Problem Title: Steel Suspension Bridge Vulnerability and Countermeasures

Research Problem Statement

Background

Large bridges can be demolished by explosives. Although this has long been useful, it presents an opportunity for a large terrorist attack as well. The first steps to eliminate this deficiency were taken in a FHWA National Pooled-Fund study on steel multi-cell towers conducted by the Engineer Research and Development Center of the Army Corps of Engineers. Next, work on suspender cables and on cable-stay bridge elements, was started under DHS sponsorship. Examination of suspension bridge countermeasures was also done – although on a limited basis – under DHS sponsorship. Limited work on concrete bridge piers was conducted under an NCHRP study. Despite these encouraging starts, bridges are still under-represented in counterterrorism research, and remain vulnerable. The experience of the early stage of research, as well as the feedback from field evaluations, countermeasure design, and construction projects, have provided a more detailed picture of the needs to be addressed in the next phase of research.

Physical testing, to date, has employed specimens built specifically for the study, that is, specimens constructed with modern steel alloys and bolted or welded connections. The specimens, because they are new, are also in pristine condition at the time of testing. A useful extension of this test program would encompass early 20th Century alloys, riveted connections, gusset plates, built-up cross-sections, and decades of environmental and traffic loading (In particular, irregular effects of corrosion and uneven live load stresses). Modeling the behavior of bridge towers, main cables, and suspender ropes is still done on a case-by-case basis. Developing this area would also increase our ability to implement countermeasures on other bridges in the field and be a useful step in developing countermeasures for the most vulnerable components on other types of bridges as well.

Project Description

FHWA's multi-year infrastructure security research program is the context for this project. The major goal is to significantly increase the resistance of suspension bridges and their components to destruction by specified attack methods, removing targets on which to plan an attack. This could be achieved in two ways. The first is strengthening existing bridge components. The second would involve replacing existing bridge components with newly developed ones. The latter will also apply to new bridge construction. The aim of this particular project is to achieve the major goal, stated above, on three components: 1) Towers; 2) Main Cables; 3) Suspenders.

The proposed program is based on the availability of a suspension bridge to be demolished: The Waldo-Hancock Bridge, near Bucksport, Maine. A limited on-site study, outlined in a prior FHWA funding request, was conducted under DHS sponsorship. A more extensive off-site study, following the demolition of the structure and removal from its present site, is the subject of this request.

Research Objectives

1. Verify and calibrate analytical predictions of the behavior of steel towers, main cables, and suspender ropes, and individual components, subjected to attack under specific methods and magnitudes.
2. Verify the predicted performance of currently-used or proposed mitigation measures.
3. Analyze and evaluate new concepts and materials for mitigation.
4. Develop new retrofits and bridge component designs and verify their performance.

Scope of Work

The study shall consist of physical, full-scale testing of steel suspension bridge elements, their connections, and, where practical, assembled groups of bridge elements, subjected to simulated attack. Attack methods include the use of vehicle bombs or other standoff charges; hand-emplaced breaching charges, cutting charges, and mechanical cutting. Direct impact by airplane, vessel, or truck is beyond the scope of this study. The full-scale explosive demolition testing will be conducted in a secure environment at a USACE test facility.

The Off-site study will be influenced by the available specimens' condition. The areas now being examined for inclusion in physical testing include: Suspender Cutting Charges; Tower Section Standoff Attack; Main Cable Shear; Main Cable Standoff Attack; and Main Cable Cutting Attack. If sections of main cable remain, a fire heat transmission study will also be conducted. After the behavior of the unprotected structure has been calibrated, the effects of retrofits will be studied. These will include: Main cable wrapping; External and internal tower reinforcement and energy routing; Suspender replacement materials; Energy-absorbing suspender sockets; and any other retrofit identified as suitable for inclusion in this study.

Research into both retrofit materials and retrofit designs are within the scope. This includes material combinations beyond those previously considered. Design issues to be considered include the typically severe size and weight limitations found on existing structures, as well as the need to address practical construction- and maintenance-imposed restrictions.

Delineation of Tasks

Task 1: TOWER RETROFITS:

The objective of this task is to increase the effective range of tower retrofits, both in size of blast loads resisted and types of steel towers effectively protected. It will establish the effective range of Tower Study No.1's results, and develop a general design procedure for use on any steel tower. Following this, it will develop new retrofit materials and designs to reduce cross-section and develop the highest resistance to very high weight explosives. The following sub-tasks are planned:

A) ESTABLISH RANGE of Tower Study No.1 RETROFITS: Determine sensitivity of the results of Tower Study No.1 to differences in size, types of materials in the original structures, connector details in the original structure, and the condition of those structural materials after years of use and wear. Develop a method, when necessary, to scale the results of Tower Study No.1 and this study, to differences in size and material condition.
EXPERIMENT: Repeat relevant tests which were conducted in Tower Study No.1 on tower components obtained from the Waldo-Hancock Bridge.
ANALYSIS: Determine the degree of consistency between results of this study and those of Tower Study No.1. Develop a working account for the inconsistencies.
VERIFICATION: Conduct tests on small-scale specimens to verify this.

B) GENERAL METHOD for RETROFIT USE on ANY STEEL TOWER: Develop a general design procedure to adapt the retrofit designs developed in Tower Study No.1 for use on any steel bridge tower size or cross-section. The modified analytical and physical test procedures will be verified by testing on representative specimens.
INVENTORY: Develop a range of predicted responses of steel tower cross-sections to a range of charge weights to account for design variations that need to be considered. Data is to be obtained only from evaluation reports for actual bridges.
TEST SPECIMEN RANGES: Compare this inventory to the specimens in Subtask A). Design test specimens with any needed changes to those developed in Tower Study No.1.
REPEAT TESTS: Repeat the testing conducted in A) for these tower specimens.
GENERAL ANALYTICAL and DESIGN METHOD: Refine the analytical methods used in Tower Study No.1.for use on any steel tower.
RETROFIT VARIATIONS: Develop recommended variations to existing retrofits to meet significant blast response changes where they have been identified. Establish a standard for testing this bridge component to permit qualification of future retrofit types.

NOTE: Sub-tasks C and D are similar in structure. It may be to the contractor's advantage to conduct portions of these (e.g. material inventory) at the same time.

C) ADVANCED RETROFITS: SIZE or WEIGHT RESTRICTIONS: Develop retrofits with reduced cross-section (or, secondarily, weight) to meet a wide range of field conditions and to overcome the installation restrictions that exist on actual bridges.
MATERIAL INVENTORY: Inventory materials/material combinations manufactured to meet requirements similar to those in the section above, including blast resistant materials from Air Force and Navy research. Select materials for the test program.

TEST PROGRAM and MATERIAL TEST SPECIMENS: Develop the test program for selected materials, based on the test program for Tower Study No.1. Specify and obtain test specimens for these materials. Perform the test program and evaluate these materials. GENERALIZE RETROFIT DESIGNS: Repeat *GENERAL ANALYTICAL and DESIGN METHOD* and *RETROFIT VARIATIONS* from Sub-task B) for materials developed here.

D) <u>ADVANCED RETROFITS: RESIST HIGH RANGE BLAST LOADING</u>: Develop retrofits to provide needed resistance to very high weight explosives. The purpose of this study objective is to increase the countermeasures' capacity to more closely match the record of higher weight explosive used in terrorist attacks.
BLAST RESISTANCE EXTENSION ANALYSIS: Remodel the results of Tower Study No.1 with changed parameters within the retrofits that were examined in the study. Estimate the potential changes in design factors, and effective combinations of these factors, that would meet performance requirements against high weight range explosives.
NOTE: These three sections are identical to the three sections in Sub-task C. This is also an examination of advanced material designs, but to meet high loads rather than restrictive site conditions.
MATERIAL INVENTORY
TEST PROGRAM and MATERIAL TEST SPECIMENS
GENERALIZE RETROFIT DESIGNS

NOTE: Tasks 2 and 3, which work on Main Cable and Suspender Ropes, follow a different course than Task 1. Products and designs have already been developed for these two applications. An essential feature of the following tasks is to develop a standardized test for these products – one that covers all of the possible attack loadings. Another is to develop improvements where necessary.

<u>Task 2</u>: <u>MAIN CABLE RETROFITS</u>

The task will verify the effect of standoff and contact (attached) explosives on main cables. It will then test the effect of previously developed retrofits on cable sections obtained from the Waldo-Hancock Bridge. This task will determine the sensitivity of main cable retrofit designs to differences in size and materials of the main cable. Comparison will be made to design conditions on W-H to the bridge that the cable retrofit was originally designed for. This includes connector details and the retrofit's sensitivity to the condition of the main cable after years of use and wear.

Prepare a Summary Report on the On-Site Waldo-Hancock Testing conducted in 2008. Comment on any effects that the results of this program will have on the present countermeasure test program. Areas of interest include:

- Cable response, including damping, from localized lateral loadings. This includes the effects of lateral shear and longitudinal waves in producing damage in the cable itself, and to anchorages and saddles.
- Load redevelopment around cut strands by comparing the response of the main cable to loading in areas where the main cable section is in relatively good condition and where it is heavily-damaged by corrosion.

The main test program under this task, retrofit testing, will concentrate on:

- Full-Charge Weight Main Cable Standoff Attack Study**:** Determine the effect of blast loadings on circular main cable sections. [Optional] Strand Load Redistribution to determine effects on cables of varying condition. Develop and Test Countermeasure Options.
- Main Cable Cutting Attack Study**:** Develop and Test Countermeasure Options.
- Effects of Fire and Heat Transfer in Main Cable Sections, Suspenders, Bands, and Sockets. Develop and Test Countermeasure Options.

A) Sub-task organization (Wording identical to Task 1A, with component changed from Towers to "Main Cable" – Other differences noted where necessary):
EXPERIMENT: (Repeat product tests conducted by COE, modified as necessary, and include both contact and non-contact charges)
ANALYSIS: (No note)
VERIFICATION: (Repeat on W-H specimens)

B) Sub-task organization (Wording identical to Task 1B, with component changed from Towers to "Main Cable" – Other differences noted where necessary):
INVENTORY: (No note)
TEST SPECIMEN RANGES: (Two products)
REPEAT TESTS: (No note)
GENERAL ANALYTICAL and DESIGN METHOD: (No note)
RETROFIT VARIATIONS: (No note)

Task 3: SUSPENDER ROPE RETROFITS

The task will verify the effect of standoff and contact (attached) explosives on suspender ropes. It will test the effect of previously developed retrofits on suspender sections obtained from the Waldo-Hancock Bridge. This task will determine how sensitive the designs of suspender system retrofits are to differences in size, materials, suspender alignment, suspender redundancy, and suspender spacing. Comparison will be made to design conditions on W-H to the bridge that the suspender rope was originally designed for. This includes connector details and the retrofit's sensitivity to the condition of the suspenders and, especially, the condition of their lower sockets, after years of use and wear. Modifications to socket design are within the scope of this task. The main test program under this task, retrofit testing, will concentrate on several areas.

A) Sub-task organization (Wording identical to Task 1A, with components changed from Towers to "Suspenders / Suspender Sockets" – Other differences noted where necessary):
EXPERIMENT: (Repeat product tests conducted by COE, modified as necessary, and include both contact and non-contact charges)
ANALYSIS: (No note)
VERIFICATION: (Repeat on W-H specimens)

B) Sub-task organization (Wording identical to Task 1B, with components changed from Towers to “Suspenders / Suspender Sockets” – Other differences noted where necessary):
INVENTORY: (No note)
TEST SPECIMEN RANGES: (Two products)
REPEAT TESTS: (As in the previous task: Determine the effects of Fire and Heat Transfer in Main Cable sections, Suspenders, Bands, and Sockets)
GENERAL ANALYTICAL and DESIGN METHOD: (Include cutting devices, contact charges, and standoff charges)
RETROFIT VARIATIONS: (Including suspender replacement materials
Energy-absorbing suspender sockets)

Task 4 – Draft and Final Reports

Prepare draft and final reports, executive summary, and presentations in accordance with FHWA and DHS guidelines.

Estimate of Problem Funding and Research Period

Recommended Funding: **$2,500,000**

Task 1:	$1,200,000
Task 2:	750,000
Task 3	500,000
Task 4	50,000

Suggested minimum contribution: $50,000 per year

Research Period: 5 years

Urgency, Payoff Potential, and Implementation

Terrorist attack on steel suspension bridges is a major concern for transportation agencies. The bridges, typically, carry much higher volumes of traffic than other structures, and are critical links in the transportation network of the regions in which they are located. The loss of such a structure would, in many cases, necessitate long detour routings over the regional network for months or years. Replacement would require Federal assistance – the costs would overmatch the emergency funds of most State DOT’s or toll authorities. In addition, many are landmark structures. They have already attracted the attention of potential terrorists. One jihadist website mentions them specifically as targets, and individuals linked to terrorist groups have been caught making notes on at least two of these bridges in the United States.

The detailed guidelines and standards that will be developed in this study, available specifically for bridges, would ultimately reduce the risk to life and economic losses from a terrorist attack against the infrastructure. Like many natural disasters, terrorist attack against a specific target is considered a "low-probability / high-consequence event." As with any natural disaster, the transportation system must be operational in the aftermath of an attack, and available for evacuation, response, and recovery efforts. Because major terrorist attacks against infrastructure targets have generally occurred in highly populated areas, and because the impact on communities from a bridge out of service can be ruinous, the payoff from any investment in counterterrorism retrofits would have local, regional and national benefits.

The solutions recommended and standards developed under this project will be available for immediate implementation by the States and other bridge owners, and for adoption into AASHTO specifications as appropriate.

Person Developing the Problem Statement

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