Processes and Techniques for Rapid Bridge Replacement After Extreme Events

Yong Bai and Seong Hoon Kim

Highway bridges, as critical components of the nation's transportation network, have received increased attention after the terrorist attacks on September 11, 2001, and subsequent potential threats to U.S. transportation systems. To respond to the potential threats on highway bridges, a pooled-fund research project was conducted to identify rapid bridge replacement processes and techniques after extreme events. These events include manufactured and natural disasters such as earthquakes, explosions, fires, floods, and hurricanes. To achieve the research objectives, the research team studied three cases of previous bridge replacements following extreme events. These cases are the I-40 Webbers Falls Bridge in Oklahoma, the I-95 Chester Creek Bridge in Pennsylvania, and the I-87 New York State Thruway Bridge in Yonkers, New York. By studying these cases, the research team first sought to identify and expand on lessons learned. Lessons learned from these cases benefit government agencies such as state departments of transportation, which are responsible for development of the enhanced emergency response plans for highway bridges, and the engineering and construction communities, which are responsible for design and reconstruction of the damaged bridges. Next, the research team determined the processes and techniques that were used in the rapid bridge replacements and outlined needed improvements so that the research community could investigate new technologies to advance current practices.

The terrorist attacks on September 11, 2001, and subsequent potential threats to the United States transportation systems have presented an urgent need to develop emergency management plans to react quickly to possible consequences of extreme events. These events include terrorist attacks and man-made or natural disasters such as earthquakes, explosions, fires, floods, and hurricanes. Highway bridges, a critical component of the nation's transportation network, have received close attention from government agencies. Bridges are key elements of the nation's transportation system for the following reasons (*1*):

1. A bridge controls the capacity of the system.
2. A bridge is the highest cost per mile of the system.
3. If a bridge fails, the system fails.

Since September 11, 2001, several research projects have been conducted to identify the infrastructure's vulnerabilities and to help government agencies develop or update the emergency management plans. AASHTO and FHWA recognized the need to address the nation's vulnerability assessment requirements for highway transportation and sponsored the development of a guide for critical asset identification and protection (*2*). Authors of the guidelines divided vulnerabilities in highway transportation into three general categories:

1. Physical facilities themselves (e.g., bridges, tunnels, roadways, and interchanges),
2. Vehicles operating on the system, and
3. Information infrastructure that monitors and manages the flow of goods, vehicles, and people on the highway system.

That guide provides a starting point for identifying and mitigating the vulnerability of highway transportation assets to terrorist threats or attacks and their consequences. A companion document, *A Guide to Updating Highway Emergency Response Plans for Terrorist Incidents,* also funded by AASHTO and FHWA and developed in parallel with the previous guide, assists government agencies in preparing and executing a coordinated emergency response to terrorist threats or attacks to the highway transportation system (*3*). Besides those two guides, AASHTO and FHWA sponsored other research projects on bridge and transportation security. One project was titled *Design of Highway Bridges for Extreme Events,* which was supervised by NCHRP. The objective of that research was to develop a design procedure for application of extreme event loads and combination loading to highway bridges (*4*). Another project was entitled *Surface Transportation Security,* also supervised by NCHRP. Results of that project were released in NCHRP Report 525 (*5*).

State departments of transportation (DOTs) also initiated efforts to investigate and develop methods to lessen the impact of terrorist attacks and other extreme events on their transportation infrastructure. A pooled-fund research project, led by Texas DOT, titled *Rapid Bridge Replacement Techniques,* was conducted to identify rapid bridge replacement processes and techniques. One of the tasks associated with that research project was to conduct several case studies of previous bridge replacements following extreme events. The research team selected three cases to conduct detailed case studies. They were the Interstate 95 (I-95) Chester Creek Bridge in Pennsylvania, the Interstate 87 (I-87) New York State Thruway Bridge in Yonkers, New York, and the Interstate 40 (I-40) Webbers Falls Bridge in Oklahoma (*6*). Table 1 provides a brief description of these cases. These bridges were chosen because they were critical components on the nation's major interstate highways, and the incidents had significant impacts on the surrounding communities and the driving public.

This paper presents the findings of three detailed case studies. The rest of the paper is organized as follows: first, the authors state research objectives and methodology; second, a general model that

Department of Civil, Environmental and Architectural Engineering, University of Kansas, 1530 West 15th Street, 2150 Learned Hall, Lawrence, KS 66045-7609. Corresponding author: Y. Bai, ybai@ku.edu.

Transportation Research Record: Journal of the Transportation Research Board, No. 1991, Transportation Research Board of the National Academies, Washington, D.C., 2007, pp. 54–61.
DOI: 10.3141/1991-07

TABLE 1 Description of Bridge Cases

Case No.	Case Title	Bridge Structure	Bridge Crossing	Incident Description	Replacement Tasks	Duration
1	I-95 Chester Creek Bridge, Pennsylvania	Steel plate girder with concrete deck and piers	Water	Gasoline tanker impact with fire on deck	Replacement of steel girders and concrete deck	42 days
2	I-87 Thruway Bridge, New York	Steel plate girder with concrete deck	Highway	Gasoline tanker impact with fire under deck	Total bridge replacement	155 days
3	I-40 Webbers Falls Bridge, Oklahoma	Steel plate girder with concrete deck and piers	Water	Barge-impacted substructure	Replacement of piers, steel girders, and concrete deck	64 days

describes the rapid bridge replacement process is outlined based on the three detailed case studies; third, techniques that have been successfully used in the rapid bridge replacement are presented; and fourth, the authors outline the needs for future improvements in the area of rapid bridge replacement. These improvements shall be accomplished through further research efforts. Finally, the authors present conclusions and recommendations.

RESEARCH OBJECTIVES AND METHODOLOGY

The objectives of the research were to identify rapid bridge replacement processes and techniques. Case study methodology was used to accomplish these objectives. By studying previous cases, the research team first sought to identify and expand on lessons learned. Lessons learned from these cases benefit government agencies such as state DOTs, which are responsible for development of the enhanced emergency response plans for highway bridges, and engineering and construction communities, which are responsible for design and reconstruction of the damaged bridges. Next, the research team determined the processes and techniques that were used in the rapid bridge replacements and outlined the needed improvements so that the research community could investigate new technologies to advance current practices.

Case studies were conducted using a three-step approach. First, the research team reviewed the literature related to the cases. The literature included newspaper articles, conference and journal papers, technical reports, and websites. Second, the research team interviewed key personnel who were involved in the case, via telephone. Those people represented state DOTs, design firms, contractors, and material suppliers. In the telephone interviews, the personnel were asked a series of questions on their roles in the case and knowledge about the case. After the first two steps, the research team developed initial impressions about each case, and any unanswered questions were clearly outlined. The third step was to conduct a survey to gain knowledge about the previously unanswered questions and additional information related to each case. The survey questionnaire addressed five aspects:

1. Contracting method,
2. Engineering,
3. Construction,
4. State DOT support, and
5. Material supplier and vendor.

Findings of the case studies are presented in the following sections.

RAPID BRIDGE REPLACEMENT PROCESS

A rapid bridge replacement process was identified based on three detailed case studies. A general model was developed to represent the process, as shown in Figure 1. The model includes three key elements: major players, major tasks, and major decisions. Major players are parties such as state DOTs, design firms, contractors, and material suppliers and vendors that have responsibilities to conduct bridge replacement tasks and make major decisions during the bridge replacement process. Major tasks of bridge replacement include traffic detour, bridge demolition, design, contract, and reconstruction. At each stage, major decisions need to be made, which have significant impacts on the outcomes of bridge replacement. For example, during the design stage, the most important decision is to establish whether the bridge should be rebuilt using an identical structure or a new structure. If the decision is to use the identical structure, then the design work is simple if the original drawings and specifications are archived. The I-95 Chester Creek Bridge replacement was an example where the original design was used. In some cases, using the identical structure may not be the best way to replace a bridge quickly. That was the situation for the I-40 Webbers Falls Bridge in Oklahoma. The bridge was hit by a towboat with two empty barges on May 26, 2002, and four spans were damaged. The original structure was a continuous haunched steel girder bridge with a 61 × 101 × 61 m (201 × 330 × 200 ft) main span combined with steel girder approach spans and a reinforced concrete deck, as shown in Figure 2. After the incident, precast, prestressed concrete girders were used in lieu of the original steel approach girders, to reduce the material delivery time (*7*).

RAPID BRIDGE REPLACEMENT TECHNIQUES

During the replacement process, various engineering and construction techniques were employed to minimize impacts to the traveling public and surrounding communities while accelerating the overall replacement schedules. Some of the techniques used in traffic detour, design, and reconstruction are discussed in this section.

Traffic Detour

Establishing temporary traffic detour routes for the traveling public is one of the most urgent tasks that state DOTs must perform immediately after an incident. Detour routes need to be available during the entire period of bridge replacement. There are three common ways to establish detour routes. The first method is to use an

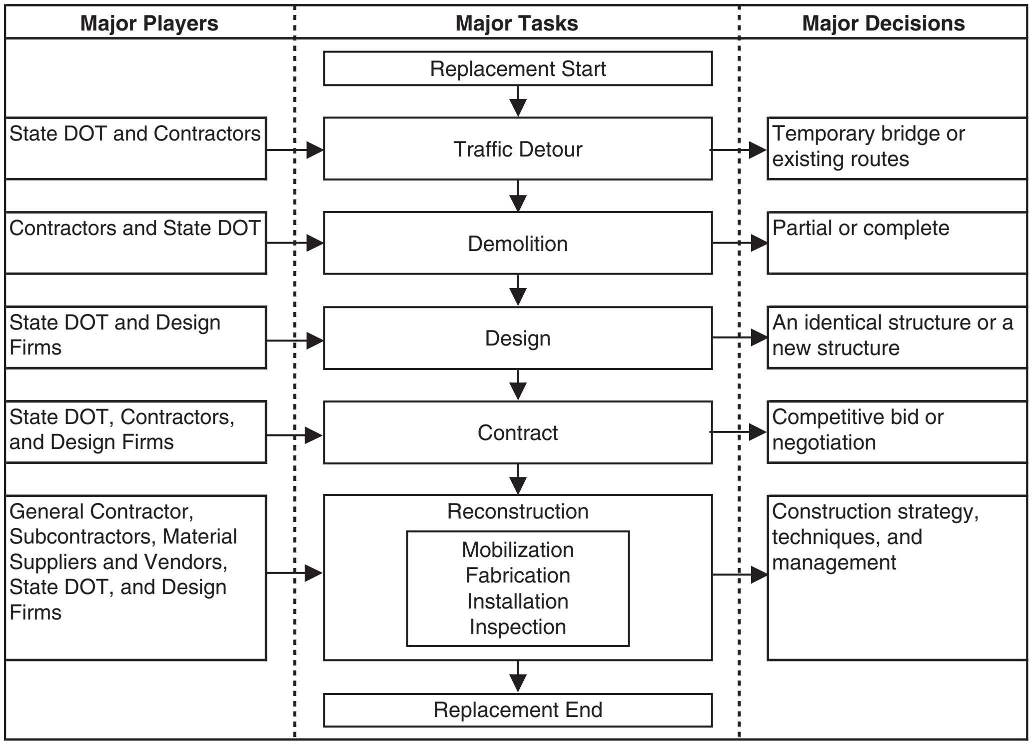

FIGURE 1 General model for rapid bridge replacement after extreme events.

undamaged portion of the bridge as detour routes. Bridge engineers from Pennsylvania DOT evaluated the I-95 Chester Creek Bridge just after the accident and found that the southbound structure (three lanes) was unsafe due to severe damage caused by the fire and that the northbound structure (three lanes) was undamaged. On the basis of this scenario, Pennsylvania DOT engineers decided to modify three lanes of northbound bridge into four lanes to carry two lanes of traffic in each direction. The modified lane width was 3.35 m (11 ft) instead of the normal width of 3.66 m (12 ft), and a 64 km/h (40 mph) speed limit was implemented and monitored closely by state police. Figure 3 shows reconstruction of the I-95 southbound bridge and the temporary detour lanes on the northbound structure.

The second method of establishing detour routes is to redirect traffic to existing roads in surrounding areas. This method was used for the I-40 Webbers Falls Bridge incident. Oklahoma DOT established the detour routes for the traveling public using existing highways because some of the bridge spans had completely collapsed into the river. Due to the large increase of traffic volume on the detour highways, it was necessary for the agency to take immediate action in the form of heavy maintenance, including overlays on portions of the detour highways, to prevent pavement failures that would endanger the traveling public (*8*). Several emergency maintenance contracts were issued to resurface highway pavements. In addition, Oklahoma DOT inspected 42 bridges on the detour routes and performed maintenance work on two bridges.

The third method to establish detour routes is to install prefabricated temporary bridges. Shortly after the incident on I-87 Bridge in Yonkers, the New York State Thruway Authority (NYSTA) deter-

FIGURE 2 Overview of damaged I-40 Webbers Falls Bridge.

FIGURE 3 Reconstruction of I-95 southbound bridge and temporary detour lanes.

mined that the use of temporary bridges would be the fastest and best way to accommodate traffic while the permanent bridge was under reconstruction. Demolition of the damaged bridge started immediately to provide space for erection of a pair of two-lane temporary bridges, one for southbound traffic and another for northbound traffic. These bridges, shown in Figure 4, were prefabricated steel panel truss structures similar to the British Bailey Bridges that were developed during World War II for use in remote combat areas. The southbound temporary bridge was approximately 44.80 m (147 ft) long, and the northbound bridge was about 47.24 m (155 ft) long. The bridges spanned over the existing abutments so that repair work on the permanent abutments could be done without interfering with the traffic above. Each bridge weighed more than 91 mega grams (100 tons). A 10-man crew assembled the temporary bridges and installed them using stationary launch rollers and a crane. Stationary launch rollers were used to allow horizontal movement of the temporary bridges, and the crane was used for vertical lifting of the cantilevered ends of each bridge. The temporary bridges were ready for use by the traveling public in only 11 days (*9*).

Selection of the most effective temporary detour method depends on incident site conditions. There is no single method that fixes all situations. Using an undamaged portion of bridge as a detour route will slow down the normal traffic flows and cause congestion. Using other highways as detour routes will increase the traffic volume on these highways and may cause early damage of pavements. In addition, people have to travel extra miles to reach their destinations, thus increasing user costs and travel time. Installing prefabricated temporary bridges near the accident site can help maintain normal travel speed and traffic capacity while reducing the inconvenience to the traveling public. However, this option is not always feasible and usually takes more time to set up. No matter what method is used, the key success factor during this stage is to reestablish a reasonable traffic flow as quickly as possible.

Design for Rapid Bridge Replacement

There are two major objectives during the design stage for rapid bridge replacement. One objective is to make sure that bridge reconstruction can be conducted quickly based on the design drawings and specifications. Another is to expedite the design process itself. The damaged bridge can be replaced using either an identical structure or a new structure. The decision maker has to consider which alternative can best deliver a quick and economical reconstruction of the bridge. After the incident on I-40, Oklahoma DOT decided to use three precast, prestressed concrete girders in lieu of the original steel approach girders because it took less time to produce concrete girders.

FIGURE 4 Two temporary steel panel truss bridges on I-87.

To expedite the I-87 bridge reconstruction and minimize impacts to the traveling public, NYSTA decided to use the Inverset Bridge System to replace the damaged bridge. A total of 12 Inverset units (modular prestressed bridge units containing a combined superstructure and deck as a single unit) were used. Each Inverset Unit was fabricated to cover the entire span but provided only a portion of the bridge's width. The units were installed side by side to complete the bridge's lateral dimension. Each modular unit was cast upside down with the steel I-beam supports on top and a concrete deck cast on the bottom. After curing in a controlled inside environment, the completed unit was turned right side up and transported to the site for installation. At the site, the units were set using a crane onto the bridge abutments. Because the Inverset units were produced inside a fabrication plant, winter weather had no impact on the production and delivery of the units. This was critical to the reconstruction of the bridge during the cold season.

In addition to using new structural members, design engineers allowed contractors to use the concrete maturity method to expedite bridge reconstruction. Concrete maturity is a method for determining real-time in-place concrete strength using internal temperature. As soon as the concrete reached 100% design strength and had a minimum of 3 days of curing, concrete forms were permitted to be removed and moment loadings were allowed to be applied to the structure. ASTM Standard C 1074, Standard Practice for Estimating Concrete Strength by the Maturity Method, specifies the concrete maturity method procedure. Although using this method speeds up the replacement process, the long-term impacts of using the maturity method to estimate the strength of the concrete components in the bridge have not been thoroughly investigated.

Other techniques used to expedite the design process include the following:

1. Offering incentive or disincentive (I/D) clauses to the design firms;
2. Providing the original drawings immediately to the design firms;
3. Having state DOT engineers on call 24 h per day, 7 days per week, to answer quickly any questions that the designers might have; and
4. Changing the state DOTs' normal operational procedures to quickly review and approve design drawings and specifications. Under normal conditions, state DOTs would take several weeks to review design submittals.

Techniques for Bridge Reconstruction

During the bridge reconstruction stage, the objective was to finish reconstruction quickly while minimizing the inconvenience to the traveling public and surrounding communities. Several construction engineering and management techniques were implemented to achieve the objective. These techniques included the use of various construction work schedules, staged construction, changing normal operational procedures, and use of I/D clauses.

Construction Work Schedules

The use of various construction work schedules can have a significant impact in the rapid reconstruction of bridges. Beyond the standard 8:00 a.m. to 5:00 p.m. work schedule, there are three schedules that warrant discussion: 24-h construction, 12-h construction, and nighttime only construction. Choice of the appropriate work schedule can be written into the contract or left to the discretion of the contractor as he or she develops the cost estimate and work plan to execute the project within the restraints of the contract (time, cost, and I/Ds). Issues that should be considered when selecting the appropriate construction work schedule include the following (*10*):

1. Increases in construction costs typically associated with accelerated construction schedules,
2. Decreases in user costs and public inconveniences associated with shorter out-of-service periods or with limited-peak traffic demand closures,
3. Availability of state DOT personnel for inspection and problem solving during off-duty hours,
4. Availability of materials and material deliveries during nonstandard hours, and
5. Loss of worker productivity, loss of quality control, and increased worker safety issues typically associated with accelerated or nighttime construction or extended work shifts.

Reconstruction projects, such as the I-40 and I-95 bridges, which were identified during this research, show that accelerated work schedules can be used to complete projects in shorter periods of time, but they typically increase the overall construction cost of the projects. However, increases in construction cost are typically offset by corresponding decreases in user costs or actual state DOTs' costs associated with temporary traffic.

Use of a 24-h construction schedule is warranted when circumstances are severe enough to justify the associated increase in cost. Special attention addressing quality control, inspection, change order approval, engineering or construction problem resolution, lighting, safety, worker fatigue, and material deliveries must be addressed as work continues 24 h a day, using either three 8-h shifts or two 12-h shifts daily. In addition to issues directly related to the construction process, others like noise, vibrations, and light that can be a nuisance to nearby property owners also have to be addressed when evening and nighttime construction is used. Guidance for these issues is provided in a NCHRP report, *Mitigation of Nighttime Construction Noise, Vibrations, and Other Nuisances* (*11*). In addition, special requirements for nighttime lighting must be addressed. Guidance for issues related to nighttime lighting is provided by another NCHRP report, *Illumination Guidelines for Nighttime Highway Work* (*12*).

Use of a 12-h construction schedule is warranted when circumstances are not severe enough to justify a 24-h schedule, along with its significant cost increase, but critical enough that a standard 8-h day will not provide an acceptable estimated schedule for project completion. Even though many of the cost increases associated with a 24-h schedule are not incurred with 12-h schedule, they must be weighed against increased construction time, user cost, and traffic congestion that will be endured. In addition, many of the issues previously discussed that require special attention during 24-h construction are eliminated or reduced during 12-h construction. Some portions of any given project may require accelerated or relaxed work schedules that vary within the project. During the demolition phase of the I-95 Chester Creek Bridge replacement project, time sequencing was not critical enough to warrant the increased cost associated with 24-h construction, so 12-h construction was used.

Use of nighttime construction is warranted when circumstances are severe enough to justify the associated increases in cost and coordination. Nighttime only construction is commonly used for bridge deck replacement projects with high-volume traffic where daytime construction would cause unacceptable traffic disruptions. During these projects, portions of the bridge deck are replaced each night during reduced traffic flow and are opened to traffic the next morning before peak traffic. This type of project typically has a heavy monetary penalty associated with any late reopening of the bridge in the morning. Key issues associated with nighttime construction that should be addressed were discussed in the foregoing section on 24-h construction.

Staged Construction

Staged construction, just as its name implies, is when bridge reconstruction is done in planned sequential stages, maintaining portions of the bridge in an operating condition for traffic while other portions are closed for replacement. Traffic can be maintained via an undamaged portion of the existing structure, adjacent parallel structure, or temporary bridge on the original or adjacent alignment.

The I-87 New York Thruway Bridge used a staged construction approach to replace the fire damaged bridge. Once the initial damaged bridge was removed, two temporary prefabricated bridges were installed on a portion of the original site to carry the traffic flow while a portion of the bridge was reconstructed. When the initial portion of the reconstructed bridge was ready for traffic, traffic was rerouted onto it, and one of the two temporary bridges was removed. When the second portion of reconstructed bridge was ready for traffic, traffic was rerouted onto it, and the last temporary bridge was removed, thus allowing reconstruction of the last portion of the bridge. Use of staged construction techniques minimized the disruption and inconvenience to the traveling public and surrounding communities.

Changing Normal Operational Procedures

Rapid bridge replacement will not be successful unless all parties involved in the process change their normal way of doing business. After the I-40 incident, the assistant bridge engineer for design from Oklahoma DOT was on call 24 h per day, 7 days per week to answer any questions that the design firm had. The agency also created a special construction residency at the project site. A 13-member team of inspectors was formed to oversee the reconstruction of the bridge. Some of the inspectors were retired employees of Oklahoma DOT. In addition to the site inspections, inspectors were sent to the steel fabrication shops to make sure that fabrication was done as designed and within specification. Under normal circumstances, the agency probably would have only two inspectors assigned to a project.

For the I-95 Bridge project, the fabrication and delivery of the steel beams were the critical activities in the reconstruction process. To meet the schedule requirement, the steel fabricator had to reschedule other work and to implement a 24-h work schedule for the replacement project. The fabrication of nine 20 to 24 m (65 to 80 ft) long girder segments, each standing 2 m (6 ft 8 in.) high, weighing 14 to 18 mega grams (15 to 20 tons), was completed in only 10 days. This accomplishment was 7 days ahead of the original delivery date (*13*). Normally, this amount of fabrication work would take 3 to 4 weeks to complete. To coordinate with the steel fabricator's schedule, Pennsylvania DOT also changed its normal operational procedures and conducted the agency-required inspections at the steel plant and fabrication shop.

Incentive and Disincentive Clause

The I/D clause is a contract technique that monetarily rewards a contractor for early completion and penalizes it for late completion of a contract. From results of three case studies, it is apparent that inclusion of an I/D clause in a design or construction contract generally assists in expediting the contract completion time. The I-40 Webbers Falls Bridge in Oklahoma required emergency reconstruction following a barge impact. I/D clauses were used in the demolition, design, and reconstruction contracts of the replacement project. Oklahoma DOT contracts provided a $50,000 per day I/D clause during the demolition phase, a $5,000/$2,400 per day I/D clause during the design phase, and a $6,000 per hour I/D clause during the reconstruction phase of the project. During project execution, the demolition contractor finished on time, the designer finished 4 days early, and the reconstruction contractor finished 10 days and 8 h (248 h) early.

The I-87 New York Thruway Bridge in Yonkers, New York, required emergency reconstruction following a gasoline tanker crash and fire under the bridge. An I/D clause was used in the reconstruction contract in the amount of $5,000 per day, with a $50,000 cap for early or late completion. The contractor finished the work 8 days early and received a $40,000 award for early completion. I/D clauses are not appropriate for every construction contract but are typically reserved for projects in which user costs are high and the impact on the driving public is severe (*14*). In addition, I/D limits should not be arbitrary amounts but should be based on user costs and state highway agency costs associated with inspection and administration of the project (*15*).

NEED FOR IMPROVEMENT

Although the three bridge replacement projects studied in this research were all finished ahead of the original schedule with a good safety record, there are still areas for state DOTs, design firms, contractors, and material suppliers to consider for future improvements. Bridge replacement is a complicated operation involving many parties. It requires each party to make technical and management decisions at different stages in a short period of time. Traditionally, each party makes decisions that best suit its interests, known as activity-level optimal. However, activity-level optimal may not lead to the best solution for the overall replacement project, known as project-level optimal. The major challenges of achieving project-level optimal for bridge replacement are communication and coordination among parties involved in the replacement process. Currently, there is no system that coordinates the different parties' tasks through gathering, processing, manipulating, storing, and distributing required information and data during the replacement process for decision-making purposes. Poor communication and coordination resulted in cost overruns and inaccurate construction schedule forecasts. For example, replacement cost for the I-40 Webbers Falls Bridge was initially estimated at $15 million, but it was finished at $30 million. The estimated time for the replacement started at 12 months; then it went down to 6 months and finished in a little over 2 months. Although the replacement was finished ahead of the original schedule, the process clearly indicated that an accurate and reliable schedule was unable to be produced and provided to the general public based on the existing construction technologies.

To enhance the capability of rapid bridge replacement after extreme events, there is an urgent need to develop new technologies to address the foregoing problems. Currently, the research team is developing a wireless real-time productivity measurement system that includes a video camera, data processor, AC transformer, two antennae, and laptop computer. See Figures 5 and 6. This system is designed to measure construction crew productivity at the bridge site without interfering with construction operations. The technology underneath the system is based on time-lapse filming (one of the time study techniques) that has proven for many years to be a very effective means for analyzing work-face activities. However, traditional time-lapse filming is conducted by employing additional people to manually collect data on the construction sites. As a result, the traditional method increases the cost, delays the analyses, and interferes with crew activities that may produce inaccurate data. The wireless real-time system overcomes these shortfalls. Using real-time productivity data, engineers and project managers may be able to accurately determine the bridge replacement progress and easily share the information with all parties involved in the bridge replacement project. Thus, the wireless real-time productivity measurement technology has a great promise to address communication and coordination issues, control cost overruns, improve construction schedule forecasts, and increase emergency response capability after extreme events. Performance of the system will be determined in the field experiments and results will be reported in the near future.

CONCLUSIONS AND RECOMMENDATIONS

This paper presents three real-world emergency bridge replacement cases: the I-40 Webbers Falls Bridge in Oklahoma, the I-95 Chester Creek Bridge in Pennsylvania, and the I-87 New York State Thruway Bridge in Yonkers, New York. Lessons learned from these cases benefit government agencies such as state DOTs, which are responsible for development of the enhanced emergency response plans for highway bridges, and engineering and construction communities, which are responsible for design and reconstruction of the damaged bridges. The paper also identifies the areas that need to be improved in the emergency bridge replacement operations. These needed improvements become subjects for future research and development.

FIGURE 5 Major components of wireless real-time productivity measurement system.

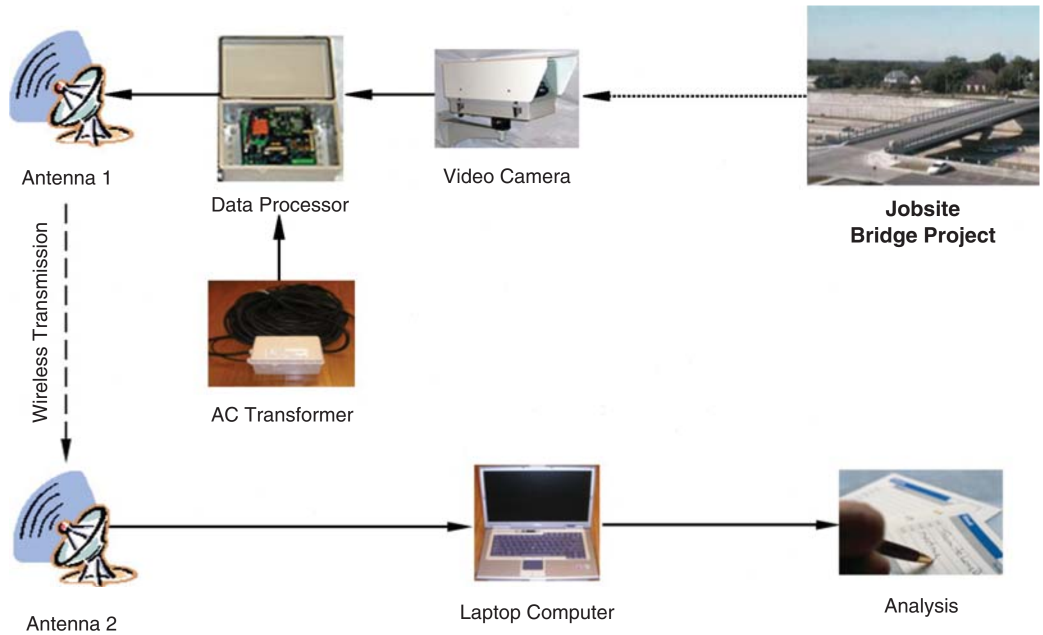

FIGURE 6 Framework for wireless real-time productivity measurement system.

There were many factors contributing to the successful responses to the three incidents discussed in this paper. To document what can be learned from these extreme events, the research team conducted detailed case studies. During the studies, the research team reviewed literature including information posted on websites, interviewed people who were involved in the replacements of the bridges, via telephone, and performed surveys. Notwithstanding their terrible consequences, the three bridge tragedies provide useful lessons for government agencies, engineering and construction firms, and material suppliers, which must plan for enhanced responses in case of future incidents. The following lessons learned are drawn from this research project:

1. Quick response to a bridge damage incident is the key to mitigating losses and easing any inconvenience to the traveling public.
2. Less time was required to design the new structure when original design drawings and specifications were immediately accessible to designers and state DOT engineers were available to answer questions.
3. It is critical to select design firms, contractors, and material suppliers that have the resources and the knowledge to accomplish replacement projects under emergency situations.
4. I/D clauses in the contracts played a very successful role in motivating design firms, contractors, and material suppliers to finish their work on time or ahead of schedule.
5. Use of prefabricated or modular elements avoids weather impact on production and delivery; thus, it shortens the bridge reconstruction process.
6. Stage construction techniques minimize disruption and inconvenience to the traveling public and the surrounding community during the replacement project.
7. Commitment of adequate resources for rapid bridge replacement, such as manpower, from all parties including state DOTs, design firms, contractors, and material suppliers, accelerates the replacement process.
8. The maturity method was used successfully to expedite the concrete construction process.
9. Community and interagency cooperation enabled the effective and smooth execution of the replacement projects.

Recommendations for continuous improvements were also identified. Specifically, government agencies and engineering and construction companies need to improve communication and coordination during the replacement process, to control cost overruns, and to improve construction schedule forecasts. To achieve these objectives, a wireless real-time productivity measurement system is being developed. Performance of the system will be determined in the field experiments and results will be reported in the near future.

ACKNOWLEDGMENTS

The authors thank Rex Mackey of Pennsylvania DOT; Robert Buckley, Craig Hoogstraten, and David Warner of Buckley & Company, Inc.; Steve Bussanmas of High Steel Structures, Inc.; Gregory Allen, George Raymond, and Bob Rusch of Oklahoma DOT; Jim Poe of Gilbert Central Construction, Inc.; Tim Purkeypile of Poe & Associates; Younus Samadzada of the New York State Thruway Authority; Peter Smith of the Fort Miller Company; and William R. Burkett, Phil Nash and Cindy Jones of Texas Tech University. Special thanks go to state DOTs that provided financial support and guidelines for this research project. These DOTs include Georgia, Illinois, Iowa, Minnesota, Mississippi, New Jersey, Ohio, South Carolina, and Texas.

REFERENCES

1. Barker, R. M., and J. A. Puckett. *Design of Highway Bridges*. John Wiley and Sons, Inc., New York, N.Y., 1997.
2. *A Guide to Highway Vulnerability Assessment for Critical Asset Identification and Protection*. Transportation Policy and Analysis Center, SAIC, Vienna, Va., 2002.

3. *A Guide to Updating Highway Emergency Response Plans for Terrorist Incidents*. Final Report. Parsons Brinckerhoff–PB Farradyne, Rockville, Md., 2002.
4. Ghosn, M., and F. Moses. *NCHRP Report 489: Design of Highway Bridges for Extreme Events*. TRB, National Research Council, Washington, D.C., 2003.
5. *NCHRP Report 525: Surface Transportation Security,* Vol. 1–2. TRB, National Research Council, Washington, D.C., 2004.
6. Bai, Y., W. R. Burkett, and P. T. Nash. Rapid Bridge Replacement under Emergency Situation: Case Study. *Journal of Bridge Engineering,* Vol. 11, No. 3, 2006, pp. 266–273.
7. Bai, Y., W. R. Burkett, and P. T. Nash. Lessons Learned from an Emergency Bridge Replacement Project. *Journal of Construction Engineering and Management,* Vol. 132, No. 4, 2006, pp. 338–344.
8. I-40 Bridge Update: Day 29 of 57 Construction Days. *Public Information,* Oklahoma Department of Transportation, July 10. www.okladot.state.ok.us/public-info/i40bridge-press/july_10_Update.htm. Accessed March 26, 2003.
9. Governor Pataki Opens Temporary Thruway Bridges in Yonkers. News release. New York State Thruway Authority, Oct. 20, 1997.
10. Burkett, W. R., P. T. Nash, Y. Bai, C. Hays, and C. Jones. *Rapid Bridge Replacement Techniques*. Final report, Project 0-4568-1. Texas Department of Transportation, Austin, 2004.
11. Schexnayder, C. J., and J. Ernzen. *NCHRP Synthesis of Highway Practice 218: Mitigation of Nighttime Construction Noise, Vibrations, and Other Nuisances*. TRB, National Research Council, Washington, D.C., 1999.
12. Ellis, Jr., R. D., S. Amos, and A. Kumar. *NCHRP Report 498: Illumination Guidelines for Nighttime Highway Work*. TRB, National Research Council, Washington, D.C., 2003.
13. Carey, K. E. The Quick Fix. *Sunday Times of Delaware County,* July 12, 1998, p. 41.
14. *Incentive/Disincentive (I/D) for Early Completion*. Technical Advisory T 5080.10. FHWA, U.S. Department of Transportation, 1989. www.fhwa.dot.gov/legsregs/directives/techadvs/t508010.htm. Accessed June 1, 2004.
15. Jaraiedi, M., R. W. Plummer, and M. S. Aber. Incentive/Disincentive Guidelines for Highway Construction Contracts. *Journal of Construction Engineering and Management,* Vol. 121, No. 1, 1995, pp. 112–120.

The Bridge Management Committee sponsored publication of this paper.