Diagram Showing Damage Levels of Wood Beams Responding in Flexure



$$I_{bar} = \frac{i b_1 h}{\alpha_1 f_y} \sqrt{\frac{E L g}{W I}}$$

$$P_{bar} = \frac{p b_1 h L^2}{\alpha_p I f_y}$$

Boundary Conditions	α_1	α_p
Simple-Simple	1.4610	8.0
Fixed-Fixed	0.8944	12.0

Figure 2. P-i Diagram Showing Damage Levels of Wood Beams Responding in Flexure

Figure 3. Comparison of Damage Data from Wood Components on Blast Loaded Houses to P-i Diagram for Wood Components Responding in Flexure

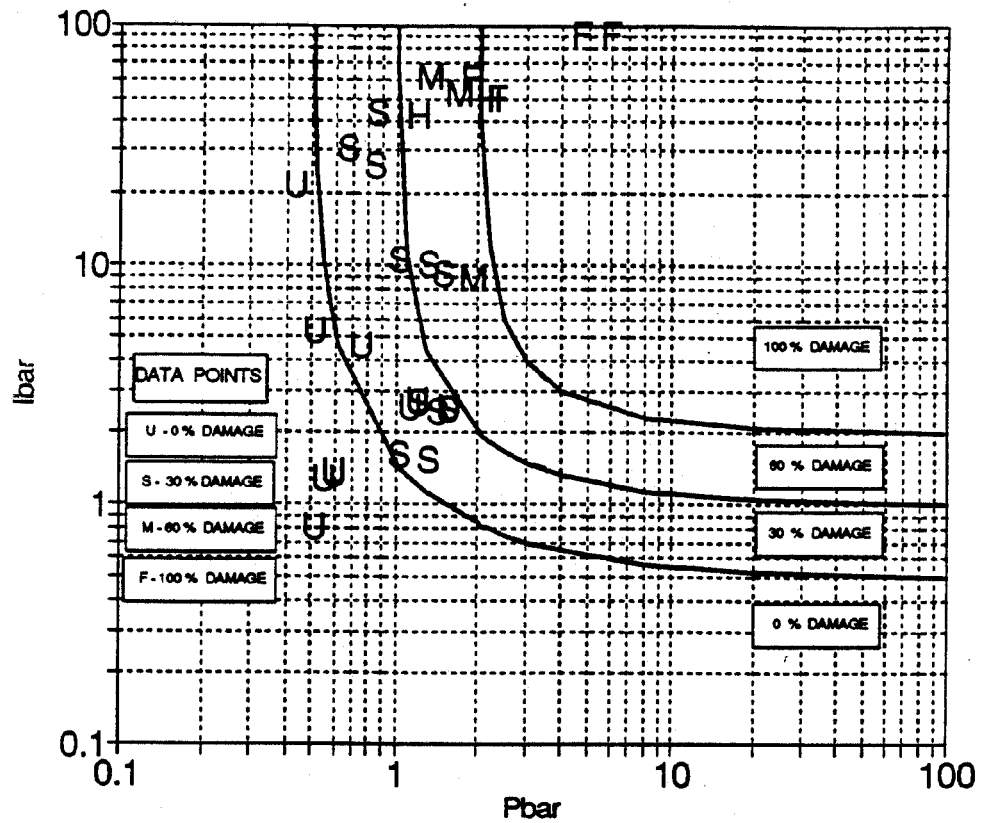


Figure 3. Comparison of Damage Data from Wood Components on Blast Loaded Houses to P-i Diagrams for Wood Components Responding in Flexure

Figure 4. Comparison of Data from Blast Loaded Corrugated Metal Panels to Theoretical P-i Curve for Elastic Plastic Beams Responding in Flexure

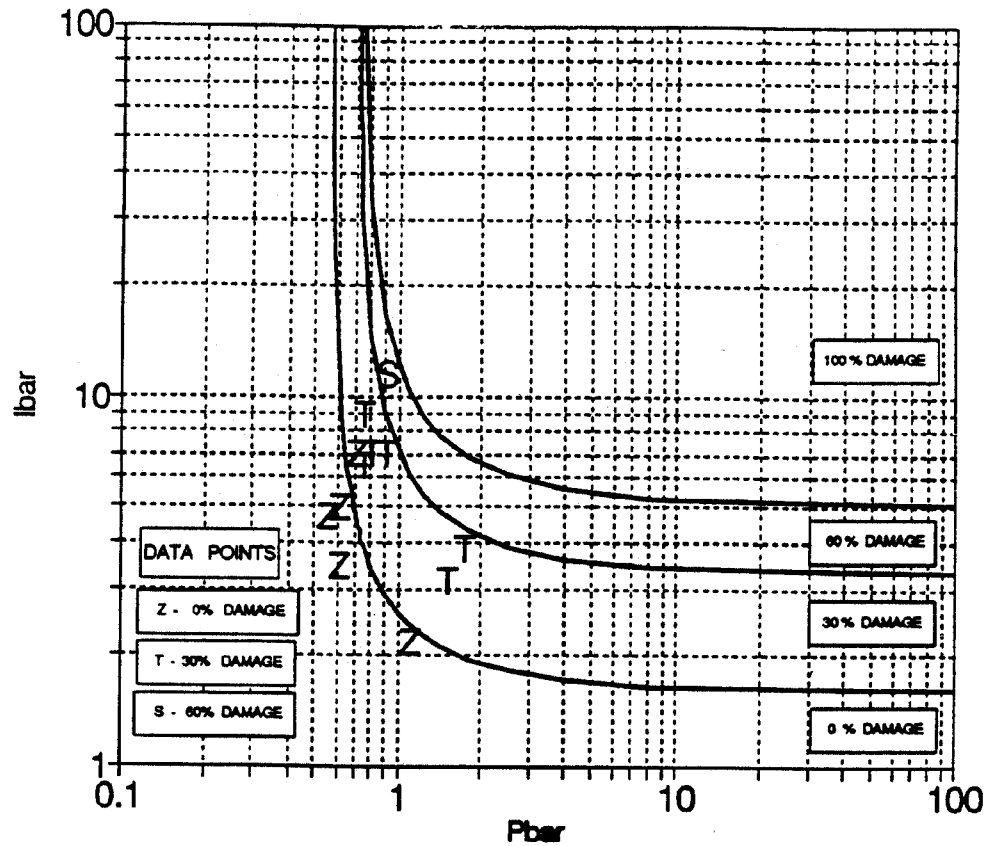


Figure 4. Comparison of Data from Blast Loaded Corrugated Metal Panels to Theoretical P-i Curve for Elastic Plastic Beams Responding in Flexure

Figure 5. Comparison of Damage Data from Steel Girts Responding in Tension Membrane with Shifted Damage Curves P-i Diagram

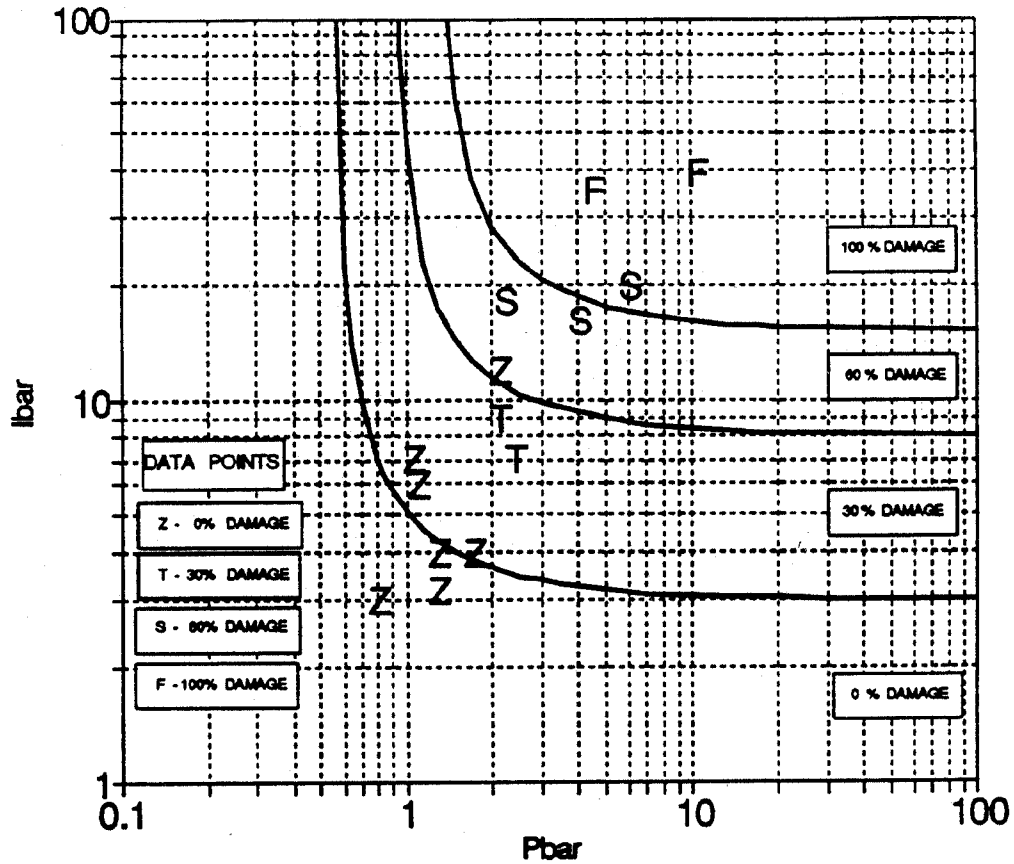


Figure 5. Comparison of Damage Data from Steel Girts Responding in Tension Membrane with Shifted Damage Curves on P-i Diagram

Figure 6. Comparison of Damage Data from Blast Loaded Steel Frames to P-i Diagram for Steel Frames

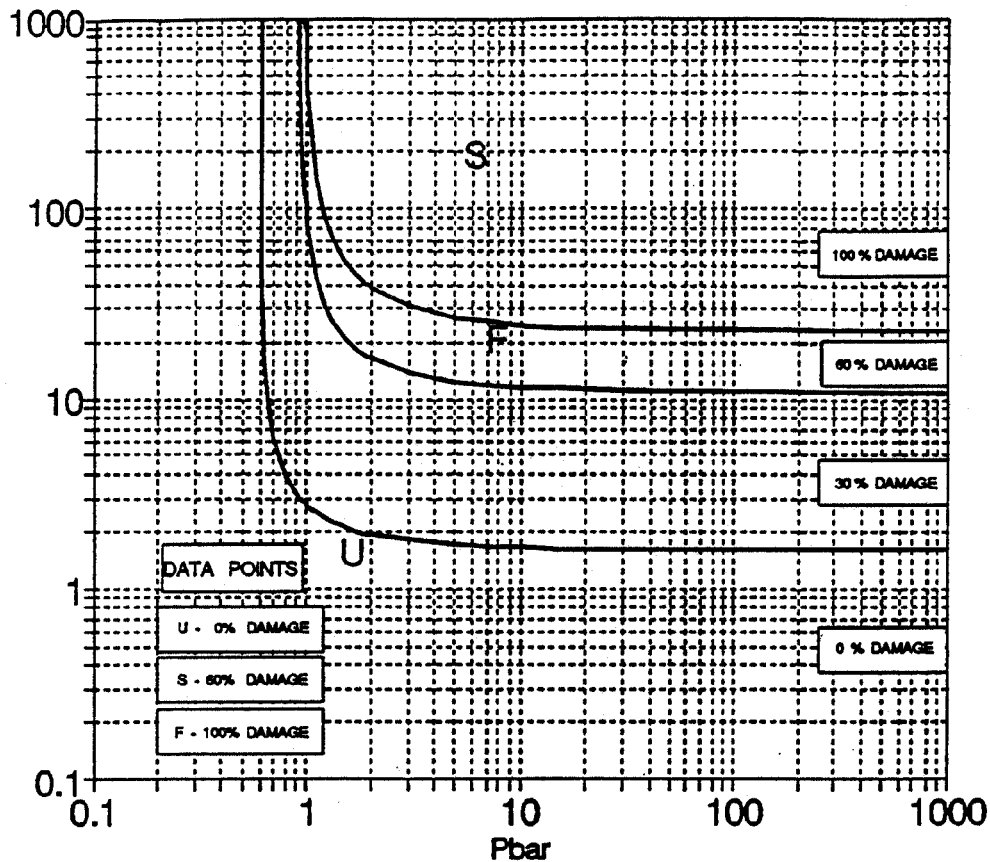
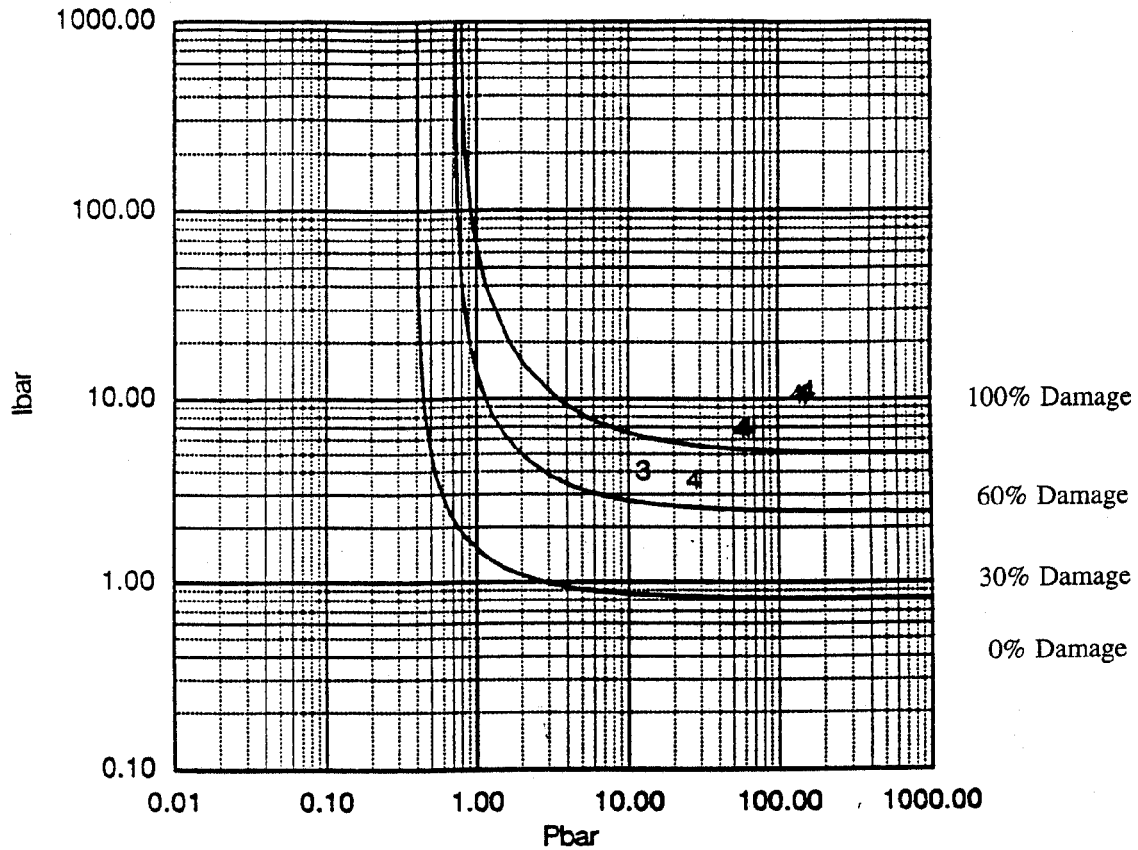


Figure 6. Comparison of Damage Data from Blast Loaded Steel Frames to P-i Diagram for Steel Frames

Figure 7. Comparison of Damage Data from Blast Loaded Reinforced Concrete Slabs to Theoretical P-i Diagram for Elastic-Plastic Slabs Responding in Flexure

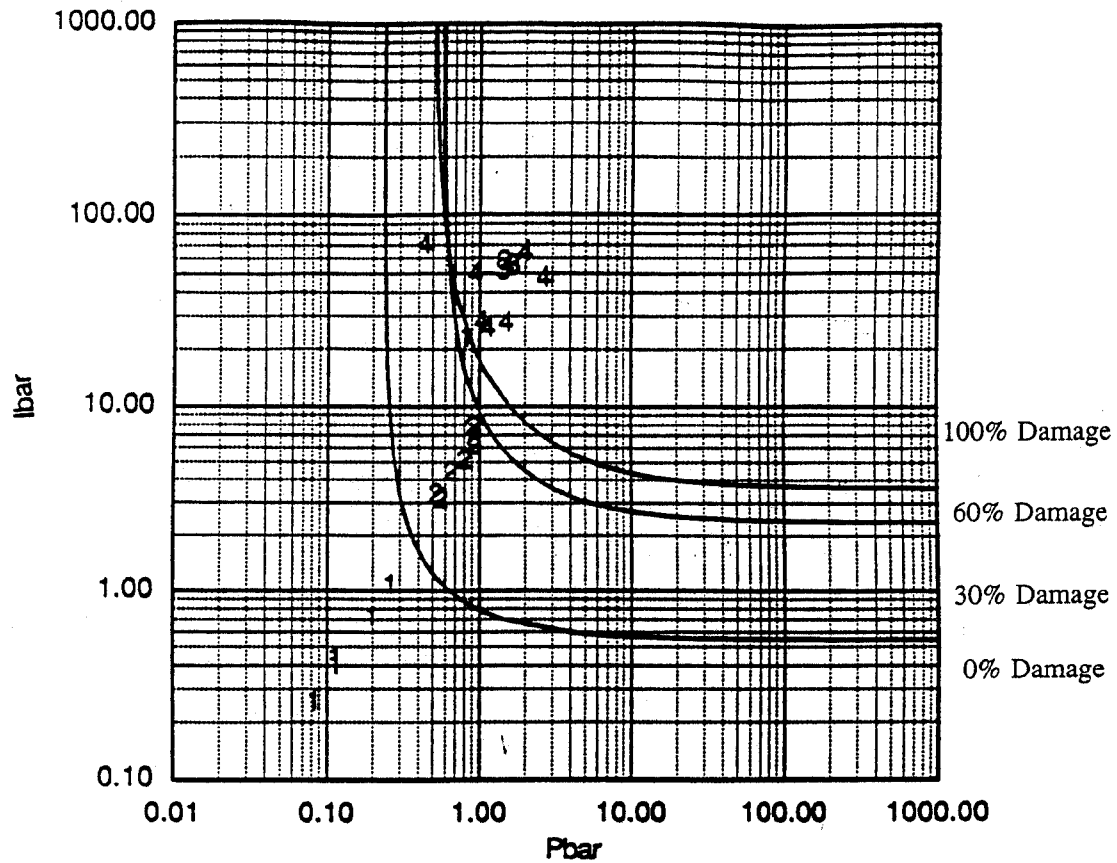


Observed Damage Levels

- 3 - Severe Damage (large deformations, just prior to collapse)
- 4 - Failure (structural collapse)

Figure 7. Comparison of Damage Data from Blast Loaded Reinforced Concrete Slabs to Theoretical P-i Diagram for Elastic-Plastic Slabs Responding in Flexure

Figure 8. Comparison of Damage Data from Blast Loaded Reinforced Concrete Two-Way Slabs with Arching to the P-i Diagram for this Component

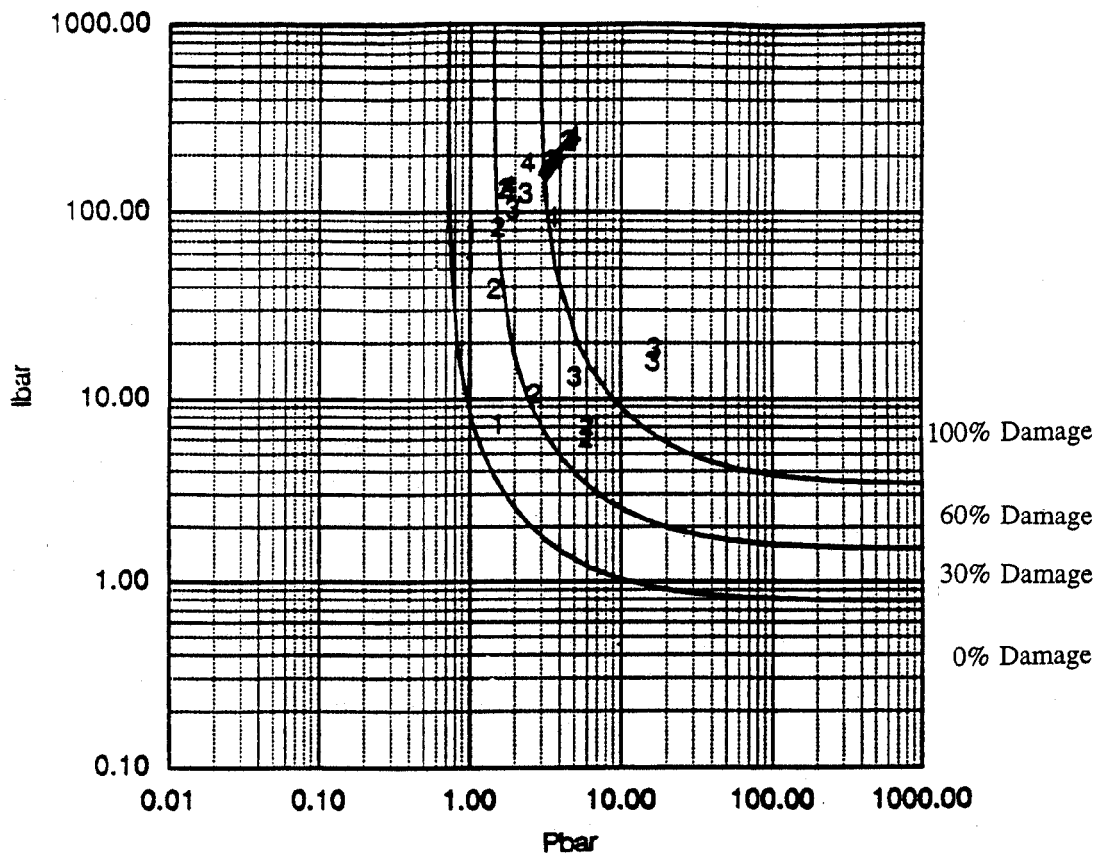


Observed Damage Levels

- 1 - Minimal Damage (little or no cracking)
- 2 - Moderate Damage (major cracking)
- 3 - Severe Damage (large deformations, just prior to collapse)
- 4 - Failure (structural collapse)

Figure 8. Comparison of Damage Data from Blast Loaded Reinforced Concrete Two-Way Slabs with Arching to the P-i Diagram for this Component

Figure 9. Comparison of Damage Data from Blast Loaded Unreinforced One-Way Masonry Walls with Arching to the P-i Diagram for this Component

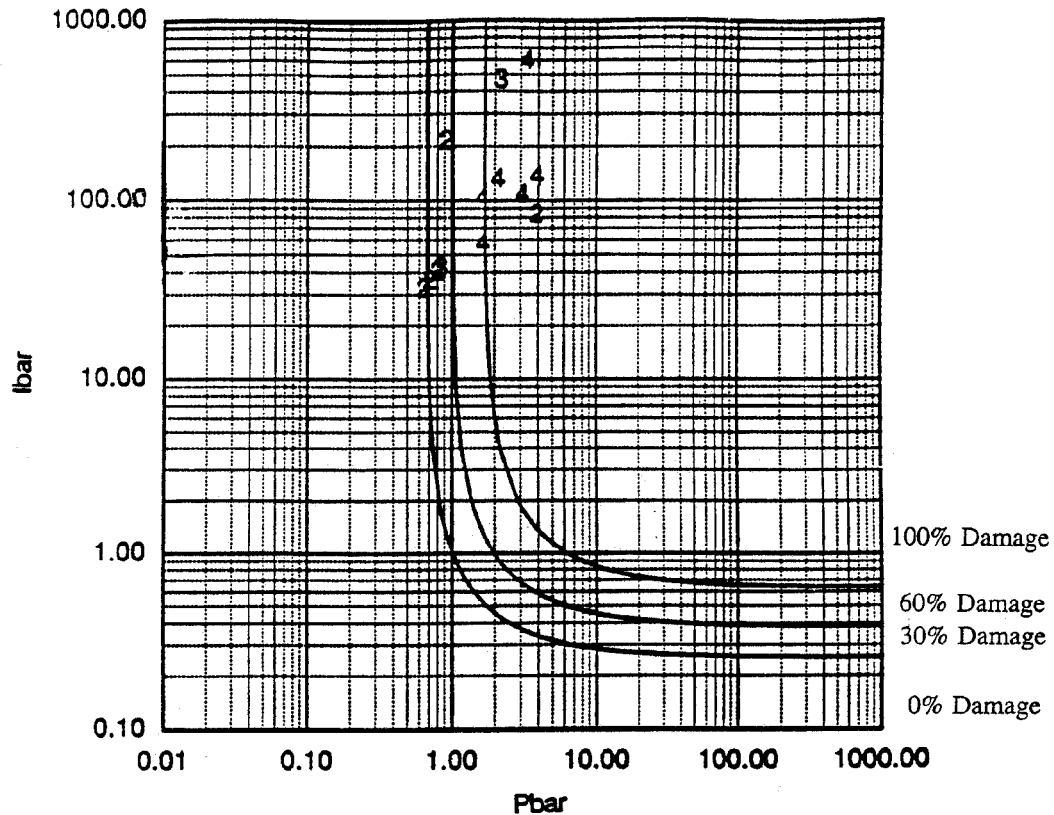


Observed Damage Levels

- 1 - Minimal Damage (little or no cracking)
- 2 - Moderate Damage (major cracking)
- 3 - Severe Damage (large deformations, just prior to collapse)
- 4 - Failure (structural collapse)

Figure 9. Comparison of Damage Data from Blast Loaded Unreinforced One-Way Masonry Walls with Arching to the P-i Diagram for this Component

Figure 10. Comparison of Damage Data from Blast Loaded Unreinforced Two-Way Masonry Walls with Arching to the P-i Diagram for this Component



Observed Damage Levels

- 1 - Minimal Damage (little or no cracking)
- 2 - Moderate Damage (major cracking)
- 3 - Severe Damage (large deformations, just prior to collapse)
- 4 - Failure (structural collapse)

Figure 10. Comparison of Damage Data from Blast Loaded Unreinforced Two-Way Masonry Walls with Arching to the P-i Diagram for this Component