CONSIDERATIONS FOR RETROFIT OF EXISTING STEEL BUILDINGS FOR RESISTING BLAST AND PROGRESSIVE COLLAPSE

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ABSTRACT

Evaluation and subsequent strengthening of existing structures for extreme loading cases, such as blast, require a realistic and pragmatic design approach. Effective communication between Owner, Structural Engineer, Architect, Risk Analyst, Insurance Providers, and other stakeholders is paramount to a finished project that is satisfactory to all. The benefits of structural steel for use in the renovation of existing buildings are well documented and are applicable to the type of retrofitting required for resistance to blast and progressive collapse. The performance of steel construction during the 1993 bombing of The World Trade Center is further evidence. Combination of the existing conditions of the structure and the nature of the threat leads to strengthening techniques that may not be the first choice in the case of new construction. Less intrusive types of strengthening are favored. The general approach for strengthening of existing buildings starts with researching the original construction documents and then performing a condition assessment of the building. Vulnerability analysis is a multi-step process where there is constant dialogue about the possibilities of non-structural methods to decrease the threat on the building. With the goal of enhancing a building's performance under an extreme event, we have provided a range of upgrades from enhanced perimeter protection to structural hardening.

INTRODUCTION

Balancing cost and vulnerability is a challenge for the security of any new building. Add considerations of an existing structure, building occupants, decades-old design criteria, and you have begun the first step in the evaluation of the hardening prospects for an existing building. Today, many building owners who are developing new buildings with a high risk profile are considering extreme loading criteria for their building designs. The pool of existing buildings, however, is much greater, and owners of these buildings are questioning how their structures would perform under similar criteria.

Evaluation and any subsequent strengthening of existing structures for extreme loading cases, such as blast, require a realistic and pragmatic design approach. Effective communication between Owner, Structural Engineer, Architect, Risk Analyst, Insurance Providers, and other stakeholders is paramount to a successful finished project. With the goal of enhancing a building's performance under an extreme event, we have provided a range of upgrades from enhanced perimeter protection to structural hardening. The benefits of structural steel for use in the renovation of existing buildings are well documented and are applicable to the type of retrofitting required for resistance to blast and progressive collapse. This paper discusses the aspects of blast hardening specific to existing facilities. Lessons learned from the 1993 bombing of The World Trade Center are described. Following a discussion on a general approach for the hardening of existing structures, we discuss common goals and situations. Due to the confidential nature of the work, project names and identifying photos are not provided.

ASPECTS OF BLAST HARDENING SPECIFIC TO EXISTING FACILITIES

Effectively protecting an existing facility by blast hardening is a relatively difficult task. Realistically, the built environment has a number of inherent weaknesses when considering the possible effects of an extreme event. Rare is the facility that has systems designed for improved performance in an extreme event. Cladding, site planning, stairs, power systems, and structures are planned to deal with more common environmental conditions. Structures are typically constructed without specific consideration of redundancy or robustness in an extreme event.

While risk analysis and vulnerability assessment are essential first steps in any security project, these steps take on a special importance for an existing facility. Due to the particular difficulties of effectively hardening an existing building, it is important that the risk analysis and vulnerability assessment result in a clear understanding by the client of the potential vulnerabilities and of the scale of construction work that may be required to mitigate or prevent damage from the identified threats.

Since the costs of hardening an entire existing facility are often so high, clients commonly choose to focus their efforts on specific locations or functions within a facility where risks are highest. They establish limited hardening objectives. Frequently, non-structural security measures prove to be the client's most practical and cost-effective alternative. Preventing or re-routing pedestrian or vehicular traffic, instituting operational changes, providing redundancy in the building's critical power and sprinkler systems and other similar measures are often the most effective techniques for enhancing the performance of an existing facility.

Perhaps the single most important aspect of existing building security projects is the identification of practical alternatives, the best of which may not involve structural hardening.

Where a decision is made to harden some part of an existing facility or a specific structural system or element, the design approach is influenced by a series of factors that include the following:

- Information about relevant existing conditions is often limited;
- Structure to be renovated is commonly hidden or obstructed by existing architectural or building services systems that are difficult or costly to remove;
- Structural renovation work is typically constrained by the need for continuity of building operations;

- Generally, renovation of a steel-framed structure is more economical than the renovation of a concrete structure;
- The use of steelwork in a renovation is generally more cost-effective than the use of reinforced concrete; and
- The level of ductility of the existing construction may limit its strength.

These factors lead to fundamental differences in the approach to blast hardening between new and existing construction.

Uncertainty about existing construction may limit the sophistication of blast analysis that is appropriate; there may be no point in a precise determination of the presumed behavior where no equally precise understanding of the existing structure or its connections is available.

Conversely, the high cost of renovating an existing structure may justify a more sophisticated blast analysis where reliable detailed information is available and where there is reason to believe that substantial savings may be achieved in the construction cost of the strengthening project.

The approach that one takes with the analysis, or the design, is a matter of effectively relating the scale of the enormous, but transient, blast pressures to the effective resistance of the structure.

In considering the construction cost of retrofitting an existing facility, it is axiomatic to consider the total construction cost, not simply the structural costs. Often, the non-structural costs will equal or exceed the structural costs; therefore, the true costs of a retrofit project relate more to the number of locations of work than to the amount of work done in each location. This relationship should influence structural design and analysis decisions. For example, sophisticated analysis that reduces, but does not eliminate, the reinforcement of an inaccessible column may have little real benefit.

In new blast-resistant construction, ductile structural systems are designed to deform inelastically under large blast-induced forces. In many instances, existing construction will have limited post-elastic dynamic capability. Often, performance is limited by the shear capacity of critical structural elements. Further, wide-spread strengthening of the construction may be precluded by the costs of removing and replacing the enclosing construction.

In steel structures, common deficiencies include susceptibility to local buckling of outstanding flanges, and lack of connection ductility. Strengthening of a limited number of structural elements is usually practical, and, as with other types of renovations, there is a relative ease of working with steel construction.

In cast-in-place concrete structures, ductility and strength are often limited by the amount and the detailing of the existing reinforcement. For columns, fiber wraps, steel plate encasement and reinforced concrete encasement alternatives are practical. In most cases, wide-spread strengthening of a cast-in-place concrete structure will be impractical. Enhancement of a limited number of structural elements, however, is usually feasible.

Generally, precast concrete structures will exhibit the worst extreme event performance characteristics of either steel and concrete construction with potential weakness both at connections and in the detailing of the reinforcement. Consequently, the potential for effectively strengthening precast concrete structures is relatively limited.

There are fundamental differences between new construction and structural renovation and these differences are equally fundamental for blast hardening projects. The best designs for blast hardening of existing facilities are based on a clear vision of the overall security goals of the project and on an equally clear understanding of the detailed limitations of that which exists.

LESSONS LEARNED FROM THE 1993 BOMBING OF THE WORLD TRADE CENTER

At 12:18PM on Friday February 26th 1993, a 1000 lb. TNT equivalent bomb, located within a van parked immediately adjacent to the columns of the south wall of the north tower, was detonated in the second basement of The World Trade Center complex.

The resulting explosion destroyed approximately 30,000 sq. ft. of the concrete flat slab floor construction located at the first and second basements and badly damaged over 25,000 sq. ft. of construction. The structural steel framing above suffered far less damage. A small opening was breached within one bay at street level and the plaza level framing was left with a prominent upward bow.

This destruction occurred outside of the footprint of the towers. The tower structures were largely unscathed, with the north tower suffering minor damage to one column and the loss of two diagonals located immediately adjacent to the blast. The primary structure of the south tower suffered no damage. At no time was the structural integrity of either tower significantly impacted.

Conversely, several steel columns that supported the north end of the 22-story Vista Hotel were rendered un-braced for a 68 foot height by the loss of the concrete flat slabs in the basements. In the days immediately following the explosion, one of the most critical structural repair initiatives was to temporarily stabilize these columns. This was accomplished through the installation of tubular steel bracing.

From the perspective of performance of existing structural systems in an extreme event, i.e. systems not explicitly designed for blast resistance, two clear lessons can be learned from this tragic event:

1. The inherent blast resistance of an existing structure will be highly dependent on the scale of the building and on the scale of the wind or seismic forces for which the building has been designed; and
2. It is likely that steel construction will perform better than concrete construction because of its greater inherent ductility.

The structures of the 110-story World Trade Center towers were essentially unaffected by the blast, while the stability of the 22-story Vista Hotel was put into jeopardy. Fundamentally, this difference is a function of the relative scale of the buildings and the type of construction within the footprints of each building.

The inherent difference in blast-resistance between the steel and concrete construction was apparent to those of us who worked on the reconstruction. All around the blast site, one observed individual steel beams and columns remaining where the surrounding concrete slabs or beams were destroyed. Where steel beams failed, one observed in the dismembered pieces dramatic evidence of the ductile behavior that preceded failure.

Also, we observed large sections of concrete floor slab suspended in mid-air by one or two reinforcing bars, evidence of both the value of inherent tensile strength and the absence of this strength that is often the weakness of existing concrete construction not designed for extreme events.

GENERAL APPROACH TO HARDENING EXISTING STRUCTURES

Risk assessment and structural vulnerability assessment

While risk analysis and vulnerability assessment are essential first steps in any security project, these steps take on a special importance for an existing facility. The structural engineering vulnerability assessment of the existing facility needs establish the global strength of the lateral load resisting system relative to the magnitude of potential extreme events. Further, the particular vulnerabilities of specific structural systems and elements need be identified.

The importance of an overall vulnerability assessment of the structural systems of an existing facility needs to be communicated to the client at the beginning of a project. A certain prominent feature of the structure, such as a column, that the client wishes to protect may well be the reason an evaluation was sought; however, the loss of a related transfer truss or girder may precipitate a similar or larger collapse.

First, one needs begin with a condition assessment of the building. Ideally, this assessment should include review of the original construction drawings, shop drawings, subsequent renovation drawings, and maintenance records. Commonly, however, the available documentation is limited. Where relevant information is lacking, a prudent assessment report may qualify the pertinent conclusions. Following a review of the documentation, one or more visits to the facility, complemented by probes at critical locations, are usually appropriate. In some circumstances, a consolidated set of drawings is created. An additional component of the assessment of the building is a load survey. We sometimes conduct load surveys in existing buildings where we are transferring columns. When it comes time to study an element or a systems demand-to-capacity ratio the data from the survey can be very useful.

With the structural condition assessment of the existing building complete, a structural vulnerability assessment may be made for either an undefined threat or series of defined threats. Regardless, one should neither finalize the structural vulnerability assessment, nor proceed with a hardening design, until the risk assessment is completed.

Preliminary Analysis - Getting into scale

Typically the risk analysis addresses the possibility of threats from explosives ranging in size from a pipe bomb up to a fully laden tractor trailer. Depending upon the project's original design criteria, i.e. which natural hazards were considered, the height of the building, and the lateral load resisting system, it is possible that the global strength of a building's structure may be overwhelmed by the larger threat scenarios.

For buildings where the global structural system may be easily compromised, alternatives to structural hardening are the preferred course of action. Often, by relocating high-risk functions, the building threat may be reduced to manageable proportions. For buildings were the global systems are able to withstand the range of forces triggered by the threat with modest intrusions, we then turn our attention to an evaluation of redundancy and specific potential weaknesses in the structure.

For the structure assessment, the following needs to be considered:

- local behavior of the items that make up the element, such as the flange of a column;
- global behavior of an element; such as large deflection of a column unable to restrain the resulting P-delta forces;
- local behavior of the connections; such as net section limitations at bolt hole lines;
- local behavior of transfer systems and trusses; and
- global behavior of lateral load resisting systems.

To analyze the effects of the blast pressures on the varying elements one of the more practical resources is the Army's TM 5-1300 "Structures to Resist Accidential Explosions" (Army TM 5-1300, 1990). This reference, in combination with the ConWep Software (USAEWES/SS-R, 1992)[1] guide you in the calculation of the pressure and related information necessary to perform an analysis for reinforced concrete construction and for structural steel construction. There is additional software and reference guides available, FRANG (NCEL, 1988), FRANG (NCEL, 1989), and even expanded code finite element analysis software like Weidlingers' FLEX, but availability, cost and performance vary considerably. In some cases, a hand calculation is sufficient. At other times the use of advanced software is necessary. For those entering the field, a good reference is *Structural Dynamics* (Biggs, 1964).

[1] Dr. Theodore Krauthammer provided an overview of available software during the "Modern Protective Structures Short Course" sponsored by SEAoNY in June 2003.

Consideration of Alternatives – Both Structural and Non-Structural

Following the preliminary vulnerability analysis the design team meets to discuss the range of non-structural alternatives and the strengthening alternatives for the project. Often, the final criteria for the strengthening of the building are decided at this meeting.

Consideration must be given to the weight of the new structure that is being added to the building. A significant increase of weight to the building, such as will accompany the addition of concrete encasement or concrete walls, may require a supplementary reinforcement of the gravity or lateral load resisting systems of the structure. Care need be taken in checking with the local jurisdiction about the applicable building code to use in the case where you are reanalyzing the lateral load resisting system of the building. As with any renovation or retrofit project, the possibility of triggering a comprehensive upgrade of the existing building to the current building code needs to be considered. In almost all cases, accomplishing such an upgrade will not be economically or functionally feasible.

Detailed design and the impact of connections

As with most renovations, the cost impact on the project is directly related to the number of locations within the building requiring work. For most hardening, steel elements provide more cost effective results than concrete. The connection of choice for field installation of steel work is welding. For detailed design, we typically turn to steel for its many advantages. As with most renovations, steel provides compact, high strength, and ductile elements which in turn bring an ease of installation and attachment.

When reviewing existing structural elements, we typically find that the connections are the first limitation to the elements performance under extreme loads. Strengthening of connections at beam-to-column joints afford another leap in capacity for the system.

COMMON GOALS AND SITUATIONS

With rare exception, both owners and architects are seeking a more secure building that does not take on the 'bunker' aesthetic. These goals can be significant hurdles until after the risk assessment has effectively communicated limited hardening objectives based on limiting low probabilistic threats.

The hardening goals may include hardening of the room/area used for mail handling/inspection, hardening of the security barrier at entry and hardening of specific structural elements that are deemed vulnerable.

Protecting specific structural elements

The damage or loss of an individual member of a transfer system or truss may result in a disproportionate degree of damage to the building structure. Hardening of these elements takes the form of connection reinforcement, element reinforcement and stiffening of buckling-prone portions of the elements, e.g. individual plates of an unfilled built-up box column.

Where the design of the site layout or underground facilities provides for key elements, such as columns, to be accessible to attack, element hardening may depend upon the space available. Where possible the entire architectural envelope around the column may be utilized for increasing the strength of the element. In some locations, there also may be room within the depth of the ceiling to provide bracing to increase the buckling strength.

Providing redundancy to structural systems

For most existing buildings strengthening of elements is costly. It can often be highly intrusive and provide only localized protection. Providing load paths or system redundancy to the critical structural systems is another means of strengthening. In this case, one assumes that a critical element of a system is lost in the event and its loads need be shed to an adjacent system. For some buildings this may take the form of simply interconnecting a series of existing trusses, girders and columns such that they act together to effectively redistribute loads. For other buildings a completely new system may need to be inserted.

Hardening a specific room or area

Mail rooms are examples of rooms which can be subject to internal explosions. Strengthening for these areas includes the walls, floors, and ceilings. Venting systems are often an efficient method of mitigating the effects of blast in the hardened room and beyond. Strengthening in combination with a venting system is often your most efficient solution.

For some agencies, their building complex may include high risk functions that are directly adjacent to areas of public access. These include areas built below open air plazas, or buildings which are built with minimal setbacks from the public roads. External explosions outside of these areas are unable to be mitigated by increasing stand-off distance unless the local authority is willing to reroute traffic (highly unlikely). In these areas, the first response is to inquire about moving the high-risk agency or function away from the area. When that is not able to occur, one looks for blast curtains or sacrificial walls to shield the area from the direct pressures of a blast.

Hardening a secure perimeter or entry

Providing a secure perimeter takes the form of a combination of building steps, blast or sacrificial walls, and bollards. Glass in lobbies presents a challenge in trying to protect lobby occupants. Retrofitting with a puncture resistant interlayer and stronger glass lites usually is too costly. Reinforcement of just the glass can be short-sighted; where the grip of the mullions to the glass is too small, a single large projectile can be created in place of many smaller projectiles.

SUMMARY

A comprehensive security risk analysis that is clearly communicated to the client is an essential prerequisite to the blast hardening of an existing facility. Often, non-structural security measures combined with partial blast hardening are the appropriate response to the perceived threat.

The existing architectural and building services systems and the operational requirements of existing facilities place practical limitations on the hardening of existing facilities.

The relative scale of the extreme event compared with the wind and seismic criteria for which an existing facility was designed may limit the potential hardening objectives that can be achieved. Similarly, the degree of ductility inherent in the existing structural framework represents another possible limitation.

Common partial hardening objectives include the protection of critical rooms or areas, the hardening of a secure perimeter or entry and the hardening of specific structural elements or systems that are required to maintain overall stability of the structure.

The best designs for blast hardening of existing facilities are based on a clear vision of the overall security goals of the project and an equally clear understanding of the detailed limitations of that which exists.

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