Recommendations for Blast Design and Retrofit of Typical Highway Bridges

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Abstract. Bridge design for security has received national attention following the terrorist attacks on September 11th, 2001. Intelligence gathered since then has revealed threats to bridges in California and New York. In addition, suspected terrorists have been arrested with materials in their possession such as video footage of critical structural elements and information on cutting devices needed to destroy bridge cables. As a result, various states DOTs and the federal government are looking into ways in which our highway infrastructure can be designed to better withstand extreme loads.

A pool-funded research project supported by seven state DOTs was conducted by the University of Texas and consultants with expertise in the structural response to blast loads. The purpose of this research was to develop economical and effective measures that can be taken to improve bridge security. Because engineers have not traditionally needed to consider security in the design of bridges, and little data exist for the response of bridges to explosive tactics used by terrorists, the primary goal of the research was to provide performance-based design guidelines that can be employed by designers with limited background in the design of structures for security. To accomplish this goal, parametric studies were conducted on five different categories of bridges including prestressed girder, plate girder, segmental box girder, truss, and cable-stayed configurations. This paper provides an executive summary of design alternatives that engineers can consider before structural hardening and, in the event these cost-effective techniques are insufficient in reducing the threat to an acceptable level, structural design and retrofit guidelines are proposed.

NEED FOR GUIDELINES

The percent of all worldwide terrorists attacks occurring against American interests has been increasing steadily every year since the early 1990s (*1*). Although bridges currently only account for approximately six percent of all attacks against transportation targets (*2*), an attack against a critical bridge could result in loss of life, costly structural damage, and effects on local and national economies due to the prolonged disruption of commercial traffic. Therefore, measures need to be taken to protect our most critical bridges. Since September 11, 2001, the design of critical bridges for security against terrorist attacks has become a national concern. Bridge owners have been examining their inventories to determine their most critical and most vulnerable bridges. Research has been conducted to examine the effects of blast loads on bridges, determine potential design parameters and retrofit solutions, and develop post-attack alternatives such as rapid bridge replacement. Additionally, risk assessment techniques specifically for bridges have been proposed (*3*).

This paper summarizes the results of a 34-month research project headed by the Texas Department of Transportation, with the goal of investigating economical, unobtrusive and effective methods to mitigate the risk of terrorist attacks against critical bridges. To develop general guidelines for a large number of bridges across the US, five representative bridge types were investigated: prestressed concrete girder, steel plate girder, segmental box girder, steel truss, and cable-stayed. Taken together, these bridge types account for approximately 70 percent of the on-system bridges in the United States (*4*). A thorough literature review was conducted to determine the best practices currently being utilized in military and civilian blast-resistant design, seismic retrofits that may have the potential to serve as blast retrofits, and accident mitigation measures for vehicle or vessel impact. Parameter studies were then conducted, and the results were used to evaluate the effectiveness and assess the relative improvement in performance of alternative design and retrofit strategies. This paper presents a brief discussion of the blast load and structural models used, and provides recommendations for enhancing the security and structural response of bridges.

PERFORMANCE-BASED STANDARDS

Bridges will differ in the amount of protection needed based on their criticality, vulnerability, and bridge type. Therefore, performance-based design standards are proposed for terrorist threats against bridges (Table 1). The design standard is based on a bridge's criticality (as defined by the bridge owner), which dictates the performance category under which it falls. These standards establish a baseline threat level for design loads (specific charge weights are omitted for security reasons) and define the acceptable level of damage under these loads. The design loads and acceptable damage for each category is based on a balanced assessment of the threats, acceptable risks, and available resources. Most-likely threat scenarios are developed by conducting a threat assessment for each structural element being designed. For example, attacks against the piers will most likely be in the form of a truck bomb or vehicle/vessel impact at ground or water level, while attacks against a steel truss could include special hand-placed charges to cut critical members or collision at deck level from a large truck. Significant barriers exist, however, which will need to be overcome before implementing these standards. Most of the blast design body-of-knowledge was developed primarily for buildings and military structures. Little information exists specifically for bridges, much less the combined effects of vehicle impact, possible explosion, and potential for sustained post-attack fires, all acting in succession on a bridge. Therefore, it will be necessary to conduct experimental studies that focus on bridges in order to improve our understanding of these effects.

Although most bridge owners possess the in-house expertise to design against vehicle and vessel impacts, few are familiar with the principles of blast-resistant design. This lack of knowledge is compounded by the fact that most of the best references and computer analysis tools for blast design are controlled by the military and have distributions limited to U.S. government agencies and their contractors. This limited distribution is necessary to prevent state-of-the-art blast design knowledge and critical technology from falling into terrorist or foreign hands. Because it is unlikely that this information will be released to the public, it will be necessary to either provide controlled access to bridge designers or allow government agencies and contractors to perform the designs. Additionally, the exact charge weights and standoff distances being used as the "baseline threats" cannot be published, as this would inform potential terrorists of the amount of explosives needed to destroy a bridge. Therefore, the best option for implementing these standards appears to be maintaining controlled access of the blast design body-of-knowledge to selected bridge engineers that have undergone a thorough background investigation. These engineers could then develop prescriptive design and retrofit specifications for each bridge type and performance category, which could then be made available to bridge owners without releasing the specific baseline threat they are designed to counter.

PHYSICAL SECURITY AND SITE LAYOUT MEASURES

Several physical security and site layout measures can be used to deter or mitigate threats to bridges. These types of measures usually provide the most cost-effective solution. However, before scarce resources are allocated, a thorough cost-benefit analysis should be conducted that considers both the initial costs as well as the long-term expenses associated with maintenance, operation, and replacement. For example, the initial costs for structural retrofits may be high relative to the costs associated with installing closed-circuit television, but the long-term expense of monitoring closed-circuit television may exceed the long-term costs associated with structural hardening. In general, physical security and site layout measures can be used to displace threats to less attractive targets, increase the likelihood of terrorists being detected and identified, keep casualties to a minimum, improve emergency response time, increase public confidence, improve structural response, or a combination of these events. Based on a literature review (*5*, *6*), the best physical security and site layout practices that are most appropriate for bridges include:

- Police patrol, surveillance, and guards
- Keyed or keyless entry systems on access panels, tower entrances, and maintenance areas
- Intrusion detection systems at critical areas (e.g., inspection platforms)
- Closed circuit television (CCTV) monitoring
- Identification procedures and verification of credentials for maintenance personnel
- Emergency telephones to report incidents or suspicious activity
- Use of an advanced warning system, including warning signs, lights, alarms that notify authorities, and railroad-type gates to deny access after span failure
- Physical barriers to restrict access to critical structural elements, such as the piers, cable anchors, and cable towers
- Improved lighting with emergency backup
- Elimination of hiding spaces and clearing overgrown vegetation
- Elimination of parking spaces beneath bridges
- Providing pass-through gates in concrete median barriers to enable rerouting of traffic and access for emergency vehicles
- Planning redundancy in individual future bridges, such as using two adjacent two-lane bridges as opposed to one four-lane bridge
- Avoiding architectural features that magnify blast effects, such as recesses or offsets in structural members or unnecessary confined areas

Additionally, threat-level-based measures can be implemented to further enhance the security plan. These measures are intended to elevate the level of security by implementing additional measures at times and locations where there is a heightened credible threat against specific bridges. Examples include implementing increased security patrols, stationing guards such as private security or the National Guard, using physical barriers to control traffic, implementing vehicle searches, putting dive teams in the water to check piers, postponing non-essential maintenance, and conducting full-scale emergency response exercises (*3*).

BLAST ENVIRONMENT

Blast loads were determined using two programs developed by the U.S. Army Corps of Engineers and their contractors. For most above-deck loads, Conwep version 2.0.9.0 (*7*) was used (distribution limited to U.S. Government agencies and their contractors). Based on *Design & Analysis of Hardened Structures to Conventional Weapons Effects* (DAHSCWE) (*8*), Conwep performs airblast calculations for a given charge type, equivalent TNT weight, standoff distance, and type of burst. The computed results provide the pressure-time history for the structural element being analyzed (Figure 1). Conwep considers only the initial, or incident, shock wave and one surface-reflected wave. Whenever a shock wave reflects off a surface, the pressure is increased by a factor as large as two. For above-deck loads, Conwep provides reasonable results as there is generally only one surface (the deck) to consider.

Explosions below the deck create a much more complex blast environment than those occurring above the deck. The effects of multiple reflections from ground and deck surfaces, reflections inside the cavities created by the girders and the deck, and the reflections near the abutments can significantly enhance blast pressures (Figure 2). Each time reflected waves merge in confined areas, the pressures acting on the structural elements are increased. To account for these confinement effects, BlastX version 4.2.3.0 (*9*) was used to generate loads for below-deck scenarios (distribution limited to U.S. Government agencies and their contractors). The BlastX computer code defines the internal airblast environment in structures with multiple chambers for both internal and external explosions using fast running analytical/empirical models. The code treats shock-wave propagation through strings of “rooms” (i.e., defined volumes and areas) and “vents” (the area between the ground and deck on both sides of the bridge) to model blast transmission through multi-room structures, such that obstructions and confinement can be considered (Figure 1). Interpretation of the results does require a familiarization with the basic blast principles outlined in the DAHSCWE manual (*8*).

As seen from Figure 2, the use of Conwep in a complicated blast environment, such as below the deck of a bridge, can result in extremely unconservative results. The impulse, or area under the pressure-time curve, is directly related to the amount of expected damage. In the case of below-deck explosions, Conwep can under-predict this impulse by factors as large as 15 (depending on the specific bridge geometry and charge weight/location). However, BlastX is more time consuming than Conwep because of the requirement to define the “rooms” and the need to adjust the results to account for curved surfaces and the clearing time, or amount of time the load acts on structural elements in the model. Details of these adjustments are beyond the scope of this paper, and are currently pending publication in the *Journal of Structural Engineering* (*10*). To facilitate the analysis of several charge weights and standoffs acting against numerous configurations of bridges, multipliers were determined for specific cases such that confinement effects could be estimated by multiplying the Conwep results by a scaling factor. This simplification could only be used in cases where the blast environment did not contain numerous reflecting surfaces and confined areas, and the factors were verified with BlastX results based on specific bridge geometries.

When a shock wave strikes a structural element, concrete may be removed through spalling (a tension failure caused by the shock wave traveling through the structural member, reflecting off the back face, reversing direction, and creating tension forces as it travels back towards the center of the member) or cratering (a compression crushing failure occurring on the blast face). The combined effects of spall and cratering can lead to significant reductions in the cross-sectional area, or possibly even a complete breach of the structural element. To predict the damaged area of structural members due to localized blast damage, empirically-based spall and breach equations developed by one of the authors (*11*) were used.

Results from the current study have shown that bridge geometry can have significant effects on the blast loads below the deck. For bridges with deep girders, confinement effects between the girders can greatly enhance the blast loads acting on the girders and top of the piers, and in some cases may result in more damage than an explosion occurring on top of the deck. The clearance can also have a significant impact on the results, as increasing the distance from the explosion to the deck can result in more damage to the girders due to the formation of a Mach front. A Mach front results when the ground-reflected wave, which is traveling faster through air that has been heated and compressed by the incident wave, merges with the incident wave and produces a single wave with significantly higher pressures (Figure 3). If the two waves strike a structural element before merging, there will be two separate pressure peaks, each much less than the merged wave in a Mach front. Although higher clearances may result in higher loads on the superstructure in some cases due to the formation of a Mach front, they always lead to lower average loads on the piers due to the larger volume of space (less confinement) under the bridge and the increased average standoff distance to a given point on the pier. Explosions occurring near sloped abutments could possibly result in more damage than an explosion at midspan due to confinement effects. Finally, round columns will experience lower loads than rectangular columns due the reduced angle of incidence of the shock wave resulting from the curved surface. A flat, rectangular column will experience the load at angles close to 90 degrees, while the angle of incidence of a round column will vary from 0 to 90 degrees. Because smaller angles of incidence result in lower pressures in the direction of the shock wave, round columns will experience approximately 20 percent less total impulse than a rectangular column.

STRUCTURAL MODELS

As previously mentioned, the goal of the research was to investigate potential countermeasure options that could be applied to a wide range of bridges. Therefore, it was necessary to vary several parameters in the analysis, including span, clearance, material strengths, and structural member types, sizes, and spacing. When combined with varying charge weights and locations (standoff distance from the bridge members), more than one thousand separate analyses were required. As a result, the structural models had to be simplified to facilitate such a large number of analyses.

The bridges' structural systems were characterized as a "stack" of uncoupled components, or as a series of single degree-of-freedom (SDOF) systems. The loads applied to all surfaces were attributed to supporting components according to load direction. Thus, the deck response was used to determine the loads applied to the girders, and the girder response was used to determine the loads on the cap beam. In some instances, multiple degree-of-freedom (MDOF) analyses were performed to verify the SDOF models. Prestressed concrete girders were modeled as simply supported members, while steel plate girder analyses considered both simply supported and continuous girder cases. Columns were modeled as having fixed supports at both ends. Though actual end conditions for most columns fall between fixed-fixed and fixed-pinned, assuming fixed-fixed resulted in conservative estimates of the damage levels because most columns were controlled by the shear response. The fixed end conditions provided more resistance to the energy imparted by the blast loads, resulting in less deflection and higher shear forces. Even with pinned-fixed end conditions, most columns tended to be governed by shear. For trusses, the typical assumption of pinned-pinned members was compared against the case in which rotational restraint could be present. This evaluation was necessary in determining the ultimate capacity of the individual truss members. For all bridges studied, the typical assumptions used for design under normal traffic loads required adjustment for the case of blast loads in which the failure limit was sought. Thus, while large deformations and inelastic material response under typical loads are not permitted, they must be accounted for under blast loads when determining the onset of failure.

To calculate the flexural response of the structural elements, SDOF software developed specifically for this research and SPAn32 version 1.3.0.0 (*12*) (distribution limited to U.S. Government agencies and their contractors) were used. Developed by the U.S. Army Corps of Engineers, SPAn32 performs an equivalent SDOF dynamic analysis taking material nonlinearity into account. The blast load pressure history is specified as an equivalent, uniformly distributed load, and can be entered directly from the BlastX or Conwep output files. Additional dead weight and external static loads can also be added to the member. SPAn32 calculates the equivalent SDOF stiffness and mass parameters based on the member geometry and material properties. Ultimate resistance is determined from the full plastic hinge capacity of the member. Though it is based primarily on the first principle solution to the ordinary differential equation of motion for the SDOF system, it makes some adjustments based on empirical data. These adjustments include incorporating dynamic increase factors to modify the material strengths based on the instantaneous calculated strain rate (strength increases occur under the high strain rates caused by blast loads). Also, ultimate moment capacity of the concrete is based on the equivalent rectangular stress distribution from ACI 318, but is reduced once the member exceeds a rotation of 2 degrees, based on empirical data. Computed results obtained using SPAn32 compared well with the developed SDOF software used for portions of this research.

Damage limits for flexural failures were based on rotational capacities of similarly loaded building members as reported in the DAHSCWE manual (*8*). Shear loads and member capacities were also calculated based on specifications in the DAHSCWE manual, and shear capacity increases for fiber-reinforced polymer (FRP) wraps and steel jackets were based on research results reported in the literature (*13*). As previously discussed, spall and breach damage was predicted using empirically-based spall and breach equations (*11*).

STRUCTURAL RECOMMENDATIONS

While the following recommended provisions are based on analytical research, some may require further validation with physical testing. However, most of the guidelines are general in nature and could readily be applied to a wide range of bridges. For the most critical bridges, a more detailed analysis may be justified.

Reinforced Concrete Columns

As previously discussed, round columns will experience lower forces from blast loads and are therefore preferred over rectangular columns. Smaller columns with diameters around 1 m (3 ft) or less are usually controlled by breaching failures and may require either standoff barriers or steel/armor jackets. Although standoff seems to provide the best solution to prevent failures, it can be difficult to achieve for most bridges. Considering the average impulse computed using BlastX for below-deck explosions with various charge weights and standoff distances, it was determined that significant impulse reductions occur for every foot of standoff provided up to 6 m (20 ft). Although additional standoff distance beyond 6 m (20 ft) will lead to smaller loads acting on the piers, the relative benefit of increasing the standoff from 6 m (20 ft) to 12 m (40 ft) is not near as great as increasing the standoff from zero to 6 m (20 ft).

When considering clearances around 7 m (24 ft) and smaller, columns with diameters greater than 1 m (3 ft), or those that have been retrofitted with steel jackets, tend to experience diagonal shear failures at the supports. Therefore, additional shear reinforcement may be needed to allow for the formation of a plastic hinge mechanism. Flexural failures usually do not govern the response of shorter columns, so retrofit solutions that increase the flexural stiffness of larger diameter columns may lead to a higher chance of experiencing diagonal shear failures due to their increased reactions at the supports. In general, FRP wraps can provide adequate diagonal shear strength to overcome their added flexural stiffness, while steel jackets are much less effective. Therefore, the best retrofit for larger diameter columns seems to be providing additional ductility and shear strength through FRP wraps, or changing the support conditions to allow for more rotation at the ends to reduce the shear reactions. Because limited information exists on the performance of FRP-wrapped columns under close-in detonations, additional research is needed to verify the assumptions made in the current study. Finally, as previously determined from seismic research, when using a steel jacket on rectangular piers, a round jacket with grout fill should be used as rectangular jackets have significantly reduced effectiveness (*13*).

Clearances larger than 7 m (24 ft) were not analyzed under the current research, but they will experience less average impulse for a given charge weight and standoff. Despite the reduced loads, it is possible that taller columns may require flexural strengthening in addition to shear strengthening.

Prestressed Concrete and Steel Plate Girders

Simply supported girders tend to experience global flexural failure under large truck bombs, and localized spall and breach damage for attacks above the deck. Little can be done to reduce the localized damage for concrete girders in a cost effective manner, as steel or armor protective plates on each girder along the entire span can be very costly. However, the most promising design and retrofit options for the flexural response of concrete girders include the use of FRP wraps to provide both additional flexural stiffness and ductility, or the inclusion of additional steel reinforcement on the top (for uplift forces coming from below the deck) and bottom faces. For steel girders, cover plates can be attached to the flanges to increase their flexural capacity, and splices need to be detailed to allow for the formation of a plastic hinge mechanism. For all girders, additional lateral bracing may be needed to ensure the formation of a plastic hinge. Additionally, minimizing the girder spacing allows for greater system redundancy (i.e., more total girders) and the ability to redistribute the load from locally damaged areas; it also lowers the average load each girder is required to carry. This lower average load will result in smaller (less deep) girders, which will also reduce confinement effects for explosions occurring below the deck (Figure 2).

The potential loss of composite action with the deck can significantly reduce a girders’ capacity to resist flexural forces for above-deck attacks. Although it might be possible to redesign the shear connectors to better resist separation from the deck for the case of below-deck loadings, this option is not recommended. For the case of loads originating beneath the deck, the presence of the superstructure helps create a blast environment with greater confinement than the above-deck load cases. As such, loads acting on the girders can be as large or larger than the above-deck scenarios even though the standoffs are typically greater for the below-deck cases. If the connection of the deck to the girders is sufficiently weak, the reactions of the deck slab will not be transferred to the girders. Thus, even though the girder capacity is less when composite action is lost with the deck, the loads transferred to the girders are also less. In fact, because localized deck failure does not pose significant risk in causing a complete span failure, a reasonable design strategy would be to allow the deck to fail locally so as to provide venting and to reduce the loads that are transferred to the girder system. Therefore, the use of a sacrificial deck with a thickness of no more than 25 cm (10 inches), or the inclusion of blow-out panels on the deck, should be considered for design.

Longer span members are more resilient to blast loads because they are more massive and generally stronger than shorter span members. However, for girders with long spans and significant ductility, span collapse due to the loss of girder seating may occur. Seismic retrofits such as restraining the girders and deck at the supports with steel cables, or the use of hinge restrainers to hold the deck to the columns, may be needed (*14*). Alternatively, abutment seat sizes can be increased or hinge seat extensions can be used under expansion joints.

Segmental Box Girders

For above- or below-deck attacks using truck bombs, the most likely damage modes are localized breach failure of the flanges and severe flexural damage to cantilevered overhangs. Localized spall and breach of the flange can be reduced by increasing the flange thickness; however, this damage is not necessarily a major concern. The post-tensioning strands are usually well protected to below-deck attack, and the box webs and cantilever overhangs provide alternate load paths to redistribute loads around a damaged flange area. Even for attacks on the deck, the post-tensioning strands are very difficult to cut. However, it may be possible to inflict serious damage to the anchor points. Therefore, diaphragms and anchors may need to be protected with steel or armor plates, and additional diaphragms may be needed for redundancy of tendon support.

Flexural failures of cantilevered overhangs can be mitigated by increasing the slab thickness or through the use of additional reinforcement on the top and bottom faces. However, this type of failure does not necessarily compromise the structural integrity of an entire span. Under very large truck bombs, flexural failure of the entire box section may be a concern, especially for explosions occurring below the deck at locations with a low clearance and long span. To prevent such a failure from occurring, resistance to upward loads can be improved by incorporating “lightly” stressed post-tensioning strands near the top of the box section (which would also require additional diaphragms or modification of the diaphragms) or through the use of supplemental reinforcement. Additionally, the wall thickness for the box could be increased.

As with all bridges, providing the maximum possible standoff will greatly reduce the effects that blast loads have on structural components. With close-in detonations, particularly in enclosed volumes, the effects of blast loads are amplified. Thus, considering an equal weight of explosives, blasts occurring inside of a box have a greater potential for damage than external detonations. For internal attacks, however, charge weights will be limited to what can be carried by hand through access portals. The best mitigation measure to prevent this type of attack seems to be permanently welding the access portals at low clearances, securing the other access points with recessed locks (to prevent cutting the locks), and possibly even the use of intrusion detection systems. Additionally, the tendon duct exterior casing and the diaphragms and anchor points could be hardened to resist localized breaching/cutting. To reduce the confinement effects of an internal explosion, additional vent holes could possibly be added to the box, but doing so would require careful detailing to ensure a sufficient amount of vent area. In addition, the vent would ideally behave as a one-way valve so that external detonations do not cause load amplification inside a box due to shock waves propagating through a vent from the exterior. Clearly, such a design approach needs careful consideration before implementation.

Steel Truss

Individual truss members and gusset plates are most vulnerable to cutting or severe localized damage from special hand-placed charges, large truck bombs on the deck, cutting devices, or vehicle impact. This vulnerability is increased at deck level and may be reduced by increasing the size of the members or by welding steel or armor plates to the critical members. The critical members include those that are smallest, the most heavily loaded, and those members at deck level. Long compression and tension members may need to be braced to prevent buckling, as lateral loads can be large for a truck bombs at deck level and explosions below the deck possess the potential to cause load reversals which may buckle members that are expected to act in tension under normal live and dead loads. Additionally, barriers can be used along the shoulder to increase standoff to the structural components of the truss.

Increasing the member size can be costly, and limited access may not be possible on all bridges. Therefore, a better solution might be to design the truss to resist progressive collapse once the structural integrity of critical members has been compromised. Progressive collapse can occur when localized damage to one or more structural components leads to the failure of neighboring elements in a cascading sequence of member failures. Statically determinate trusses are the most vulnerable. Progressive collapse can be prevented by providing redundant members to redistribute internal loads away from damaged areas. Determination of where to place these members can be made by conducting a structural analysis on the truss, and examining the truss's ability to redistribute loads to remaining components once a critical member has been removed. Additionally, gusset plates can be detailed to provide rotational restraint, which will help to redistribute loads. The connections should also be detailed to ensure they can support 125% of the connecting member's static plastic capacity to account for increased member strengths that occur under high rates of loading. Providing this level of strength may require the use of minimum allowable toughness standards for weld material.

Cable-Stayed

Most cable-stayed bridges possess sufficient redundancy to redistribute loads in the event of the loss of two or three cables. Additionally, cables can be very difficult to cut with standoff charges due to their small, rounded profile which absorbs small amounts of the blast energy, their flexibility to deform under distributed lateral loads, and the shear strength of the steel. In general, special hand-placed cutting charges, non-explosive cutting devices, or vehicle impact will be required to cut the cables. Therefore, when considering the typical deck-level separation distance of the cables which increases the difficulty in cutting several cables at once, the most vulnerable areas of a cable-stayed superstructure seem to be the cable anchorages and the tower wall at deck level.. Based on recent analyses conducted by the U.S. Army Engineer Research and Development Center, the most promising mitigation option for the tower seems to be the use of multiple internal diaphragms to shorten the laterally loaded wall spans and/or thickened walls in the vulnerable zones near traffic level.

FURTHER RESEARCH

Much of the analyses to date are based on the response of building structural elements to blast loads. Although the military has conducted experiments on bridges, most of these tests used cased weapons rather than improvised explosives or large truck bombs. There are significant uncertainties associated with the response of typical bridge structural components, which tend to be larger and more robust than building elements, and bridge geometries, which usually include larger spans and higher clearances. Therefore, experimental validation of the structural response and damage limits specifically for bridge components subjected to terrorist tactics needs to be conducted.

Because of its cost-effectiveness in bridging long spans, prestressing and post-tensioning are frequently used in modern bridges. Additionally, these longer span bridges tend to be more critical. However, little data is available for prestressed or post-tensioned structures subjected to blast loads. Under the current research, the damage limits were estimated based on the limits for conventionally reinforced concrete. They need to be validated experimentally, to include the effects of load reversals and the potential loss of cover which may expose internal tendons. Additionally, the effects of using internal versus external tendons should be investigated.

Bridge piers tend to be the most critical, and possibly even most vulnerable, component of bridges. Loss of a pier could significantly increase repair time and may even lead to collapse of several spans. Experimental validation of the proposed retrofit effectiveness needs to be conducted, including FRP wraps, steel jackets, and shear reinforcement requirements. Resistance to localized spall and cratering, experimental validation of the flexural and shear responses, effects of varying support conditions, and the effects of foundation stability due to possible ground cratering should be included in this study.

The American Association of State Highway Transportation Officials (AASHTO) has recently sponsored a project to research effective design detailing for blast and impact-resistant highway bridges. Administered by the National Cooperative Highway Research Program (NCHRP), the 36-month project aims to identify critical areas of bridges and determine effective structural hardening strategies to resist reasonable blast loads. Included in the project's scope is the investigation of blast effects specifically related to bridges, the potential dual use of current seismic strategies as blast retrofits, the development of analysis guidelines, and the development of post-attack damage assessment techniques.

CONCLUSIONS

Based on the results of the current research, practical and economically feasible design and retrofit solutions can be implemented to provide reasonable protection levels for threats from truck bombs, hand-placed charges, and vehicle or vessel impact. Bridges could be categorized based on their criticality, with the more expensive solutions being applied only to the most critical bridges. Relatively unimportant bridges do not need to be protected, while the most critical bridges may require significant levels of protection. Less important, but still critical, bridges may require intermediate levels of protection. Physical security and site layout measures, used in conjunction with threat-level based measures, seem to provide the most cost-effective solution in most cases. However, structural hardening may be justified for the most critical bridges. For security reasons, bridge criticality, the exact design threat levels, and protective measures for an individual bridge should not be made available to the public.

Pending further experimental testing, the proposed design and retrofit practices could be incorporated into bridge design specifications to assist engineers in mitigating the effects of extraordinary loads from blast, impact, or the potential for progressive collapse. Due to the limited availability of blast design software and references, the specifications may need to be prescriptive in nature and developed by selected bridge designers that have undergone a background investigation. The possibility of terrorism presents unique challenges to bridge engineers, and difficult decisions will be required to deal with such threats. Through appropriate allocation of limited resources and innovative design approaches, critical bridges can be constructed and maintained to counter potential terrorist acts.

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TABLE 1 Performance Based Standards for Bridges (Terrorist Threats)

Category 1 (Very Important Bridges) Concept: Each structural element is designed to withstand 2 separate cases, large loads with repairable damage and smaller loads with negligible damage.[1]

Design Loads – Case 1 (small loads):

"most-likely" threat scenarios using the following at worst possible locations for each structural element being designed:

- mid-size truck bomb [2]
- mid-size hand emplaced explosive scenarios
- mid-size static load for vehicle impact scenarios

Acceptable Damage – Case 1 (small loads):

local deck failure; support system still intact with negligible damage; truss / cables / piers *still capable of supporting design loads when considering structural redundancy*; no unrepairable foundation instabilities and no span loss;

steel girders < 5% max deflection to length ratio, reinforced concrete girders < 4%

Design Loads – Case 2 (large loads):

"most-likely" threat scenarios using the following at worst possible locations for each structural element being designed:

- large truck bomb
- large hand emplaced explosive scenarios
- large static load for vehicle impact scenarios

Acceptable Damage – Case 2 (large loads):

local deck failure; support system still intact with minor damage; *not capable of supporting design loads but easily repairable*; no unrepairable foundation instabilities and no span loss;

steel girders < 12% max deflection to length ratio, reinforced concrete girders < 8%

Category 2 (Important Bridges) Concept: Designed to withstand smaller loads with repairable damage.

Design Loads – Same as category 1, case 1

Acceptable Damage – Same as Category 1, Case 2

Category 3 (Slightly Important Bridges) Concept: Designed to withstand smaller loads with no more than one span loss.

Design Loads – Same as category 1, case 1

Acceptable Damage – no more than one span loss (no progressive collapse)

Category 4 (Insignificant Bridges)

No standard

Notes: 1. Design explosive loads for some Category 1 bridges may need to be increased based on a detailed threat assessment.

2. Exact design charge weights have been omitted for security reasons.

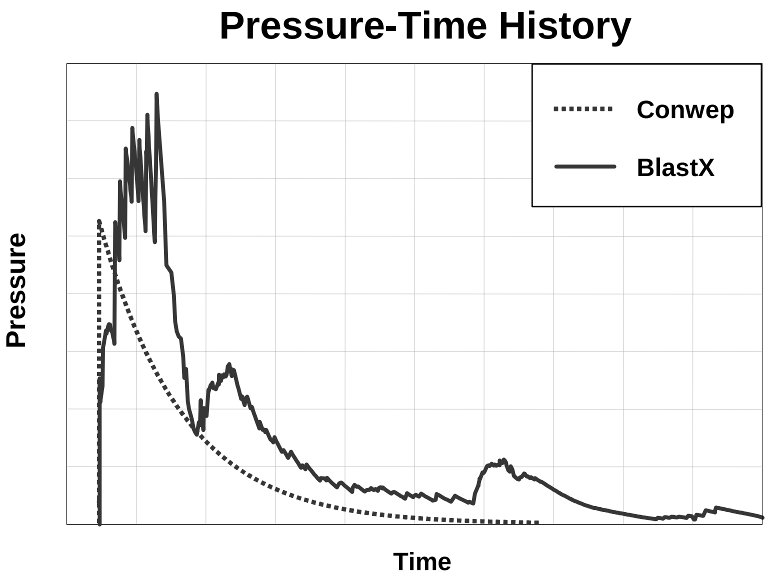
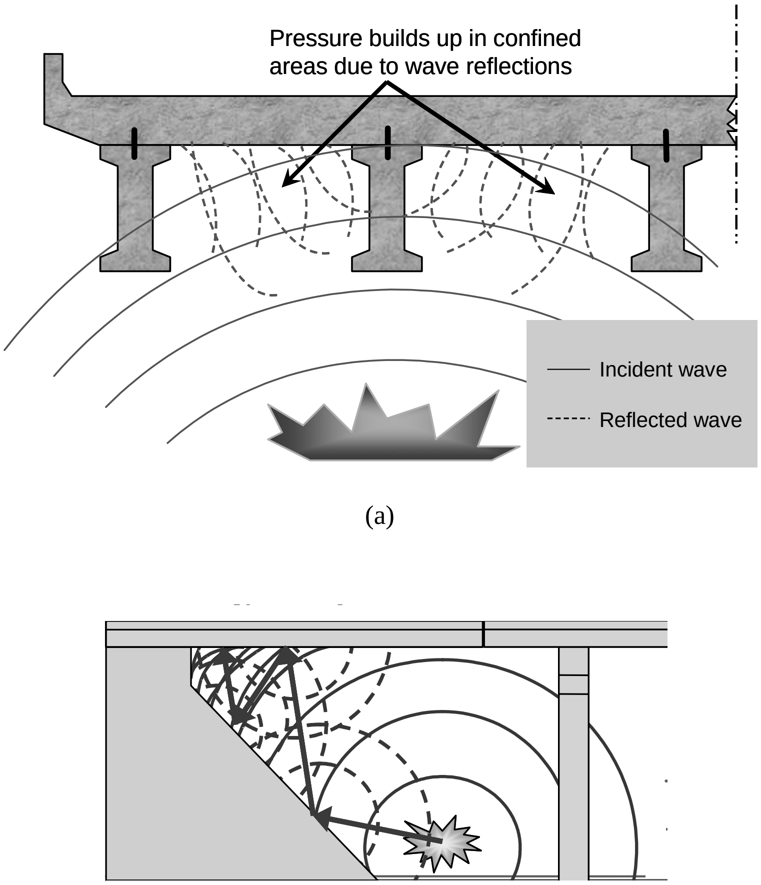


FIGURE 1 Sample Pressure-Time Histories for Conwep and BlastX.



(a)

(b)

FIGURE 2 Confinement Effects (a) Under the Deck and (b) At the Abutments.

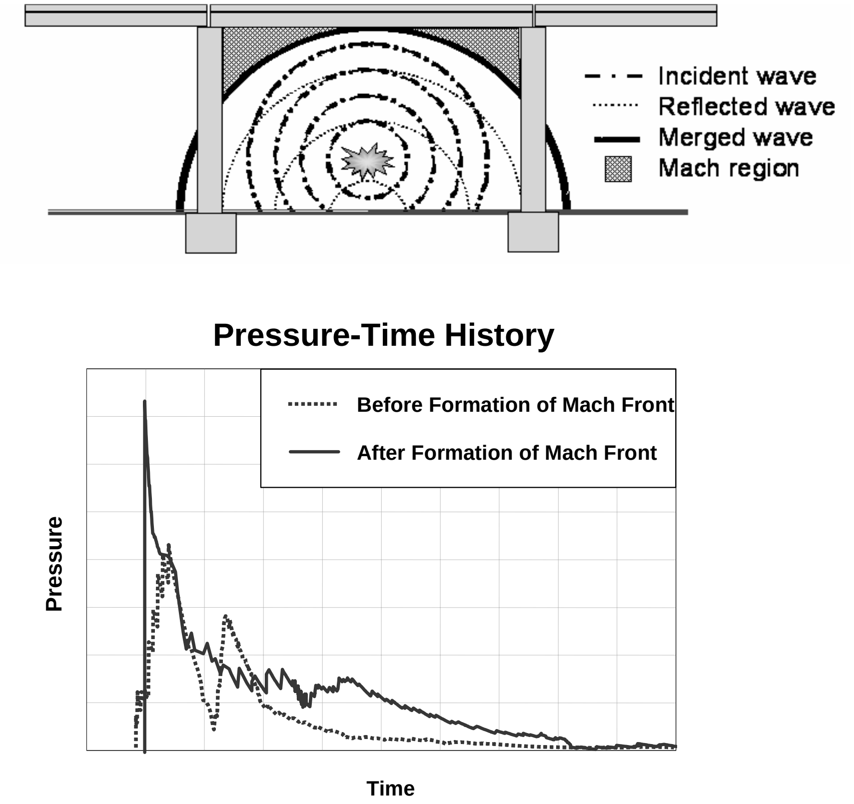


FIGURE 3 Mach Front.