

CONCRETE AND BLAST EFFECTS

Editor
William Bounds



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Concrete and Blast Effects

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PREFACE

This publication contains papers presented at several technical sessions sponsored by ACI Committee 370, Short Duration Dynamic and Vibratory Load Effects. All of the papers included in this publication concern blast-resistant design, the major subject of the committee's work. Committee 370 was established to address the general area of short duration dynamic and vibratory load effects, to evaluate existing knowledge, and to propose related recommendations for the design of structural concrete. Short durations were defined as durations being shorter than seismic loads, including such occurrences as blast and impact. The committee has sponsored a number of technical sessions at ACI conventions and addresses such issues as the standardization of test procedures, the interpretation of laboratory results, and the development of design criteria. Committee membership includes individuals with a broad range of engineering backgrounds including design, government and academic interests. The committee actively seeks input and participation from interested individuals.

The field of blast-resistant design is currently of great interest to a diverse variety of individuals and organizations. Accordingly, the papers describe a range of applications for this seemingly narrow area of structural engineering: design to resist or discourage terrorism against civilian and governmental buildings, design to eliminate or minimize destruction from industrial accidents, and design to protect military facilities. To assist the reader in focusing on a particular level of interest, the papers have been grouped into three sections. Section One; Design Aspects, relates directly to the design process. Section Two; Current Procedures and Recent Developments, provides an overall viewpoint. Section Three; Theoretical Developments, focuses on research issues. Each of the papers in this publication was reviewed and approved through established ACI procedures.

Finally, two individuals are to be recognized for their work in compiling this publication. Eve Hinman originated the work on this publication and brought together many of the early development concepts. Theodor Krauthammer, until recently, was the chairman of ACI Committee 370 and provided assistance leading to its final development.

William Bounds
Editor

Stanley Woodson
Chairman, ACI Committee 370

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Section 1: Design Aspects

Approach for Designing Civilian Structures Against Terrorist Attack

by Eve Hinman

Abstract: Hardening structures against weapons effects has been, until recently, of concern almost exclusively of the military. However, with the increase of terrorist activities directed against civilian targets, there is a growing interest in applying these principles to the design of non-military structures. A design approach is presented for civilian structures subject to an external explosion. The issues addressed are threat assessment, countermeasures, weapons effects, analytical techniques, and optimization techniques used.

Introduction

In military terminology, terrorism is considered low-grade warfare. As such, many of the principles used to design military targets are applicable to the protective design of civilian targets subject to terrorist attack. However, the objectives of design are different for civilian targets. For military facilities the primary objective is to maintain function after attack. 'Function' refers to essential activities such as launching a missile or maintaining communications or intelligence. For civilian facilities the primary objective is to save lives while preserving the non-military character of the facility; maintaining function becomes a secondary issue.

Because of this difference, protective design principles need to be reevaluated. In this paper the fundamental principles of military facility design are used to develop a rational approach to the design of new civilian structures. These ideas are also applicable to the retrofit of existing structures.

This paper is partially based on work done for the Foreign Buildings Office of the US Department of State in developing engineering guidelines for protecting US embassies abroad.

Threat and Countermeasures

There are many possible threats to be considered in the design of civilian structures (Fig. 1). Some threats are excluded, such as aerial attack or nuclear attack because they are impractical to design for. Other threats are not

Keywords: blast resistant construction; explosions; optimization

considered here because they do not cause structural damage, such as chemical/biological contaminants.

The most serious threat against a civilian structure in the recent past has been the "car-bomb", i.e., a large external explosion. If the facility is able to resist this threat, it should be able to withstand (with minor modifications) many of the other threats shown in Fig. 1.

The designer needs to be concerned with four broad groups of countermeasures: "deterrence," "keep-out," "deception," and "hardening." These terms are listed in order of decreasing effectiveness. "Deterrence" refers to the perceived protection level of the facility. If effective, the facility will not be selected as a target because it presents more obstacles than the intruder is willing to overcome. If deterrence is not effective, then the next tier of protection is "keep-out." This refers to devices such as fences, walls, etc., which prevent the intruder from reaching the target or at least delay him until outside help arrives. If the "keep-out" measures are overcome, then the attacker is confronted by "deception." This diverts his attention from the most vulnerable or valuable part of the facility towards a more visible, less important part. If all these countermeasures are overcome, then as a last resort, the building is "hardened" to protect the occupants and contents against the effects of the explosion.

The objective of the physical security design is to maximize the protection level within the design constraints of the project. This paper focuses on the role of the engineer, however, it is important to be aware that a successful design can be achieved only if the architect, engineer, and security specialist cooperate. Also, for a cost effective design, security issues should be addressed throughout the design process -- not as an afterthought during the final design phase.

Countermeasures may be divided into active or operational, which require human intervention, and passive or physical, which do not require human intervention. Security specialists are needed to define active countermeasures which include:

- Intelligence
- Guards
- Sensors
- Search
- Surveillance
- Active Defense
- Access Control
- Rescue

Passive countermeasures (Fig. 2), which facilitate the operational measures, are the responsibility of architects and engineers. Architects are responsible for incorporating planning and functional security measures, engineers for the design the structural components to resist blast effects. A generic site plan, showing a variety of physical security measures discussed, is given in Fig. 3.

Weapons Effects

An explosion is a very rapid release of stored energy characterized by an audible blast. Part of the energy is released as thermal radiation, and part is coupled into the air (air-blast) and soil (ground-shock) as radially expanding shock waves. Air-blast is the principal damage mechanism. The shock wave propagates by compressing the air molecules in its path, producing the ambient over-pressure or incident pressure. It propagates with supersonic velocity, and when it encounters the building (see Fig. 4), it is reflected, amplifying the over-pressure by a factor of as much as twelve. The air-blast penetrates through window and door openings, subjecting floor slabs, partitions, and contents to pressure. Diffraction of the wave occurs as the shock propagates around corners, creating amplifications and reductions in pressure in these regions. Finally, the entire building is engulfed by the shock wave, subjecting all building surfaces to the over-pressure. The pressure decays exponentially in time and space and eventually becomes negative (negative loading phase), subjecting the building surfaces to suction forces.

A secondary effect of the air-blast is dynamic pressure or drag loading, which is a very high velocity wind. It propels the debris generated by the air-blast, creating secondary projectiles. Also, the building is subject to the ground-shock, which produces ground motions somewhat similar to a high intensity, short duration earthquake.

All air-blast phenomena take place in very short time intervals, measured in milliseconds. Also, initial peak pressure intensity may be several orders of magnitude higher than the typical live loads. The magnitude of the pressure, P , is roughly proportional to the amount of explosive used, W , and inversely proportional to the cube of the distance from the center of gravity of the charge, R :

$$P \propto \frac{W}{R^3} \quad (1)$$

e.g., if the range is doubled, the peak intensity is decreased by a factor of eight. In relation (1), the amount of explosive, W , is called the yield or charge weight, measured in equivalent lbs. of TNT. Typical car bomb yield ranges from 200 to

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12000 lbs. As a comparison, it is worth noting that the usual aerial bombs used to attack military targets have yields ranging from 500 to 2000 lbs. (see Fig. 5).

In addition to over-pressure and reflected pressure there are some other important blast parameters -- such as the time of arrival of the shock wave, shock velocity, duration, and impulse. There are tables for determining these parameters for a given yield and range [1]. These tables are not directly applicable to buildings which have complicated architectural features and cause significant wave diffractions.

Ground-shock loads may be determined using Ref. 3. Internal pressure may be determined using the charts provided by Luwa [5]. An analytical description of the internal loading phenomena is given in Ref. 2.

The response of a building to a large explosion occurs in distinct phases (Fig. 6). Initially, as the blast wave contacts the nearest exterior wall of the building, windows are shattered, and the walls and columns deflect under the reflected pressure (Fig. 6a). As the blast wave expands and diffracts around the building, it exerts an over-pressure on the roof, side walls and, finally, on the walls of the far side. Although the pressure levels on the three sides facing away from the blast are smaller than those on the front, they are significant. It must be remembered that because the location of the explosion cannot be anticipated, each building face must be designed for the worst case, i.e., an explosion normal to that face.

The internal pressure which penetrates through openings, exerts a downward and upward pressure on the floor slabs (Fig. 6b). The upward pressure is important because columns and slabs are not ordinarily designed for such loads. This pressure may also cause injury to lungs and blood vessels. Occupants may also be injured by glass fragments and other debris. Internal pressure may be reduced by decreasing the size and number of openings or by using blast resistant glazings and doors.

Finally, the frame responds to the loads induced by an explosion (Fig. 6c) as the inertia of the building becomes mobilized. The side sway experienced by the building is similar to what might be expected due to a short duration, high intensity earthquake.

Structural Design Issues

It is usually impractical to design a civilian structure to resist large explosions so that it remains intact. A realistic objective is to protect the occupants, contents, and essential functions. After an explosion we require only that the

structure is still standing in order to permit rescue of occupants, removal of contents, and maintenance of emergency functions. We accept that the structure may be heavily damaged and in need of substantial repairs.

The structural design must assume that the plans are in agreement with requirements of the active and passive countermeasures. Major structural components have the characteristics described below.

Exterior Walls: These are usually constructed of reinforced concrete with two-way reinforcing on both faces and ties at bar intersections. Breaching due to ballistic attack or contact charges must also be considered. Special reinforcing and anchors are provided around blast resistant window and door frames. Masonry walls may be inadequate.

Exterior Columns: These are designed to resist the reflected pressure including the load transmitted by the wall. The reinforcing must provide for: elastic rebound, tension induced by the upward loading on slabs, and stability.

Roof Framing: The primary loading on the roof is the downward over-pressure. Secondary loads include the suction upward during the negative loading phase and the upward pressure due to the blast which penetrates through openings.

Floor Framing: The floors are subject to the blast which penetrates through the openings. Blast pressure may act from above or below. In plane forces due to the airblast loads are also considered.

Lateral Frames: The frame responds to the total blast acting on the building and also to the ground-shock. Often the exterior concrete walls alone are sufficient to transmit the load to the foundation. Progressive collapse criteria must also be satisfied. These criteria ensure that there is redundancy in the design so that if a critical supporting element fails, it will not cause the total or partial collapse of the structure.

In the design of these elements, the blast loads are combined with the effect of dead load by using a load factor of unity. The strengths of the concrete and steel are increased by 10%-20% for strain rate effects. Also, the 1-year concrete strength is used instead of the 28-day strength. The design takes advantage of the energy absorption due to inelastic deformations.

Because of the sensitivity of air-blast to the geometry of the target, unusual building shapes become very time consuming to analyze. Diffraction modeling on large computers is costly, justified only for military structures.

Dynamic Analysis Techniques

Non-linear dynamic analysis techniques are similar to those currently used in advanced seismic analysis. Analytical models range from equivalent single-degree-of-freedom (SDOF) models to finite element (FEM) representation. In either case, numerical computation requires adequate resolution in space and time to account for the high intensity, short-duration loading, and non-linear response. The main problems are the selection of the model, the appropriate failure modes, and finally, the interpretation of the results for structural design details. Whenever possible, results are checked against data from tests and experiments on similar structures and loadings.

Components, such as beams, slabs, or walls can often be modeled by a SDOF system. The response can be found by using the charts provided by Biggs [1] and military handbooks [3,6]. For more complex elements, the engineer must resort to numerical time integration techniques. The time and cost of the analysis cannot be ignored in choosing analytical procedures. SDOF models are suitable for numerical analysis on PC's and micro-computers but the most sophisticated FEM systems (with non-linear material models and options for explicit modeling of reinforcing bars) may have to be carried out on mainframes (Fig. 7). Because the design analysis process is a sequence of iteration, the cost of analysis must be justified in terms of cost benefits to the project and increased confidence in the reliability of the results. In some cases, an SDOF approach will be used for the preliminary design and a more sophisticated approach using finite elements will be used for the final design.

Optimization Studies

The cost of protection has two components -- fixed and variable. Fixed costs are those for security hardware, space requirements, hardware maintenance and security personnel. These costs do not depend on the level of an attack, e.g., it costs the same to keep a truck away from a building whether the truck contains 500 or 5000 lbs. of TNT. Blast protection, on the other hand, is a variable cost. It depends on the threat level which is a function of the explosive charge weight and the stand-off distance. We have no control over the amount of explosives used, but we are able to keep it at a stand-off distance by providing a secured perimeter.

The optimal stand-off distance is determined by defining the cost of protection as the sum of the cost of protection (construction cost) and the cost of stand-off (land cost). In the example shown in the top graph on Fig. 8, these two costs are considered as a function of stand-off for a given explosive charge weight,

W. The cost of protection is assumed proportional to the peak pressure level, as expressed by relation (1). The cost of land is given by the square of the stand-off (R^2). The optimal stand-off is the one for which the sum of these costs is minimum.

If additional land is not available the required floor area of the building is distributed among several floors. As the number of floors is increased, the footprint decreases, providing an increased stand-off distance. Taking into account the increasing cost of the structure (due to the added floors) and the corresponding decrease in protection cost (due to added stand-off), we find the optimal number of floors for which the cost of protection is minimum.

The above methods are used for the maximum credible explosive charge. If the cost of protection for this charge weight is not within the budgetary constraints, then the charge weight must be modified. A study is conducted to determine the largest yield and corresponding level of protection which can be designed within the given budget.

If the primary objective of protection is to save contents or maintain function, we are able to provide a design solution which minimizes the cost of attack. The cost of attack consists of the cost of protection, the cost of loss, and the cost of repairs. This optimization is illustrated in the bottom curve of Fig. 8. We calculate the minimum cost of protection, as previously shown, for a range of threat levels. These minimum costs are compared with the corresponding cost of an attack for an unprotected structure. The optimal threat level is the one for which the sum of these costs is minimum.

Conclusion

The design of structures to survive the effects of an explosion requires knowledge of several disciplines (see Fig. 9). The threat and associated weapons effects need to be evaluated based on site specific vulnerability of the facility. Risk analysis is required to evaluate a reasonable level of protection and the appropriate design criteria within the budgetary and other constraints of the project. Design-analysis requires an understanding of the dynamic character of the loads and the anticipated response mechanisms, verified by test data. The end product is a balanced design achieved through an interdisciplinary approach combining the skills of the architect, engineer, and security specialist involved throughout the design process. The cost of implementing these design principles can be cost effective particularly for new buildings where it is estimated that the added cost is on the same order of magnitude as implementing seismic code requirements in the San Francisco Bay area.

References

1. Biggs, J.M., *Introduction to Structural Dynamics*, McGraw-Hill Book Company, Inc., New York, 1964.
2. Britt, J.R., and J.L. Drake, "Penetration of Short Duration Airblast into Protective Structures," *The Shock and Vibration Bulletin* 54 (Part 2 of 3 Parts), June 1984.
3. *Fundamentals of Protective Design For Conventional Weapons*, Technical Manual TM5-855-1, Headquarters, Department of the Army, Washington, D.C., November 1986.
4. Kingery, C.N., and G. Bulmash, *Airblast Parameters From TNT Spherical Air Burst and Hemispherical Surface Burst*, Technical Report ARBRL-TR-02555, US Army Armament Research and Development Center, Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, April 1984.
5. *Luwa Shelter Technology: Behavior of Blast Waves in Tunnels*, Luwa Ltd., US Office, Defense Products division, Bethesda, Maryland 20814, n.d.
6. *Structures to Resist the Effects of Accidental Explosions*, Dept. of the Army Tech. Manual, TM5-1300, Dept. of the Navy Pub., NAVFAC P-397, Dept. of the Air Force Manual, AFM 88-22, Depts. of the Army, the Navy and the Air Force, June 1969.

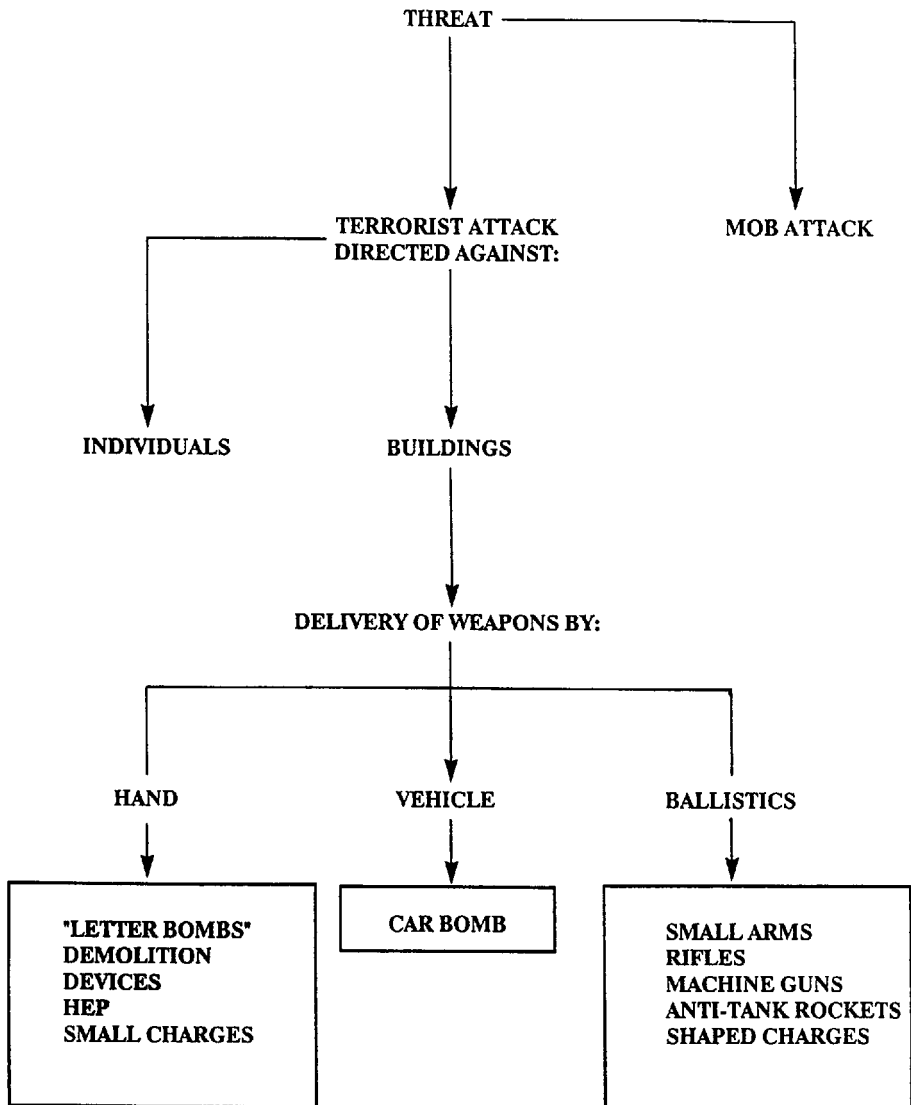


Fig. 1—Threat definition

PASSIVE COUNTERMEASURES

PERIMETER PROTECTION	Intrusion Detection Alarms Fence/Wall Bollards/Planters Street Countermeasures
ACCESS CONTROL	Vehicle Barriers/Traps Chicanes Guard House
FUNCTIONAL PLANNING	Crisis Management: Search & Rescue Evacuation & Assembly Access Control Driveway Geometry
PHYSICAL PLANNING	Fragment Mitigation Geometry Glazings Window Frames Emergency Equipment
HARDENING	Walls Columns Floors Frame Roof

Fig. 2—Passive countermeasures



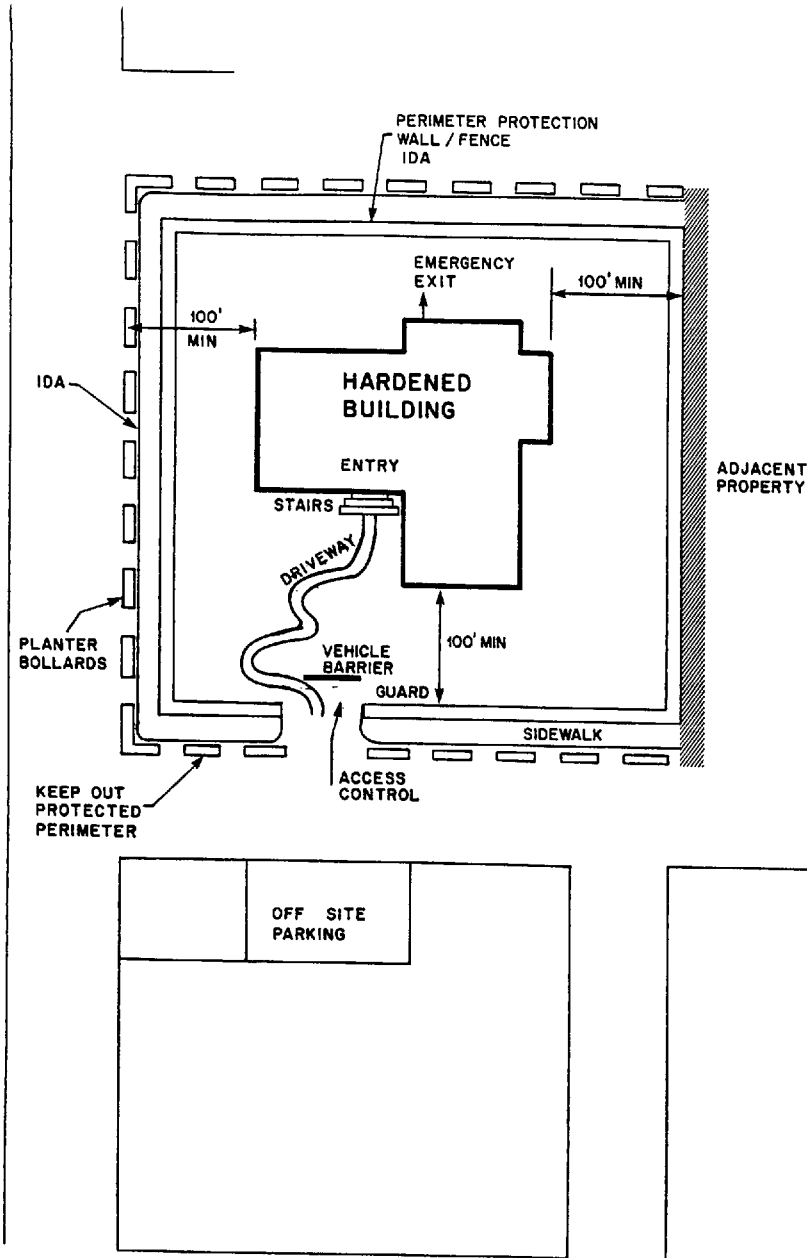


Fig. 3—Implementation of physical security and protective construction measures

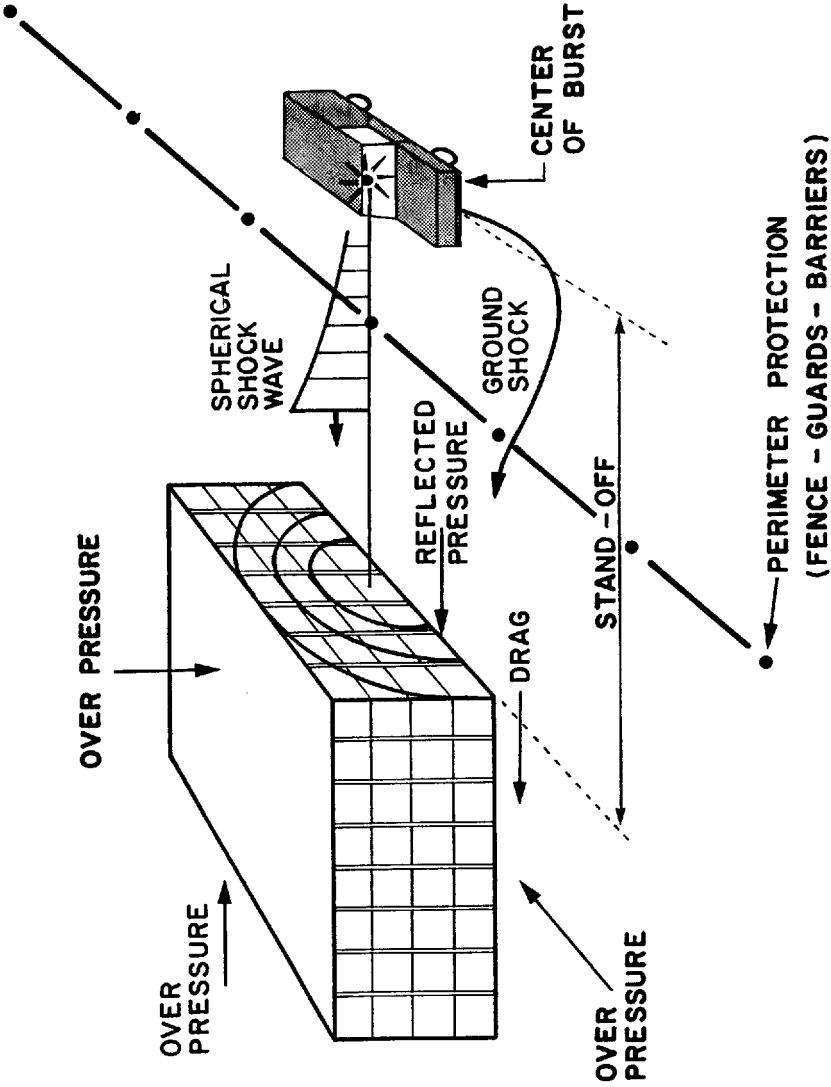


Fig. 4—Blast loads on a building

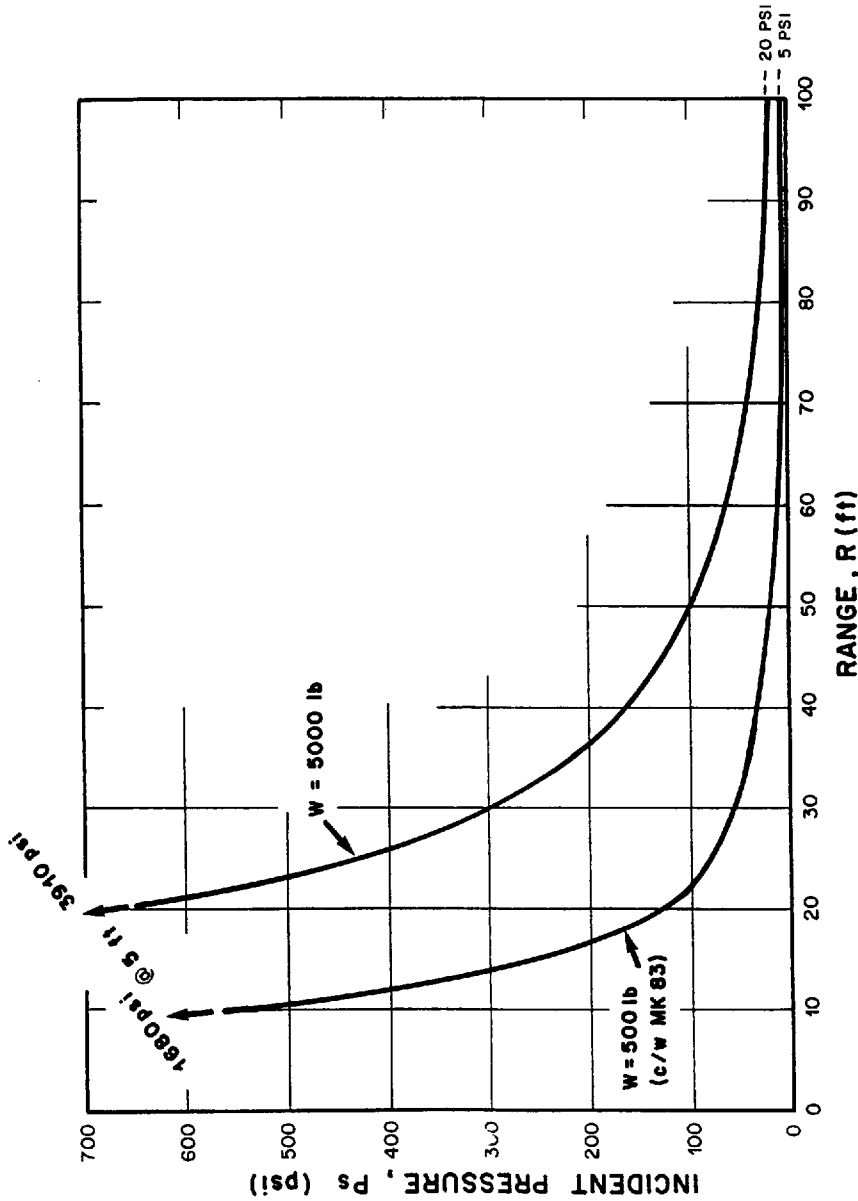


Fig. 5—Incident pressure versus range

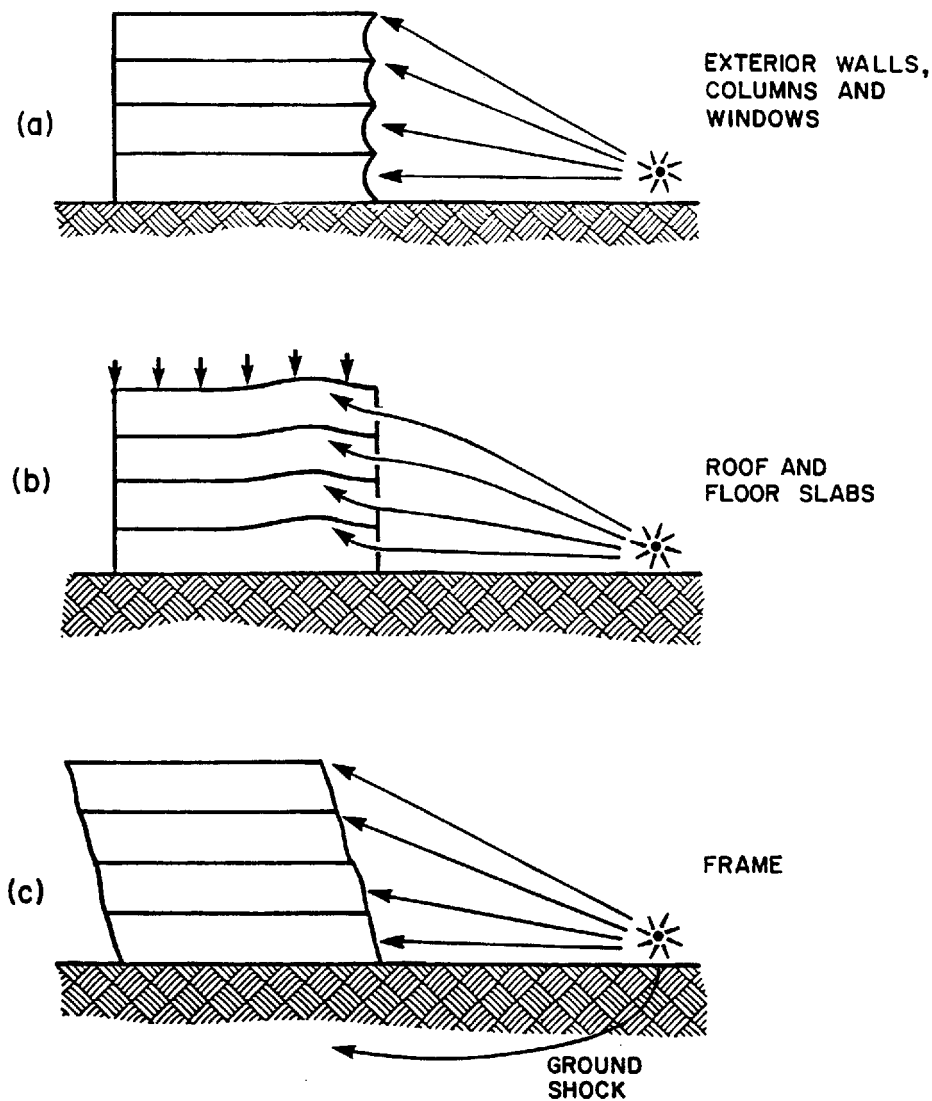


Fig. 6—Sequence of air blast response

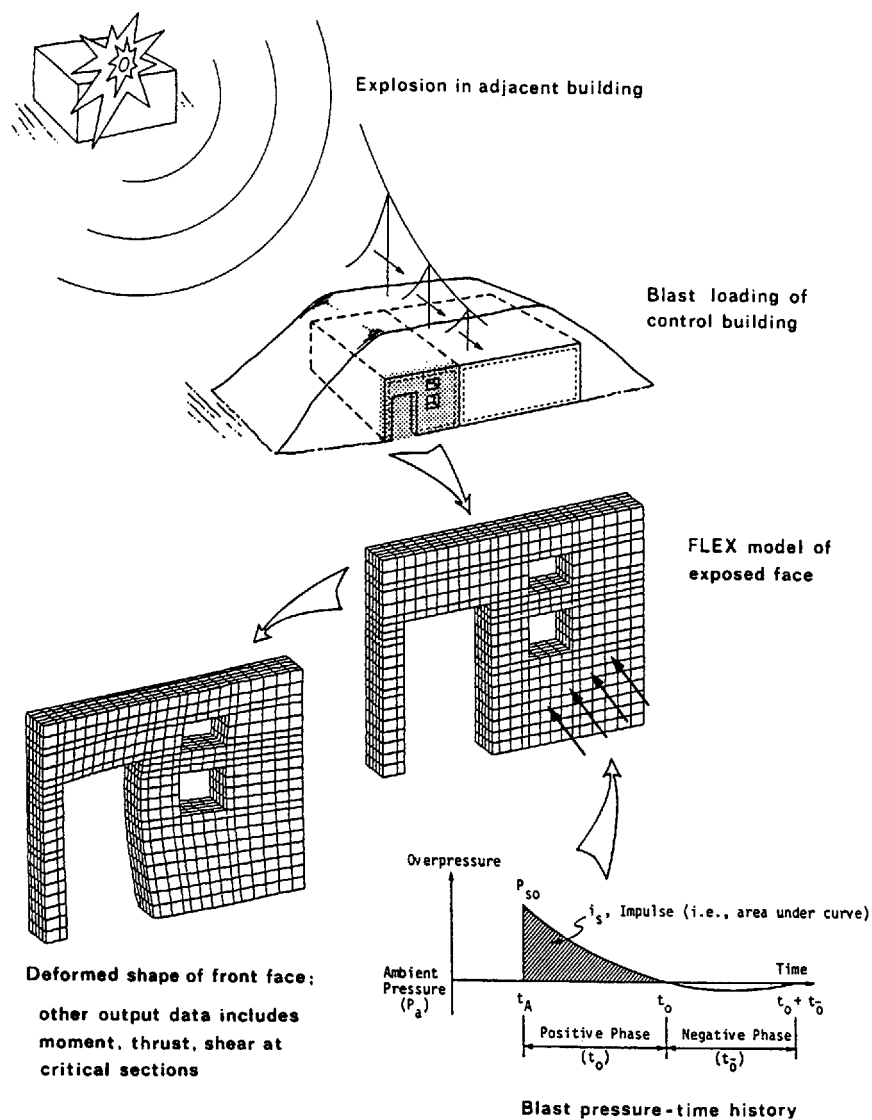


Fig. 7—Nonlinear analysis of structural response

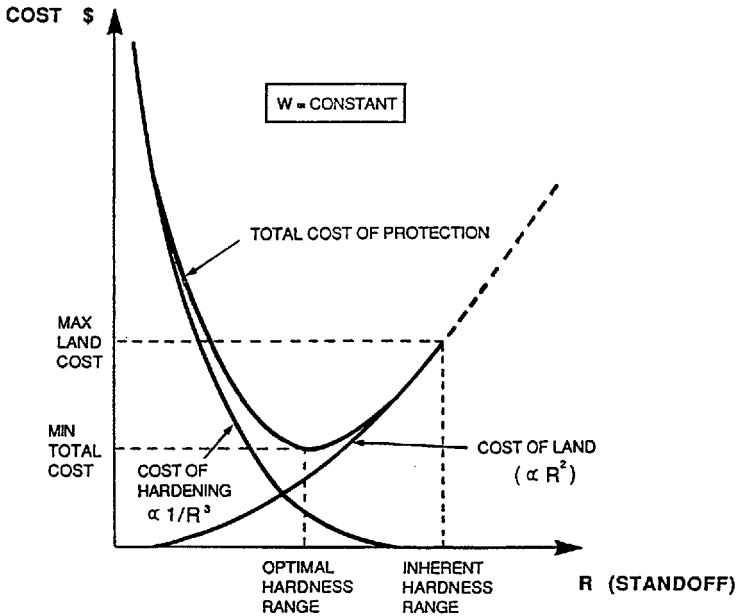
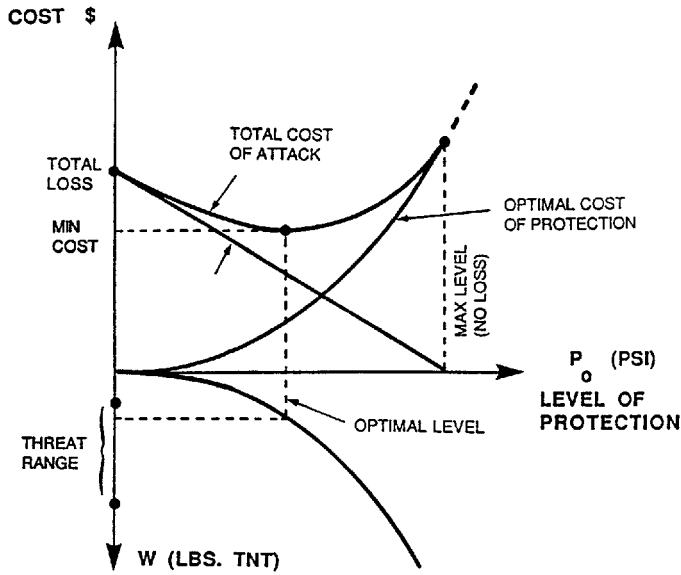


Fig. 8—Optimization of protection level and enforced standoff distance

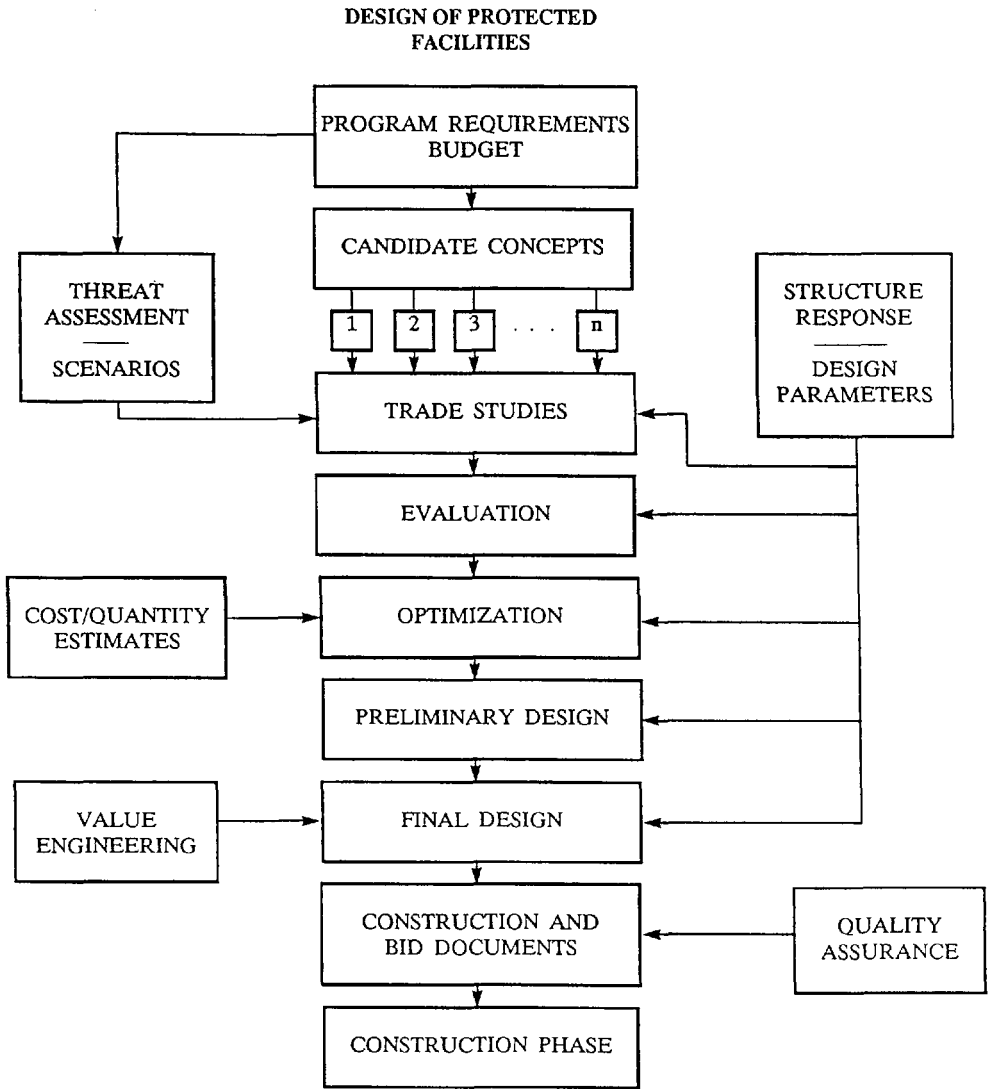


Fig. 9—Design sequence

Industrial Blast Resistant Facilities: an Engineer's/Constructor's Viewpoint

by William Bounds, Madhav Nene and Hsitoung Ko

Synopsis:

The number of blast resistant facilities planned, designed, and constructed recently in petrochemical plants points to an increased interest in this specialized type of design. This paper deals with the numerous decisions to be made in designing blast resistant buildings.

First, the need for a blast resistant design must be evaluated. Then, design objectives and relative cost must be balanced to produce an optimal design. Design practices must be established as there are various company, military, and professional publications available. Detailing practices also require careful consideration as there are differences in the implementation of shear reinforcing, precast elements, penetrations, and exterior doors.

Several actions would greatly benefit the design of petrochemical blast facilities. A clear definition from government and insurance sources is needed on what facilities need to be protected from explosions. Improvements are needed in the evaluation of blast loads within petrochemical facilities. A consensus on engineering calculations and construction details would help unify design approaches.

Keywords: blast resistant construction; evaluation; reinforced concrete; shear properties; structural design

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INTRODUCTION

Changes in safety consciousness, injury liabilities, and stiffening government safety regulations have resulted in an increased demand for blast resistant design capabilities, particularly in the petrochemical industry. Several well publicized plant accidents and fines or citations associated with unsafe operations illustrate the need for blast resistant design. Smaller accidents occur much more frequently and show that minimal blast loads may occur more than once in the life of a building.

Fluor Daniel Inc., has designed and constructed a number of blast resistant facilities over the years. These facilities have included control buildings, containment for hazardous vessels, protection of emergency safety equipment, and protection of critical plant utilities. In this paper, emphasis is placed on design decisions for the most common type of blast resistant facility, control buildings. From our experience, there are two observations which can influence design decisions.

First, a control building is never the sole project objective. A blast resistant control building is nearly always a component of a larger project. Control buildings are built for grassroots plants, for expanding process units, for additional process units, or as a part of an instrument modernization program. The implications of this are:

- The cost to make a building blast resistant is significant for the control building, but greatly less significant when compared to the total project cost.

- Client emphasis is usually with the primary purpose of the project, not with blast resistance. The objectives, layout and siting considerations, costs, and benefits of blast resistant design may need to be emphasized with the client.

Second, the design firm cannot view the petrochemical client as a single remote entity, but as a collection of client groups who are involved in many detailed design decisions. These client groups can include: project management, plant operations, design specialists, labor, and safety. As many petrochemical firms are quite large, so are their staffs. The effects of this are:

- It takes longer to obtain a decision from the client, especially on a subject as unusual as blast resistance. This delay should be anticipated when preparing project schedules.
- Because opinions are heavily based on perspective, differing influences should be expected from within the client's staff. In general, there is a balance to be achieved between lowering initial construction costs and minimizing long term operating expenses. These influences are eventually reconciled, but they sometimes result in blast details that are workable, but less than optimal.

With these observations in mind, a series of decisions must be made, jointly with the client, as a part of the design process. These decisions are identified and discussed in the following portions of this paper.

IS A BLAST RESISTANT DESIGN REQUIRED? WHAT ARE THE ALTERNATIVES?

This is a major decision to be made by the combined project team. Often this is not a straightforward decision, but will require the consideration of many factors. A number of these factors are discussed below.

The client may have an issued standard which clearly defines which structures require blast resistant design and under what situations. Many major petrochemical companies are cognizant of the importance of blast resistant structures and have produced detailed criteria for the design of particular structures at their facilities. These criteria may cover a number of plant facilities, such as control buildings, substations, and field auxiliary rooms. Client standards often identify blast sources and provide preferable separation

distances to essential control facilities. Most standards will also specify types of construction, material strengths, analysis procedures, and design details. If a client standard is available, decisions related to blast resistant design are usually straightforward.

It should be noted that client standards are rarely the same and the differences between standards can be quite significant. Differences relating to loading, analysis methods, structural details, and architectural details are to be expected. Usually dynamic analysis procedures are specified, however occasionally pre-designed structural elements are provided in lieu of an analysis. In addition, there can be provisions which are not consistent with the design firm's preferences and expertise. It is always necessary to carefully examine any design standard prior to implementation.

A number of the large design firms in the petrochemical industry have issued their own design standards covering blast resistant design. There are also industry standards such as SG-22 from the Manufacturing Chemists Association (ref 1) and 7-45S from Factory Mutual (ref 2). Because the petrochemical companies, and not the design firms, make the basic project funding decisions, these standards will not settle the basic issue of what to make blast resistant unless they are fully reviewed and accepted.

Even if a design standard is available and accepted, it is always prudent to identify the potential sources of blast, not only near the particular building site but also within the surrounding area. Because it is difficult to estimate the magnitude and location of potential explosions, especially vapor cloud explosions, most design standards specify an industry standard blast load. SG-22 describes a load of 1 ton of TNT at a distance of 100 feet. This standard loading is commonly used, but its unquestioned use could result in unnecessarily conservative designs or potentially underdesigned buildings. A study should be considered to determine possible explosions based upon potential blast sources. Actual conditions may increase or decrease the need for blast protection and result in a more economical plant design. A detailed site investigation may even negate the need for significant blast protection.

OSHA requirements are a mandatory consideration. However there are no specific regulations concerning which facilities are to be blast resistant. Due to the nature of industrial explosions, OSHA opinions appear to surface after an event which causes damage. One ruling, made after an explosion, indicates the necessity to meet criteria generally accepted within the industry for the spacing of occupied

facilities from process units. If industry spacing criteria such as IRI (ref 3) are not met, then supposedly these facilities must be protected.

Insurance requirements and an economic analysis of hazards may also be key factors in making a decision. The client's insurance company may have requirements regarding blast resistant design. Additionally, a hazard analysis which considers the probabilities of accidents in different types of process units, spacing of facilities, and types of construction can be used. It should be noted that this type of analysis is economic and does not include subjective concerns such as the effect of injuries on maintaining a quality workforce.

Siting is another important consideration which could indicate alternatives to expensive blast resistant construction. Plot plan development studies could determine the possibility of locating structures as far away as possible from blast sources. Clearly, minimal protection is needed if a building site is far enough from any potential sources of explosions. Modern control buildings with Distributed Control Systems (DCS) can easily be located farther from an operating unit. This usually involves the lengthening of a couple of coaxial cables. The plant layout should consider the effective utilization of the available project site weighing the possible integration of structures requiring blast resistance.

The preferences of plant operations personnel often play an important role in plant design. Fluor Daniel has had to deal with a number of relevant considerations from operations personnel, though it is important to note that every project is unique and every client is unique. Two of these considerations are:

- The prospect of adding a new blast resistant control building into an existing plant with conventional control buildings can create resentment by operations personnel assigned to the older facilities. In rare instances, blast designs have been avoided for this reason. Alternatives can be planned to prevent this situation, such as the combination of old facilities into new, or a commitment to a phased upgrade of control buildings throughout the plant.
- Operations personnel prefer to be near the process unit. This facilitates operation of the unit by easily being able to walk to a particular item of interest. This preference may be negated by the increased use of centrally located control buildings for multiple process units.

facilities from process units. If industry spacing criteria such as IRI (ref 3) are not met, then supposedly these facilities must be protected.

Insurance requirements and an economic analysis of hazards may also be key factors in making a decision. The client's insurance company may have requirements regarding blast resistant design. Additionally, a hazard analysis which considers the probabilities of accidents in different types of process units, spacing of facilities, and types of construction can be used. It should be noted that this type of analysis is economic and does not include subjective concerns such as the effect of injuries on maintaining a quality workforce.

Siting is another important consideration which could indicate alternatives to expensive blast resistant construction. Plot plan development studies could determine the possibility of locating structures as far away as possible from blast sources. Clearly, minimal protection is needed if a building site is far enough from any potential sources of explosions. Modern control buildings with Distributed Control Systems (DCS) can easily be located farther from an operating unit. This usually involves the lengthening of a couple of coaxial cables. The plant layout should consider the effective utilization of the available project site weighing the possible integration of structures requiring blast resistance.

The preferences of plant operations personnel often play an important role in plant design. Fluor Daniel has had to deal with a number of relevant considerations from operations personnel, though it is important to note that every project is unique and every client is unique. Two of these considerations are:

- The prospect of adding a new blast resistant control building into an existing plant with conventional control buildings can create resentment by operations personnel assigned to the older facilities. In rare instances, blast designs have been avoided for this reason. Alternatives can be planned to prevent this situation, such as the combination of old facilities into new, or a commitment to a phased upgrade of control buildings throughout the plant.
- Operations personnel prefer to be near the process unit. This facilitates operation of the unit by easily being able to walk to a particular item of interest. This preference may be negated by the increased use of centrally located control buildings for multiple process units.

Cost is a major consideration and can be the deciding factor in blast resistant design. Though specific locations and methods of construction can vary significantly, the structural cost (steel and concrete) of a typical blast resistant concrete box type control building may be more than twice that of conventional construction. The total building cost (including architectural, electrical and HVAC, but not process control equipment) may be as much as 60% higher. This cost difference, however, does not vary greatly within the usual range of design overpressures. This is because once the type of construction is selected, a little extra reinforcing or concrete makes little cost impact. So, unless a building can be located far enough to change the basic type of construction, building costs will not change greatly. There are, however, several ways to minimize costs for a blast resistant building:

- Minimize the size of the building. This usually involves eliminating all but essential office space from the control building. Sometimes, HVAC equipment is located outside the blast protected enclosure.
- Minimize the size and number of external entrances. Blast resistant doors are expensive, long delivery items.
- Consider design details which use precast concrete walls. Depending on project circumstances, this can save on the cost of field labor as well as shorten the project schedule.

Note that the design load itself is closely related to the decision to provide a blast resistant building and is often established at the same time.

WHAT ARE THE OBJECTIVES OF A BLAST DESIGN?

The design objectives will indicate what level of material resistance is needed. Because it is not economical to design blast resistant control buildings to be free of any damage, objectives and material resistance are linked. For example, if the objective is only for the structure to remain standing, large plastic deformations can be tolerated. This will result in significant deformations and greater cracking in concrete. On the other hand, if the objective is minor repairable damage, then the level of plastic deformation must be greatly restricted. This will result in less permanent deformations and cracking, but will require stronger structural elements. Blast resistant designs commonly use plastic deformations to absorb blast energy as a tradeoff to requiring greater structural strength.

The objectives discussed in this section come from our experience with a number of clients. One main item of note is that these objectives are always considered independent of each other. Sometimes all objectives are to be implemented. Sometimes a client will be concerned strictly with the safety of personnel, and is not concerned about the protection of control equipment or reuse of the building. Unmanned buildings housing relatively rugged equipment, may not require attention to interior architectural detail. With the unique design objectives established, material resistance and design details can be determined which will economically serve the client's requirements.

The most common objective is to save lives. Even if plant alarms provide an adequate warning, operations personnel usually remain at their control consoles. Therefore, buildings should prevent the significant entry of blast overpressures as well as explosion generated debris. Some form of protection should be provided from the entry of gaseous byproducts, though this may be provided in the form of portable breathing equipment. The building should be designed to remain standing with internal components designed to prevent injury. After being subjected to a design level explosion, the building may not be reusable.

Another objective often specified by clients is the protection of control equipment used to operate multiple process units. Accidental explosions can heavily damage one process unit while leaving an adjacent unit with minimal damage. These adjacent units can be repaired quickly and brought back to production, if control facilities are still available. Because process control equipment is an expensive item requiring a long delivery, blast protection is often justified. To meet this objective, buildings must protect equipment as well as people. The equipment supporting floor should be isolated from blast resisting structural elements. Pedestal flooring will require bracing to prevent collapse. Greater attention should also be given to securing architectural building components in the vicinity of the control room. Under this objective, a building should be reusable after only a moderate amount of repair.

Still another objective is the orderly shutdown of operating units immediately following a process accident. Many major secondary problems can be avoided if control of the production process can be maintained. Under this objective, stricter limits on plastic deformations should be used to greatly minimize building damage. Cable entry details should be used which will allow building movements without affecting cable integrity. This objective also has implications beyond the limits of a control building in that essential

utilities and control connections must be maintained. Blast protection may also be needed for substations, transformers, local rack rooms, and automatic fire control equipment.

Under any objectives, minor plant accidents should not cause significant damage to a hardened control building. Under major accidents, some amount cracking and permanent deformations will occur, depending on the design objectives. Inspection and repair is then expected prior to reuse. In this manner, rational objectives are fulfilled.

WHAT TYPE OF DESIGN PROCEDURE WILL BE USED?

At the heart of every design is the proportioning of structural elements. Because there is no single commonly used method for blast analysis, a variety of calculation methods are currently in use. The selection of a form of analysis is normally based on either the engineering firm's or the client's issued criteria. If conflicting standards exist, the differences must be resolved prior to design. If no such criteria exists, then the selection of a form of analysis is up to the engineer's judgment and experience. A number of published texts and government documents are also used to aid in the analysis (refs 4, 5, 6, 7). Detailed calculation methods fall into three main categories:

- Equivalent Static Design
- Simplified Dynamic Design
- Numerical Integration

Exact implementation of each category can vary significantly. Selection of a particular method depends on how much is known about the loading, the intended complexity of the calculation, and the desired accuracy of the results. It would be prudent to use calculation methods which are at least as accurate as the blast load determination. These categories are described below.

Equivalent Static Design is sometimes referred to as equivalent wind design. This is a strictly conventional static analysis where the blast force is applied in similar manner as a very large static wind load. Because of the nature of this method, commonly used analysis procedures, and software, are used to determine the distribution of forces within a structure. Either Ultimate Strength Design or the Alternate Design Method, as appropriate for concrete or structural steel, can be used to proportion materials.

This method is conceptually similar to the static force procedure commonly used in seismic design. From the Uniform Building Code (ref 10), a fairly simple formula ($V = (ZIC/R_w)W$) is used to compute a conservative static load on a structure based on possible ground movements. Factors which influence the dynamic response are included in the procedure either as factors in the equation or as limitations to its use. There is also an extensive history of use with this procedure to establish its accuracy.

In blast design, the determination of a static design load is the weakness in this method's accuracy. There is no general equation to determine a conservative static load. Not only can the magnitude of accidental explosions vary widely, the dynamic properties of typical building elements can also vary. In seismic design, a base shear load is computed for the entire building using the building's dynamic properties. Loads are then distributed to different structural elements within the building. In blast design, a load is often computed for each element using the element's dynamic properties. No overall building load is used. These differences make it unlikely that a general formula will yield consistent results. A list of static equivalents can be compiled by assuming a specific blast load and specific structural element properties. These charts would then be limited only to very similar situations.

Given a static load equivalent, this calculation is very easy to perform and is preferred by many engineers because it does not require a nonlinear analysis. Some petrochemical companies specify Equivalent Static Design in their standard design specifications.

Simplified Dynamic Design is the most commonly used category. Simple formulas and charts are used to establish the nonlinear response of a given structural element to a given dynamic load. Ductility is confirmed through the use of code ductility criteria as well as by providing adequate shear capacity. The popularity of this method reflects a compromise between ease of implementation and accuracy of results. Computers are generally not needed though simple spreadsheets can be used for ease of computation.

In most implementations of this form of analysis, structural element properties are computed from trial element dimensions. The blast load is obtained as a load-time function. The mass and stiffness of each structural element are computed and factors are applied to convert to a single degree of freedom (SDOF) equivalent. A response chart is selected which closely resembles the load-time distribution of blast forces and the non-linear element response. The SDOF equivalents, the element's ultimate capacity, and load data are used

with the response chart to compute a peak deflection. Allowable deflections are determined from standard criteria based on the element's ductility.

There are limitations to this method. First, the blast load used must correspond closely to an available response chart. Second, element coupling must be neglected. Third, element reactions cannot be determined for use on the supporting element. Fourth, the configuration of structural elements must correspond closely to one of the SDOF equivalent charts. Within this method, one can always compute new charts to cover a unique configuration. The complexity of calculations then increases greatly and thus is rarely done.

Foundations are usually designed by reverting to equivalent static methods with loads derived either from element capacities or from the original blast loads. The lack of element reactions, the complex combination of vertical and horizontal forces, and the lack of foundation deflection criteria does not justify the extension of dynamic methods to foundation design.

Traditionally, this being a manual calculation, Simplified Dynamic Design is viewed as acceptable considering the accuracy in determining typical industrial blast loads. Thus the majority of company design standards specify this form of analysis.

Numerical Integration, even for uncoupled structural elements, is viewed as too complex and tedious for a reliable manual calculation. Computer programs capable of coupled non-linear dynamic analysis exist, but are rarely used due to the need for specialized software. Given the nature of accidental explosions, the accuracy of specialized software isn't worth the computing power and data input effort. Computer spreadsheets however appear ideally suited to the effective use of simplified versions of numerical integration.

In simplified forms of Numerical Integration, a given load-time function and an assumed structural element are analyzed numerically to determine an element's deflection and reaction both as functions of time. Coupling is still neglected and SDOF factors are still applied to each element.

Most of the advantages of a simplified Numerical Integration deal with analysis flexibility. First, because response charts are not used, load-time functions need not match a predetermined standard. Second, element reactions can be computed as a function of time and applied to the supporting element. Third, element coupling can be implemented, though the complexity of the calculation increases.

Fourth, methods are available, though not commonly used, to dynamically analyze foundations. Acceptable foundation deflection criteria would still need to be determined.

Though most textbook references on blast design cover the principles of Numerical Integration, industry design standards do not, except to indicate that these are accepted forms of analysis. Numerical Integration removes some of the inaccuracies of simpler calculation methods by a more general analysis of the equations of motion.

WHAT TYPES OF CONSTRUCTION ARE USED?

Several different types of construction have been used for blast resistant design. Types utilizing reinforced concrete are most common. Reinforced concrete wall and roof elements can be designed to provide a predictable ductile response as well as to provide an effective barrier for debris generated by an explosion. Some client's design criteria specify the use of reinforced concrete structures due to construction labor and material costs in the local area.

Overseas, there are countries which prefer to use precast concrete frames composed of beams, girders, and columns. Domestic construction still has a very limited use of precast concrete for a blast resisting system. For the same reasons that precast building systems are not common in high seismic zones, they are not common in blast design. The difficulty of providing reliable ductile connections inhibits the use of precast building systems. When designed, the use of precast elements includes planks, tees, and double tees for floors; tilt-up panels for walls; and columns for the vertical supports. For lateral load resistance, precast wall panels are used as shear walls. Seldom are precast rigid frames used to carry both gravity and lateral loads.

Precast wall panels are used in combination with other supporting materials. Precast panels offer the blast resisting advantages of cast-in-place concrete walls as well as greatly reduced field labor by eliminating costly wall forms. A variety of connection details have been used to provide ductility and to facilitate construction.

A frequent item of discussion with clients involves the use of reinforced concrete block. Because concrete block can be found in many existing control buildings, new concrete block buildings are initially suggested. Construction costs may be less than for cast-in-

place concrete walls or precast walls, however strength and ductility become a major design problem. The strength of the block, limitations on the placement of reinforcing, and the lack of shear reinforcing in walls generally limits the use of concrete block construction to minimal blast load situations.

Though prefabricated metal buildings can be designed to provide blast resistance, the thin wall panels do not provide the projectile penetration resistance of concrete. Metal buildings do tend to remain standing after accidental plant explosions, however this is usually after most of the steel siding has been torn loose. Metal buildings with separate interior office structures might be an economical choice for sparsely occupied plant facilities such as warehouses.

Most commonly used in the petrochemical industry is a combination of structural steel and reinforced concrete (figure 1). This combination makes use of the procurement and installation costs of each material. As mentioned above, reinforced concrete is preferred for walls and roofs to resist blast overpressures and blast generated debris. Structural steel is used for interior beams and columns in order to avoid scaffolding and forming costs. Steel decking is used on top of the steel framing as a roof form and is left in place. Fluor Daniel Inc. has used combined structural steel and reinforced concrete systems for a number of domestic and overseas projects.

This combined system uses the steel beams, girders and columns to take vertical conventional and blast loads. Steel members are designed with stiffeners to prevent local buckling before their full plastic capacities are developed. Joints and connections are designed to be capable of developing the full capacities of the connected members. Bolts and welds are designed using the plastic design criteria of the AISC specification (ref 8).

The reinforced concrete walls and roof of a combined system are used not only to resist external blast pressures, but also to resist lateral loads. Most design standards impose the seismic ductility requirements of ACI 318 (ref 9) chapter 21 for blast design purposes. Referred to as a $R_w = 8$ seismic building by UBC (ref 10), this combined system simplifies engineering analysis, design, and drafting efforts. There is no tedious concrete rigid frame design work involved. For construction, costs are eliminated for rigid frame scaffold, forming, and pouring.

WHAT DESIGN DETAILS SHOULD BE USED?

The detailing used within blast resisting buildings is as important as the design of the structural elements. Details must cover structural as well as non-structural items. Several important considerations related to details are:

- To provide ductility, the bending capacity of structural elements must control the design. For all members, connections should be designed for loads 20% in excess of the member's bending capacity. Also, the shear capacity should be 20% in excess of the member's bending capacity.
- The use of higher concrete strengths is recommended. In petrochemical work, concrete strengths of 3,000 psi to 4,000 psi are standard, however higher strengths may be readily available with a minimal increase in cost. For walls, construction crews prefer not to deal with the installation of shear ties. Stronger concrete helps to reduce the need for wall shear reinforcing, and for shear reinforcing in general. Even with higher concrete strengths, additional design time may be required to simplify wall reinforcing in order to reduce more expensive field labor costs.
- Interior walls need to be strengthened, braced, and function independently of exterior walls. The failure of non-structural building elements could cause injury or damage to important equipment. Because alternatives are readily available, heavy brittle materials such as concrete block are not recommended for interior walls. To reduce the transmission of blast movement, some form of isolation of interior walls from external blast resistant walls is recommended.
- Important equipment which might be needed following an explosion should not be mounted on the interior face of exterior walls. Because exterior walls can be expected to undergo movements on the order of several inches, items mounted on these walls would be unlikely to survive in an operable condition. Furthermore, unless special attachment details are provided, wall mounted items could become hazardous to the building's occupants.
- Aboveground cable entry details should be established which will allow substantial building movement without affecting

the integrity of adjacent support structures. Isolating cable tray supports from building walls is usually simple to accomplish.

Though not in widespread use, precast walls are often preferred for blast resistant buildings by construction managers. This preference is because of savings from reductions in field labor and in a shortened schedule. In conventional construction, plates embedded within precast elements are typically welded to connecting members. In blast resistant building designs, a variety of precast details have been used, some based on strengthened versions of conventional construction. The use of conventional precast details should be used with care. There are several reasons for this:

- Because of a lack of ductility, connections are the weak link in any precast design. In the past, conventional buildings using precast connections have had problems handling earthquake loads. Design details for seismic loads are the subject of continuing study and refinement.
- Construction preferences and local labor costs vary. Additionally, the capabilities of nearby precast suppliers may vary from one jobsite to another. Each building design should be reviewed for unique characteristics.
- Precast buildings, or any other type of blast resistant building, almost never face an actual explosion. While this is good news to the occupants, it provides little feedback on the performance of precast details. The development of design criteria from experimental studies is recommended where possible.

A variety of non-conventional precast details is also used. One of the more conservative approaches is to mimic cast-in-place construction (figure 2). Such an approach is used to provide a building which is well tied together. Another approach is to use some form of bolting at the base of wall panels (figure 3). Though simpler to construct, the connections become a greater design concern to provide adequate ductility.

Exterior blast doors are always carefully evaluated because of their high cost relative to conventional doors. Upon occasion, the designer will need to clarify perceived notions to clients and internal decision makers about exterior doors:

- Exterior concrete block enclosures add nothing to the door's blast resisting capability and may result in a pile of rubble blocking an emergency exit. Further, by creating wall pockets,

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enclosures detract from the clearance of a blast wave from a building. Entry enclosures are used as airlocks for pressurized buildings and to prevent wind, dust, and rain from entering the building. These airlocks should be placed interior to the building wall.

- Two conventional doors, one behind the other in an airlock, are not equivalent to one blast resistant door. This idea was once offered by a client to eliminate the need for expensive custom designed doors. An additional conventional door adds very little protection.

Properly designed doors can be specified and designed to withstand the same loads as the exterior walls. Additional protection is not needed. Blast resistant doors can be provided by several suppliers and custom designed to individual needs. These doors are not cheap, and they must be ordered early enough for frames to be cast into exterior walls. If timely frame delivery cannot be assured, self-fabrication of door frames can be performed from drawings supplied by the door manufacturer.

Typical control buildings require utilities, control cabling, and air ducts to penetrate exterior walls. Depending on the details used, some amount of blast overpressure will be admitted into the building. Of course, the number and size of penetrations should be minimized to reduce internal damage.

Air ducts are of the greatest concern. Cabling and utility penetrations can be sealed or routed underground. Blast valves are used to protect air intakes in some control buildings, but not all. The manufacturer's designs can be selected to fit air intake ducts and designed to resist design blast wave pressures (ref 11). Closing times can be on the order of 2 milliseconds. Though most valves reopen automatically, they can be designed to remain closed until manually reopened to prevent the entry of hazardous gasses. Blast valves are not always used because of the additional cost, the fact that they do not totally eliminate blast overpressure entry, and because blast valves considerably increase the size of the air duct penetration. Consideration should be given to the size of openings relative to total building size, the protection of items near air duct openings, and the orientation of openings relative to the direction of explosion generated debris.

Plant personnel frequently prefer windows, sometimes large picture windows, to view the process unit. Though convenient for operating purposes, windows should be eliminated from blast resistant

buildings. Windows provide little strength, have a lack of ductility, and provide no penetration resistance. Windows, being the weakest component in blast resistant structures, break and become blast generated projectiles themselves. There are alternatives to windows. For single unit control buildings, small hardened observation ports can be provided using fully tempered glass. Control buildings which control large or multiple process units commonly use video monitors to observe items of interest. Video systems have the additional advantage of being able to view items not directly observable from the control building.

CONCLUSIONS/RECOMMENDATIONS

Within the petrochemical design industry, blast resistant facilities are rapidly becoming more accepted as a necessary part of overall project requirements. However, there are a couple of hindrances to better design and detailing which appear unique to blast design:

- A single set of design criteria does not presently exist. Petrochemical design firms are exposed to a variety of client and industry standards. This is because design standards seem to make their way informally from one company to another. The different approaches described by these standards are often left unexplained because of a lack of a uniform accepted standard. However, ACI and ASCE committees, with representation from a number of operating companies and design firms, is presently working to establish a set of guidelines for general use.
- A number of engineers who attempt blast resistant design are quite adept at conventional design, but are less adept at blast design. As mentioned previously, blast resistant facilities are usually a small part of a larger project. It is common for a team of engineers to handle the design of all structures on a project.

Each blast resistant design should be optimized to suit particular project, client, construction, and jobsite requirements. Despite this, improvement can be made to provide more uniform application of blast design principles within the petrochemical plant design environment:

- There is a legitimate need for design oriented technical seminars, especially those structured for the designers of petrochemical facilities. This is because there is little in the

- way of formal training in blast design principles. Though special conferences are held, these often concern research oriented subjects.
- A clear and consistent definition of blast design requirements is needed from government, industry, constructors, and insurance companies. Presently, design requirements are determined from a potpourri of government manuals, textbooks, client standards, and design firm standards. A primary goal would be to consistently define which buildings require protection and under what circumstances.
 - A continued effort to improve the evaluation of potential blast forces is needed. The determination of blast forces easily remains the most uncertain step in providing a reliable design.

Implementation of these three suggestions would greatly help to promote interest on the subject of petrochemical blast design. With greater interest in blast resistant structural design, significant progress could be made in the evaluation and implementation of more effective design methods and improved methods of construction.

REFERENCES

1. Safety Guide SG-22, *Siting and Construction of New Control Houses for Chemical Manufacturing Plants*, Manufacturing Chemists Association, Washington, DC, 1978, pp 1-18
2. 7-45S, *Process Control Houses and Other Structures Subject to External Explosion Damage*, Factory Mutual Engineering Corporation, Boston, MA, 1980, pp 1-4
3. IRI, *General Recommendations for Spacing in Refineries, Petrochemical Plants, Gasoline Plants, Terminals, Oil Pump Stations, and Offshore Properties*, Industrial Risk Insurers, Hartford, CT, 1984, pp 1-9
4. Biggs, John M., *Introduction to Structural Dynamics*, McGraw-Hill Book Company, New York, NY, 1964, pp 1-341
5. TM5-1300, *Structures to Resist the Effects of Accidental Explosions*, Department of the Army, Navy, and Air Force, Washington, DC, November 1990

6. ASCE manual 42, *Design of Structures to Resist Nuclear Weapons Effects*, Committee on Dynamic Effects, American Society of Civil Engineers, New York, NY, 1985, pp 1-301
7. ACI 349 appendix C, *Code Requirements for Nuclear Safety Related Concrete Structures, Special Provisions for Impulsive and Impactive Effects*, ACI 349 Concrete Nuclear Structures, American Concrete Institute, Detroit, MI, 1985, pp 86-89
8. AISC LRFD, *Load and Resistance Factor Design Specification for Structural Steel Buildings*, American Institute of Steel Construction, Chicago, IL, 1986, pp 1-121
9. ACI 318, *Building Code Requirements for Reinforced Concrete*, American Concrete Institute, Detroit, MI, 1989, pp 1-353
10. UBC, *Uniform Building Code*, International Conference of Building Officials, Whittier CA, 1991, pp 1-1050
11. Carroll, T.P., *Criteria for the Selection of Blast Valves for Protective Structures*, paper presented at The International Symposium on the Interaction of Conventional Munitions with Protective Structures, Mannheim, Germany, 1987, pp 1-19

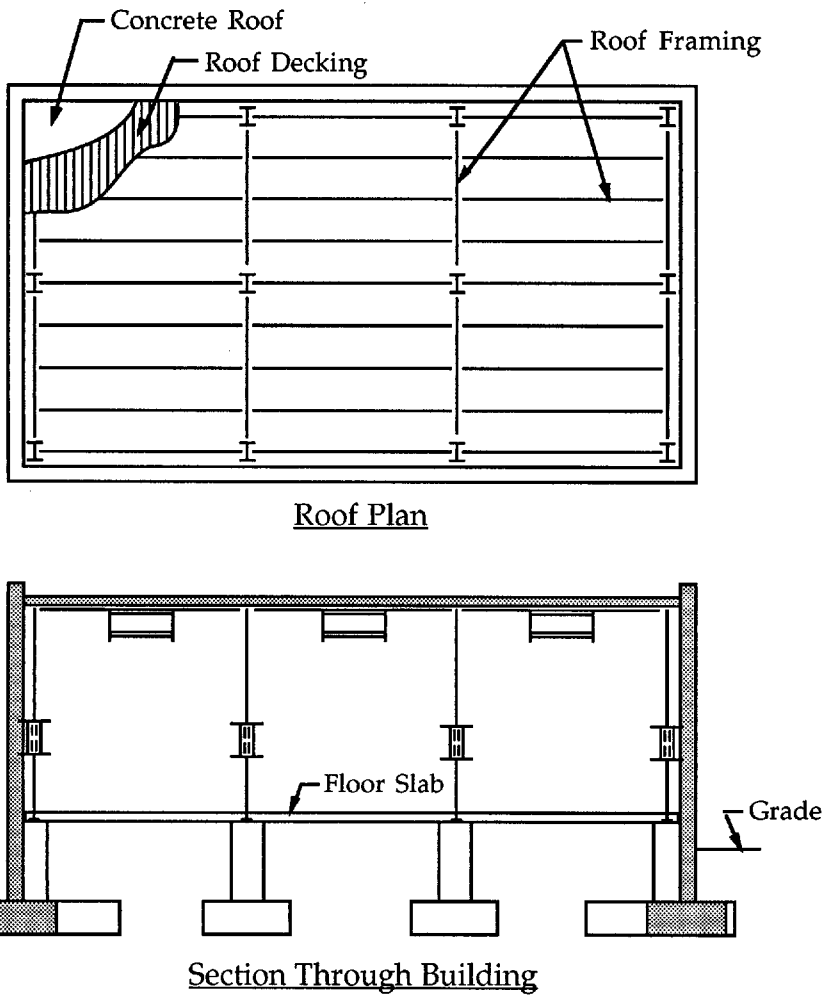
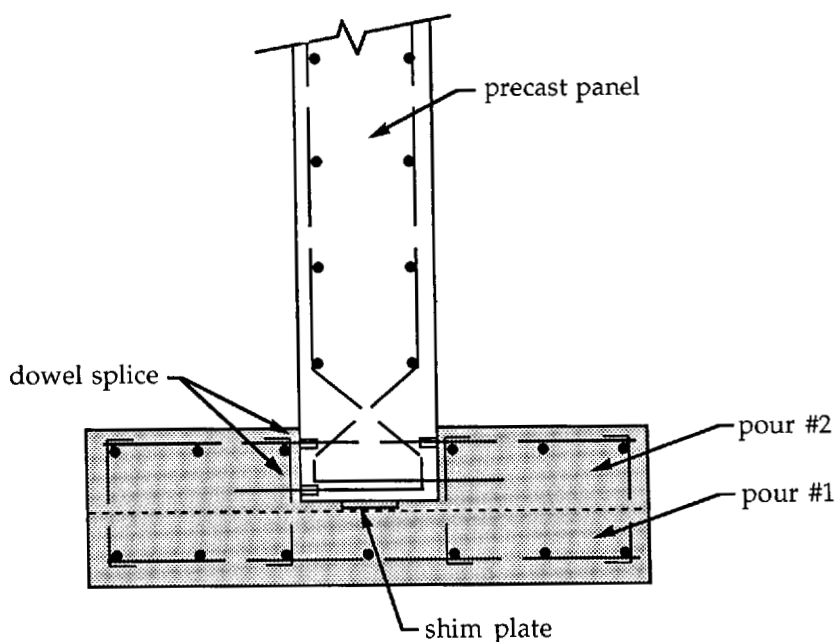
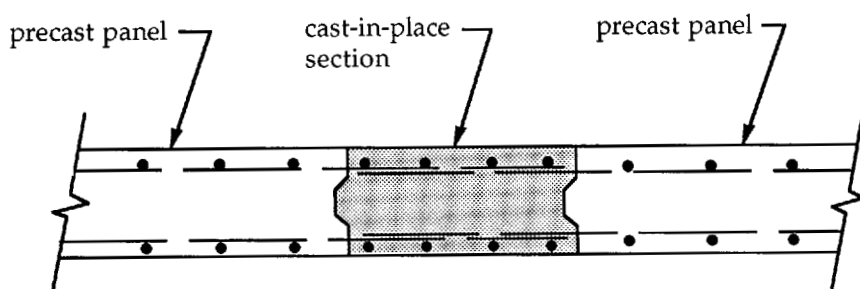


Fig. 1—Combined steel / concrete construction



Section Through Continuous Footing



Plan: Typical Wall Joint

Fig. 2—Precast /cast in place wall details

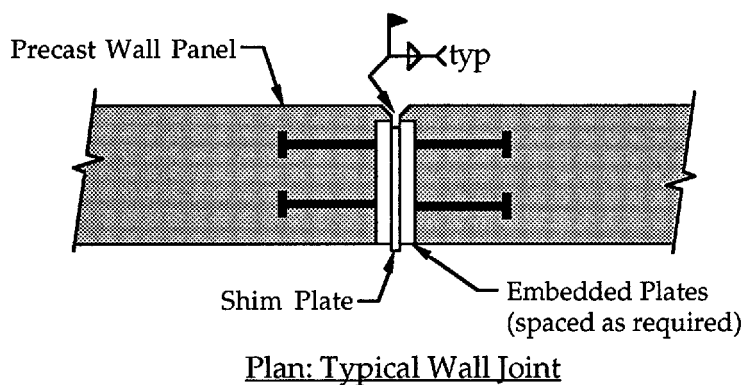
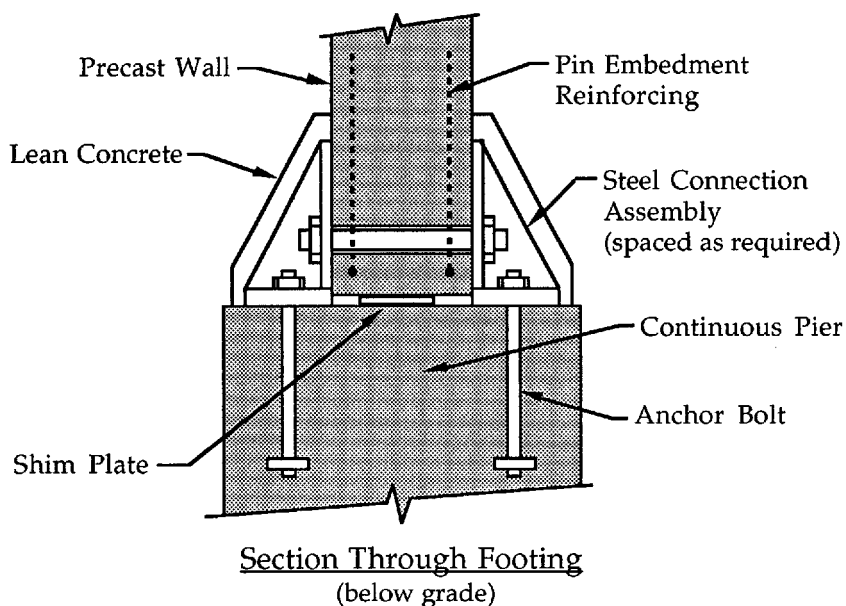


Fig. 3—Bolted precast construction

Impulsive Loading Analysis and Design Procedures for Nuclear Power Plant Facilities

by Rahmat Rabizadeh and Branko Galunic

Synopsis: Nuclear power plant structures, systems and components may be subject to a variety of impulsive loads caused by accidental explosions and or high energy pipe ruptures. Examples of such loads are jet impingement, reactor vessel sub-compartment pressurization, pipe whip restraint reaction and blast pressure. Various US NRC Regulatory Guides and Standard Review Plans specify required loads and provide acceptable methods for structural design. The design of concrete structures, subject to impulse and impact loads is governed by the ACI-349 Code. Acceptable analysis techniques vary from simplified quasi-static methods for single degree of freedom systems, to detailed computer analysis techniques accounting for material and geometric non-linearities. This paper reviews briefly the impulsive loads and the procedures for analyzing and designing structures found in nuclear facilities.

Keywords: ductility; explosions; nuclear power plants; structural design; tornadoes

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INTRODUCTION

Structures, systems and components (SSC) that are essential for the safe operation and shutdown of the nuclear power plant may be subject to a variety of loads. The United States Code of Federal Regulation 10CFR50, Appendix A provides General Design Criteria for the design of Nuclear Power Plant facilities. Criteria 2, 3 and 4, Design Basis for Protection against natural phenomena, Fire Protection and Environmental and missile design bases, require that the safety related SSC's be designed to withstand the effect of natural phenomena, fire, explosions and postulated accidents that may result from equipment failures and from events and conditions outside the nuclear power plant.

Impulsive loads caused by explosions and/or high energy pipe ruptures are one category of loads that require consideration. Explosions may occur due to a variety of reasons that need to be identified and for which the probability of occurrence may need to be quantified. In the United States, explosions that have a probability of occurring of less than 10^{-7} per year do not need to be considered in the design (1). Several U.S. Nuclear Regulatory Commission Standard Review Plans (2 to 5) and Regulatory Guides (6) specify loads and provide acceptable methods for analysis and design of the safety related SSC's.

The identification of potential for explosions is an ongoing process due to additions, modifications or other changes that are being implemented in operating Nuclear Power Plants. (7 to 12). The purpose of this paper is to present an overview of the impulsive loads and the analysis and design procedures used to protect the safety related SSC's from the effect of these loads.

IMPULSIVE LOADS

In consideration of impulsive loads in the design of safety related structures, the following load types are discussed:

- Accidental Explosions
- Intentional Explosions
- Jet Impingement
- Pipe Whip Restraint Action
- Tornado Induced Pressure Drop

Each of these load types, as well as characteristics of each type, is discussed in the following sections.

ACCIDENTAL EXPLOSION

A possible source of an accidental explosion is the release of explosive liquified gas from off site storage tanks during transport or land storage. The released gas when combined with air forms a vapor cloud which can be ignited, resulting in a deflagration or an explosion. Examples of explosive gases includes the hydrocarbon gases such as Ethylene, Ethylene oxide, methane, butane, ethane, propane and propylene. The transportation mode may be gas tankers for sea or inland waterway traffic, railway tank cars, tank trucks, or pipe lines. The gases may also be stored in storage areas of the industrial complexes close to the nuclear plant facilities.

The explosion of vapor clouds can evolve in the form of deflagration waves with a limited over-pressure. A deflagration with its slow burning speed is characterized by a pressure pulse with relatively long duration and low amplitude. In the deflagration process, turbulent flame acceleration also may lead to a blast type pressure pulse. There is also a possibility that under adverse circumstances a detonation rather than a deflagration could occur (13) that generates substantial pressure shock wave. A detonation causes a blast wave with sudden pressure rise and high peak value but short duration. Several studies have been done on the characteristics of the vapor cloud explosion of various concentrations with different ignition sources (13 to 16). Most studies conclude that the concentrated hydrocarbons in a free cloud deflagrative ignition will not result in a detonation.

The storage and transportation of other high explosive dangerous, material such as dynamite and other munitions close to a Nuclear Power Plant is a concern and has been the subject of various studies (8, 17). Studies on the accumulation and burning of hydrogen for long period of time in the Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) containments during a postulated core melt accident scenario (8, 19) show that there is a potential for a hydrogen detonation condition for small containments.

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Such detonation is likely to cause pressure waves with maximum pressure several times design levels. The hydrogen detonation is not presently postulated in the design of containments. To minimize the risk of hydrogen detonation, the characteristically smaller BWR containments are inerted during plant operation, by replacing the atmosphere with a mixture of nitrogen.

BWR plants have storage facilities for hydrogen and oxygen in the gas or liquid states. Hydrogen is used to prevent the corrosion of stainless steel piping in BWR's. Addition of hydrogen into the feedwater piping reduces the aggressiveness of water toward the piping material. Oxygen is injected into the condensate and feedwater systems to regulate reactor feedwater-dissolved oxygen and to minimize corrosion of the carbon steel in the condensate and feedwater system components. The rupture of storage vessels or tanks containing gaseous or liquid hydrogen results in a turbulent release of the gas that leads to hydrogen explosion with blast waves propagating outward from the vessel or tank rupture site (7).

Accidental rupture of other pressurized vessels inside the containment structure and other safety related structures, causes sub-compartment pressurization that is considered in the design of the safety related structures, systems and components.

INTENTIONAL EXPLOSIONS

Although the U.S. Regulation does not require consideration of explosions due to terrorist attack and other act of war in the design of Nuclear Power Plant structures, other countries postulate and consider such explosions (20, 21). Studies have been performed for the event when a penetrating warhead is detonated inside a containment. Also a pressure wave in the form of blast loading is prescribed by various codes to postulate the detonation of explosives close to the Nuclear Power Plant structure. The blast loading is supposed to envelope the intentional and accidental explosions in the vicinity of the power plants. The air blast phenomenon is characterized by an air pressure time variation with an instantaneous rise time to a maximum pressure, followed by a decline to sub-atmospheric pressure, then a gradual return to the normal atmospheric pressure. The below atmospheric pressure portion (the negative phase), is less important than the above atmospheric (the positive phase), and is neglected for design. The postulated blast loads are idealized forcing functions with a rapid rise in pressure, a small drop and then a constant pressure for a short duration.

JET IMPINGEMENT

Jets resulting from a postulated rupture of high pressure piping exert an impulsive load on the affected area. The ruptured pipe may contain steam-