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Senior Thesis
Architectural Engineering
Structural Option
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Spring 2006

The 400
Bremerton, WA

THE 400

414 Washington Ave ♦ Bremerton, WA

Building Statistics

- Usage – Condominium Complex
- Size – 124,117 square feet
- Stories – 6; 4 above grade, 2 parking below grade
- Project delivery – design-bid-build
- Construction begin – September 2005
- Estimated construction end – March 2006

Project Team

- Owner – Bremerton Waterfront L.L.C.
- Architect – Mithun Architects+Planners+Designers (www.mithun.com)
- Surveyer - Holmvig, Dewitt & Associates, Inc.
- Civil Engineer - Team4 Engineering
- Geotechnical - Golder Associates (www.golder.com)
- Structural Enginer - Coughlin Porter Lundeen, Inc (www.cplinc.com)
- M/E/P Consultant – Interface

Major national mode codes

- Building – 2003 International Building Code (IBC)
- Mechanical – 2003 International Mechanical code (IMC)
- Plumbing – 2003 International Plumbing Code (IPC)

Architecture

- Private courtyard and patio
- Public plaza and walkway
- Along the Port Washington Narrows

Building envelope

- Portions of two previously existing buildings are used in the façade design
- Steel stud walls
- Brick veneer

Fire Protection

- NFPA 13 automatic sprinkler system
- Several features still used from existing buildings

Structural

- Seismic design category D
- Parking – post-tensioned slab
- Interior deck slab – ½” metal form deck, 2 ½” concrete cover
- Steel frame (joists, studs, etc.)
- 12” shear core walls throughout the building

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All pictures courtesy of Windermere Real Estate

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Executive Summary

The 400 is a condominium currently under construction in Bremerton, WA. The Structural Blast Resistance of the building along with several general recommendations for blast resistance was designed for this thesis report. A progressive collapse study was the conducted, mostly in accordance with the blast resistant design. Lastly, the details of the building envelope of The 400 were evaluated to resist failure, mostly due to water penetration.

Structural Blast Resistance

It was determined that it was feasible for The 400 to be designed to resist blast loads. The 400 was then upgraded to be considered blast resistant. The same floor system, non-composite steel, was used for the new design. As expected, the member sizes of both girders and columns increased slightly as a result of the additional design loading. The two rules of thumb of increasing the design loading and removing an interior column proved to yield similar designs, although the connections were the limiting factor of the new design.

Progressive Collapse

The possibility of a progressive collapse of The 400 was then analyzed because when a building is considered for blast resistance, the most common cause of failure is progressive collapse. To study the possibility of progressive collapse, it was originally intended to research and evaluate the most common causes of progressive collapses. Then, possibilities to prevent these progressive collapses from occurring would be determined and evaluated. Progressive collapses were researched, and the results for blast resistant design were very similar for design against progressive collapse. While the loading is critical, the connections are not often considered to be controlling, but during a blast, the loading creates additional rotation that would otherwise not be present.

Building Envelope Study

In any location, it is possible for water to seep through the envelope of the building to affect the inside the structure, deteriorating the structural support of the building. In an area of increased precipitation, such as Bremerton, special consideration must be taken to make sure water does not penetrate the envelope and deteriorate the structural integrity of the building. The building envelope of The 400 was evaluated to determine possible areas of consideration for seepage into the structure. The current building envelope proved to be fairly representative of an ideal building envelope design, and few improvements were made. The reality of construction proves that no matter how well-designed the structure, the design means nothing unless it is constructed properly. Site investigations should be performed to determine if construction procedures are actually followed.

Introduction

The 400 is a condominium under construction in Bremerton, Washington. It is located along the waterfront and within walking distance of the ferry to Seattle. Currently, there are no condominiums in the area, but there are several in planning or under construction in the vicinity.

The mention of the city of Bremerton to anyone in the area means one thing—Navy. Bremerton, Washington is primarily a Navy base, and tourists for the most part do not visit the area unless they are visiting the Navy base. While Bremerton is not by any means the United States' largest Navy base, it is made up of a substantial population of military personnel.

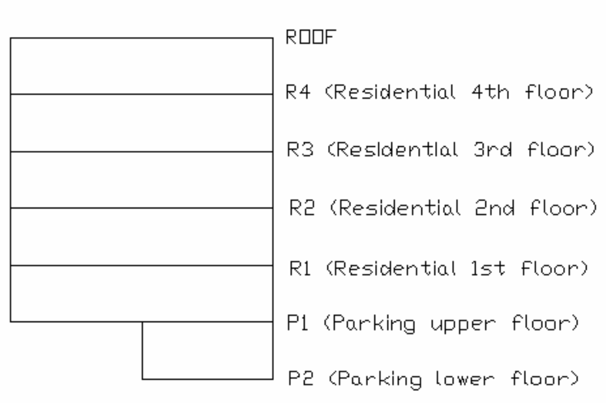
The bottom two stories of The 400 consist of slab on grade or post-tensioned slab parking (generally 8" normal weight). Four stories of light gage steel residential frame construction are built above the two levels of parking to complete the condominium. Wooden trusses are then used to frame the roof. The gross floor area for The 400 is approximately 124,000 square feet.

The building envelope of The 400 consists of a masonry veneer with rigid insulation and sheathing connecting to the metal studs of the structural system underneath. Each floor's building envelope is supported by a ledger, and the masonry veneer is connected to the metal studs by veneer anchors.

Background

Figure 1 shows the general elevation and ordering of floors. The foundation is very critical to the structure, and three foot wide square spread footings typically one foot deep are located throughout the lower parking level. The depth, however, can reach up to three feet, depending on the location of the footing.

Figure 1: Elevation of The 400



A four inch slab-on-grade with one #4 for reinforcement at 18 inches on center each way is the primary slab of the lower parking level (P2), while a 6 inch slab with an f'c of 4,000 psf is used at the exterior edge on this 25,844 gross square feet level. This level is supported by 7'6" square pilecaps 48 inches deep and is connected with standard hooks on both top and bottom; the footings reach a height of 5'10". Control joints are spaced so as to not exceed 225 square feet.

Of the 13,685 gross square feet upper parking level (P1), approximately half of the level contains a 4" slab-on-grade just like the lower level, and the other half contains an 8 ½" post-tensioned slab. The post-tensioned slab contains 9'4" square drop panels 4 ¼" deep at each column, and four #4 are used continuously on the top and bottom.

The upper parking level contains 8" exterior concrete walls. One corner contains a 3'9" x 3'9" x 4 ¼" drop cap because of the poor soil which is located in the southeast building corner. Unique to this level, however, is a three foot closure/pour strip and an extra stair well for access to the upper parking level.

Each residential floor is approximately 21,000 gross square feet. The wall framing consists of metal studs spaced typically 2 feet on center. The typical deck slab is made up of ½" metal form deck with 2 ½" concrete topping. The floor joists used are generally 10TDW16 steel joists 24" on center, supported by W14x22 girders and the typical bay size is 25'6" x 27'10".

The lateral system of The 400 is made up of twelve concrete shear walls, each 12" thick. Most reinforcing for the shear walls is one #5 at 18" on center each way, each face. At critical points, reinforcement can reach up to nine #6 at 3" on center, each face, and the lap splices range from 16" to 132", depending on bar size and concrete strength.

Purpose of Thesis Research

Structural Blast Resistance

Suppose that the owner is intending to rent the condominium spaces to the families of the military either stationed in Bremerton or with Bremerton as their United States home base. Because the intention of The 400 would be to house families of the military and because of the proximity of The 400 to the military base in general, there is a possibility of a terrorist attack of The 400. The building itself can be either a direct target or an indirect target from a bomb or explosion intended for the Navy base.

To fulfill the building proposed by the owner, the original intent of this thesis was to design The 400 to withstand a terrorist attack on the building. The same structural system was used for the new design: non-composite system of steel floor joists supported by girders for the floor system and steel studs for the walls. It was originally predicted that the member sizes of both girders and columns would increase slightly.

A second prediction originally considered was that the new design would result in an increased weight of the overall system due to increased steel member sizes and additional strengthening materials. The additional weight of the increased steel members would then, in turn, add more load to the foundation, resulting in increased design of the foundation. The foundation was never intended to be redesigned in the scope of this thesis, but the size and resistance of the foundation would need to be increased and considered for a complete design. The increased weight of the entire structure may result in a problem, such as a new or improved foundation, because the soil is relatively weak, especially in the southeast corner.

Progressive Collapse

When a building is considered for blast resistance, the most common cause of failure is progressive collapse. For the same reasoning blast resistance was to be evaluated for The 400, progressive collapse is to be evaluated. Ideally, a blast would not occur, but in the event one would take place, the likelihood of a progressive collapse must be evaluated.

To study the possibility of progressive collapse, it was originally intended to research and evaluate the most common causes of progressive collapses. Then, possibilities to prevent these progressive collapses from occurring would be determined and evaluated.

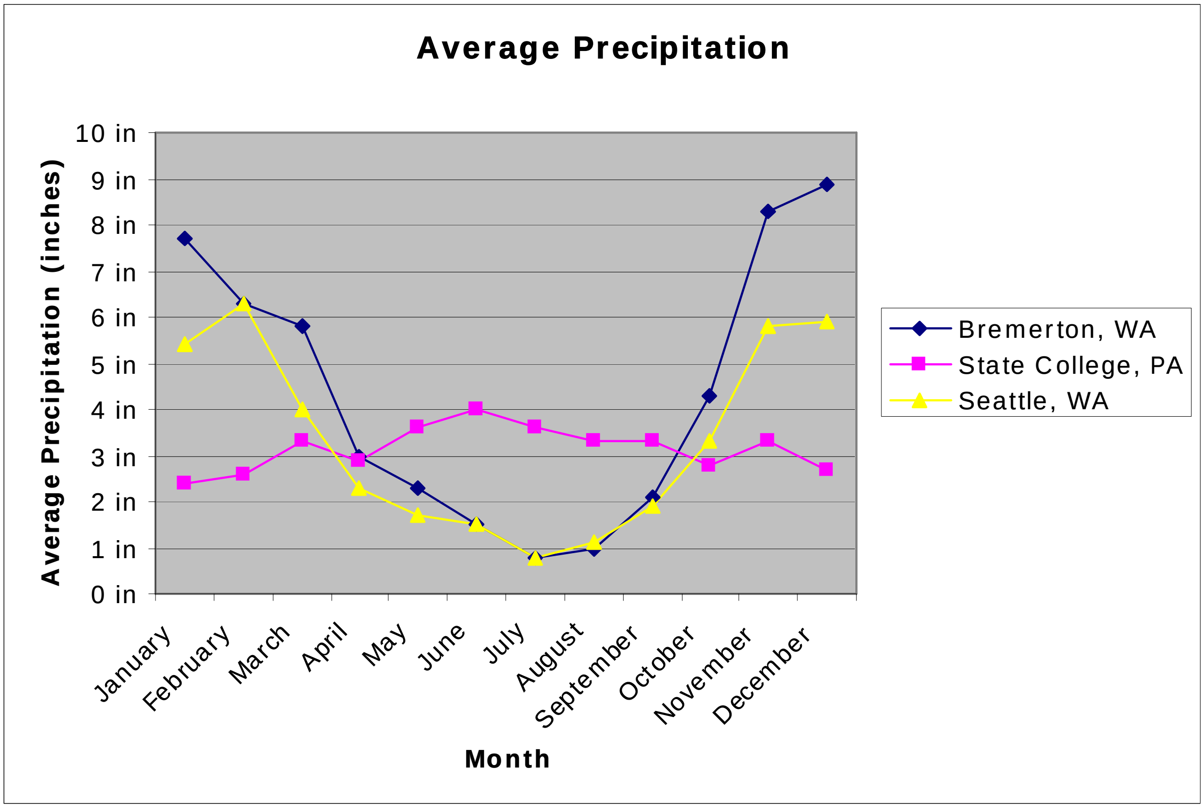
Building Envelope Study

The 400 is currently under construction in Bremerton, Washington. As shown in Figure 2 on the following page, Bremerton typically has more rainfall than even Seattle! In addition, when compared to State College, PA, the highest amount of precipitation in Bremerton is more than double the highest amount of precipitation in State College.

In any location, it is possible for water to seep through the envelope of the building to affect the inside the structure, deteriorating the structural support of the building. In an area of increased precipitation, such as Bremerton, special consideration must be taken to make sure water does not penetrate the envelope and deteriorate the structural integrity of the building. To effectively evaluate this possibility, the original intent of this thesis was to evaluate the building envelope of The 400 to determine possible areas of consideration for seepage into the structure. Research was to be conducted on failure modes of building envelopes. Based on the possible failure modes, updates to the current envelope system or a proposed new envelope would then be completed to determine an ideal design with the smallest chance for building envelope failure.

The reality of construction proves that no matter how well-designed the structure, the design means nothing unless it is constructed properly. Site investigations should be performed to determine if construction procedures are actually followed. A recommendation of ideal steps in a building envelope investigation was to be determined and recommended.

Figure 2: Comparison of Average Precipitation Among Locations



BLAST RESISTANT DESIGN

Case Studies

The World Trade Center

The National Research Council performed a study on how to protect buildings from bomb damage and presented both military and civilian approaches. Several buildings were considered for research, one of which was the World Trade Center towers.

Figure 3: Location of Explosion World Trade Center Bombing

This book was written in 1995, so the extent of the World Trade Center tower research was the terrorist car bomb which exploded on February 26, 1993. This explosion killed six people, injured some, and created hundreds of millions of dollars in repairs. The bomb was about 900 kg of explosives and was located along the south wall of the north tower. It was detonated two levels below grade in the parking garage, where most of the damage occurred. Smoke clogged up many of the air locks, causing more problems with other building functions and accessibility throughout the building, such as communication, life-safety, electrical, and control center operations. As shown in Figure 3, there was significant localized damage, but the structural portion of the building as a whole did not suffer any major damage. The hotel next door, the Vista Hotel, did sustain substantial damage.

This example of an explosion proves that not only should the structural integrity of your building be evaluated for loads of blasts occurring inside the building, but the loads that can affect your building from and explosion nearby should also be considered. Luckily, The 400 is currently the largest building or comparable to the largest building in the area, so The 400 should be able to withstand damage from an explosion in a nearby building as long as it is designed to resist that same explosion inside The 400.

Oklahoma City Bombing

A second building researched by The National Research Council was the Alfred P. Murrah Federal Building of Oklahoma City, Oklahoma, better known as the Oklahoma City Bombing. This blast occurred on April 19, 1995 and was even more catastrophic than the World Trade Center explosion. The blast killed 167 victims and injured an additional 782 victims. The homemade car bomb used in a rental truck on this building contained approximately 2177 kg of explosives and was within 5 meters of the building. As expected, the most extensive damage was located where the bomb exploded on the north side of the building, as shown in Figure 4.

Figure 4: Damage to the North Side of the Alfred P. Murrah Building

The blast was so powerful, however, that it caused about $652 million in total damage to all nearby buildings. Figure 5 shows the impact the blast in the Alfred P. Murrah Building had on the buildings surrounding it. Structural damage or even a collapsed structure extended to several blocks from the Alfred P. Murrah Building. Figure 6, on the following page, shows specific damage to the restaurant which was the closest building to the bomb which exploded in the Alfred P. Murrah Building. The biggest and most impressive feature of this building was the glass façade, which was designed to allow excessive day lighting. During this explosion, however, what was considered to be the best feature of the building proved to be the most detrimental to the surrounding buildings as shards of glass became missiles flying through the air.

Figure 5: Damage to Buildings Surrounding the Alfred P. Murrah Building

Data from: The City of Oklahoma City, Public Works Department, Map Prepared by Geographic Information Systems, "Building Inspection Area," May 1995.

Figure 6: Restaurant Next to the Alfred P. Murrah Building

This nine-story building was made of reinforced concrete slabs and was two bays wide, limiting the redundancy of the structure. Losing one transfer girder would cause a 40 ft x 35 ft part of the structure to collapse while losing one primary column could cause an 80 ft x 35 ft part of the structure to collapse. The actual impact then caused three out of the four front columns and one centerline column to be destroyed, causing 8 of the 10 bays located on the side of the explosion to collapse.

Because of the extent and location of the damage, it is speculated that more than one bomb was used in this attack. In fact, a retired Air Force general hypothesized that two bombs were used, although the government has not yet fully accepted this hypothesis yet.

After the explosion, the Alfred P. Murrah Federal Building was rebuilt to become blast-resistant. After the renovation, the new standoff distance was increased to over 50 feet, which is over three times as large as the distance the bomb was from the building when it was originally detonated. The strength of the renovated building is focused on where the building is most vulnerable, while the least defensive part of the building is where it is least vulnerable. For architectural aesthetics, a stone wall was used in the renovation. A stone wall, however, is not structurally sound to resist blast loading, so it was secured to the concrete walls with 4,000 psi grout, showing that even though a blast-resistant building that is aesthetically pleasing may be difficult to design, it is not impossible.

The Alfred P. Murrah bombing was similar to the World Trade Center bombing in that both buildings strongly impacted the structural integrity of the buildings surrounding them. The Oklahoma City bombing, however, proved to be more catastrophic because the building was not very redundant. If blast resistance or creating a redundant structure was practiced when the original Alfred P. Murrah building was constructed, the building would most likely have survived the explosion. The Oklahoma City bombing points out the benefits of considering alternate load paths or the effects on the structure if a critical or key element is removed from the design of the building.

The layout of The 400 is 5 bays wide by 10 bays long. Even though the bays are twice as long as they are wide, 5 bays is much more redundant than 2 bays. While the removal of a column in The 400 could affect approximately 740 ft^2, that is under 3% of the area on one floor, compared to nearly 10% of a floor and the entire width of the building that could have been affected by one key element in the Alfred P. Murrah building.

The United States Pentagon

On September 11, 2001, the United States was changed forever. A renovation of the Pentagon was in place, upgrading the windows and exterior walls to be more pressure-resistant. One-fifth of this renovation was completed prior to September 11. This cast-in-place system had 5 ½" slabs spanning 10 ft – 20 ft. A Boeing 757-200 with 64 passengers on board and enough fuel to go to Los Angeles (5300 gallons) was hijacked by a terrorist who intentionally flew the plane into the Pentagon. The damage to the columns, beams, and slabs was merely cracking and spalling in the area where the building was hit by the plane. The windows directly hit by the plane were obviously broken, but the renovated windows for the most part remained in place during the blast. It is thought that additional windows that were broken were from the actual fire or firefighters instead of the plane itself. An aerial view of the destruction to the Pentagon is shown in Figure 7. It is very clear that this plane crash caused a localized collapse of The Pentagon. The analysis team concluded that approximately 30 first-floor columns were completely destroyed by the crash and about 20 additional columns along the line of the crash were destroyed as well. The crash created a total damaged area of approximately 75 feet by 230 feet. Figure 8 shows a plan of the columns which were damaged due to the impact of the plane. Following the crash, the fire caused from the fuel then caused spalling of the concrete in a few areas as well as heat damage to other areas.

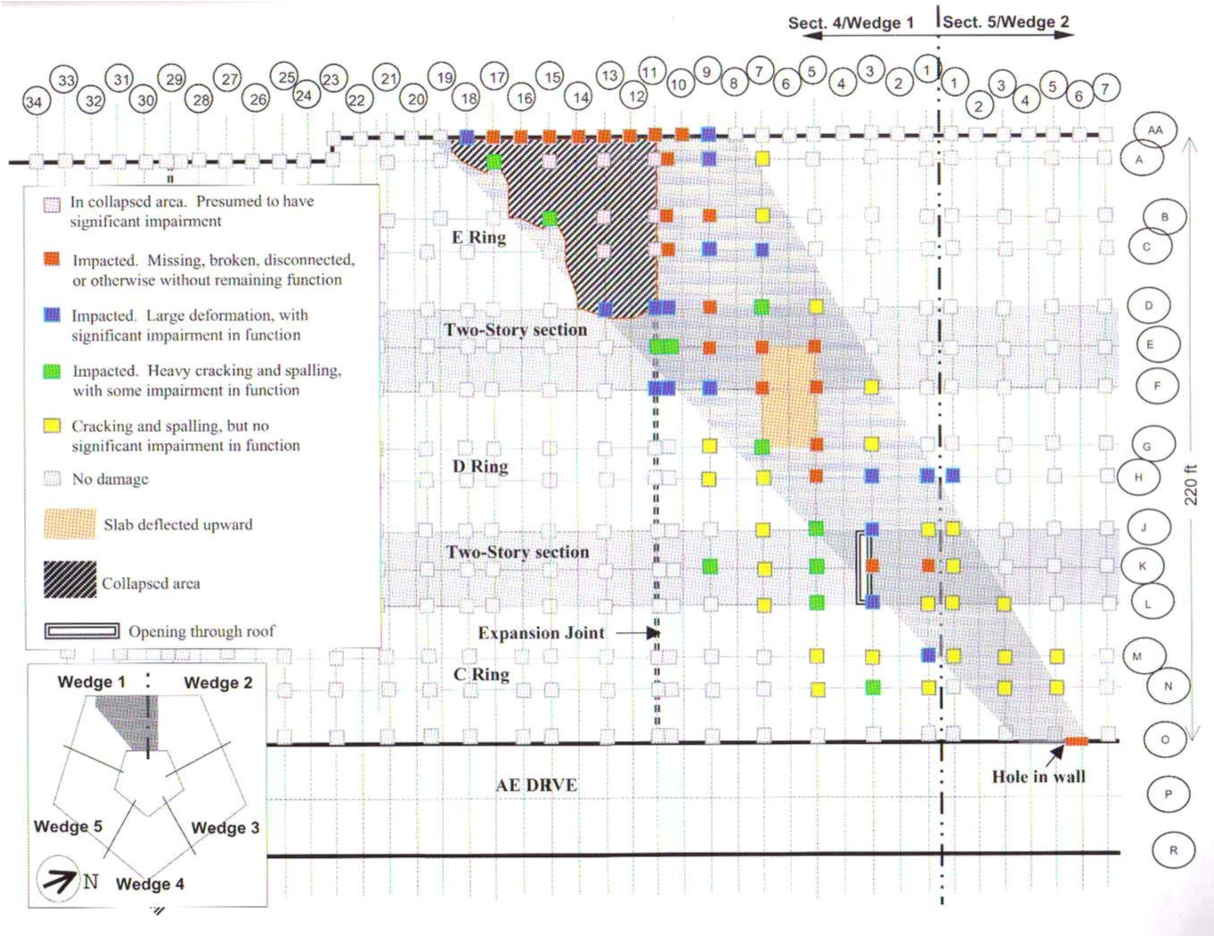
Figure 7: Aerial View of the Pentagon Blast

The results of this catastrophe were not nearly as bad as it could have been. Total or more extensive collapse was prevented because of:

- A redundant structure which was able to create alternative load paths throughout the floor system
- Short spans between columns, limiting the load transferred by each individual column
- Continuous reinforcement through the supports
- Design for loading above and beyond service loading
- Spirally reinforced columns
- Exterior walls which performed as transfer girders, creating alternate load paths

All of these preventative measures are excellent recommendations to help design a building as being blast resistant. Some of these recommendations and suggestions were used when designing The 400 to be blast resistant.

Figure 8: Column Damage to the Pentagon



Causes of Attacks

To truly understand blasts, you must start with the cause—why and how do blasts occur? A common motive for a terrorist attack on a building is to exert political pressure or to make a symbolic statement. Many people cannot comprehend specific motives to cause the effects of a bomb and the human lives that are lost in the process, but truth remains that there are several people in the world that possess these motives even considering the consequences because bombings still occur.

The National Research Council performed a study analyzing all of the bombings of any structure between 1989 and 1993. The results of this study are summarized in the following charts and tables. Figures 9-11 show the percentages of deaths, injuries, and incidents that occurred between 1989 and 1993. Exact numbers of incidents are summarized in Figure 12.

Figure 9: Total Deaths in Bombings

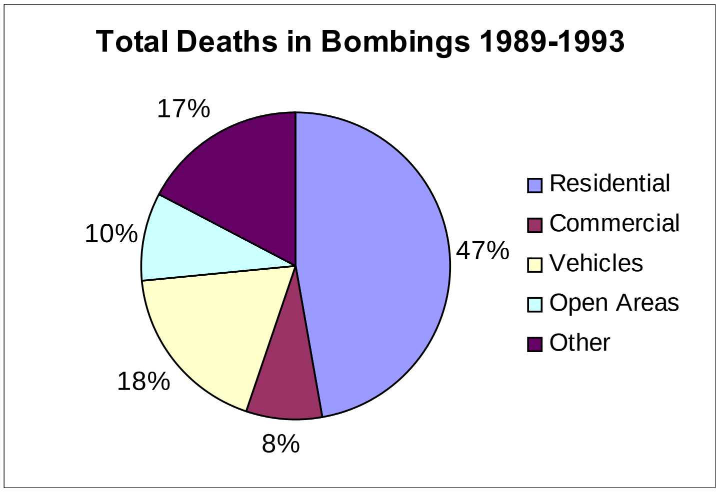


Figure 10: Total Injuries in Bombings

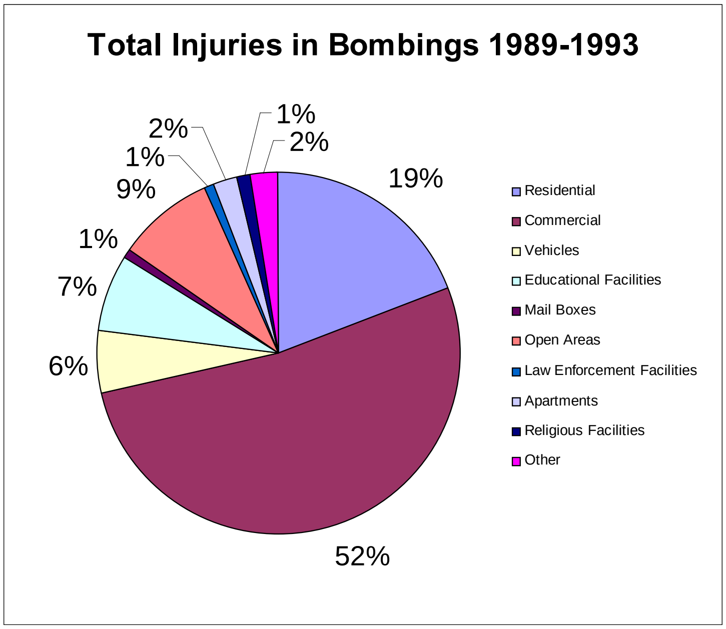


Figure 11: Total Bombing Incidents

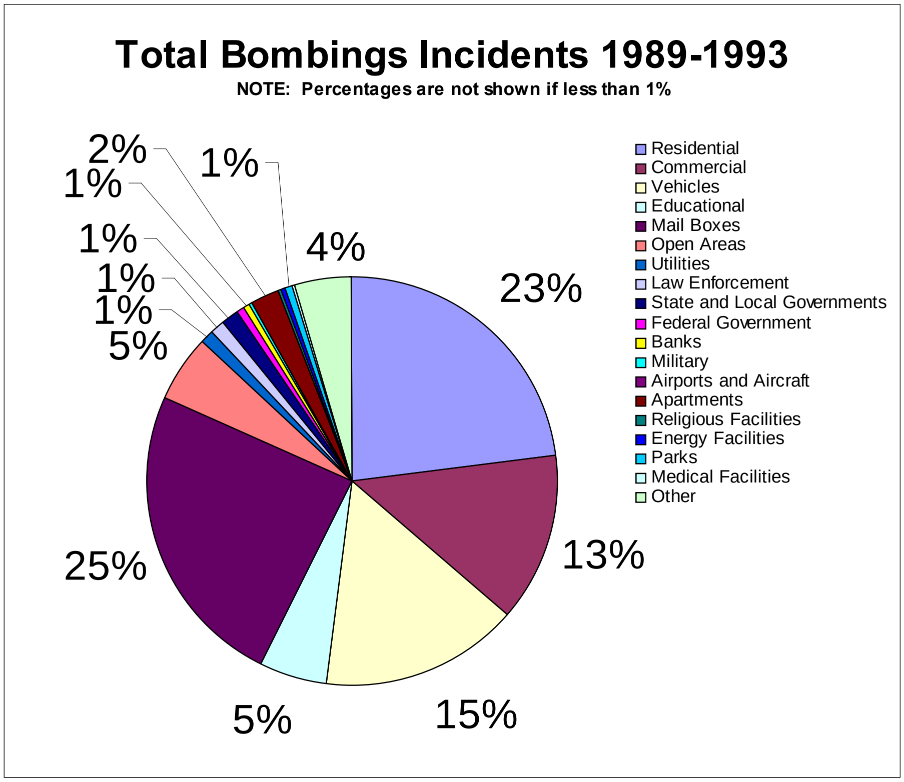


Figure 12: Total Bombing Incidents Chart

Target	*Total number of incidents*
Residential	2,553
Commercial	1,468
Vehicles	1,698
Educational	573
Mail Boxes	2,712
Open Areas	568
Utilities	143
Law Enforcement	108
State and Local Governments	155
Federal Government	48
Banks	72
Military	27
Airports and Aircraft	10
Apartments	244
Religious Facilities	30
Energy Facilities	11
Parks	89
Medical Facilities	26
Other	481
TOTAL:	***11,016***

Because 19% of the total injuries, 47% of the total deaths and 23% of the total incidents that occurred between 1989 and 1993 were to residential buildings, it is feasible to suggest that The 400 be designed to resist blast loads. Additionally, because 17% of the deaths, 52% of the injuries, and 13% of the total bombings were targeting commercial structures, it is also feasible to consider designing commercial buildings to be blast resistant.

Types of Attacks

The most detrimental realistic damage to a building by a bomb is caused by a vehicle bomb. Additionally, the most damage to a building occurs from an internal explosion. For example, an interior column supports four times as much tributary area as an exterior corner column. Most of the building functions are also located in the bottom or basement of the building, and they would be destroyed if a bomb was detonated in the basement or lower floor. Additionally, in several commercial structures, parking is located below the building structure, creating easy access for cars and generally low security for bomb detection.

There are several methods of attack that have the possibility to occur, but structurally almost nothing can be done to design against an aerial or nuclear bomb. While a vehicle bomb may be one of the most common methods of attack and causes the largest effect, several other methods of attack may occur. Examples of such attacks are mail bombs, truck bombs, briefcase bombs, and pipe bombs. While these other methods may be considered, a vehicle bomb is considered to be the most critical, so when designing a building to be blast resistant, it is crucial to design against a vehicle bomb, which in turn will be able to resist the other reasonable forms of blast attacks.

For any bomb exploding at the bottom of a structure, the smoke can easily and quickly travel up ventilation systems and other openings, such as elevator shafts. This makes the search and rescue after an explosion much more difficult than if the smoke was contained just in the area of the explosion. Systems which block smoke from transferring throughout the whole building are preferred. This was previously discussed as a major problem in the bombing of the World Trade Center.

How is Designing for Dynamic Loads Different From Wind or Seismic Loads:

There is a difference in designing a building to resist wind or seismic loads when compared to the dynamic loads created by a blast. When designing against wind or seismic loads, having light floors, especially at the top of the building is most preferred. Wind and earthquake loads are relatively long (seconds to minutes) periodic waves, while dynamic loads are relatively short (milliseconds) aperiodic waves. When a terrorist bomb is located in a building, it is generally located near the bottom of the building, where it can cause the most damage. Therefore, to most efficiently design a building against blast-loading, it is beneficial to increase the weight and resistance of the bottom of the building to resist the short aperiodic waves created from the dynamic loading of the blast.

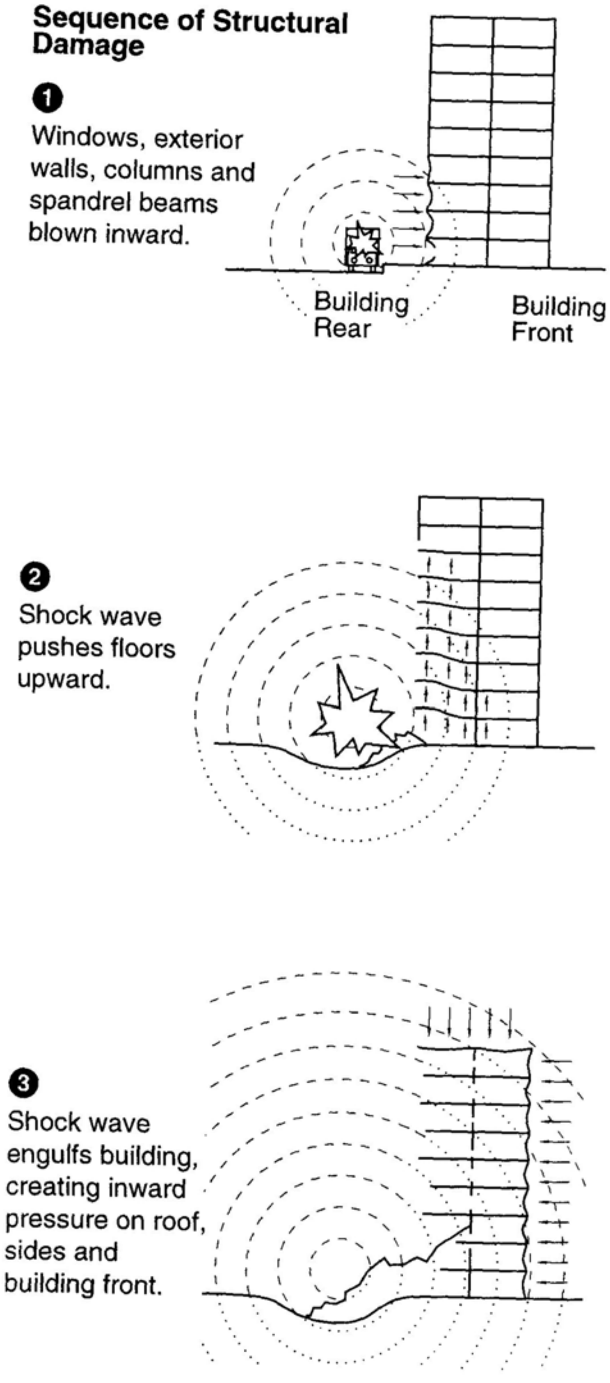


Figure 13: Blast Effects on a Building

The intensity of dynamic loading from a blast generally exceeds 100 psi (14,400 psf), which is much higher than the loads normally considered for wind or seismic loads.

The Explosion Itself

Blast loading effects on a building can generally be summarized into three steps, defined in Figure 13, if it occurs from the outside. First, the blast load pushes in on the vertical surface of the building closest to the location of the blast. Generally this is the façade and exterior columns. Once the blast enters the building, it puts an upward force (generally in the form of a shock wave) on each floor. This upward force is generally never designed for unless blast resistance is considered.

Lastly the blast then creates suction on all remaining walls and the roof. The severity of each of these three steps varies depending on the size and placement of the bomb that the building is designed to resist. Punching shear is a very common failure of floor slabs during a blast because of their large spans and the upward force followed by the suction.

When a member is removed from a structure, the loading which was originally going to be distributed to that element then needs to get redistributed to the surrounding elements. If the immediately surrounding elements can support the redistributed load, the damage has stopped, but if the surrounding members cannot support the additional load, the collapse can continue to propagate, either vertically or horizontally. While no collapse is ideal, a localized collapse is preferred because the damage is relatively small when compared to a progressive collapse.

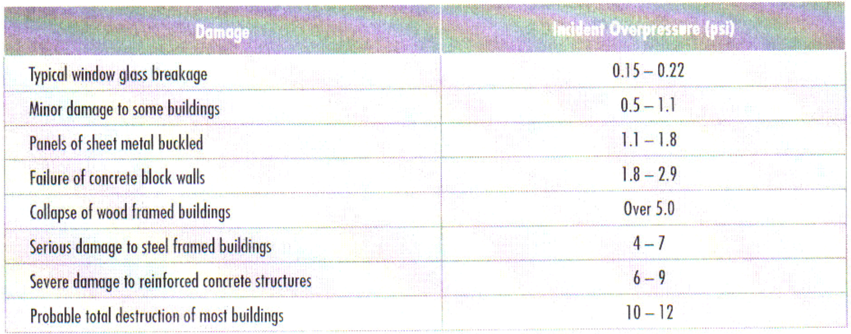
For an explosion occurring on the outside of a building, part of the energy is absorbed by the ground. If the blast is large enough, it can form a crater and waves similar to those experienced in an earthquake. Figure 15 compares and contrasts blast loads to earthquake loads. The largest concerns for blast loads in addition to earthquake loads are upward pressure and the fact that entire members can be completely blown away and not just impaired. While earthquake loading can get intense, earthquake loading generally gradually increases in intensity, unlike the large initial impact created by blast loading.

How Can a Building be Designed Against a Blast?

The two crucial aspects of designing against a bomb threat are:

1) Size of impact (in TNT)
2) Distance of impact from important structural members

Figure 14: Incident Pressure and Corresponding Damage



Damage	Incident Overpressure (psi)
Typical window glass breakage	0.15 – 0.22
Minor damage to some buildings	0.5 – 1.1
Panels of sheet metal buckled	1.1 – 1.8
Failure of concrete block walls	1.8 – 2.9
Collapse of wood framed buildings	Over 5.0
Serious damage to steel framed buildings	4 – 7
Severe damage to reinforced concrete structures	6 – 9
Probable total destruction of most buildings	10 – 12

Each bomb creates a pressure on the building. Figure 14 summarizes the damages that each pressure causes. Note that even as little as 0.15 psf overpressure can cause windows to break.

Based on the size of the explosive most likely to be used and the maximum damage the building is to be designed to resist, Figure 16 can be used to calculate the required standoff distance to keep the building safe. Additionally, if the size of the explosive to be designed to resist and the standoff distance allowed on the building site are known, the incident overpressure which the building must be designed to resist can be calculated. As shown in Figure 16, the larger the blast, the harder it is to resist. For instance, for a truck bomb with minimal damage to the building, over 1,500 feet of standoff distance is required. Unless the building is constructed in the middle of the countryside with security guards watching all the entrances, a building with that large of a standoff distance is very impractical. Figure 17 and Figure 18 show the exponentially different variations in radii between a car bomb and a truck bomb at the same location.

Figure 15: Blast Design Versus Earthquake Design

Comparison of Blast and Earthquake Effects on Reinforced Concrete Frame Structures

Blast	Earthquake
Blast pressure damages all adjacent structure that is susceptible. Floor slabs and beams are usually extremely vulnerable to upward pressure and may be completely shattered. Weaker columns may be blown away, but larger, heavily loaded columns most often are not initially shattered.	Shaking damages dynamically brittle, vertical supporting elements (columns, short wall piers). Floor slabs and beams usually have little initial damage.
Blast pressures radiate from the point of detonation but decay very rapidly with distance and time. As the shock wave passes over a building, the pressures may change direction.	Shaking affects the entire structure and damage will occur because of mismatch in strength/stiffness ratio. Irregularities, both vertical and/or horizontal, will focus the damage to those most vulnerable areas (soft stories, short col.) Shaking may last for more than one minute.
Gravity acting on the damaged structure will cause it to seek a new state of stability.	Gravity acting on the damaged structure will cause it to seek a new state of stability.
The lack of lateral support, because of shattered floors can lead to buckling failure of adjacent columns and then to the collapse of one or more bays of the structure. If columns are shattered by blast, collapse of its supported floors will be likely.	The lack of vertical support, coupled with gravity acting on the heavy, relatively undamaged floor, will tend to cause a pancake type collapse of one or more stories.
Parts of the structure more distant from the blast may survive intact and have the potential of supporting one edge of some of the damaged floor slabs.	Earthquake damage can be focused in specific sections of the frame because of vertical and/or horizontal irregularities (soft story, short column, torsion, etc.). Partial collapse may then occur with slabs being draped from the remaining structure.
Blasts detonated in basements may cause even greater damage because of the initial confinement of blast pressures.	Earthquake shaking rarely affects basements since much smaller inertia forces are generated and basement structures are normally surrounded by strong, stiff, concrete walls.
Survival of victims is unlikely because of the initial effects of the blast and the initial shattering of concrete floors leads to relatively compacted, less survival voids.	Survival voids are often created in even complete pancaked collapse since the relatively strong floor slabs can bridge and drape over projections.
Secondary collapse is possible, especially if rescue operations require removal of collapsed slab structures that have become the temporary lateral bracing to remaining, free standing columns.	Aftershocks will cause additional lateral loading, which usually leads to some sort of readjustment to the structure (secondary collapse).
Victim removal may be accomplished by relatively easy removal of the shattered concrete, after appropriate stabilization of the remaining structure has been accomplished.	Victims are most often accessed by cutting thru the relatively solid floors (from the top) in a very labor-intensive process. Local and overall stabilization may be required.

Figure 16: Required Standoff Distance

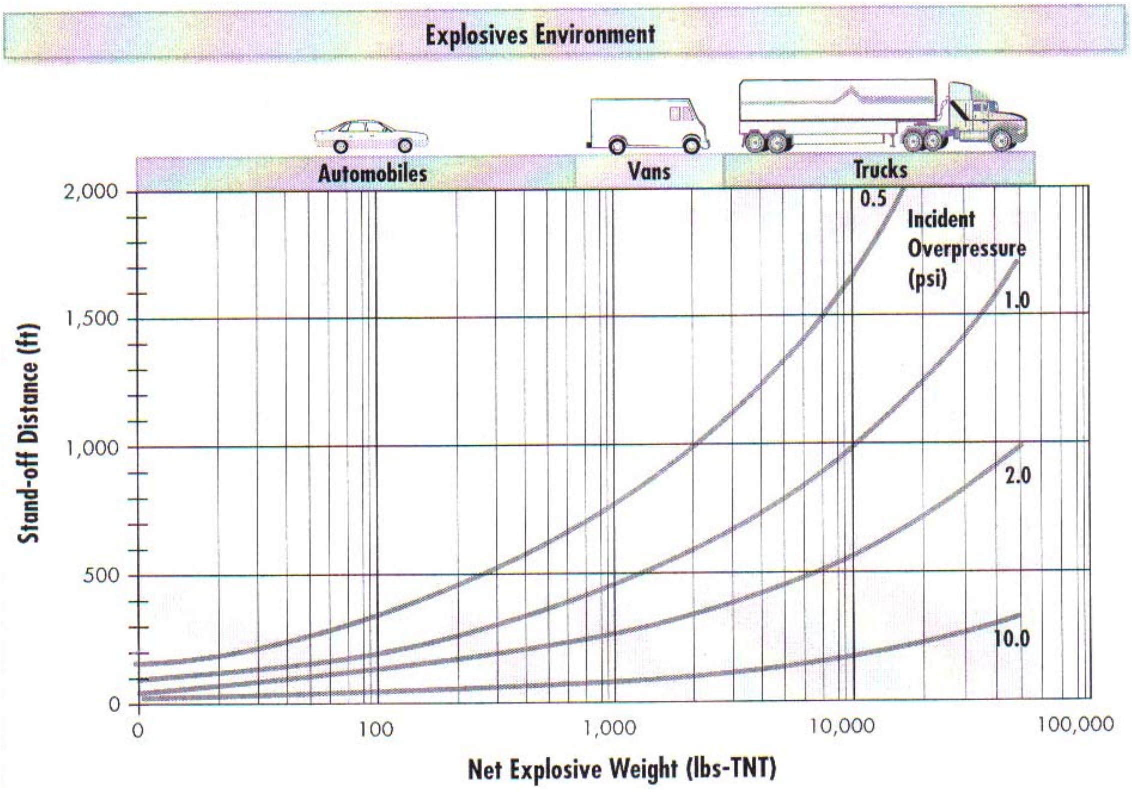


Figure 17: Radius of Car Bomb

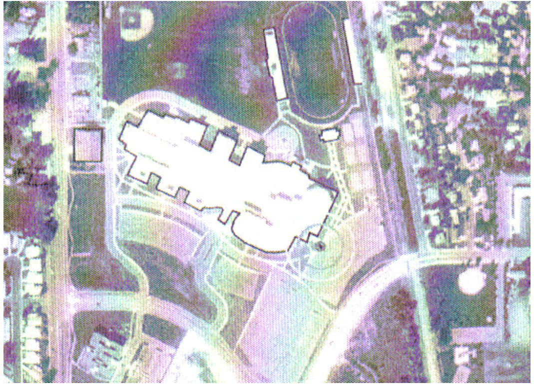
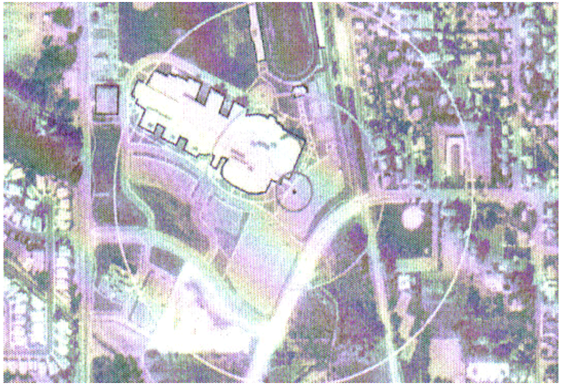


Figure 18: Radius of Truck Bomb



While ideally it is beneficial for the building to be designed with no civilian access anywhere close to the building, that design would generally contradict the purpose of the building to help the occupants and be very impractical. Therefore, access of civilians from the outside of the structure needs to be limited as much as feasible.

Because the largest damage to a structure is generally caused from the bottom center of the structure, it is not recommended to have underground parking, but rather off-site parking. If off-site parking is not a possibility, other precautions, such as increased security or vehicle size limitation during entry to the parking garage, may help mitigate potential blasts.

Common weak points in a building are: underground parking garages, loading dock entrances or other indentations of the building floorplan, lobbies, mail rooms, and retail spaces. Special attention to detail, such as the increased security previously discussed or additional strengthened material will help to make any of these weak areas less vulnerable to an attack.

Common questions that must be considered when attempting to design a building to be blast-resistant are:

- Who or what is the threat?
- Is a bomb a possible choice of weapon?
- What are the most likely scenarios or tactics for introducing a bomb into or near the building?
- What resources, including technologies, are available to respond to the threat?
- What are the costs of applying those technologies?
- What will building tenants and occupants tolerate in the way of inconvenience or added expense for security measures?

The following are recommendations to increase the blast resistance of a building:

- Continuous reinforcement through girders and columns
- Redundant structure, both shape and system
- Spirally reinforced columns
- Increase design load to compensate for the additional loading created by the blast
- Staggered lap splices to allow the reinforcement to be fully developed
- Limited deflection of materials
- Additional shear reinforcement, such as ties and stirrups
- Ductile steel connections
- Minimal column spacing, decreasing the tributary area to each element
- Small floor-to-floor height (less than 16 feet)
- Fully-grouted CMU if masonry is used
- Horizontal floor and roof diaphragms that tie together both framing systems so that if one system fails, the other system can compensate for the failed system

Additionally, to increase the structural integrity of the building, the designer can use additional mass, but additional mass increases the seismic design loads. Additional strength can also be acquired by modifying the boundary conditions, such as additional supports. Reducing the span or loading can also increase the strength of the building. The larger the bay size, the larger the load carried by each individual member, therefore the larger the probability that a progressive collapse will occur.

Creating a redundant structure, both with floor systems and bay sizes, allows the most strength of a building. A redundant structure by default creates alternate load paths, decreasing the chance of a progressive collapse. Corner columns are made redundant mostly due to the steel members framed into them. Exterior columns are made redundant by the framing on three sides in addition to the concrete slab. Interior columns are made redundant by either the framing from all four directions, the deck slab, or a combination of both the framing and the slab. If a curtain wall makes up the façade of the building, particular attention must be given to the openings, such as in windows and doors because of the increased suction which forms around all openings during a blast. Because glass is generally the first material to break during a blast, the extra pressure at these openings is almost guaranteed to be present.

As shown in the Oklahoma City Bombing, during an explosion, glass is the most lethal element of the structure. Forty percent of the injuries (excluding deaths) of the Oklahoma City bombing were attributed to glass, and 25-30% of the injuries to people in nearby buildings were attributed to glass. Broken glass can reach up to miles away from the initial location in a building, causing damage to several surrounding buildings and people.

Windows, however, can be reinforced and/or strengthened to aid in resistance to blast loads. Possible window reinforcement include polyester fragment retention films, polyethylene terephthalate (PET) backing or interlayer, heat-strengthened and tempered glass, polycarbonate-sheet and urethane/glass composite glazing, and polyvinyl butyrate (PVB) interlayer or combined PVB-PET laminated glazing. Additionally, there are several mesh curtains that can aid in mitigating blast effects on the building. There are even blast resistant doors available for design which are described in great detail is ASTM F2247-03.

Several computer programs can be used to determine a building's ability to resist blasts as well. Several of these are Finite Element Analysis programs, but not all computer programs need to be. Additional programs include ALE3D, ALEGRA, BLASTX, CONWEP, CTH, DYNA3D, EPSA-II, FLEX, FEFLO, FOIL, FUSE, HULL, MAZe, and SHARC.

How Much Will it Cost?

Popular design generally suggests strong, light material is more economical than heavier material. The weight of the building is directly proportional to the design forces, creating a problem. Increased forces means increased strength of members, which means increased cost. As with any benefit, blast resistance comes at a cost; the owner and/or designer needs to decide just how much is willing to be sacrificed or how much premium the owner is willing to pay for a building to be blast resistant.

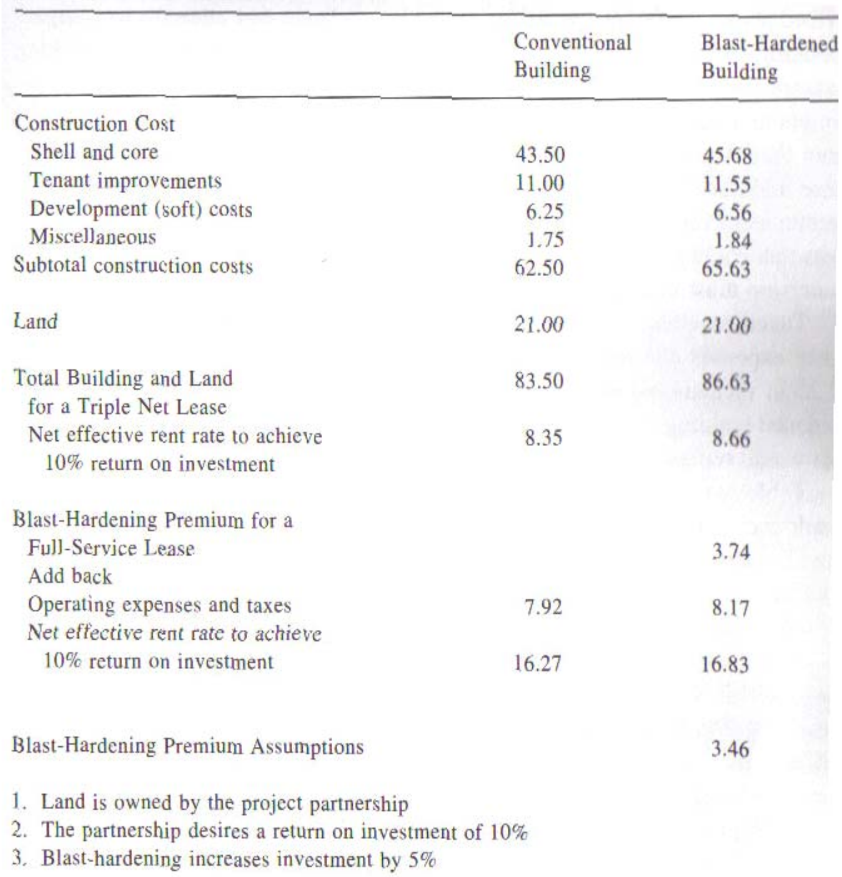
The larger the standoff distance, the less damage that can be caused from the same bomb. It is generally unrealistic to design a building to be blast resistant if the standoff distance is less than 20 feet. The increased cost of the building is too large in comparison to the initial design to be worthwhile. A standoff distance of 50 feet or more is considered to be the most cost effective.

Most people who were offered a blast resistant building over a non-blast resistant building with all other factors equal would choose a blast resistant building, but the fact of the matter is that money plays a large role in making a blast resistant building feasible. In addition to the initial costs of the building, such as the increased member sizes, there is the increased cost to operate and maintain the building, such as increased security that may be needed to ensure a blast resistant building. These costs are also true for an existing building which is being upgraded to become blast resistant, although an existing building would have the additional costs of retrofitting.

After performing research about additional costs incurred from blast resistance, the committee formed by the National Research Council determined that for a building considered to be built of reasonable blast resistance, the premium of construction is increased by 5%, while the lease premium is increased by merely 3.5%. For a tenant who understands the increased security for a small price increase, this would be a win-win situation. But, it’s very difficult to advertise a building as being blast resistant without drawing more attention to a building (which otherwise would have been average) or inviting terrorists to try to find a way to destroy the building.

For a typical commercial office building with 250,000 square feet of rentable space with five year leases, it was determined that the cost to build such a building is approximately $83.50 per square foot for everything from the land to the construction to the development costs. While building costs are increased in a blast resistant building, the land costs remain the same. To make the described building blast resistant, the 3.5% increase in cost would be $86.63 per square foot if there is a 10% return on investment. General operating costs (including operating, repair, and maintenance) increase from $7.92 per square foot to $8.17 per square foot. A summary of these increased costs according to the study of the National Research Council are located in Figure 19 on the following page.

Figure 19: Increased Cost of Blast Resistant Building



	Conventional Building	Blast-Hardened Building
Construction Cost		
Shell and core	43.50	45.68
Tenant improvements	11.00	11.55
Development (soft) costs	6.25	6.56
Miscellaneous	1.75	1.84
Subtotal construction costs	62.50	65.63
Land	*21.00*	*21.00*
Total Building and Land for a Triple Net Lease	83.50	86.63
Net effective rent rate to achieve 10% return on investment	8.35	8.66
Blast-Hardening Premium for a Full-Service Lease		3.74
Add back		
Operating expenses and taxes	7.92	8.17
Net effective rent rate to achieve 10% return on investment	16.27	16.83
Blast-Hardening Premium Assumptions		3.46

1. Land is owned by the project partnership
2. The partnership desires a return on investment of 10%
3. Blast-hardening increases investment by 5%

How Can a Current Building be Upgraded to be Blast Resistant?

The easiest and most effective way to increase the blast resistance of a current building is to increase the distance civilians are allowed to come within a building. Other measures may be taken, such as upgrading the windows by adding a polyester film coating or changing the floor system, but most of these can get rather expensive. Additionally, it may be cheaper to alter the inside functions of the building rather than concentrating on the structure itself.

What if a Building is Attacked?

While having a building remain unharmed when attacked by a blast (or any other load for that matter) would be nice, the reality of the matter is that a designer cannot possibly predict everything that could go wrong in a building and generally does not have the budget to design against every possible loading condition. It is the ethical responsibility of a designer for the lives of the occupants of the building, so the ultimate goal when designing against blast resistance is to protect the lives of the occupants during a blast.

Because a designer wants to make sure that after a blast the building remains standing long enough to safely evacuate all of the occupants, special attention must be paid to the life functions of the building: electrical, communication, plumbing, ventilation, and circulation systems.

What Does the Code Say About Blast Resistance?

For normal buildings, there are no code requirements to design against blast resistance. For what are considered to be hazardous buildings, however, the Uniform Building Code states to design against an internal pressure of 100 psf for the blast loads alone. There are several detailed design guides available for government buildings, but special clearances are generally required to obtain such information. For general civilian structures, designers are usually forced to use engineering judgment when determining loads and pressures to design buildings to resist. There are some requirements, such as in ASCE 7-02 that say to design against progressive collapse, but definitions are vague and design recommendations are even more vague. Additional design guides for progressive collapse are referenced in the following section, Progressive Collapse.

PROGRESSIVE COLLAPSE

Designing Against Progressive Collapse

Progressive collapse is generally the most common large failure during a blast. It is defined as an effect disproportionate to the cause; for example, a small load that causes a catastrophic collapse of a building. A progressive collapse generally starts one problem which initiates a whole chain of events leading to the collapse of the building. Many techniques to design against blast loads are similar to designing against progressive collapse, but additional considerations are:

- Two-way slab system supported by beams on four sides to provide an alternate load path
- Ties placed along the entire length of beams, girders, and columns to provide confinement
- Continuous top reinforcement in slabs to resist the upward load
- Continuous vertical reinforcement on both sides of exterior walls to increase the ultimate capacity of the envelope
- Seismic detailing at connections
- Continuous reinforcement in floor systems or staggered lap splices that develop the full strength of the reinforcement
- Proper anchorage of reinforcement bars
- Continuous bottom reinforcement in slabs along column lines
- Exterior and interior columns in public areas for unbraced lengths of at least two stories
- Outer designed bay to resist progressive collapse initiated by the loss of a ground floor column or other primary support

Other systems may be used and can effectively resist progressive collapse, but special attention must be paid to both anchorage and shear reinforcement. Generally if progressive collapse will occur, it starts in the first few seconds following the blast. Since it is not cost-effective to incorporate all of these techniques into every design, several rules of thumb have been developed to allow the building to better resist a progressive collapse.

Rules of Thumb for Design Against Progressive Collapse

One rule of thumb to help design against progressive collapse after a blast is to remove one or more of the columns and show that only relatively small damages or collapses will occur. For accurate design, all of an interior, exterior, and corner column (if they have the possibility of getting destroyed by a bomb) should be considered, although an interior column will usually be the most critical case.

Additionally, for steel buildings, moment-resisting frames are recommended to resist progressive collapse. Braced frames cannot withstand blast resistance, and if they are removed during a blast and braced frames are the only lateral resistance, no lateral resistance would be present in the building. Proof that moment-resisting frames mitigate the chances of progressive collapse exists from the World Trade Center bombings. The North Tower remained intact for almost two hours after impact and the moment frames in building six limited the collapse. The drawback, however, of using moment-resisting frames, is the additional cost; moment connections are extremely costly, especially if moment frames are not required for any other reason in design.

A second recommendation for design against progressive collapse is to design against twice the dead loading plus one half of the live loading. This loading combination is considered because it represents a value closer to the true loading rather than the maximum allowable loading. If each member is designed to resist this additional loading, then if one member is removed from a blast, the other members should be able to fully support the building. Moment ratios of elastic moment to plastic moment capacity are said to be limited to 2 for compact framing and 3 for non-compact framing.

The traditional reinforced concrete slab over steel decking (either composite or non-composite) has proved to be an effective blast resistant floor system. The thickness of the concrete slab, however, differs depending on the size of the blast to be designed against. Slabs are designed to resist downward loads, but they are not generally designed to resist the upward loads created during a blast. A second layer of reinforcement in the slab would help to resist against these upward loads. Additionally, normal-weight concrete is more effective to resist blast loading than light-weight concrete because of the additional strength of the material.

As far as beam design for blast resistant buildings, W-shapes or HSS (hollow structural section) are generally common for design. HSS members are more resistant to torsional loading, so where torsional loads are maximized or considered to be severe, HSS members are beneficial.

As previously described, in addition to designing against the loading for your particular building, you must be conscientious about the surrounding buildings as well. If an explosion occurs in a nearby building, the explosion itself or the missiles (pieces formed from the explosion) of that particular building could cause damage to your building.

The highest uplift pressures are in the corners of the roof. For residential structures, the connections are generally the most likely to fail, specifically shingle-to-sheathing, sheathing-to-rafter, rafter-to-top plate, top plate-to-stud, stud-to-bottom plate, and bottom plate-to-foundation.

Common Design for Alternate Load Paths

The U.S. General Service Administration (GSA) guidelines focus on alternate load paths. The GSA approach to blast resistant design considers only one element at a time to be removed from a potential blast. The GSA prefers a three-dimensional, linear-static approach for analysis. The loading combination to be used for analysis is 2 (Dead Load + 0.25 Live Load). The live load in this analysis is reduced to 25% of the design live load to mirror the actual loading predicted to be present rather than the maximum loading to be experienced. Additionally, doubling the entire load for analysis is done because of the instantaneous removal of an element, resulting in a dynamic amplification factor. This recommended approach is based on removing a vertical support and determining if the supporting members and connections are adequate for the loading.

The Department of Defense blast resistant design criteria demands that all buildings at least three stories tall need to be designed against progressive collapse. The design approach is based on LRFD approaches and defines several different approaches combining linear and nonlinear as well as static and dynamic formulas. This method is based strongly on the British Standards and Tie Forces, which include the strength of the continuity and ductility of the structure. The load combination used for this approach is (0.9 or 1.2) D + (0.5L or 0.2S) + 0.2W.

The British Standards demands that all buildings over four stories need to be designed to resist a disproportionate collapse. Like the Department of Defense criteria, the British Standards account for the strength of all the ties between steel connections, steel reinforcement, and steel mesh reinforcement. The load combination used for this approach is $D + {}^{1}/_{3}\,L + {}^{1}/_{3}\,W$.

BLAST RESISTANT DESIGN OF THE 400

Original Structural Design of The 400

As previously stated, the floor system of The 400 is a non-composite steel system with ½” metal form deck with 2 ½” concrete. The load path of The 400 starts at the concrete slab and then travels to the joists, the girders, the columns, the footings, and finally, the soil. The floor joists typically used are generally 10TDW16 steel joists 24” on center, supported by W14x22 girders and the typical bay size is 25’6” x 27’10”. Figure 20 shows the general layout, excluding dimensions of the bays that were modeled to represent the floorplan of The 400. A summary of all of the design loads are located below:

Live Loads (From ASCE 7-02 Table 4-1):

Roof live load (including snow)	25 psf
Floor live load (parking)	40 psf
Floor live load (corridors/lobbies)	100 psf
Floor live load (residential units and decks)	40 psf
Attic live load (non-simultaneous with roof live load; no storage or living)	10 psf
Stair live load	100 psf
Guardrails/balcony rails	50 plf / 200 lb

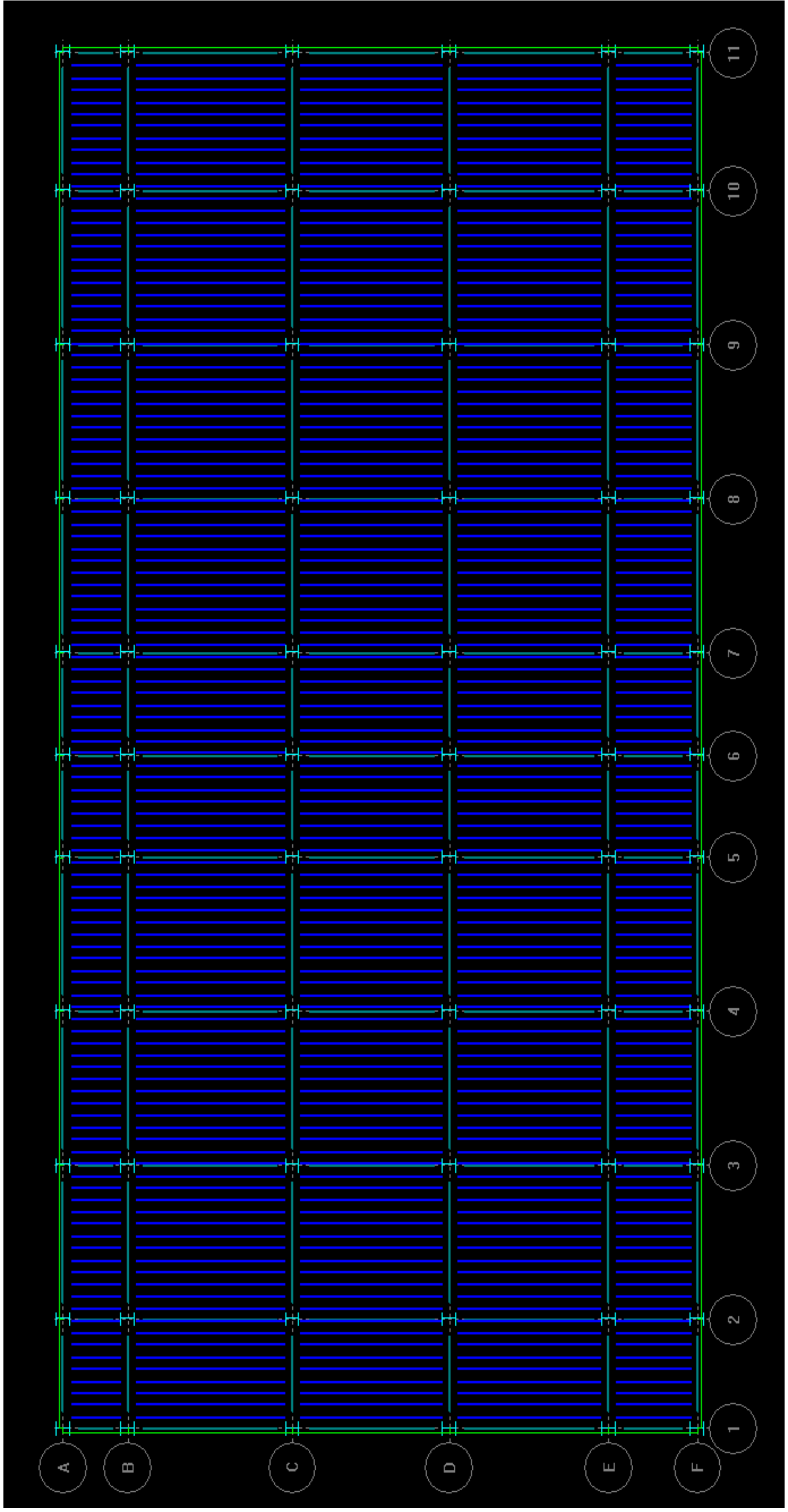
Table 1: Design Live Loads

Dead Loads:

Metal Roof Deck	2 psf
Trusses (roof)	20 psf
Ceiling	5 psf
Mechanical/Electrical/Plumbing	15 psf
Concrete (with metal deck)	30 psf
Concrete Slab (parking)	100 psf
Perimeter Wall	15 psf

Table 2: Design Dead Loads

Figure 20: Typical Floorplan of The 400



New Structural Design of The 400

The method of analysis for The 400 is mirrored off of the AISC's Nonlinear Static Pushover Analysis' energy balance approach. An interior column is considered to be the most critical element, and is therefore the element considered for analysis of The 400.

For analysis of the removal of a column, the circled column in Figure 21 was removed and was replaced by the force which the column would have supported with the actual estimated loading of (D + 0.25L) loading combination provided for the most critical design as detailed in Figure 22.

Figure 21: Column to be Removed

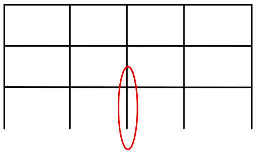
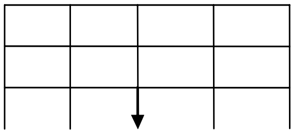
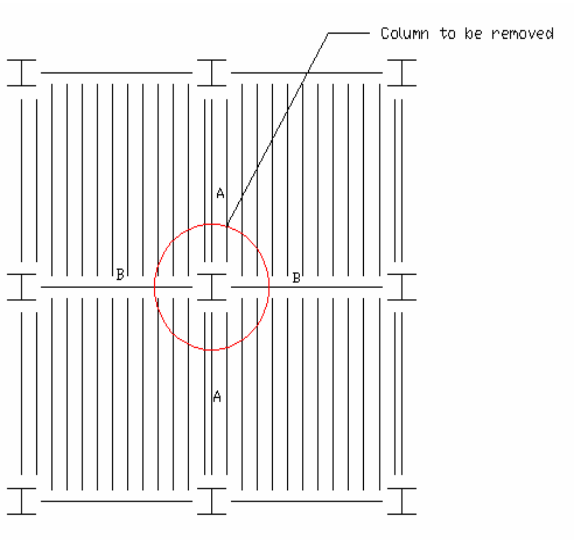


Figure 22: Force Representing Removed Column



First, the structure in Figure 23 was analyzed according to the nonlinear static pushover analysis recommended by the AISC disregarding the steel joists. The vertical displacement at the column removal location was determined to be approximately 65 inches out of the approximate 138 inches of floor-to-floor height.

Figure 23: Force Representing Removed Column



When the contribution of the adjacent joists was considered, the vertical displacement was decreased to 40 inches, which created up to a 7.45 degree rotation in the girders, with the joists resisting anywhere from 0.088 degrees to 6.74 degrees rotation. The original connections of The 400 are not moment connections, and while moment connections are recommended, they are not required. Double angles could easily allow for this rotation in the new connection.

For blast design, two loading conditions were considered: 2 (D + .25L) and (D + L). For the design loading of 2 (D + .25L), W16x26 and W24x55 are typically used for girders. Note that this is a slight increase in the original design for

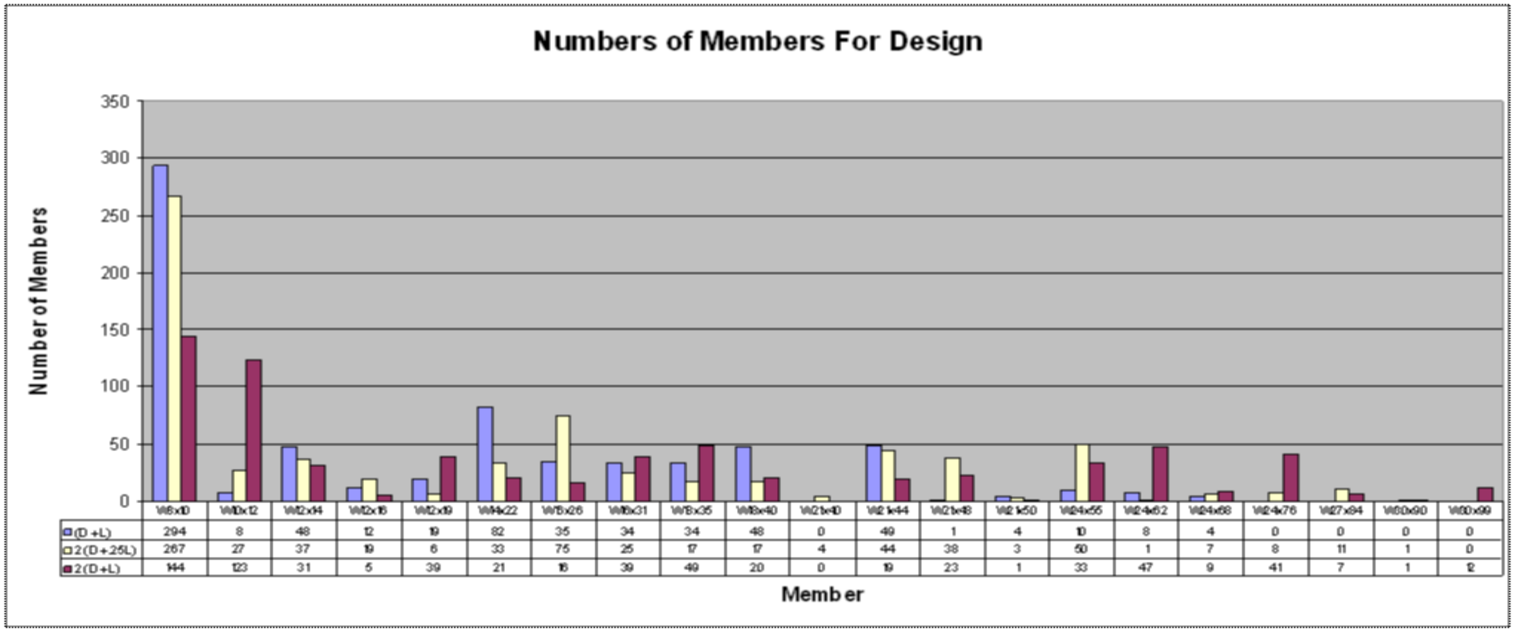
W14x22 girders. Lastly, the design loading of 2 (D + L) was considered. While twice of all of the loading would definitely be over-design, this loading was evaluated solely for comparison reasons. The girders necessary to support this loading condition require mostly W18x35, W24x62, and W24x76. As expected, these sizes are slightly larger than the 2 (D + .25L) loading and much larger than the original (D + L) loading. The quantity of girders necessary for each of these three designs are summarized in Figure 24 on the following page. In general, the higher the loading, the larger strength girder necessary.

The conclusion of checking the rule of thumb of designing a structure to resist the loading combination of 2 (D + 0.25L) with the rule of thumb to remove a column is that while the capacity of the members themselves is important, the connection between these members is also just as important, if not more!

As previously stated, The 400 is considered to be a redundant structure and is 5 bays wide by 10 bays long. The 400 is also designed by one design team, limiting interpretation errors among various design teams. The window can also be upgraded or include an upgraded glazing to withstand a reasonable blast load.

Currently, the standoff distance of The 400 is 0 feet because parking is located on the lower levels. If parking was moved off-site, the standoff distance would be increased to 15 feet. While 15 feet is still considered to be a small standoff distance, it is much better than 0 feet and feasible considering The 400 is located downtown. Because there are several condominiums in planning or under construction in the vicinity of The 400, a possible condominium parking garage could be built in which all condominium owners park there instead of under their building.

Figure 24: Summary of Sizes Used in Various Loading Conditions



	W8x10	W10x12	W12x14	W12x16	W12x19	W14x22	W16x26	W16x31	W18x35	W18x40	W21x40	W21x44	W21x48	W21x50	W24x55	W24x62	W24x68	W24x76	W27x94	W30x90	W30x99
🟦 (D+L)	294	8	48	12	19	82	35	34	34	48	0	49	1	4	10	8	4	0	0	0	0
🟨 2(D+.25L)	267	27	37	19	6	33	75	25	17	17	4	44	38	3	50	1	7	8	11	1	0
🟥 2(D+L)	144	123	31	5	39	21	16	39	49	20	0	19	23	1	33	47	9	41	7	1	12

BUILDING ENVELOPE DESIGN RECOMMENDATIONS

Building Envelope Design Considerations

Moisture penetration into the building envelope is the biggest reason for building envelope failure. It causes decay, corrosion, mold growth, and indoor air quality problems. However, the building envelope cannot be completely airtight because if moisture gets in there, even at the time of construction, it has no way to dry or get out. In the past ten years, research shows that air penetration can be the reason for moisture penetration into a building envelope.

Special design considerations to decrease failure of the building envelope are:

- Air permeability
- Continuity with other air barrier materials
- Structural integrity
- Durability
- Water penetration resistance
- Water vapor permeability
- Mechanical ventilation
- Construction details and sequencing
- Code compliance
- Climate

While most of these considerations may apply to several buildings, they do not all necessarily apply to all building envelopes.

Durability of the ideal building envelope includes:

- Resistance to puncture
- Resistance to pests—rodents, termites, carpenter ants, and other insects
- Resistance to low but sustained negative pressures from building stack effect and HVAC fan effect
- Ability to withstand stress from thermal and moisture movement of building materials, and stress from building creep
- Resistance to UV degradation (during the construction period)
- Resistance to mold growth
- Resistance to abrasion

Water Penetration

While the engineer may argue that the structural system is most important to a building, the structural system is nothing if it cannot perform to the best of its ability. The building envelope is generally the first line of defense against any detrimental element, be it a blast, termites, or water. Water is considered to be one of the largest (if not the largest) reasons why building envelopes fail. Especially because The 400 is located near

Seattle, Washington, where the rainfall is much higher (relatively speaking) when compared to other geographical locations, water penetrating the building envelope must be seriously considered.

Very simply stated, a surface cannot leak if it does not get wet! It is nearly impossible, however, to ensure that a building does not get wet. There will always be rain and there will always be snow and there will always be wind. Water does not penetrate the building only when it rains; when it is cold enough that icicles are formed, when they melt, they can cause problems and enter the building envelope. Most of the time, water gets into the building envelope through an opening in the wall. This opening generally let's in air or water, which then escalates into causing several other problems. One major problem, especially recently with condominiums, is mold growth. Mold exists and there's nothing that can be done about that, but problems arise when it comes in contact with moisture. Mold and mildew cannot grow without water and air. Mold can most easily grow on wooden structures, which is why it has been a problem in the past with condominiums. Since The 400 is built of steel, mold is not as likely to grow as it would have been in a wooden structure.

While water and air penetration into the building envelope is most common, temperature control systems can also cause moisture in the building envelope. If excessive humidity develops because of an inadequate temperature control system, excessive moisture can develop in the building envelope. It is imperative to understand how the building functions as a whole because other systems, like temperature control systems, can indirectly affect various parts of the building, such as the building envelope.

It is common practice to use a vapor barrier in a building envelope to keep water out of the building. In geographical locations of high humidity in the South, the vapor barrier should be placed on the exterior side of the building, while it should be placed on the interior side of the building for buildings located in the north. Where there is no real vapor pressure difference, a vapor barrier is not needed.

The ideal barrier must consist of four important characteristics: continuity, air impermeability, strength, and durability. Continuity is important because a break in the barrier allows a place for intrusion of many elements, including air and water. Air impermeability is important because it keeps the air from penetrating the building envelope. Strength is important because it must be able to resist problems such as excessive wind or deflection caused by various loading patterns. Durability is important because the longer the building envelope lasts, the longer the building lasts.

Air Penetration

Once additional unplanned air (either in the form of a blast, removed section of a building, or small air penetrations) enters a building, several responses could occur.

The more openings added to a wall, the higher the chance for air to enter. While caulking and other materials are used around doors and windows to prevent air from entering the building, because of the vast amount of openings in a wall (especially in the form of doors and windows), the probability that a small section of sealant will fail is extremely high. The additional unplanned air entering the building then creates additional internal pressure, pulling the roof downwards. Increased suction is also created immediately surrounding the opening in the wall.

While some air leaks in the building envelope are very easy to detect, ASTM E1186-03 identifies several methods to detect any air leakage through a building envelope. The first method is the Depressurization Practice, which uses infrared scanning methods to detect differences in adjacent interior surface temperatures. The Smoke Tracer Practice uses smoke seeded air to allow visual detection of leaks. Another method is known as the Anemometer Practice. This practice uses depressurization to develop a jet-like airflow around any wall openings. An anemometer is then used to locate differences in air velocities. The drawback of the Anemometer Practice, however, is that the practice can only be used on sites that can be reached for surveying. Lastly, an Acoustic Practice is based on the idea that sound travels easily through openings. This practice is very low cost and fairly easy to perform.

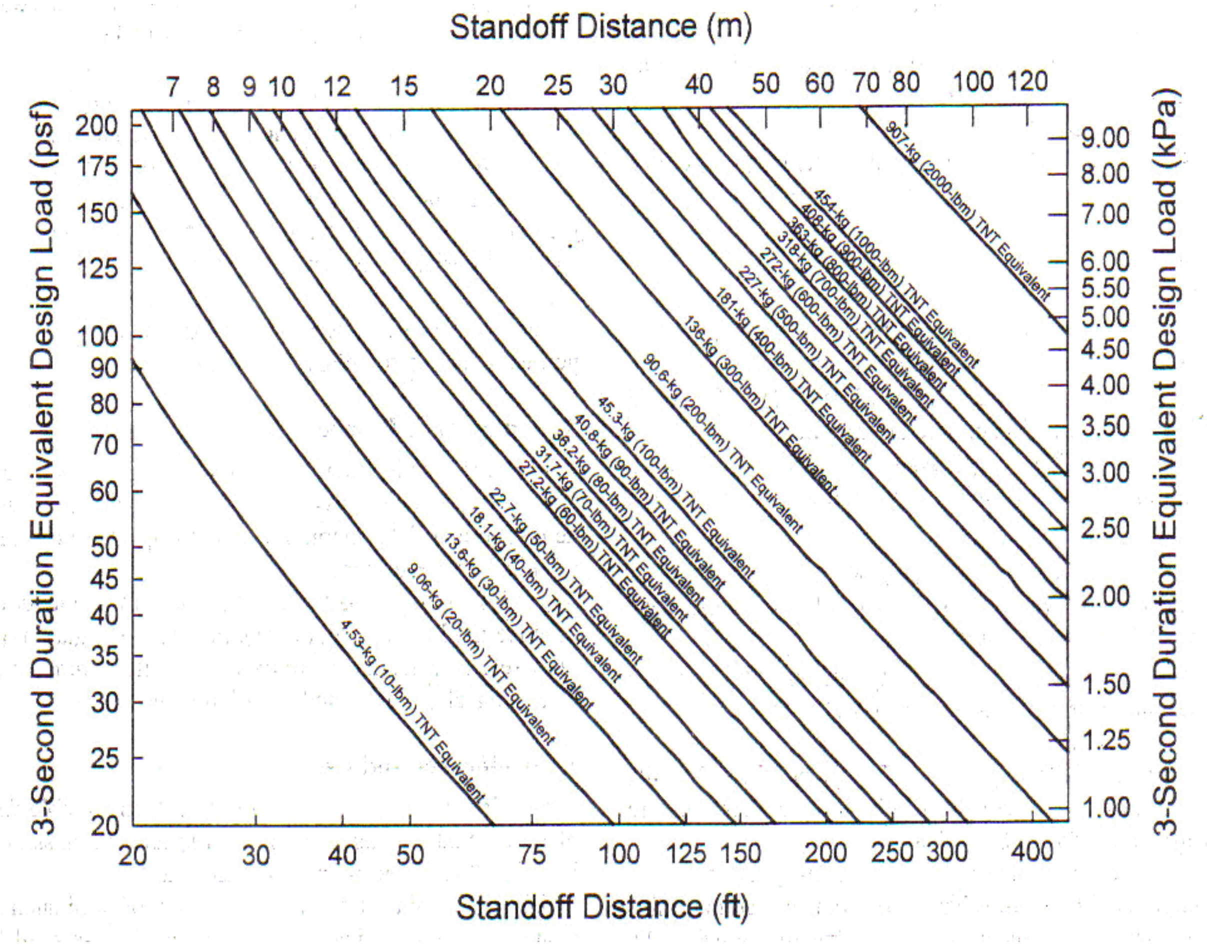
In a survey of residential buildings conducted in 1998 in Seattle, Washington, approximately 70% were damaged by moisture. These damages ranged from small miniscule penetrations to large leaks with water flowing almost continuously. To fix these repairs, it was predicted to cost about $70 million.

A possible recommendation to prevent building envelope failures is to have one design team work on the entire project. If several design teams are working on various parts of the complete project, the locations where all of the pieces come together can create some problems. If one design team completes the entire project, odds are that the same vision and ideas of all the small details will remain constant throughout construction.

Typically, building owners perform a very thorough investigation of the roof, but they lack giving adequate attention to the remainder of the building envelope. There is no telling where a building envelope can fail, and proper care and investigation should be given to the entire building.

Glazing is the part of a building envelope which often fails during a blast but is rarely ever evaluated to become blast resistant according to ASTM F2248-03. Failure of the glazing on a structure allows the pressure from the blast to enter the building, increasing the building damage. An increased blast resistant glazing will most likely limit the number and size of glass particles formed during a blast. Since glass missiles are extremely destructive during an explosion, blast resistant glazing would prove to be a worthwhile investment. Figure 25 on the following page shows a chart in which the

Figure 25: Design Load for Gazing Based on Standoff Distance and Blast Load



equivalent loading which the glazing must be designed to resist based on the standoff distance and the size of the bomb is shown. As expected, the larger the bomb to resist, the larger the design load for blast resistant glazing.

Specialty Companies

Several precautions may be taken to ensure that a building envelope does not fail. While it is possible to make adjustments to building design at all stages of construction, it is most efficient and economical to make as many adjustments as possible during the design phase. Several companies exist for that specific reason in particular, and they can be hired for the sole purpose of making recommendations to your building envelope. One such company is Simpson Gumpertz and Heger Inc. They take a proactive and preventative approach to stop problems before they start. While hiring a specialty company may not always be economical for all projects, for very large projects, it is a relatively small investment to have plans reviewed before construction than fixing a building envelope failure after construction has commenced.

Whether a specialty company is hired or not, the plans of the building should be reviewed in detail, especially where horizontal and vertical elements meet. Where details do not exist, a detail needs to be developed. In addition to building plans, specifications must also be reviewed. The specifications give a more detailed look at the function of all of the materials of the building and how they are supposed to respond to certain situations. By simply reviewing all of these documents, potential call-backs and future disputes or even lawsuits can be avoided.

A perfect building envelope design means nothing unless it's built properly. You can take several steps to ensure a building is constructed according to design. Quality assurance is probably the most effective and economical solution to ensure proper construction. The amount of time spent to review construction can and should vary depending on each building. More intricate building designs obviously require more supervision and greater detail. No matter how much time must be spent for quality assurance to make sure a building is constructed properly, the investment almost always pays for itself because it will prevent much more catastrophic building failures in the building envelope.

Industry Practices

ASTM E2270-05 summarizes recommended standards of practice of periodic inspections of building facades. The steps recommended in this standard are not considered to be the most strict guidelines, but merely minimum requirements. Periodic investigations in general are required because any or all of the age of the structure, the maintenance conducted, and design or construction errors.

Service history is necessary for a complete investigation mainly because it provides an insight into past problems and leakage patterns. Additionally, the service history itself can provide insight into the possibility that inadequate maintenance was a failure. Lastly, the service history is necessary because it provides the information for all of the repairs or modifications to the original structure, which would not be included on merely the structural drawings.

The ideal steps for the most accurate building façade investigation procedure as defined in ASTM E2270-05 are:

1. Review of Project Documentations
2. Preparation of Inspection Drawings
3. Determination of Service History
4. Assessment of Watertight Integrity

5. Façade Inspection
6. Reporting Procedures for Unsafe Conditions
7. Standard Reporting Procedures
8. Maintenance of Reports
9. Frequency, Extent and the Required Level of Periodic Inspection of Building Facades for Unsafe Conditions
10. Detailed Assessment of Water Tightness Integrity of Exterior Facades

The first step, reviewing the project documents, consists of gathering all of the available project documents including, but not limited to, architectural, structural, and shop drawings. To be used for evaluation purposes, enough verifications of drawings to building construction must be made to determine the validity of the drawings. Additionally, if the façade is considered to be historical or was built according to older practices, design reference books from the time the design originated are necessary for verification purposes.

The second step, preparation of inspection drawings, consists of gathering a site plan to determine the building location in relation to adjacent buildings and pedestrian access in the form of sidewalks or road access. Additionally and most importantly, wall and construction details are to be gathered in this step.

The third step in this process is determining the service history. The more detailed the service history, the better. At bare minimum, maintenance schedules, repairs, modifications, and performance problems are necessary. In this step, it is very important to identify locations which have been repaired in the past, as a change in building material can prove to be an inviting location for a leak or failure to propagate from. Past records of water infiltration are very helpful at this stage as well. Wherever leaks occurred in the past prove to be potential locations for future or concealed leaks. Whenever possible, interviews with all relevant parties to review maintenance schedules is highly recommended, as a first-hand account of building problems is extremely helpful. These building failures include, but are not limited to, leaks, rust stains, cracking, and spalling.

The fourth step consists of assessing the watertight integrity of the building. Based on visual observations of either leaks or potentially hidden leaks provide a summary of locations which can be evaluated in great detail using instruments such as probes or moisture meters.

The fifth step in the process is the façade inspection itself. ASTM E2270-05 divides the façade inspection into a general and detailed inspection. The general inspection consists of a view of the building from farther than 6 feet. This inspection, because it is at a distance from the building, is more for large visual problems rather than small intricate details. The detailed inspection is necessary to view all of the connections holding the building together. Special attention should be given to areas that can pond water as well as any locations of unusual displacements, both horizontally and vertically. Checking for water damage as well as general material deterioration is also extremely crucial. Especially for facades with ornamentation, pushing or pulling on the physical façade elements themselves can prove to give an insight into the stability of the structure.

Step six in this process is reporting on unsafe conditions. It is the ethical responsibility of the inspector to report any conditions which are hazardous or unsafe to authorities as soon as the problem is apparent. Additionally, the owner of the building must be notified of a severe condition which titles the building as hazardous or unsafe.

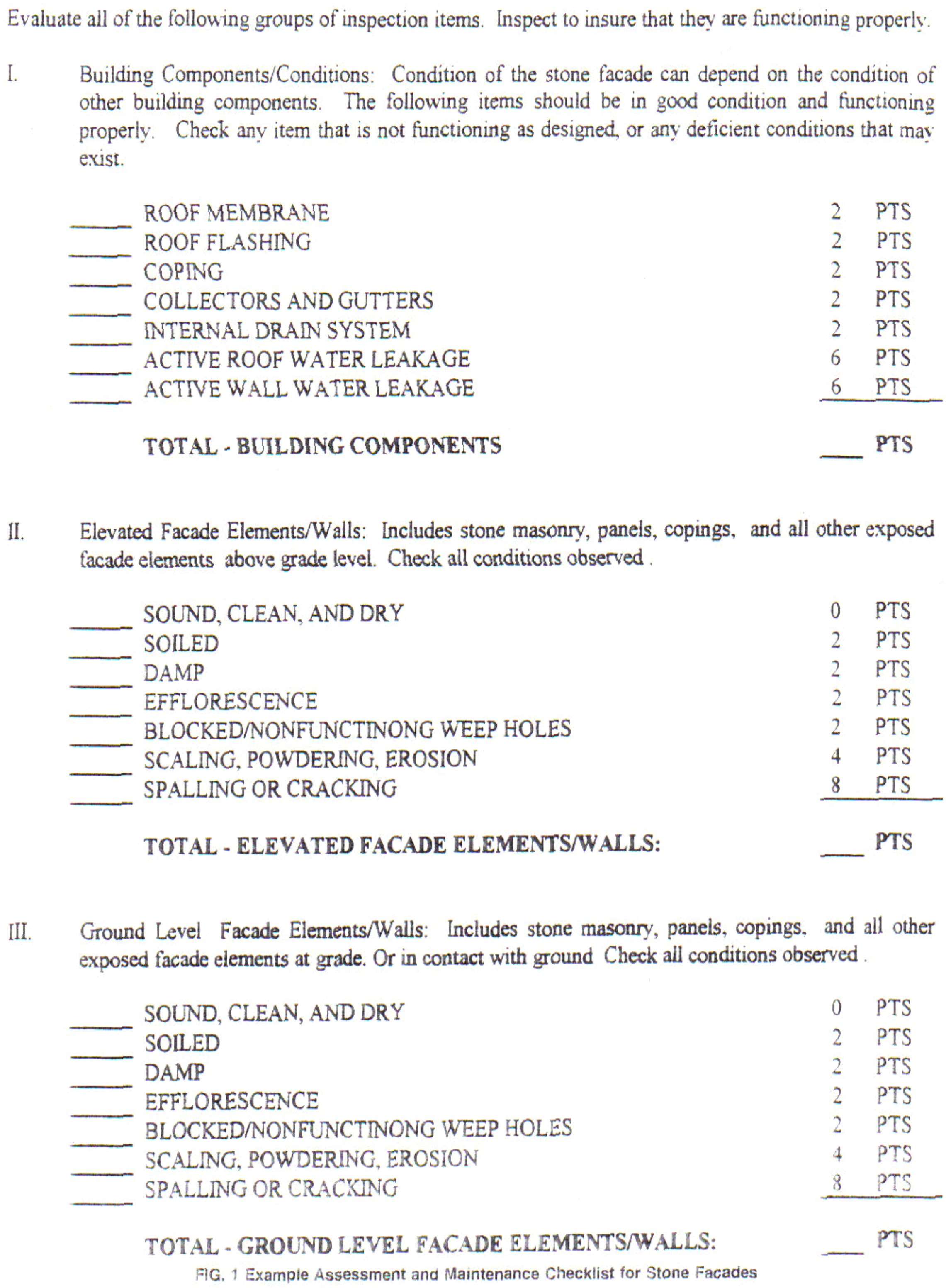
The standard reporting procedures consist of preparing a report of the findings of the investigation. All sources must be clearly identified with supporting necessary documentation. A summary of the previous steps, one through six, are required in as much detail as possible, including relevant pictures to clearly convey ideas and observations. Last but not least, this report must include the signature and seal of the party responsible for the inspection. This report needs to be readily available from either the owner or inspection party if it is needed for reference in the future, which is considered to be step eight.

The final two steps in the ASTM E2270-05 summary of an ideal building envelope inspection are merely for frequency and attention to detail. The minimum inspection frequency providing there are no problems is once every five years. Increased inspections are necessary for intricate facades or facades which are exposed to excessive weathering or loading.

Prolonging Necessary Repairs

ASTM C1496-01 summarizes consequences to delaying several problems in the building envelope. While this standard is written for a stone façade, many of the principles are still the same. If there is a crack, prolonging the repair would cause the crack to elongate and widen, allowing more water to enter the building. A sample of a recommended inspection evaluation is shown on the following pages in Figure 26 and Figure 27. The evaluation sheet includes analyzing all building components, elevated façade elements, and ground façade elements. Additionally, specific sections are included for evaluating façade joints and window joints. Based on the points awarded to each section, recommendations are determined and range from merely routine maintenance to seeking a professional consultant immediately.

Figure 26: Building Envelope Inspection Sheet Page 1



Evaluate all of the following groups of inspection items. Inspect to insure that they are functioning properly.

I. Building Components/Conditions: Condition of the stone facade can depend on the condition of other building components. The following items should be in good condition and functioning properly. Check any item that is not functioning as designed, or any deficient conditions that may exist.

_____	ROOF MEMBRANE	2	PTS
_____	ROOF FLASHING	2	PTS
_____	COPING	2	PTS
_____	COLLECTORS AND GUTTERS	2	PTS
_____	INTERNAL DRAIN SYSTEM	2	PTS
_____	ACTIVE ROOF WATER LEAKAGE	6	PTS
_____	ACTIVE WALL WATER LEAKAGE	6	PTS
	TOTAL - BUILDING COMPONENTS	____	**PTS**

II. Elevated Facade Elements/Walls: Includes stone masonry, panels, copings, and all other exposed facade elements above grade level. Check all conditions observed .

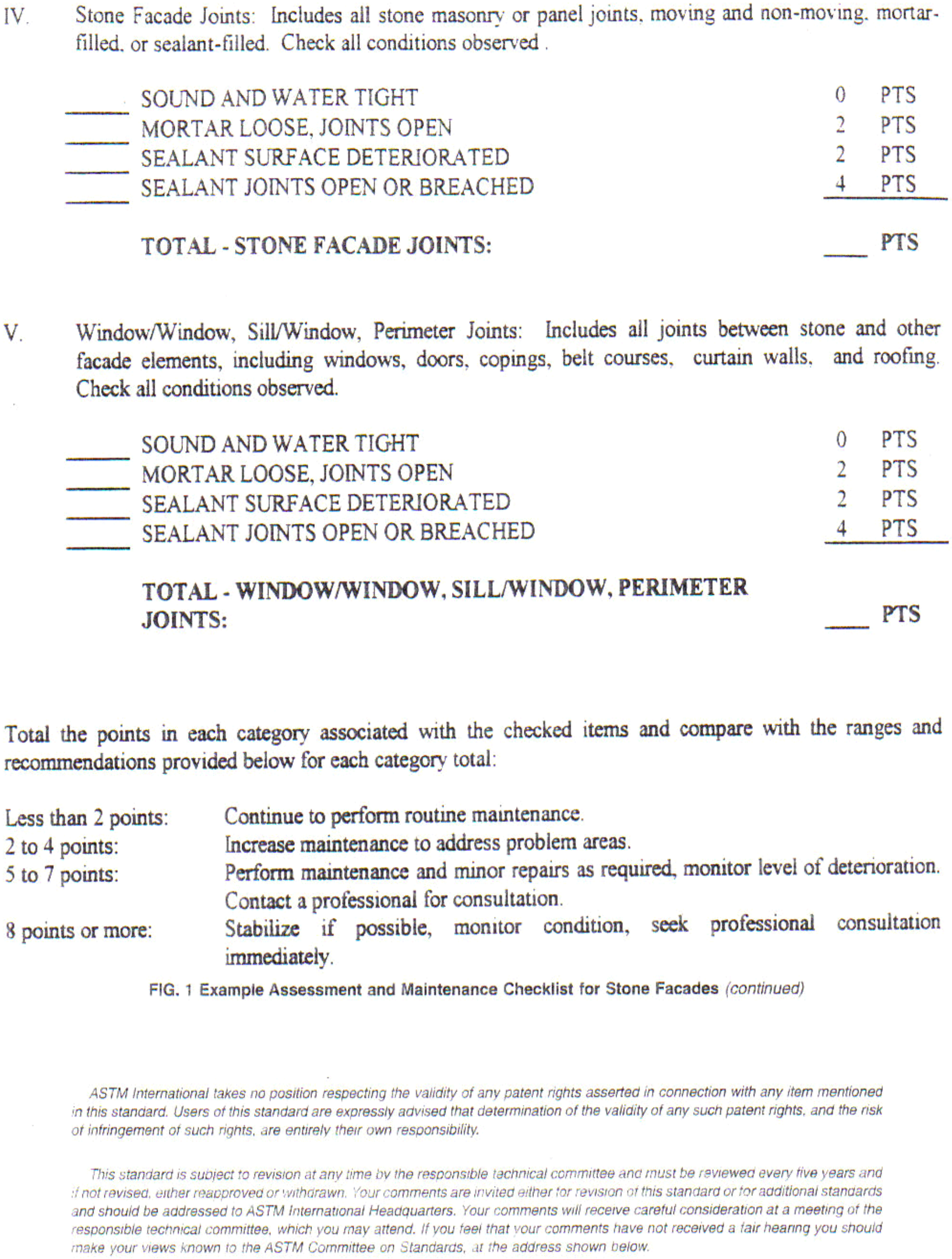
_____	SOUND, CLEAN, AND DRY	0	PTS
_____	SOILED	2	PTS
_____	DAMP	2	PTS
_____	EFFLORESCENCE	2	PTS
_____	BLOCKED/NONFUNCTINONG WEEP HOLES	2	PTS
_____	SCALING, POWDERING, EROSION	4	PTS
_____	SPALLING OR CRACKING	8	PTS
	TOTAL - ELEVATED FACADE ELEMENTS/WALLS:	____	**PTS**

III. Ground Level Facade Elements/Walls: Includes stone masonry, panels, copings, and all other exposed facade elements at grade. Or in contact with ground Check all conditions observed .

_____	SOUND, CLEAN, AND DRY	0	PTS
_____	SOILED	2	PTS
_____	DAMP	2	PTS
_____	EFFLORESCENCE	2	PTS
_____	BLOCKED/NONFUNCTINONG WEEP HOLES	2	PTS
_____	SCALING, POWDERING, EROSION	4	PTS
_____	SPALLING OR CRACKING	8	PTS
	TOTAL - GROUND LEVEL FACADE ELEMENTS/WALLS:	____	**PTS**

FIG. 1 Example Assessment and Maintenance Checklist for Stone Facades

Figure 27: Building Envelope Inspection Sheet Page 2



IV. Stone Facade Joints: Includes all stone masonry or panel joints, moving and non-moving, mortar-filled, or sealant-filled. Check all conditions observed .

_____	SOUND AND WATER TIGHT	0	PTS
_____	MORTAR LOOSE, JOINTS OPEN	2	PTS
_____	SEALANT SURFACE DETERIORATED	2	PTS
_____	SEALANT JOINTS OPEN OR BREACHED	4	PTS
	TOTAL - STONE FACADE JOINTS:	____	**PTS**

V. Window/Window, Sill/Window, Perimeter Joints: Includes all joints between stone and other facade elements, including windows, doors, copings, belt courses, curtain walls, and roofing. Check all conditions observed.

_____	SOUND AND WATER TIGHT	0	PTS
_____	MORTAR LOOSE, JOINTS OPEN	2	PTS
_____	SEALANT SURFACE DETERIORATED	2	PTS
_____	SEALANT JOINTS OPEN OR BREACHED	4	PTS
	TOTAL - WINDOW/WINDOW, SILL/WINDOW, PERIMETER JOINTS:	____	**PTS**

Total the points in each category associated with the checked items and compare with the ranges and recommendations provided below for each category total:

Less than 2 points:	Continue to perform routine maintenance.
2 to 4 points:	Increase maintenance to address problem areas.
5 to 7 points:	Perform maintenance and minor repairs as required, monitor level of deterioration. Contact a professional for consultation.
8 points or more:	Stabilize if possible, monitor condition, seek professional consultation immediately.

FIG. 1 Example Assessment and Maintenance Checklist for Stone Facades *(continued)*

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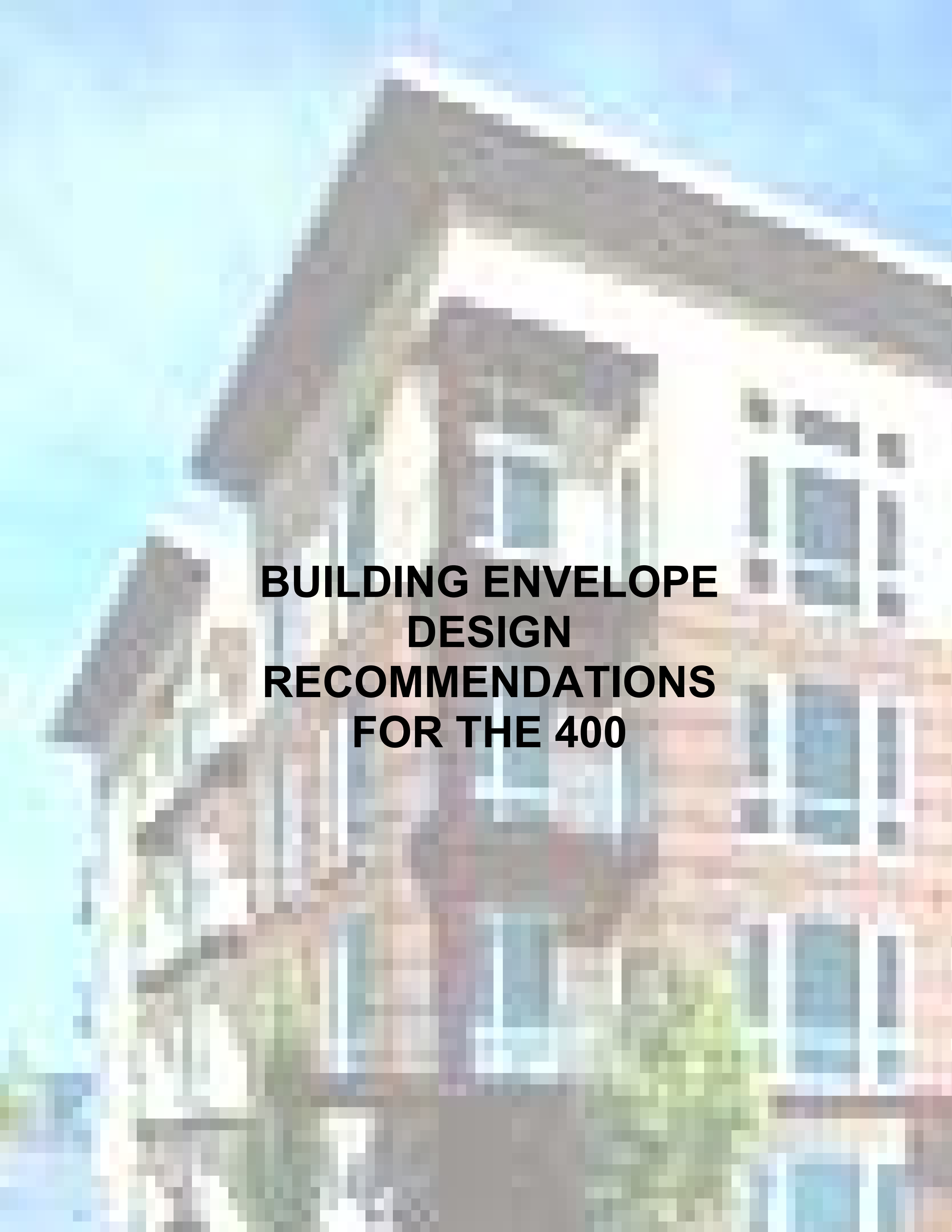
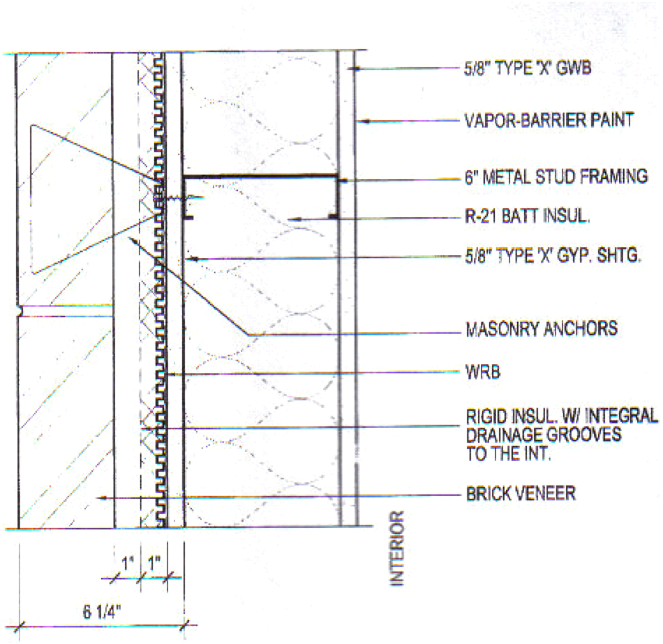


BUILDING ENVELOPE DESIGN RECOMMENDATIONS FOR THE 400

The building envelope of The 400 is made up of steel studs. The most crucial problem with a steel stud envelope is water penetrating where the brick tie anchors attach to the metal studs. Typically when metal studs are used in close proximity to the ocean, rust is generally a very large concern. Because The 400 is located along the water, not only is water intrusion a potential problem, but rusting of the metal studs, therefore diminishing their strength, is also a problem to be considered. A detail of the building envelope of The 400 is shown in Figure 28.

Figure 28: Building Envelope Detail
The 400



According to ASTM E2270-05, a brick façade should last at least twenty years if it is properly maintained. A brick façade is defined as façade category inspection category A in which an inspection is required every five years. The extent of required inspection for a general inspection is all 100% of the façade. The detailed inspection is necessary for at least 25% of each façade. Additionally, three probes are required for each façade, and three pull-tests in which general adhesive on exterior materials are performed at each elevation.

Because the building envelope consists of metal studs, the most probable water infiltration is through the sheathing where the brick tie anchors attach the sheathing to the stud. This is a very typical problem near the ocean or any other high precipitation area. The water in combination with the air in the cavity can very easily rust, diminishing the strength of the metal studs.

The current building envelope does contain an air cavity, generally about one-inch thick. An air cavity is recommended because it allows for a space where water can properly transfer to weep holes, allowing for water to leave the envelope if it enters. A potential problem, however, is for the cavity to get clogged with mortar snots from the mortar used for the brick. For building envelopes with an air cavity, the mortar strength must be weaker than the brick strength to allow proper evaporation of moisture. A solid brick or solid masonry wall, however, is probably considered to be the most durable. However, Type N mortar or softer is generally recommended to allow for proper evaporation of moisture. Another issue with a solid wall, though, is if it enters the building envelope, there is no cavity to allow for water to leave.

While the details themselves do not contain any major problems, flashing is a very important detail and it must be constructed properly. Special care and site investigations are recommended during construction to verify that details are built in accordance with the plans.

Summary and Conclusions

Blast Resistant Design and Progressive Collapse

The original intent of this thesis was to redesign the building to be blast resistant. Because blast resistant design is a relatively new phenomenon, I first encountered several obstacles to obtain design guides because I do not have a security clearance. While there are several rules of thumb which were previously summarized, the bulk of blast resistant design to date is engineering judgment. While it is possible to determine the dynamic loads of a unique blast on a building, there is no ultimate but reasonable loading to always design against. Even in the time it takes a building to be constructed, the technology of bombs could become so advanced that the loadings of a new bomb could be doubled or even tripled. For example, during design, the World Trade Center was able to resist a plane crash, but the plane that was crashed into the building on September 11, 2001 was so much larger than planes during the time of design that the designers could not have possibly accounted for it.

There is no building that can be designed to resist ANY attack, because some (like a nuclear attack) are just too large to even comprehend. The driving factor in a blast resistant design is what the owner or tenants are willing to pay and what design will make them feel safe enough to actually live there.

To conclude, yes, a design load equal to 2 (Dead + 0.25 Live) is comparable to taking out a column, but the limiting factor in design would then be the connections, as generally construction does not usually account for excessive rotation. Several other precautions could be taken to prevent progressive collapse, but the question remains: Where do you draw the line? Life itself is full of risks, and blast resistant design is no exception. It merely forces you to think of the probability that a blast would occur in your building and just how much you're willing to pay to design your building to withstand that blast.

Building Envelope

There are so many factors that cannot be accounted for in a building envelope. As previously discussed, a building can have the best detail in the world, but if it is not constructed properly, it can still fail. Likewise, a building can have the worst detail in the world or no detail, but the experienced contractor can construct all of the connections perfectly. The best conclusion I have reached from this thesis is as a designer, design the best detail you can and ensure that it is either constructed in perfect accordance or that the contractor is familiar enough with the material to make a judgment call. Ideally, the designer and contractor should be in agreement on all details, but the reality proves otherwise.

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ASTM Standards

ASTM C1496-01
ASTM E1186-03
ASTM E2270-05
ASTM F2242-04
ASTM F2247-03
ASTM F2248-03