Report for the Design of Concrete Structures for Blast Effects

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Reported by ACI Committee 370

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This report addresses the design of structures to resist blast effects due to explosions. It describes the state of the practice for the guidance of structural engineers charged with the design of civil facilities that may be subjected to blast loads. This report addresses the steps commonly followed in this practice, including determination of the threat, calculation of structural loads, behavior of structural systems, design of structural elements, design of security windows, design of security doors, and design of utility openings. These steps can applied to the design of new structures or to the retrofitting of existing structures.

Keywords: blast; blast analysis; blast-resistant buildings; blast-resistant design; ductility; dynamics; explosions; retrofit for blast; shock; overpressure.

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CHAPTER 1—INTRODUCTION

The design of concrete structures for blast resistance has been of great interest to the military and other federal agencies for several decades. In addition, certain specialized segments within the engineering community have also had to consider blast loads on structures as a result of potential accidents. For example, the petrochemical industry has designed for blast resistance in their facilities for many years. Even though there is considerable history in the design of structures to resist blast effects resulting from accidents or intentional acts, it is only recently that the general structural engineering community has shown a strong interest in the response of structures subjected to explosions and other high-rate loading phenomena, such as impact.

Following the attacks on the World Trade Center in New York and the Pentagon in Washington, DC, on September 11, 2001, the vulnerability of the nation's infrastructure to terrorism became a top priority for many state and federal government agencies as well as private consulting engineers. Though the significance of these attacks greatly increased engineering interest in the design of structures to resist extreme loads, statistics show that US interests have been targeted by terrorists with increasing frequency during the last several decades (U.S. Department of State, 2003), leading to significant financial and personal losses. As a result, the engineering community has learned important lessons that have allowed for improved methods of analysis and design to be developed. For example, lessons learned from the Oklahoma City bombing in 1995 and the U.S. embassy attacks in Tanzania and Nairobi in 1998 shaped present design guidelines for prevention of progressive collapse.

While the field of blast- and impact-resistant design is not as mature as other fields, such as seismic-resistant design, historical events such as those described are important to note because they help shape current practice and research interests. Just as the field of seismic-resistant design has advanced by learning lessons from past incidents, engineers working in protective design can similarly benefit from being aware of historical events and corresponding data. Although such information is typically outside the scope of work routinely undertaken by design engineers, awareness of these issues is important for understanding potential threats and associated loads that may result. While historical data can be used with reasonable confidence for predicting natural loads such as earthquakes and floods, the same claim cannot be made for man-made loads associated with potential terrorist threats. Thus, the intent of the discussion herein is to bring awareness to engineers and designers that many factors can influence the loads to which a structure may potentially be subjected, and it is only through awareness and consideration of the factors that affect the threat environment that engineers can estimate design loads.

1.1—Overview of report

Given the trends in terrorism and the required protection of building occupants at petrochemical facilities, it is clear that structural engineers must be able to design structures to resist the blast effects due to explosions. Drawing on research and engineering practice, the goal of this document is to compile essential information on the design of concrete structures to resist blast effects. Information is gathered from research reports, military design guidelines (when publicly available), and expertise from the petrochemical industry to provide a thorough introduction to the design of concrete structures to resist blast effects.

Several of the chapters in this report address topics that are nonstructural. When designing for blast effects, engineers must take into consideration that the loads that act on structures are strongly dependent on the distance between the structures and potential blast locations. In addition, there is a chapter on windows and openings because glass fragments from a blast typically contribute to injuries and fatalities. Thus, in designing structures to provide a safe environment for the inhabitants, structural engineers must consider other design issues that fall outside of their usual responsibilities when designing structures for more typical loads. Accordingly, it is important that engineers become familiar with these topics and play an active role in the decision-making process used to site buildings and select a façade system, doors, and windows.

Providing standoff is often the most cost-effective solution for mitigating the hazards associated with a blast load. In many cases, however, it may not be possible to provide sufficient standoff distance for a structure to eliminate the need for considering structural response to blast effects. Under these conditions, structural hardening is likely required. If consideration is given to structural modifications during the design stage, the costs of hardening can be minimized, and the aesthetic impact on the structure under consideration can, in many cases, be completely eliminated. As a retrofit, structural hardening can be expensive, although necessary for the safety of a building and its occupants. To address these design challenges, significant guidance is provided in this document on the selection of structural systems for blast resistance, methods of analysis, and design considerations. In addition, an entire chapter is dedicated to describing methods of retrofitting structures to achieve adequate blast resistance.

Although this report provides great breadth in the topics it addresses, it is not intended to be a stand-alone volume for practicing engineers. The purpose of this report is to provide a well-organized introduction that will serve as a starting point for identifying key issues associated with the design of concrete structures to resist blast effects. For engineers looking to familiarize themselves with this topic, it will serve as a concise guide. If more detailed information is needed, an extensive list of references has been provided.

1.2—Background and history

To develop an appreciation of the extent to which terrorists have targeted U.S. assets, it is helpful to review several previous events. The events described in the following are not intended to be an exhaustive list of attacks against U.S. interests. Rather, the intent of the discussion is to allow engineers unfamiliar with these incidents to gain an appreciation of the threat environment that they may have to design against, which will dictate the loads that they must consider. Reasonable estimates of design-basis loads can only be developed once the potential threats and sources of loading are understood. Further discussion on threat environment is provided in Chapter 3, whereas Chapter 4 includes a discussion on hazard assessment and risk analysis. In Chapter 5, readers can find a description regarding how to predict blast loads for a given threat.

On February 26, 1993, an explosive device was detonated in the parking garage of one of the World Trade Center towers in New York City. As a result of this attack, six people were killed, and 1042 were injured. Damage was observed over seven floors, and property damage was over 500 million dollars. According to the FEMA/ASCE accident investigation (McAllister 2003), the compartmentalized layout of the building structure was credited with minimizing the propagation of damage and preventing progressive collapse.

Two years after the bombing of the World Trade Center, the Alfred P. Murrah building in Oklahoma City was attacked on April 19, 1995. As a result of a large truck bomb, 169 people were killed, over 500 were injured, and damages exceeded $100 million. From an engineering perspective, there was great concern over the structural configuration of the Murrah building. This nine-story structure incorporated a transfer girder at the third floor that allowed the column spacing from the floors above to be doubled from 20 to 40 ft (6.1 to 12.2 m) for the bottom three stories. Because the bomb blast likely caused the failure of three of the columns that supported the transfer girder, the high loads from the floors above could not be redistributed to the remaining columns. As a result, the Murrah building failed due to progressive collapse. Because of this event, research into progressive collapse has become a great concern to the structural engineering community, and engineering guidelines to resist progressive collapse have been developed by the Department of Defense (UFC 4-023-03) and the General Services Administration (PBS-P100).

These events that took place on U.S. soil are quite familiar to much of the population, yet several other events in recent years have shown that U.S assets all over the world are susceptible to terrorist attacks. Though it is not necessary to describe all of these events in great detail, it is helpful to discuss the incidents that have implications related to structural engineering. One such event includes the bombing of the Khobar Towers in Saudi Arabia on June 25, 1996. This facility was used to house U.S. and allied forces. There were 19 fatalities and approximately 500 U.S. personnel wounded in the attack. Other events that raised awareness of the need to protect against terrorist activities took place on August 7, 1998. On this date, two U.S. embassy buildings were bombed in Africa. As a result of these attacks, 11 Americans were killed, and over 30 were injured. The response of the two embassy buildings differed greatly. The embassy building in Tanzania fared quite well, and damage was limited. The Nairobi embassy building, however, suffered severe damage and underwent a partial collapse in a similar progressive fashion as the Murrah building.