Blast Resistant Bridge Piers

By Michel Bruneau, Ph.D., P.Eng., Shuichi Fujikura and Diego Lopez-Garcia, Ph.D.

Recent terrorist attacks, such as the one on the Alfred P. Murrah Federal Building in Oklahoma City (1995) and the one on the tallest towers of the World Trade Center in New York City (2001), are clear examples of the fact that the destruction of civil engineering structures has become one of the objectives of terrorist activity. Although no attack has been made on bridge structures so far, terrorist threats received by the state of California to its main suspension bridges and the detailed shots of the Golden Gate and Brooklyn bridges found among the possessions of terrorists captured in Spain indicate that bridge structures are definitely being considered as potential targets by terrorist organizations. The terrorist threat on bridges, and on the transportation system as a whole, has been recognized by the engineering community and public officials, resulting in the recent publication of a number of documents addressing this concern.

One of the courses of action by which terrorists might seek the destruction of bridge structures consists of detonating an explosive device. The explosion creates an atmospheric blast wave, which in turn induces pressures of significant magnitude on structural members. Since these pressures, usually referred to as "blast loads", are not typically accounted for in the design process, intentional explosions can result in significant damage to structural members, which in turn might result in partial or total collapse of the structure.

There is a need to develop structural systems capable of providing an adequate level of protection against intentional blast loads. The most important constraint to be satisfied is the fact that, due to the limited resources available to reduce the vulnerability of the transportation system, the characteristics of such systems — e.g., size, structural configuration, materials and cost — should not be significantly different from those of the systems being commonly used in bridge structures.

Any blast-resistant structural system must still be able to perform satisfactorily under all of the other loads acting on bridge structures. In this regard, it is interesting to note that there are some important similarities between seismic and blast effects on bridge structures: both major earthquakes and terrorist attacks are rare events, and, due to economic considerations, most of the energy imposed on structural members by these events is dissipated through inelastic deformations, rather than elastically absorbed. Given that current codes require that bridge structures be designed for some level of seismic action virtually anywhere in the US, and that blast and seismic loads often control the design, there is a need for structural systems capable of performing equally well under both seismic and blast loads.

The objective of this research project is to develop and experimentally validate a multi-hazard bridge pier concept, i.e., a bridge pier system capable of providing an adequate level of protection against collapse under both seismic and blast loading, and whose structural, construction and cost characteristics are not very different from those of the pier systems currently found in typical highway bridges in the US. The proposed pier system consists of concrete-filled circular steel (CFST) columns that are framed into beams made up of C-shape steel sections embedded in the fiber-reinforced concrete foundation and pier cap.

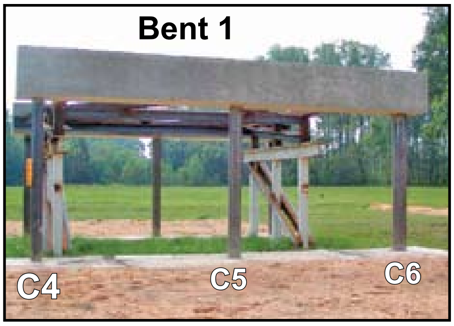

Figure 2: Test specimen (Bent 1)

Scope of Research

The multi-hazard bridge pier-bent concept proposed in this study is intended for use in typical highway bridges. Although the terrorist threat to this type of bridge is usually assumed to be of lesser magnitude than that assigned to large signature bridges, the threat, especially to the ones strategically located, is nevertheless real and worthy of consideration. In fact, terrorist groups might prefer to attack typical highway bridges because their destruction requires less effort — in terms of necessary expertise, amount of explosives and need to account for surveillance — than that required to destroy a large signature bridge. The target bridge in this research is a three-span continuous highway bridge with a total length of 90 meters (300 feet) and a column height of 6 meters (20 feet).

There are many possible courses of action by which terrorists might intend to destroy a bridge structure. The proposed bridge pier-bent concept was developed considering only one type of terrorist threat: the detonation of explosives located inside a small vehicle placed below the deck at a close distance from the pier. Other possible attack tactics, such as the detonation of hand-placed explosives and collisions using large vehicles, were not considered.

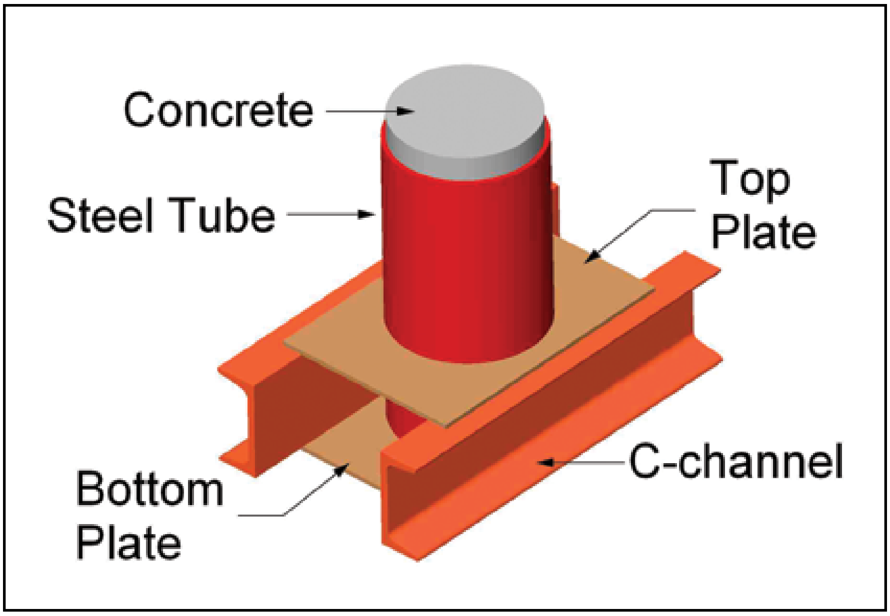

Figure 1: Details of column-to-foundation beam connection

Assumed Blast Scenario

The horizontal distance between the center of an explosive charge and the pier, referred to as standoff distance, was set based on what is found in typical highway bridges; the exact value is not indicated here for the security reasons. The vertical distance between the center of an explosive charge and the ground was set equal to 1.0 meter (3.3 feet) based simply on the geometry of a typical car carrying explosives.

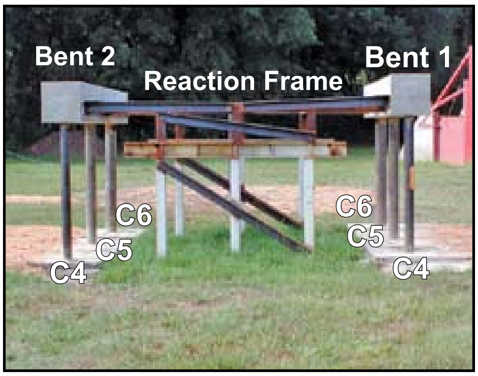

Figure 3 : Test setup from side view

Because of the nature of intentional threats, it is virtually impossible to predict accurately the explosive charge weight to be used in a terrorist attack. Reasonable estimations, however, can be made by taking into account certain characteristics of terrorist actions. For instance, there is a relationship between the size of the vehicle used to carry the explosives and the maximum possible charge weight, especially since the explosives will most likely be somehow hidden to avoid detection by simple visual inspection. Also, while high-tech explosives are expensive and difficult to handle, especially in large quantities, fertilizer-based explosives can be fabricated relatively easily using commercially available ingredients, which make them much more likely to be used. The explosive charge weight adopted in this study was based on these.

Multihazard Bridge Pier Concept

Breaching typically controls the design of substructure concrete members subjected to intentional blast loading. The behavior of such members could be substantially improved if breaching could be somehow prevented. In that perspective, encasing concrete in a steel shell would seem to be an adequate approach to provide blast-resistant piers. The addition of steel jackets has been shown to be a viable strategy for the seismic retrofit of concrete bridge pier columns, but using such a jacket alone was estimated to be insufficient to provide adequate resistance to the large shear forces that develop at the base of piers subjected to blast loads. As such, using a fully composite concrete-filled steel tube (CFST) continuous into the footing was deemed to be a more appropriate solution. Therefore, the pier concept considered in this study is a multi-column pier-bent with CFST columns. Tests showed that CFST columns subjected to cyclic loading exhibit good energy-dissipation capabilities. The foundation beam consists of concrete-embedded C-channels linked to the columns through steel plates. This connection concept is schematically illustrated in *Figure 1*. This type of foundation beam performed successfully in the tests because it allowed the composite column to develop its full moment capacity. Conceptually, the channels are designed to resist the full composite strength of the columns, and the concrete in the foundation beam does not need any reinforcement for strength purposes; however, fiber-reinforced concrete is recommended to prevent cracking of the concrete and subsequent water infiltration into the footing.

Figure 4: Blast fire ball (column C4 of Bent 1)

Figure 5: Column C5 of Bent 1 after test

Experiment on ¼-Scale Bridge Piers

Two identical multi-column bents, Bent 1 and Bent 2, were fabricated and a series of tests was performed at the U.S. Army Corps of Engineers Research Facility in Vicksburg, Mississippi. Due to constraints in the maximum possible blast charge weight that could be used at the test site and specimen cost considerations, test specimen dimensions were set at ¼-scale of the prototype bridge piers. An experimental specimen (Bent 1) is shown in *Figure 2*. Each specimen consists of three piers with same height of 1.5 meters (4.9 feet) and different diameters, D, of 102 millimeters (4 inches), 127 millimeters (5 inches) and 152 millimeters (6 inches) — C4, C5 and C6, respectively — connected to a steel beam embedded in the cap-beam and a foundation beam. The bent frames were braced in what would correspond to the bridge longitudinal direction at the level of the cap-beams (*Figure 3*). A reaction frame was built for this purpose. The cap-beams were not connected to the frame but in contact with it.

Figure 6: Damage at foundation (column C5 of Bent 2 after test)

A total of nine tests were carried out for six columns in Bent 1 and 2 at various charge levels. Some induced elastic response, and the columns could be re-tested; some aimed at inducing a target maximum inelastic deformation of the columns; and a few tests were attempted to push the columns up to fracture of the steel shell. Explosives were located either at a lower height of 0.25 meters (0.8 feet) or a middle height of 0.75 meters (2.5 feet) of the columns. The lower height represented the height from the assumed blast scenario, which was 1.0 meter (3.3 feet) for the prototype bridge. Mid-height of the bridge column was considered because it was expected to provide the most severe damage to a column.

Some of the test results are shown in *Figures 4* to *6*. *Figure 4* shows the blast fire ball of the test for Column 4 of Bent 1. This picture was taken by a high speed digital video camera at 1,000 frames per second. Bent 1 was engulfed in flames and the fire ball almost reached Bent 2 on the other side of the test set-up. *Figure 5* shows Column 5 of Bent 1 after the test. The objective of the test was to induce a maximum deformation of 53 millimeters (2.1 inches) at mid-span of the column. The resulting deformation was 76 millimeters (3.0 inches). The CFST columns exhibited ductile behavior under blast load. Note that no significant damage was suffered by the concrete cap-beam and foundation beam as a result of the blast pressures. *Figure 6* shows the damage to the column and foundation of Column 5 of Bent 2. The explosive was located at the lower height. Buckling of the steel tube was observed near the height where maximum deformation occurred. The steel tube fractured halfway around the base of the column. A small crater into the foundation reached the embedded C-channel connection. No damage was observed at the cap-beam. Note that the connection concept considered in this experiment performed successfully under blast loading, as the embedded C-channel connection and the C-channels themselves did not suffer damage and allowed development of the full composite strength of the columns.

Conclusion

This article has presented the findings of research to establish a multi-hazard bridge pier concept capable of providing an adequate level of protection against collapse under both seismic and blast loading. A series of experiments on ¼-scale multi-hazard bridge piers was performed. The CFST columns exhibited ductile behavior under blast load.▪

Michel Bruneau, Ph.D., P.Eng., is the Director of the Multidisciplinary Center for Earthquake Engineering Research and a Professor in the Department of Civil, Structural and Environmental Engineering at the University at Buffalo (The State University of New York). He may be contacted at ***bruneau@buffalo.edu****.*

Shuichi Fujikura is a Graduate Research Assistant at the Multidisciplinary Center for Earthquake Engineering Research and a Ph.D. Student in Structural and Earthquake Engineering at the University at Buffalo (The State University of New York). He may be contacted at ***fujikura@buffalo.edu****.*

Diego Lopez-Garcia, Ph.D., is a Profesor Auxiliar in the Departamento de Ingenieria Estructural y Geotecnica at the Pontificia Universidad Catolica de Chile. He may be contacted at ***dlg@ing.puc.cl****.*

References

Williamson EB, Winget DG (2005). "Risk management and design of critical bridges for terrorist attacks." *Journal of Bridge Engineering*, 10(1), 96-106.

FHWA. (2003). *Recommendations for Bridge and Tunnel Security*. Prepared by the Blue Ribbon Panel on Bridge and Tunnel Security, Federal Highway Administration, Washington, D.C.

Winget DG, Marchand KA, Williamson EB (2005). "Analysis and design of critical bridges subjected to blast loads." *Journal of Structural Engineering*, 131(8), 1243-1255.

Marson J, Bruneau M (2004). "Cyclic testing of concrete-filled circular steel bridge piers having encased fixed-based detail." Journal of Bridge Engineering, 9(1), 14-23.