Structural Blast Design

By

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B.S. in Civil Engineering
Washington University in St. Louis, 2002

Submitted to the Department of Civil and Environmental
Engineering in Partial Fulfillment of the
Requirements for the Degree of Master of Engineering
in Civil and Environmental Engineering.

At the

Massachusetts Institute of Technology

June 2004

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ABSTRACT

Blast design is a necessary part of design for more buildings in the United States. Blast design is no longer limited to underground shelters and sensitive military sites, buildings used by the general public daily must also have satisfactory blast protection. Integrating blast design into existing norms for structural design is a challenge but it is achievable. By looking at the experience of structural designers in Israel over the past several decades it is possible to see successful integration of blast design into mainstream buildings. Israel's design techniques and policies can be used as a paradigm for the United States.

A structural design for a performing arts center is analyzed within the context of blast design. Improvements in the design for blast protection are suggested. These design improvements include camouflaging the structural system, using blast resistant glass, reinforced concrete, and hardening of critical structural members.

It is shown that integration of blast design into modern mainstream structures is achievable. New techniques and creative problem solving must be used to adapt blast design to work alongside current design trends.

Thesis Supervisor: Jerome J. Connor

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1. Introduction

Structural blast design is the design of structures to withstand loading due to explosions. This includes the protection of the building's structural integrity as well as the protection of people and equipment inside the building. Explosions that need to be designed for can come from many different sources. These sources include but are not limited to nuclear devices, gas explosions, high explosive bombs, vehicle bombs, package bombs, and missiles (Smith and Hetherington, 1994). Some of these explosions can be accidental, but the majority are intentionally detonated to cause human and material damage. For all of these cases it is impossible to predict when or if a building would be subjected to such a loading. In this paper I will be focusing on blast loading due to close range explosives such as vehicle bombs and other forms of terrorist activity.

Blast design is becoming a necessary part of design for more buildings in the United States. As terrorism is becoming more widespread throughout the world building design must adapt to protect people as well as possible. In the past, shelters were designed under the assumption that people would have enough time to be evacuated from the building they were in and reach the shelter. In situations such as terrorist attacks where there is no warning time, shelters must be integrated into the building itself. Blast design is no longer limited to underground shelters and sensitive military sites. People must now be protected from explosions on a day to day basis.

As blast design is integrated into mainstream construction it will have to coexist with other components that influence a building's design such as architecture and economics. Modern architecture is developing in the direction of light, graceful structures, with extensive exterior glazing. These architectural trends make buildings even more dangerous in the event of an explosion. Many of the injuries sustained by the occupants of a building during an explosion are due to glass fragments and flying debris (Eytan, 2004). In many cases this can be more of a threat to the people then the actual explosion. If the architectural design for a building calls for extensive glazing laminated or blast resistant glass must be used. Architects should also keep several guidelines in mind while designing a building. The cladding system of a building should be designed so that the fixings are easily accessible so that it can be easily inspected and fixed after an explosion. In addition architects should avoid designing a facade with deep indentations because it provides places for concealing explosive devices, and also the indentations can magnify blast effects by reflecting the pressure wave off of the many surfaces (Mays and Smith, 1995).

All of these considerations in design increase the cost of a building. Just like with seismic design, a building's risk as well as its desired state after an event must be analyzed and an appropriate level of protection for the building must be determined. The building owner must decide what state the building should be in after an attack, whether the building should be usable after the attack or just repairable. Then based on how much money the owner is willing to invest in protection of the building, he must decide what kind of protective design should be used (Mays and Smith, 1995). This added protection in design does add cost to a building project, but in the end it could save building owners a lot of money.

2. Israel as a Case Study and Paradigm

Over the course of its history, Israel has adapted military blast design to blast design to be used as a part of civilian structures. Israel's methods for integrating blast protection into its society can be used as an example for the rest of the world as it is increasingly subjected to more security threats.

When the state was founded in 1948, Israel had already constructed underground shelters across the country (see Figure 2.1). Underground shelters were the first forms of civilian blast protection because "one of the most effective methods of providing protection for a structure is to bury it (Smith and Hetherington, 1994)". Underground bomb shelters do have some benefits; they are generally larger than what could be provided for inside of a building so they are more comfortable for long periods of time. In addition, when the shelters were not in use they could be used for recreational purposes (Einstein, 2003). Many shelters were turned into libraries and meeting places for youth groups (see Figures 2.2 and 2.3). These underground shelters became a part of Israeli culture.

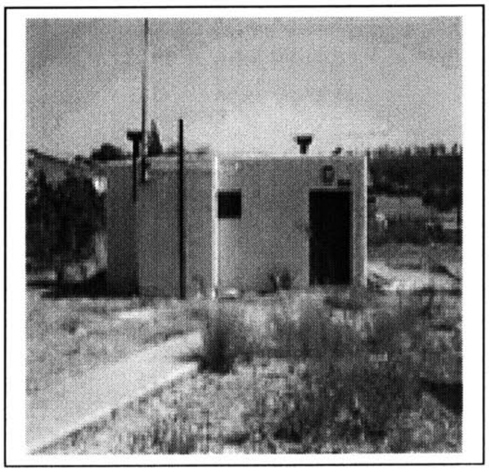

Figure 2.1. Entrance to an underground shelter in Israel (Israeli Home Front Command, 2004).

Figure 2.2. Shelter used as a playroom (Israeli Home Front Command, 2004).

Figure 2.3. Shelter used as a playroom (Israeli Home Front Command, (2004).

In the 1970's civilians in Israel were being threatened along its border with Lebanon. Katusha rockets were being launched over the Lebanese border into the Israeli cities on the other side, and Israel needed to provide its citizens with protection from the attacks. Throughout northern Israel rooms designed to protect a building's inhabitants from an explosion were included in most homes as well as schools and public buildings

(Sandler, 2003). This was the beginning of the transition from underground shelters, separate from buildings, to shelters integrated into daily structures.

The biggest change in Israel's policy toward protecting its citizens came in 1991 with the Gulf War. Saddam Hussein threatened Israel with Scud missiles and this not only increased the threat due to explosions, but it also introduced the strong possibility of bio-chemical threats. People were now required to have protected spaces within every home, office, and public space (see Figure 2.4 below). The windows had to be able to be sealed around the edges, and doors would have a wet towel placed at the bottom. The room also had to be blast proof so that in an attack cracked walls and windows would not allow poisonous gas to seep in.

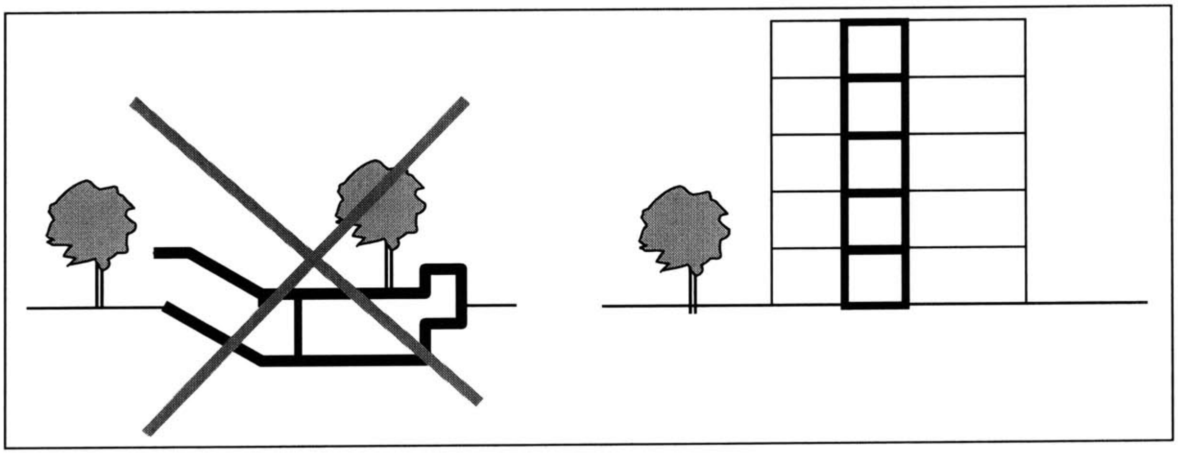

Figure 2.4. The change from underground shelters to protected spaces (Einstein, 2003).

New building requirements to have these protected spaces in all civilian structures, and how to design these spaces were developed and known as "Haga" requirements (Einstein, 2003). These regulations were fully integrated into the Israeli building code and continue to be maintained in order to protect Israeli civilians. While the regulations being put into the building code was instigated by a need to provide protection against chemical warfare, the importance of regulating the integration of protected spaces into buildings remains and extends into blast protection.

Protecting a building from explosions is now an integral part of a building's design. It has forced Israeli structural engineers to design "out security risks while preserving the essence of the design (Einstein, 2003)". Israeli society can not have all of its buildings feel like concrete fortified structures even if they really are. Figures 2.5, 2.6, and 2.7 are examples of Israeli blast designed structures, versus the current blast designed structures in the United States.

Figure 2.5. Example of Israeli structural blast design (Einstein, 2003).

Figure 2.6. Example of Israeli structural blast design (Einstein, 2003).

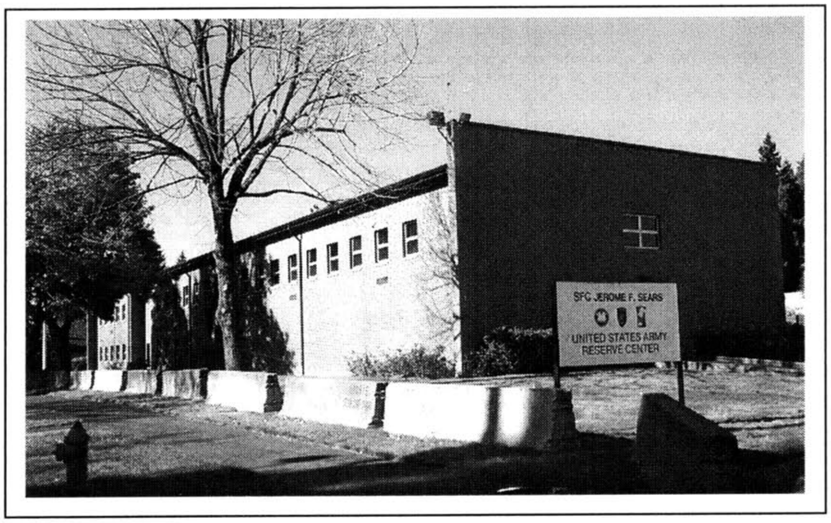

Figure 2.7. Example of traditional American structural blast design (Einstein, 2003).

Since September 11, 2001 and the destruction of the World Trade Center due to terrorism, it has become apparent that the U.S. must also change its approach to protecting its citizens from explosions. Israel has successfully integrated blast protection into its society and buildings as a result of years of terror and threats. By making blast protection a permanent part of the building code, professionals have been forced to come up with new ways of designing buildings that protect their inhabitants but still maintain people's quality of life (Einstein, 2003). Because of the increased and continuing threat to the United States it is clear that structural engineers here too will have to make blast design an integral part of all structures. The more this mentality is put into practice the sooner blast design will be able to coexist with current structural design considerations such as architecture, sustainability, usability, and economics.

3. Design Principles for Protection of Structures

Designing a building to withstand blasts includes more than just hardening the structure. A lot of thought must go into the design to take into account more conceptual design aspects such as preventing an attack to begin with, maintaining a large stand-off distance incase of an attack, and designing the building so that it will remain standing in the case of localized damage. While discussing the principles of blast design I will focus on the protection of structures in the event of a close range bomb, most similar to present terrorist activities. This includes explosions due to suicide bombers near or inside a building, truck and car bombs near or driven inside a building, and package bombs.

Preventative Measures

The first step in making a building blast resistant is to try to prevent a terrorist attack from occurring in the first place. This can be accomplished by making a terrorist's job as difficult as possible. There is less of a chance of a terrorist targeting a building if he feels that the chance of success is small (Mays and Smith, 1995). Preventing access into the building is the first way to deter a terrorist. Heavy security as well as physical barriers can make entering a building difficult. Also, if space allows, spreading out a complex makes an effective terrorist attack more difficult to execute. A bomb in one location will have less overall effect on a building if all of the building's assets are spread out (Mays and Smith, 1995). This strategy is only effective for buildings that are not set in the middle of the city and can afford to expand outwards. In addition, sites that could be possible terrorist targets such as intelligence or defense buildings should be kept anonymous if possible (Mays and Smith, 1995)

The next thing to consider is how to disguise the critical parts of a building. If the energy from a bomb is wasted on an unimportant part of the building the consequences of an attack can be much less severe (Mays and Smith, 1995). It is important to prevent the placement of explosives near sensitive structural members. Ways of accomplishing this include hiding columns and other important structural members, especially near the ground floors of a building where the structural members are the most critical (Eytan, 2003). By using tinted glass you can hide the exact structural system from outside viewers as well.

One of the most important principles with blast design is to keep a large stand-off distance between the building and the potential blast. The strength of a blast decreases in relation to the cube of the stand-off distance from the explosion ((Mays and Smith, 1995) refer to chapter 4 for more details), this indicates that as you get farther away from the blast the intensity of the peak pressure dies off substantially. Smith and Hetherington illustrate this by saying that, "keeping vehicle bombs away from your structure is probably the single, most cost-effective device you can employ".

Hardening of the Structure

Then next principle in structural blast design is to harden the structure in the case that a blast does take place. The main way to harden a structure is to design the structure with a lot of ductility integrated throughout the system. Explosions generate an enormous amount of energy and the role of the structure's ductility is to absorb this energy. As a result steel and reinforced concrete are the best materials to use in a blast resistant structure. Other structural concerns include how the floors are attached to the rest of the structural frame. Floors need to be securely tied to the frame and be able to withstand stresses in the direction opposite the normal gravity loads (Mays and Smith, 1995). Explosions cause a strong uplift pressure that can dislodge floors from their supports if they are not tied securely. Floors many times work as a diaphragm that carries lateral load in a structure, as a result, if the floor is removed from the rest of the structural system progressive collapse can ensue (Mays and Smith, 1995).

Glazing is a major concern when hardening a building. Because normal glass is a brittle material it has almost no chance of remaining intact during an explosion. Secondary injuries and damages due to shards of glass flying at high speeds through the air can be very severe and are usually very frequent. There are several techniques for increasing the blast resistance of glazing. These techniques in combination with dynamic design of the structural frame can greatly increase the performance of glazing in an explosion (Mays and Smith, 1995). These techniques include:

- Using blast resistant glass.
- Applying polyester anti-shatter film to the inside surface of the glass.
- Installing bomb blast net curtains inside of the glass (to prevent the shards from entering the interior of the building).
- Installing blast resistant glazing inside the existing exterior glazing (Mays and Smith, 1995).

In order to further protect the occupants of a building it is important to design the building so that it is at least three bays wide (Mays and Smith, 1995). This provides space so that in the case of an explosion people can move away from the exterior of a building. Also, the center area of the structure should be designed as a concrete core. This concrete core can be designed as a hardened area that can be used as protected space for the building occupants.

In addition to all of these design techniques Eytan has developed a method of hardening a structure in layers. Hardening a structure in layers is effective because it ensures that the failure of one hardening layer will not lead to the catastrophic failure of the structure due to redundancy of the protective systems. The first hardening layer is the layer farthest away from the structure. The role of this layer is to prevent a terrorist's forced entry into a building (like a vehicle crashing into the building), and to protect the rest of the structure from a large explosion outside of the building.

The second layer is the envelope of the external structural system. The role of this layer is to prevent a terrorist's forced entry further into the building. It should shield the rest of the building from flying debris and shrapnel from a bomb. In addition, it should protect main structural elements from close range explosions. And, of course it should further protect the structure from the pressure wave created by a bomb outside of the building.

The third layer, is the layer that protects the internal structural system. This layer needs to protect the building from all of the things that the second layer is designed to protect. In addition, this layer must be able to protect the structure from explosions detonated inside of the structure.

Preventing Progressive Structural Collapse

After all of these other hardening techniques are used the most important thing is that a building be designed so that progressive structural collapse does not occur in the case of severe structural damage. As we have seen in events such as the World Trade Center bombing, as destructive as the explosion itself was, the greatest damage and loss of life was due to the eventual collapse of the structure that was as a result of structural damage. Preventing structural collapse is necessary so that as many people as possible can get out of a building safely after an attack. If progressive collapse occurs it magnifies the effect of any terrorist event and allows a terrorist to accomplish more damage then they ever could on their own. There are several guidelines that should be kept in mind in order to design a building to be protected from structural collapse (Eytan, 2004):

- Create many different load paths and redundancies within a structure so that it will not collapse in the case of several columns of critical members being damaged or destroyed.
- Design floors to withstand reverse loading (as mentioned previously).
- Design connections to withstand greater loading (as mentioned previously).
- Design critical members, such as lower floor columns, to withstand a higher blast loading to prevent severe damage to the most important members.
- Design critical members to be surrounded by energy absorbing materials or members.

Some other techniques (developed by Eytan) for protecting columns inside a structure include: using composite material shields around the column with an air gap between the shield and the column. Columns can be designed to be part of heavy walls so that they will not experience local failure. The strength of the columns is improved if they are designed as part of a moment frame where the connections can carry a large amount of moment and dissipate a lot of energy. Also, columns should be designed to withstand a greater buckling load in case its unsupported length is increased by damage to adjacent beams, joists, and slabs.

4. Structural Response to Blast Loading

> "When a bomb is detonated, very high pressures are generated which then propagate away from the source....When the wave strikes the target, a transient load is applied to the structure (Smith and Hetherington)."

Blast Characteristics and Behavior

When an explosive is detonated an immense amount of energy is generated which causes the explosive gas to expand forcing the surrounding air out of the space that it previously occupied. This produces a layer of compressed air which forms the blast wave. The blast wave contains most of the energy generated by the explosion (Smith and Hetherington, 1994) and propagates quickly in a hemispherical form away from the blast site (see Figure 4.1).

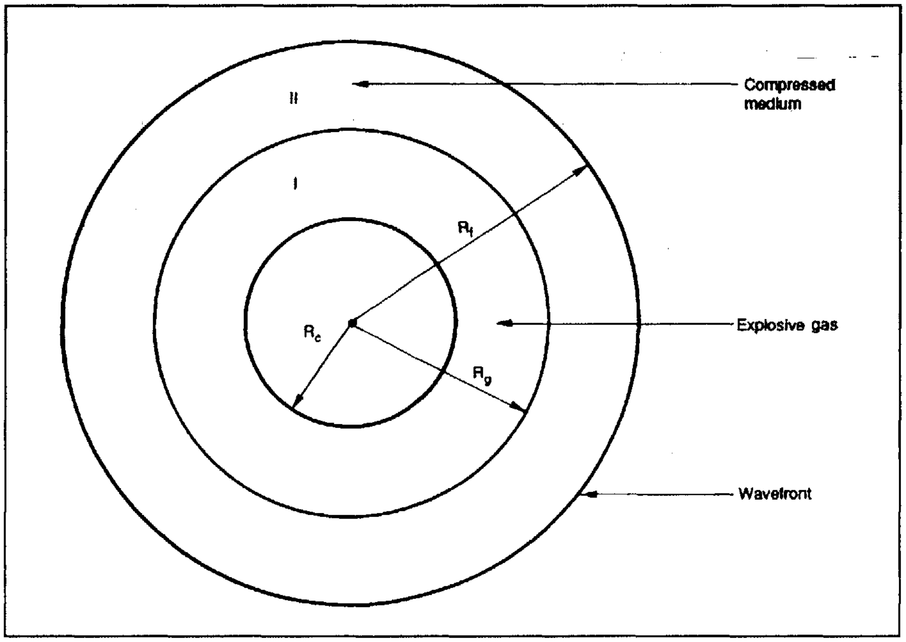

Figure 4.1. Schematic of a blast (Smith and Hetherington, 1994).

At the blast wavefront (at radius R_f), the pressure is known as the peak static overpressure, p_s, this quantity is given by:

for $p_s > 10$ bar
$$p_s = \frac{6.7}{Z^3} + 1 \qquad (4.1)$$

for $0.1 < ps < 10$ bar
$$p_s = \frac{.975}{Z} + \frac{1.455}{Z^2} + \frac{5.85}{Z^3} \qquad (4.2)$$

where Z is the scaled distance and it is given by:

$$Z = \frac{R}{W^{1/3}} \qquad (4.3)$$

Here R is the distance from the center of a blast in meters, and W is the mass of the explosive given in kilograms of TNT. Below, Table 4.1, lists values that are used to convert different types of explosives into kilograms of TNT. The first range of p_s given above is for the peak overpressure closer in to the center of the blast, where the second range is for when the peak overpressure is farther away from the center of the blast. Other equations have also been developed to estimate the peak overpressure. The equations for the close range tend to very the most because of the complexity of the gas movement close to the center of the blast (Smith and Hetherington, 1994).

Explosive	*Mass Specific Energy* *Q_x (kJ/kg)*	*TNT Equivalent* *(Q_x/Q_{TNT})*
Amatol 80/20 (80% ammonium nitrate, 20% TNT)	2650	0.586
Compound B (60% RDX, 40% TNT)	5190	1.148
RDX (Cyclonite)	5360	1.185
HMX	5680	1.256
Lead azide	1540	0.340
Mercury fulminate	1790	0.395
Nitroglycerin (liquid)	6700	1.481
PETN	5800	1.282
Pentolite 50/50 (50% PETN, 50% TNT)	5110	1.129
Tetryl	4520	1.000
TNT	4520	1.000
Torpex (42% RDX, 40% TNT, 18% Aluminum)	7540	1.667
Blasting gelatin (91% nitroglycerin, 7.9% nitrocellulose, 0.9% antacid, 0.2% water)	4520	1.000
60% Nitroglycerin dynamite	2710	0.600

Table 4.1. Conversion factors for different types of explosives (after Smith and Hetherington, 1994).

The velocity of the wavefront is known as U_s, and the maximum dynamic pressure is known as q_s (Smith and Hetherington 1994). All of these quantities are given by the equations below:

$$U_s = \sqrt{\frac{6p_s + 7p_o}{7p_o}} \cdot a_o \tag{4.4}$$

$$q_s = \frac{5p_s^2}{2(p_s + 7p_o)} \tag{4.5}$$

where:

p_o = Ambient air pressure ahead of wave

a_o = The speed of sound in ambient conditions

Another important quantity with respect to blast waves is the duration of the positive phase, T_s, which is the amount of time after an explosion when the pressure is greater than the ambient pressure. This value is important because in the design process it is compared to the natural frequency of a building to determine the structures response to the blast. Ts can be determined from the graph in Figure 4.2 below where different parameters are plotted against Z. And i_s, the specific impulse of the wave, which is the area under the pressure-time curve from time ta to the end of Ts. A typical pressure-time curve for a blast is shown in Figure 4.3 below.

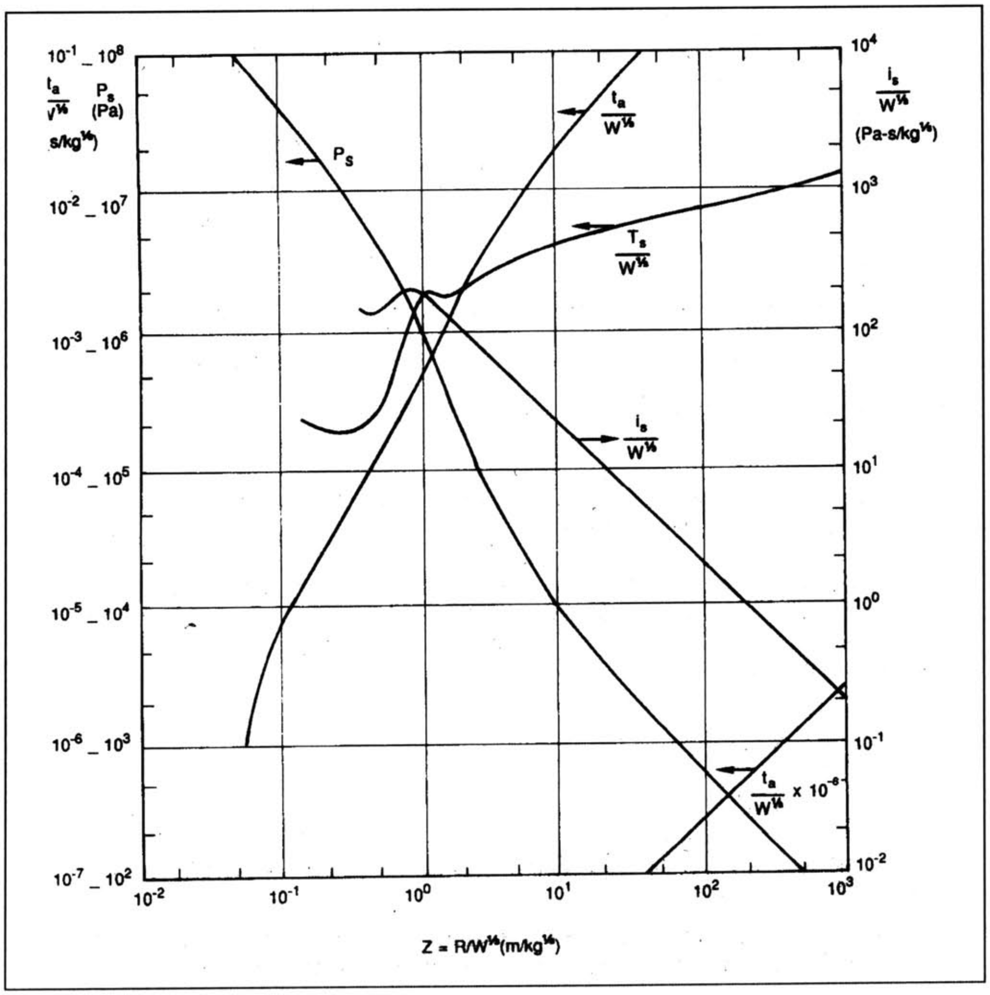

Figure 4.2. Blast wave parameters (Smith and Hetherington, 1994).

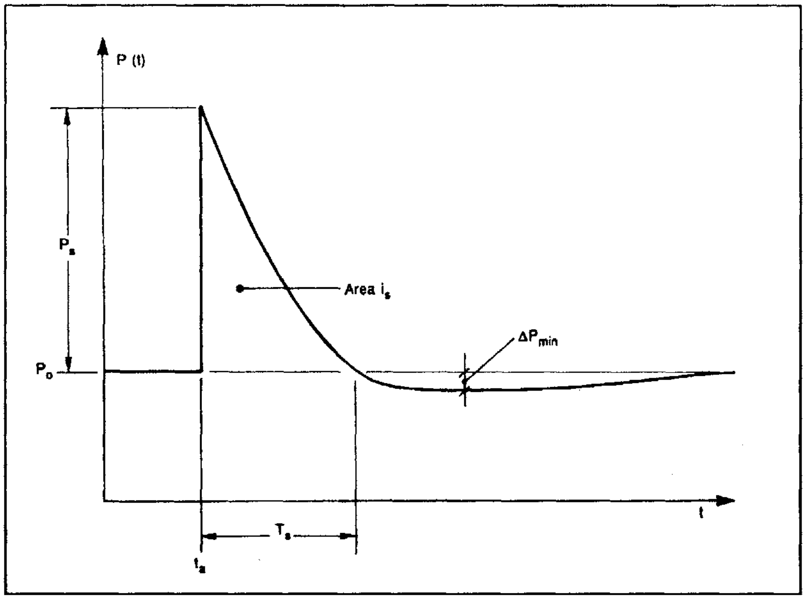

Figure 4.3. Blast wave pressure-time profile (Smith and Hetherington, 1994).

When a blast wave comes in contact with an object more dense then its original transmitting medium it reflects off of it. When a blast wave is reflected, the air molecules, that are already compressed, are compressed yet again as they are forced to come to a stop at the solid object. This results in a new blast wave that has an even greater over pressure than the original wave (Smith and Hetherington, 1994). This is why, as mentioned previously, keeping a building's facade smooth is important when considering blast loading. This behavior also means that closely spaced city streets cause a "funneling effect" for the blast wave, and it will take a longer distance for the wave to drop off than if it was in an open space (Mays and Smith, 1995). For zero incidence, the peak reflected pressure, p_r, is given by:

$$p_r = 2p_s + (\gamma + 1)q_s \tag{4.6}$$

where :

$$\gamma = \frac{C_p}{C_v} = \text{Specific heat ratio}$$

$$q_s = \frac{1}{2}\rho_s u_s^2 \qquad (4.7)$$

where:

$$\rho_s = \text{The density of the air}$$

and u_s is the particle velocity behind the wavefront, given by:

$$u_s = \frac{a_o p_s}{\gamma p_o}\left[1 + \left[\frac{\gamma + 1}{2\gamma}\right]\frac{p_s}{p_0}\right]^{-\frac{1}{2}} \qquad (4.8)$$

Equation 4.6 can now be rewritten as:

$$p_r = 2p_s\left[\frac{7p_o + 4p_s}{7p_o + p_s}\right] \qquad (4.9)$$

Structural Response

Two things need to be considered when determining the response of a structure due to blast loading. The behavior of the structure when modeled as an elastic dynamic single degree of freedom (SDOF) system, and how T_s, the positive phase duration of the blast load, relates to T_n, the natural period of the structure (Mays and Smith, 1995).

Positive Phase Duration versus Natural Period

According to Smith and Hetherington (1994) as well as Mays and Smith (1995) by comparing the positive phase duration of an explosion and the natural period of a structure you can categorize how the structure will respond to the loading.

If T_s is substantially longer compared to T_n then the response of the structure can be categorized as quasi-static. The maximum deflection has occurred long before the force has decayed substantially. In this case the displacement is a function of the stiffness and the peak blast load, F.

If T_s is much shorter than T_n then the response can be represented by an impulse loading. In this case the blast has finished acting before the building has had a chance to deflect at all because most deformation occurs at times later than T_s.

When T_s is very similar to T_n the structure acts dynamically. This behavior is similar to how a building is excited by an earthquake that has a period close to its natural period. In this case the equation of motion of the structure must be determined using dynamic analysis. This is discussed later in the chapter for a single degree of freedom system.

Response Limits

A graphical representation of the three response regions discussed above, quasi-static, dynamic, and impulsive, can be developed by determining the asymptote limits of quasi-static loading and dynamic loading (see Figure 4.4 on the following page). For each case the work done on the structure by the loading is equated to the strain energy developed by the deforming structure (Mays and Smith, 1994).

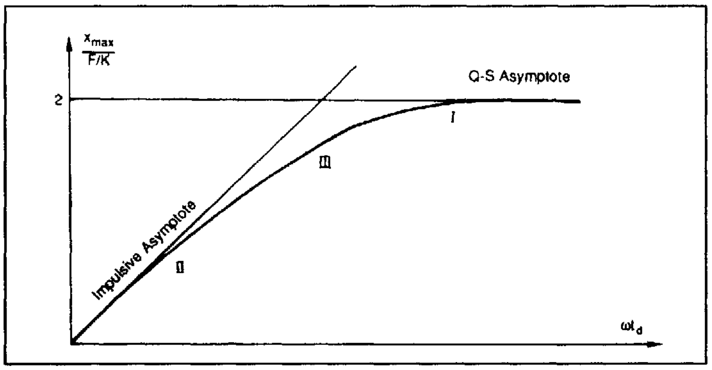

Figure 4.4. Response of system for all three regions (Smith and Hetherington, 1994).

The work done on the structure is:

$$W = Fx_{\max} \tag{4.10}$$

The strain energy developed by a structure as it deforms is given by:

$$U = \frac{1}{2}Kx_{\max}^2 \tag{4.11}$$

By equating equations 4.10 and 4.11 you get:

$$\frac{x_{\max}}{F/K} = 2 \tag{4.12}$$

Here F/K is the displacement that would occur if F was a static load. This results in a value of 2 for the upper limit of the response, in this case quasi-static, and can be plotted as the upper asymptote (Smith and Hetherington, 1994).

In order to find the second asymptote, the impulsive asymptote, a different principle is used. When an impulsive load acts on a structure it causes an instantaneous velocity change, and as a result the structure takes this kinetic energy and converts it to strain energy as it deforms (Smith and Hetherington, 1994). The instantaneous velocity given to a structure by an impulse load is:

$$v = \frac{I}{M} \tag{4.13}$$

Where:

I = The impulse generated by the load, given in eqn. 4.18

As a result the kinetic energy imparted on the structure by the impulse is:

$$KE = \frac{1}{2}Mv^2 = \frac{I^2}{2M} \tag{4.14}$$

Equating the kinetic energy to the strain energy we get:

$$\frac{1}{2}Kx_{\max}^2 = \frac{I^2}{2M} \tag{4.15}$$

Inserting I in terms of F and rearranging we get the impulsive asymptote:

$$\frac{x_{\max}}{F/K} = \frac{\frac{1}{2}FT_s}{(F/K)\sqrt{KM}} = \frac{1}{2}\omega T_s \tag{4.16}$$

Determining these two asymptotes allows us to draw the entire response of the structure shown in Figure 4.4 on the previous page.

SDOF System

The dynamic response of a structure subjected to a blast loading, to be used when evaluating the dynamic region of a structure's response, can be modeled as a single degree of freedom (SDOF) elastic system subjected to an idealized blast load. The blast load is represented by a triangular pulse that has the duration T_s and a peak force F (Mays and Smith, 1995). This force is given by:

$$F(t) = F\left(1 - \frac{t}{T_s}\right) \qquad (4.17$$

The impulse generated by this loading is:

$$I = \frac{1}{2} F T_s \qquad (4.18)$$

If we write the equation of motion for this system from the free body diagram shown in Figure 4.5 below, we get:

$$M \ddot{x} + Kx = F(t) \qquad (4.19)$$

Where:

M = The mass of the structure

K = The stiffness of the structure

F(t) = The force applied to the system, given above in eqn. 4.17

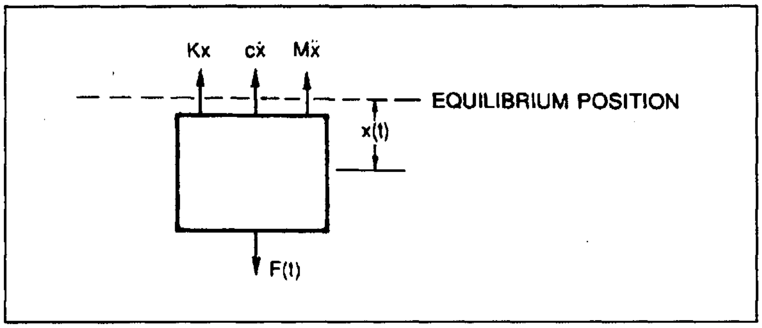

Figure 4.5. SDOF free body diagram (Smith and Hetherington, 1994).

By solving the differential equation of motion we get the solution:

$$x(t) = \frac{F}{K}(1 - \cos \omega t) + \frac{F}{KT_s}\left(\frac{\sin \omega t}{\omega} - t\right) \qquad (4.20)$$

where: $\omega = \sqrt{K/M}$

In order to get x_{max}, the worst case displacement for the structure we differentiate eqn. 4.12 to get the velocity equation and then set it equal to zero. The maximum displacement will occur when the velocity is zero (Smith and Hetherington, 1994).

$$0 = \omega \sin \omega t_m + \frac{1}{T_s} \cos \omega t_m - \frac{1}{T_s} \qquad (4.21)$$

Here t_m is the time at which x_{max} occurs, and can be solved for from this equation (Smith and Hetherington, 1994).

5. Connor Center for the Performing Arts Blast Analysis and Design

Introduction

In April, 2004 a replacement for the Fleet Pavilion in Boston was designed by Michael Chen, Ray Kordahi, Krystopher Wodzicki, and me. The replacement is known as the Connor Center for the Performing Arts (CCPA), and when built it will be a large venue for different arts events in the Boston area.

The CCPA will be a high profile structure within Boston, and in addition it will house events that concentrate thousands of people into one location at one time. These factors make the building a very possible target for terrorists. It is important too analyze this structure within this context in order to protect the thousands of people who will use this building, as well as the large investment of the building owner. In the remainder of this chapter, the current design for the CCPA with respect to blast protection is analyzed using the design principles discussed previously in chapter 2, and changes in the design that should be made in order to design this structure to withstand a blast are discussed.

Background

The current Fleet Pavilion structure (see Figure 5.1 below) is an open-air amphitheater on the south Boston waterfront that seats approximately 5,000 people. It is used mainly for concerts in the summertime. The structure itself is a fabric-covered frame that sits on top of asphalt, where folding chairs are used as seating for the audience. Our task as structural engineers was to design a structure to be used as a replacement for the current structure. The structure we were to design would have to be suitable for year round use, have a similar if not larger seating capacity, and be a unique landmark structure.

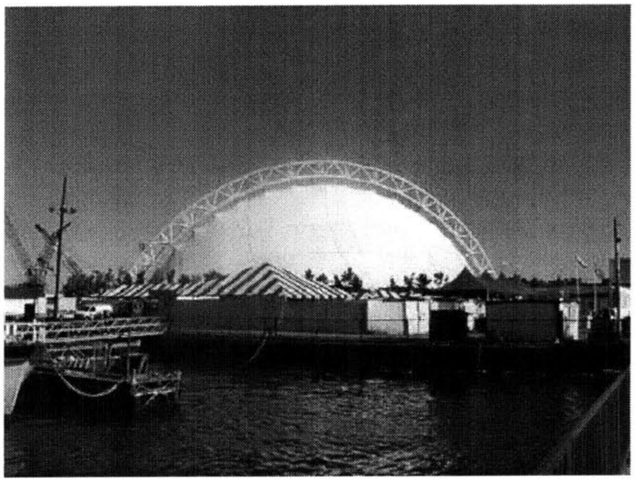

Figure 5.1. Current Fleet Pavilion (Chen et al., 2004).

The new design for the performing arts center is an aluminum shell design (see Figure 5.4 on page 33), please refer to Chen et al. (2004) for a detailed design of the structure. The main structure sits on a man made "island" right off the coast of downtown Boston. The island will be constructed out of a concrete pad supported by piles in the water. The island will have the main performing arts structure, a smaller structure for concessions, an outdoor amphitheater, and two pedestrian bridges to connect the island to the mainland. See Figures 5.2 and 5.3 on the following page for the layout of the island.

The main structure itself can be broken up into the exterior structural system and the interior structural system which work independently from each other. The exterior system is a shell system made up of a rib skeletal system (see Figure 5.5 on page 33) covered by an aluminum shell. The rib system is made up of extruded aluminum pipes, a steel perimeter pipe, and steel columns. The system has been divided up into the

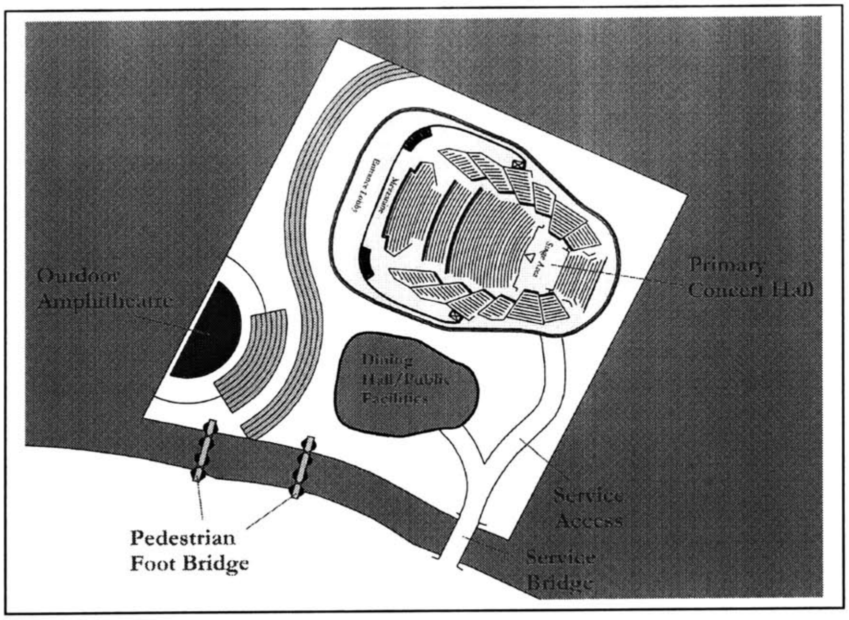

Figure 5.2. Site layout for CCPA (Chen et al., 2004).

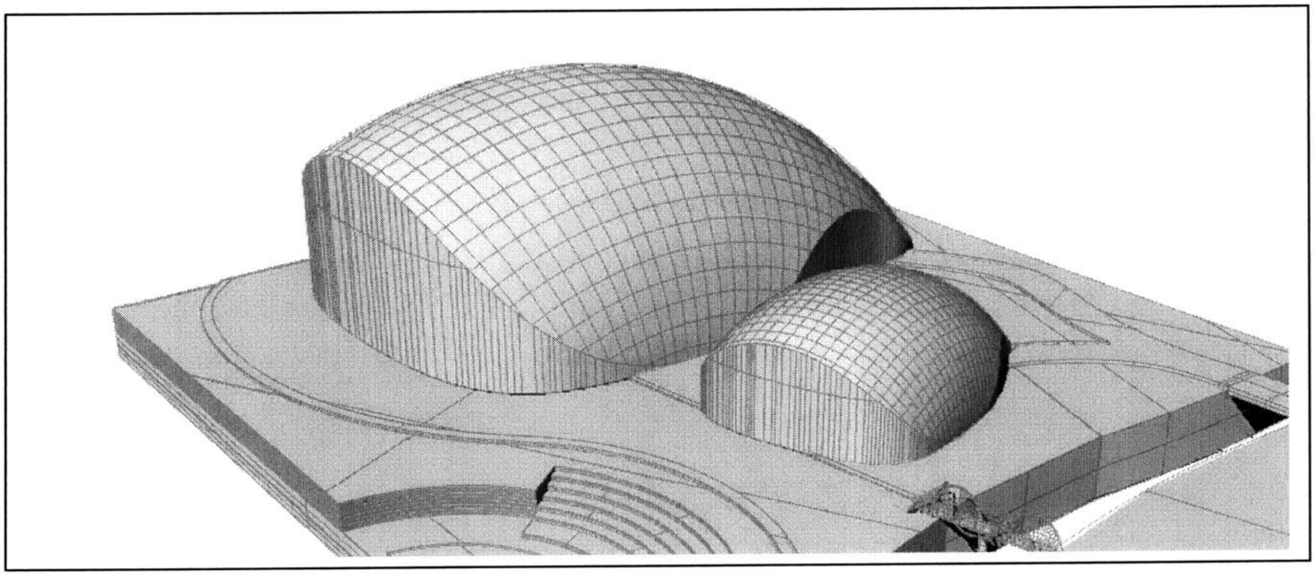

Figure 5.3. Site rendering for CCPA (Chen et al., 2004).

primary ribs which run transversely across the shell, and the secondary ribs which run longitudinally across the shell. The aluminum pipes are made up of several cross sections. The primary ribs have a cross section with a nine inch diameter. The thickness of the pipe wall varies from one quarter of an inch to an inch, depending on where the rib is located. The pipes near the front and back edges tend to have larger thicknesses. The secondary ribs have a cross section with a six inch diameter, and a wall thickness that varies from one quarter of an inch to three quarters of an inch. The aluminum pipe ribs connect to a steel pipe that runs around the perimeter of the shell. This pipe is nine inches in diameter and has a wall thickness of a half an inch.

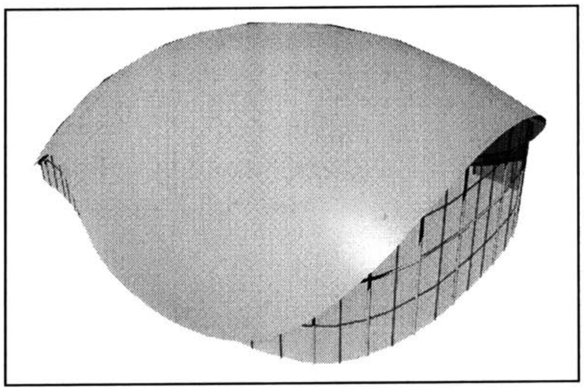

Figure 5.4. Aluminum shell design (Chen et al., 2004).

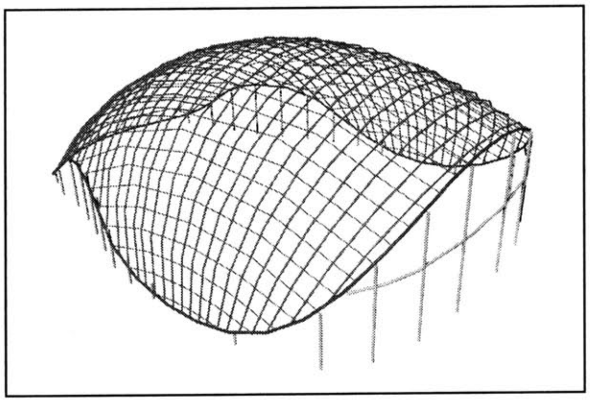

Figure 5.5. Rib structural system (Chen et al., 2004).

The interior system is a traditional beam and column design made with steel wide flange members (see Figure 5.6).

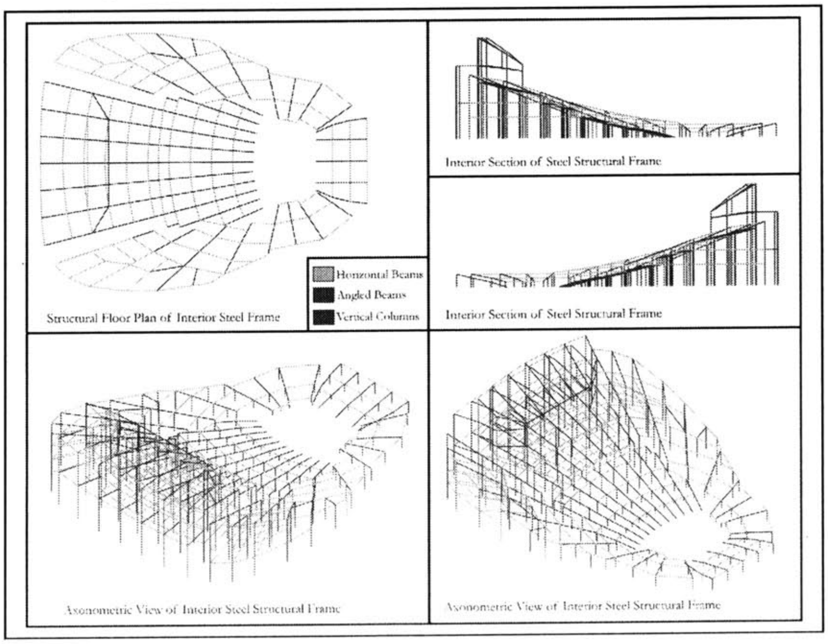

Figure 5.6. Interior design (Chen et al., 2004).

All of the connections in the structure are designed to be moment carrying connections.

Blast Analysis

Preventative Measures

The CCPA design has characteristics that help protect it from blasts as well as characteristics that make it more vulnerable to blasts. The fact that the structure is on an island is both good and bad with respect to blast protection. Being on an island allows the structure to maintain a safe stand-off distance from any vehicle that would attempt to approach the structure. Also, having two pedestrian bridges limits the flow of the people on to the island and creates a situation where people are more easily monitored. At the same time, being on the water exposes the structure to bombings from approaching boats. If an explosion were to occur outside of the structure the blast would dissipate more quickly and be magnified by nearby buildings less than if the structure was in the middle of the city.

Another drawback to the structure is that the exterior has a very "naked" structural system (see Figure 5.7 on the next page). The modular panel system of the aluminum traces out the pattern of the internal ribs and allows outside observers to really see how the structural system is set up. This exposes the structure to attacks that can target critical parts of the structural system. The interior is not as vulnerable to this threat as the outside is. The interior is a very hidden from the outside view and most of the beams and columns will be hidden within walls for aesthetic purposes.

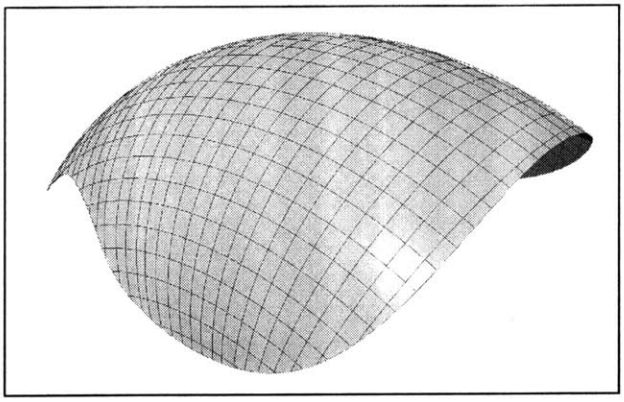

Figure 5.7. Aluminum roof design (Chen et al., 2004).

Hardening

This structure does not have many characteristics which make it hardened to blast loading. The structure has a substantial amount of glazing on the front and sides of the building (see Figure 5.4 on page 33). This makes the structure very dangerous in the event of a blast. Thousands of injuries could occur from glass fragments alone. A good thing is that the rest of the structure is very ductile. The entire shell is made out of aluminum and the interior out of steel. This can dissipate a lot of energy in the case of an explosion.

Progressive Collapse Analysis

A SAP 2000 model of the interior and exterior of the building was used in order to determine whether the structure would collapse in the case of extreme damage to critical structural members.

The exterior system survived fairly well to damaged members. By analyzing the undamaged exterior structure it is apparent that most of the load is carried by the perimeter beam near the columns, and the columns themselves (see Figure 5.8). The light gray rectangles are the areas of the structure that take most of the load.

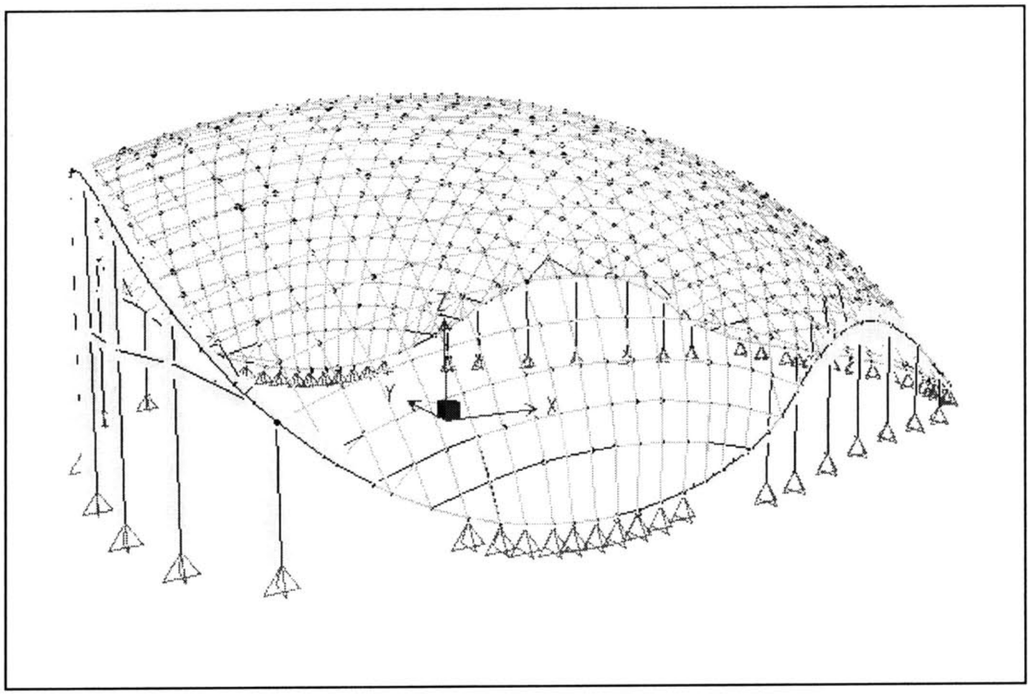

Figure 5.8. Axial load in undamaged exterior shell.

This analysis indicates that the exterior will be most sensitive to damage along the columns and the perimeter beam. This is due to the fact that the shell part of the structure distributes the load very evenly across the members. Even if the shell were to be damaged it has so many redundancies built in that the loads would just be redistributed and it would remain standing.

A simulation was run where the two main front columns were removed as if damaged in an explosion (see Figure 5.9 on the next page). In this case the maximum displacement was .9 ft, this occurred where the columns were removed. Besides this there was minimal excessive deformation to the shell. This indicates that the shell could still support itself even with these members destroyed.

Next the model was run where the three front cross beams were knocked out. This is critical because the two front columns are approximately 75 feet long without the cross beams, an unbraced length that is very difficult to design for. The results of this simulation are shown in Figure 5.10 on the next page. While the maximum displacement along the structure is approximately .007 ft, which is minimal, the columns are still supporting too much load for their current unbraced length.

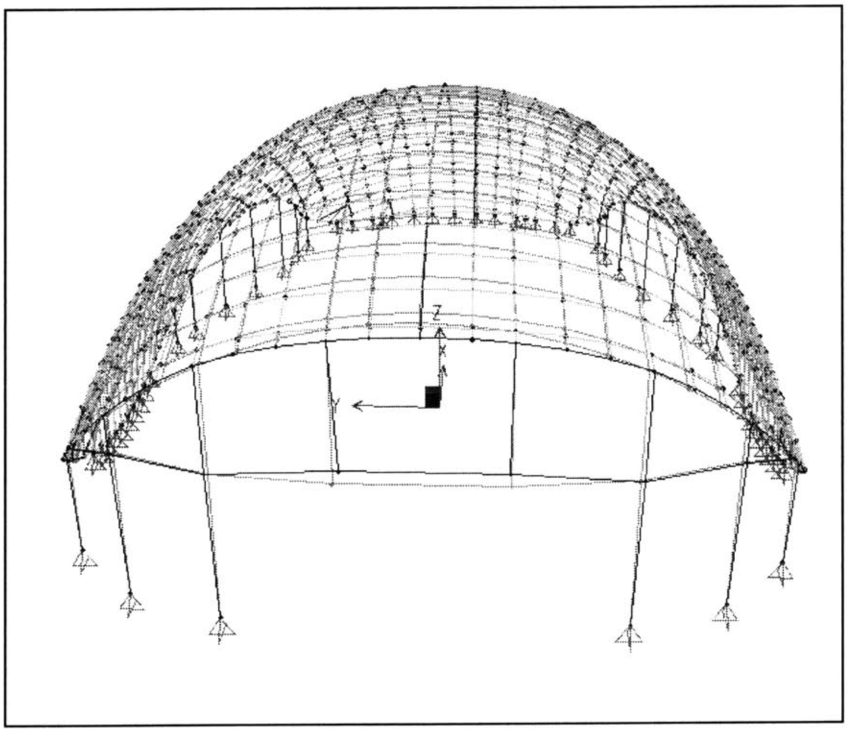

Figure 5.9. Deformation of shell with front columns removed.

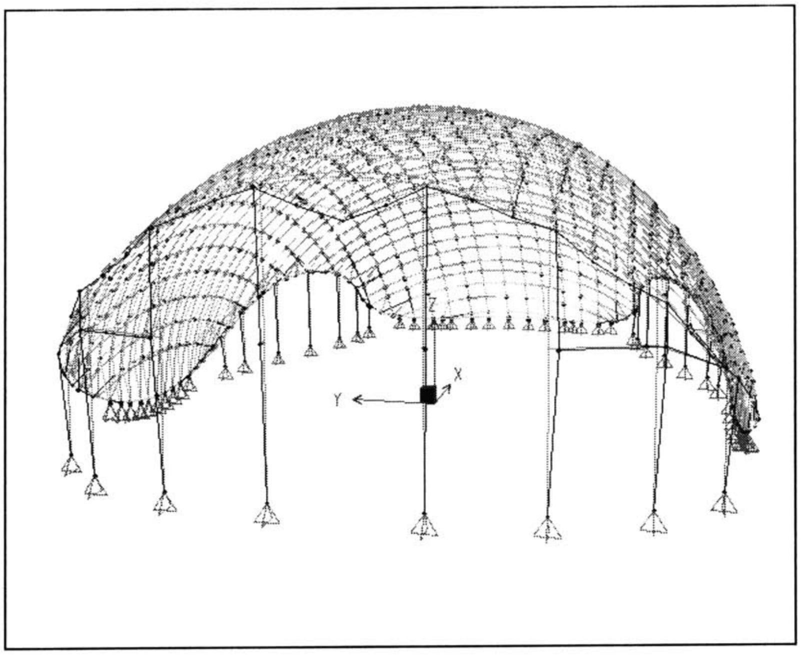

Figure 5.10. Deformation of shell with front cross beams removed.

The interior structural system also survives fairly well with localized damage to critical structural members. This is due to the numerous members and bays creating structural redundancies and the fact that the system is broken up into three independent sections. This allows damage in one region to not affect the other regions. First, by analyzing the undamaged structure, it is clear that the most load is carried by the columns under the balcony area and the cross beams at the front of the balcony (see Figures 5.11 and 5.12).

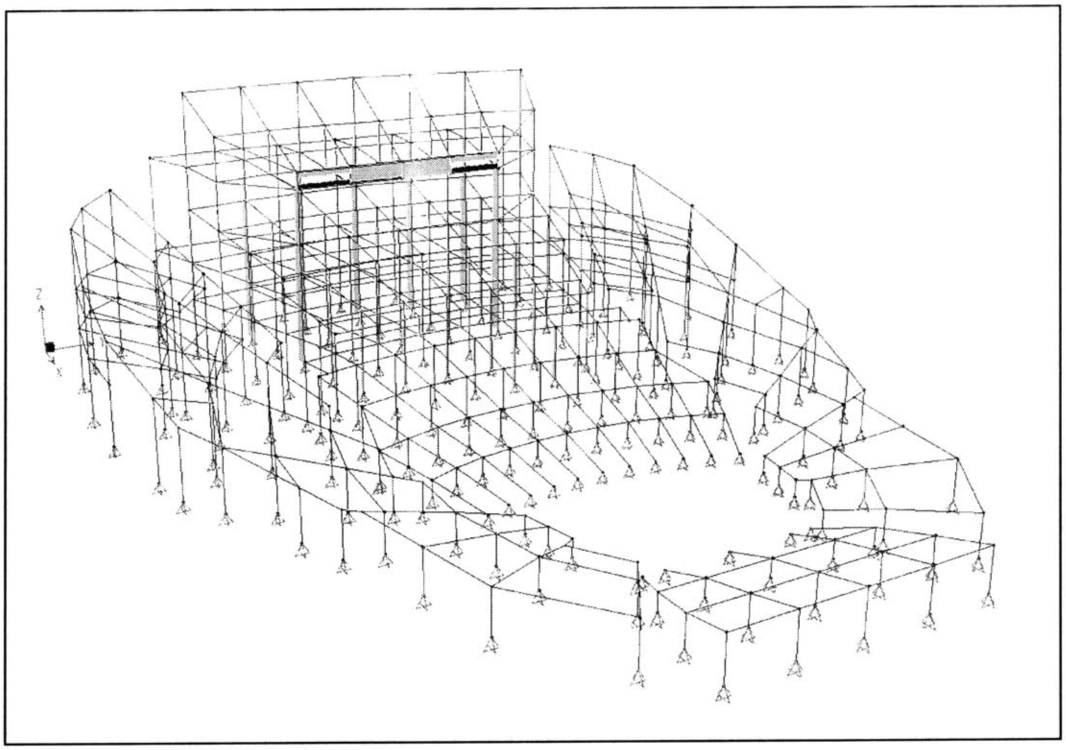

Figure 5.11. Axial load in interior system.

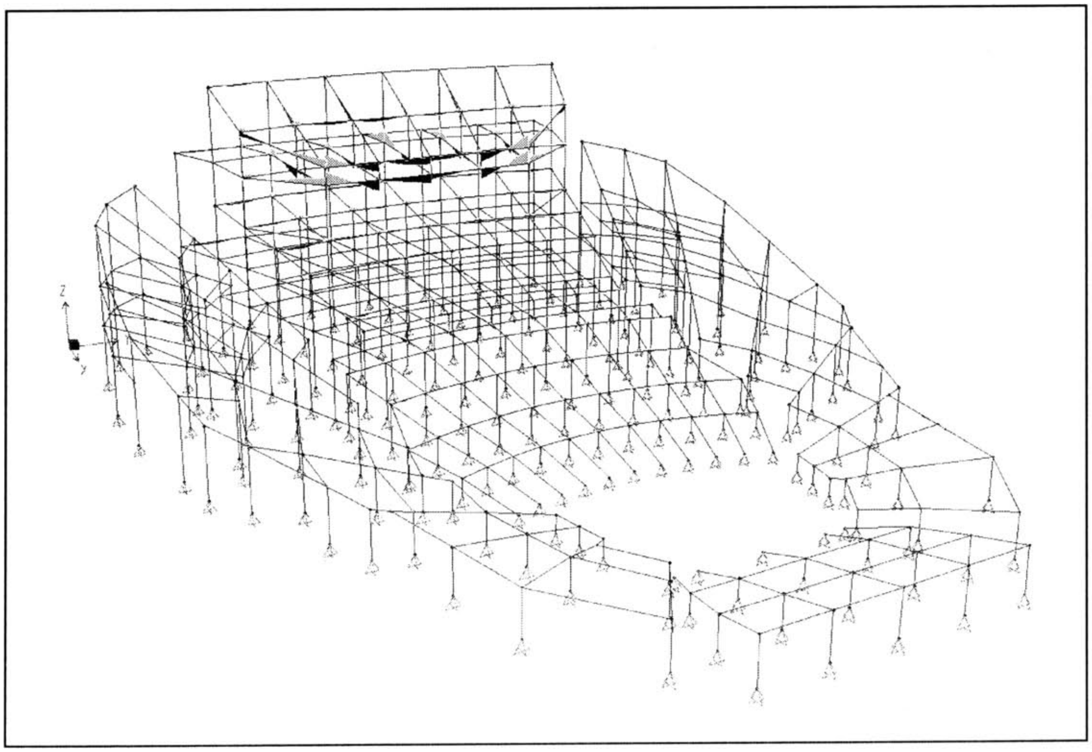

Figure 5.12. Moment in interior system.

A simulation was run where bottom columns underneath the balcony were removed. The results are shown in Figure 5.13 below. There is a maximum deflection of 2 inches and this occurs on top of the balcony, directly above where the columns have been removed. Axial forces in the surrounding remaining columns increase from about 75 kips to 120 kips, indicating the redistribution of load.

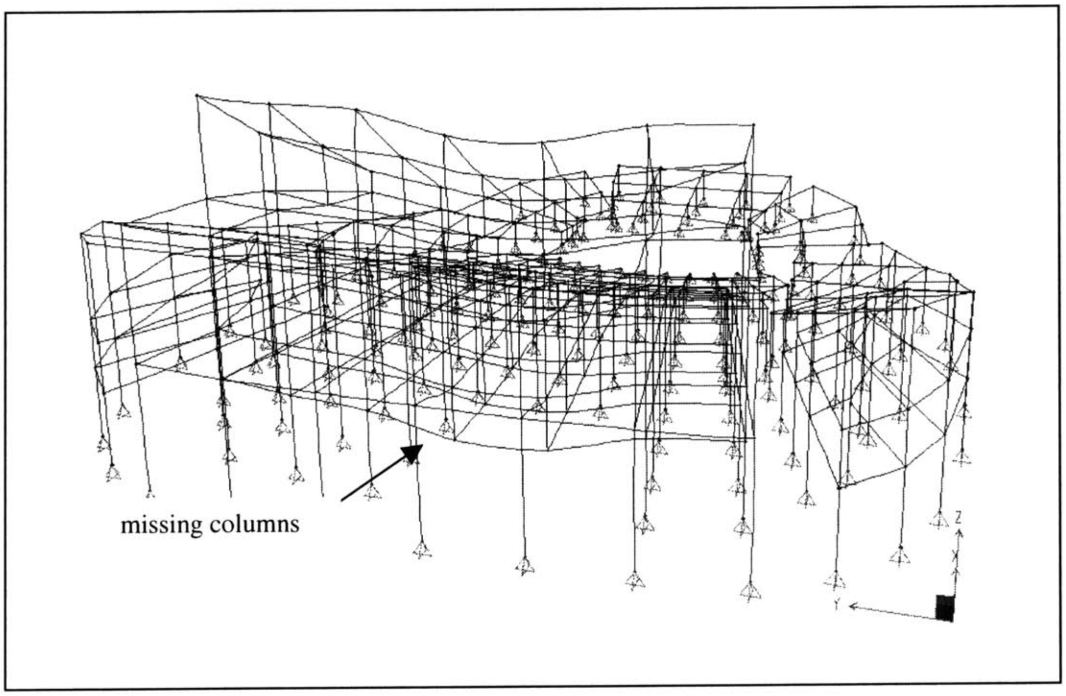

Figure 5.13. Deformation of structure after removal of interior columns.

The amount of damaged done to the structure was increased and the model was run again. The results of this simulation are shown in Figure 5.14. This time the deformation at the top of the balcony is approximately 5 inches while underneath the balcony, where the columns have been removed, the deformation is 7 inches. This time the loads in the remaining columns go up to 200 kips from their original 75 kips.

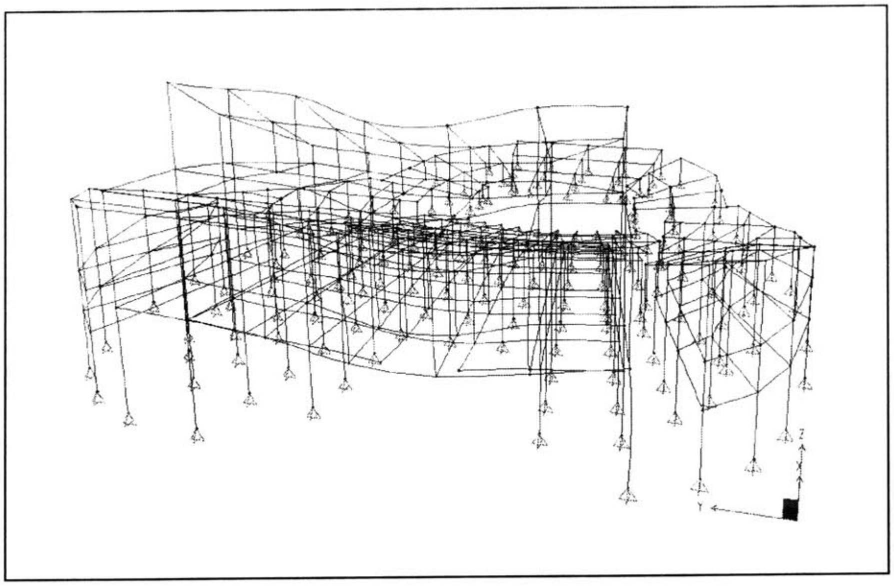

Figure 5.14. Deformation of structure after removal of many interior members.

Blast Design

With the structures current design CCPA is minimally prepared to handle an explosion. The following are design modifications that I suggest for the CCPA design.

Preventative measures

- Security checks at all pedestrian bridges leading on to the island to make it more difficult for a terrorist to get into the building.
- Patrol boats during events to prevent a boat approaching with explosives.
- Video monitoring of the underwater piles. The piles under the island add another dimension of the structure that can be targeted.
- Design the shell to have a reinforced concrete exterior instead of aluminum panels. This will give the look of a smooth exterior and hide the structural details from outside viewers.

Hardening

- Use blast-resistant glass or laminated glass for all of the glazing surrounding the facade.
- Design the exterior shell as a first layer of hardening. Because it works independently from the interior system, if the exterior was damaged by an explosion the structure would still have the interior standing. The reinforced concrete for the shell (as indicated above) can be designed to dissipate more energy then the current aluminum design would.

Progressive Collapse Prevention

Due to the fact that the exterior is a shell there are many redundancies within the structure. If any part of the shell were to be damaged the loads could be quickly redistributed and collapse of the exterior would be unlikely. The columns in the front facade are fairly critical to the structure. They take a lot of the load and are very slender. In addition, they are right behind the glazing and are hard to hide from outside viewers. These columns need to be able to withstand an explosion and the connections between the beams and the columns along the glass need to be designed to dissipate a large amount of energy. It is important that the beams and columns remain intact because the unsupported length of the front columns is virtually impossible to design for, due to buckling, without the cross beams.

From the analysis of the interior above it is apparent which of the members of the interior system are critical. The members in the area under the balcony are the most critical and could cause the most damage to the overall structure if they were destroyed. These critical members should be designed with extra capacity and be able to withstand a blast. In addition they need to be designed for more than twice their normal capacity in case of redistribution of loads due to loss of other members.

6. Conclusion

Terrorism is a daily threat that continues to spread throughout the world. Places such as the United States, that have only had to deal with terrorism on extreme occasions now have to consider terrorism when determining daily policies. These daily policies include the design of most public buildings. Blast design for structures was only used for military and extremely sensitive buildings until now. As a result, structural engineers have not had to mesh blast design with other aspects of structural design. Because blast design was only used for very few, specific buildings it was acceptable for blast protected buildings to look like concrete warehouses. It takes a lot of innovation and creative problem solving to design a building that is protected from explosions and is still aesthetic, economic, and a place that people can live and work in. The only way that structural design in this country will overcome this challenge is for engineers to realize that this is the reality we are living in and structural design has to adapt. Only with practice, like the Israelis have had, can structural engineers design everyday structures to be safe as well as beautiful and functional.

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