Rapid Replacement/ Construction of Bridges

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16. Abstract

Bridges are a key element of the transportation system because they control system capacity and are normally built at the highest cost to the system. Once a bridge reaches its useful design service life, it needs to be replaced or reconstructed in order to safely accommodate traffic and efficiently utilize the system. While highways can be repaired relatively quickly, bridges require special planning, engineering, materials procurement, and longer periods of construction time. This study synthesized current state-of-practices of rapid bridge construction methods, developed a decision-making framework for determining the feasibility of adopting rapid bridge replacement/construction, that considers issues of criticality of the bridge, contractor's prefabrication ability, contractor's construction management, and agency and user costs of bridge construction. The findings provide highway agencies with a framework to determine whether it is appropriate to utilize rapid bridge replacement/construction techniques for specific bridges. Based on these findings, a decision support framework using Analytical Hierarchy Process (AHP) is presented to allow for agencies to rank order priorities amongst those assets (bridges) that are determined to be candidates for rapid replacement/construction. Finally, a preliminary analysis was performed to explore a conceptually new bridge design and construction system that may be considered as a candidate for rapid replacement/construction of bridges with similar geometric design standards governed by comparable traffic conditions and site characteristics.
Major technical issues addressed in this study include: 1) identifying existing literature on rapid bridge replacement/construction techniques developed worldwide; 2) finding current state-of-practices of rapid bridge replacement/construction in the United States; 3) developing a decision-making procedure for justifying the use of rapid bridge replacement/construction techniques over the conventional bridge construction methods; and 4) exploring a new conceptual bridge design and construction system that supports rapid construction. This report provides both technical and non-technical information. Some readers may wish to skip over the analysis details and focus on broader concepts of the analysis strategy.

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Final Report

Rapid Replacement/Construction of Bridges

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EXECUTIVE SUMMARY

Once a bridge reaches its useful design service life, it needs to be replaced or reconstructed in order to safely and efficiently accommodate traffic. While highways can be repaired relatively quickly, bridge replacement/construction requires special planning, engineering, materials procurement, and longer periods of construction time. This report documents the findings of a review of existing literature on rapid bridge replacement/construction techniques developed worldwide with emphases given to materials, prefabrication, and machinery techniques. Then, the report documents summarized findings of a survey that aimed to collect pertinent information to synthesize current best practices of rapid bridge replacement/construction in the United States. The key findings of the survey are:

- Most of the participating states have adopted a centralized hierarchy for bridge management.

- Most of the participating states are using rapid bridge replacement/construction technologies to mitigate traffic disruption during on-site construction. However, the extent of bridge work that utilized rapid bridge replacement/construction technologies is less than 10 percent.

- Most of the participating states do not have specific restrictions for adopting rapid replacement/construction technologies for bridge work. Some states do limit such technologies to only small-span bridges.

- Most of the participating states do not query a list of contractors or vendors for rapid bridge replacement/construction work.

- The potential benefits of rapid bridge replacement/construction mainly come from mobility improvements, safety enhancements, and mitigation of adverse impacts to local businesses and communities.

- The key factors affecting the selection of rapid bridge replacement/construction strategies include criticality of the bridge, construction cost, road user mobility and safety, socioeconomic impacts, and construction worker safety.

- Two-thirds of the participating states have found that the outreach efforts are effective in promoting the use of rapid bridge construction techniques. Such efforts are mainly made in the pre-construction phase.

- The types of innovations in rapid bridge replacement/construction include the use of new materials, prefabrication of bridge components, and innovative contracting. High performance concrete and steel are new materials that are commonly used in rapid bridge replacement/construction. Prefabrication is

concentrated on the superstructure and deck. Innovative contracting methods primarily include incentives and disincentives, A+B, design-build, and lane rental.

Next, a rapid bridge replacement/construction decision-making procedure framework was developed to help determine whether the use of rapid bridge construction techniques is feasible. The system of rapid bridge replacement/construction is primarily concerned with materials, prefabrication, and machinery. Specifically, adequate use of prefabrication to produce bridge elements can be both cost-effective and time-effective in a way that will help meet rapid construction requirements. In this regard, the factors that affect the selection of prefabrication techniques are the criticality of the bridge, contractors' prefabrication abilty/history, contractor's construction management strategies for mitigating safety and environmental impacts, and agency and user costs of bridge construction. Issues regarding the criticality of the bridge are mainly associated with whether the bridge is accommodating a high traffic volume, involved in emergency recovery, located on an evacuation route, involved with lane closures, or affecting the construction duration of a larger highway project. Issues pertaining to a contractor's prefabrication ability are concerned with prefabrication of bridge elements and standardization. Issues related to a contractor's construction operations management strategies are relevant to safety impacts, environmental impacts, and bridge site conditions. Issues within the category of agency and user costs of bridge construction may examine bridge construction costs including the cost of traffic, user costs, the bridge owner agency's operations, and the contractor's operations, as well as impacts on bridge life-cycle agency and user costs. Rapid construction is justified after confirming the criticality of the bridge, the contractor's prefabrication ability, the contractor's construction management, and savings in the total expenditure of the agency and user costs. The report also includes the framework for a decision support system using Analytical Hierarchy Process (AHP) to rank order bridges that are identified as candidates for rapid replacement/construction.

After confirming the feasibility of adopting rapid bridge replacement/construction, an exploratory analysis of a conceptually new rapid bridge design and construction system was conducted to determine the rapid bridge replacement/construction method that was best suited to the project. The findings of this exploratory analysis reveal that rapid design and construction can be considered as a candidate in lieu of rapid replacement in those instances where the geometric design standards and traffic and site conditions are comparable. . A preliminary analysis was conducted to explore an innovative system that supports rapid bridge replacement/construction. The analysis covers rapid construction considerations, preliminary structure analysis, foundation type considerations, conceptual cable-stayed bridge design and construction, and a conceptual construction method. .

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation officials
AHP	Analytical Hierarchy Process
CFIRE	Center for Freight and Infrastructure Research and Education
CMA	Compressive Membrane Action
DOT	Department of Transportation
FE	Finite Element
FHWA	Federal Highway Administration
FRP	Fiber Reinforced Polymer
GFRC	Glass Fiber Reinforced Concrete
HPS	High Performance Steels
LRFD	Load Resistance Factor Design
NCHRP	National Cooperative Highway Research Program
SAP	Structure Analysis Program
SFRC	Steel Fiber Reinforced Concrete
SPMT	Self-Propelled Modular Transporter
TRP	Technical Review Panel

CHAPTER 1:
INTRODUCTION

1.1 Project Statement

A large share of freight tonnage in the United States is moved via highways, particularly through Interstate highways. At any given point in time, over ten percent of the Interstate Highway system is under construction. The consequent traffic disruption has significantly affected the freight hauling industry. Bridges are a key element of the transportation system because they control the system's capacity and are normally built with the highest cost to the system (Barker and Puckett, 1997). If a bridge on a major highway fails, it would likely affect the efficiency of the transportation system. Once a bridge reaches its useful design service life, it needs to be renewed in order to safely accommodate traffic and allow for efficient utilization of the system. While highways can be repaired relatively quickly, bridges require special planning, engineering, materials procurement, and longer periods of construction time. This study proposes to synthesize the state-of-practice of rapid bridge construction methods, develop a bridge replacement/construction decision-making framework, and exploit innovative methods for rapid construction of highway bridges that explicitly address materials, design and prefabrication of bridge elements, as well as construction machinery for assembling the structural components. The findings provide highway design authorities with both a framework to select appropriate rapid bridge replacement/construction techniques for a variety of situations as well as a guide to procuring the needed materials, prefabricated bridge elements, and construction machinery for assembling the structural components both off-site and on-site of construction.

1.2 Research Objectives

1.2.1 Background

The current practices in rapid construction of highway bridges are concerned with materials, prefabrication, and machinery for the construction of substructure, superstructure, and deck components. High performance materials including high performance steel and concrete, fiber-reinforced concrete, and fiber-reinforced polymer composites have outstanding individual properties. When integrated into the design of bridge structures, these materials will significantly enhance bridge durability, productivity, mobility, and safety. The use of prefabrication techniques to produce elements of structure components can be both a cost-effective and time-effective solution to bridge construction complexities. These technologies have two major advantages. First, the quality of prefabricated elements is improved as the prefabrication is completed in a controlled environment circumventing many job-site limitations. Second, prefabricated elements are brought to the site ready for installation, minimizing the need and duration for lane closures, detours, and use of narrow lanes. Major machinery needed for bridge construction may include excavators and bulldozers, launching girders, cranes, and self-propelled modular transporters.

1.2.2 Study Objectives

A general objective of this project is to advance technology, knowledge, and expertise in the planning, design, construction, and operation of sustainable freight transportation infrastructure through education, research, outreach, and training. The specific objectives are as follows:

- Developing a highway bridge replacement/construction decision-making framework to determine whether rapid replacement/construction of a bridge is a feasible choice for the given condition, , possible construction alternatives if rapid replacement/construction is feasible, and cost/benefit considerations; and
- Exploring new system that could promote rapid highway bridge construction.

1.2.3 Delineation of Tasks

Task 1: Information Search

1-a: Literature Review

The literature review was conducted based on documents made available by the Federal Highway Administration (FHWA), Federal Railroad Administration (FRA), and state transportation agencies regarding rapid bridge replacement/construction. Emphasis was given to issues to be considered in the decision-making framework for rapid bridge replacement/construction, and innovative techniques for rapid bridge construction regarding materials, schematic design and prefabrication, machinery.

1-b: Questionnaire Surveys

A survey questionnaire was distributed to all 50 state transportation agencies to collect information on best practices of rapid highway bridge construction in the country.

Task 2: Development of Decision-Making Framework for Determining the Feasibility of Rapid Bridge Replacement/Construction

The literature search in Task 1 helped establish the list of issues that needed to be considered as part of developing the decision-making framework for rapid bridge replacement/construction. The “issue items” list will be used to develop a decision-making framework to determine whether rapid bridge replacement/construction is feasible considering issues of rapid on-site construction needs, construction operations management, and construction costs. The research team sought input from engineers regarding their perception about factors that they would use to determine the feasibility of rapid replacement/construction of a bridge using the Analytical Hierarchy Process AHP technique. AHP is a systematic method for comparing a list of objectives or alternatives. It helps to structure a problem in a hierarchical manner and a sequence of pair-wise comparison of criteria. The problem needs to be structured in a hierarchical manner (Figure 1). The first level denotes the overall goal of this exercise. In this case, it is to provide help with relocation decision process for individuals.

The user is required to perform pair-wise comparison rankings for each of the main criteria. The outcome of the AHP is a prioritized ranking or weighting of each decision alternative. These inputs were obtained in a multitude of ways ranging from structured questionnaires to phone conversations.

Task 3: Exploitation of a Conceptually New Bridge Design and Construction System for Rapid Replacement/Construction

This task focused on i) the evaluation of bridge structure types, configuration, and geometry; ii) the assessment of the properties of materials used for bridge structures; iii) an engineering analysis of typical types of bridge structures; iv) an assessment of prefabrication of structural components and machinery needs; and v) a preliminary life-cycle cost analysis of typical types of bridge structures.

Sub-tasks i) to iv) reflected the implementation of a top-down approach to develop a conceptual method for rapid construction of the prototype bridge design. Sub-task v) facilitated tradeoff studies of alternative types of bridge structures designed using different types of materials.

Task 4: Report Preparation, Submission, and Implementation Plan

Interim reports documenting the information search, the decision-making framework, and the new conceptual bridge design and construction system for rapid bridge replacement/construction were submitted within 6, 9, and 21 months of approval of this proposal, respectively. A final report on findings of Tasks 1-3 and an implementation plan was submitted in the 24th month after approval of this proposal.

1.3 Report Organization

The report is comprised of six chapters. Chapter 1 discusses the increasing need for rapid replacement/construction of bridges, as well as research objectives and tasks. Chapter 2 documents the findings of the literature review on techniques used for rapid replacement/construction of bridges worldwide. Chapter 3 synthesizes the findings of surveys on the use of rapid bridge construction techniques across the country. Chapter 4 discusses a decision-making framework for determining the feasibility of rapid bridge replacement/construction. Chapter 5 documents an exploratory analysis of a new conceptual rapid bridge design and construction system. Finally, Chapter 6 contains a summary of the study and the conclusion.

CHAPTER 2:
LITERATURE REVIEW

2.1 General

The simultaneous process of bridge replacement/construction with minimal traffic disruption requires innovative methods to i) *reduce the frequency of bridge work*; and ii) *significantly shorten the duration of on-site bridge replacement/construction*. As the first step of the research, a literature review was conducted on current rapid bridge replacement/construction practices as summarized in the following sections.

2.2 State-of-Practice Technologies for Rapid Replacement/Construction of Bridges

The current state-of-practice technologies for rapid replacement/construction of bridges are concerned with materials, prefabrication, and machinery for substructure, superstructure, and deck components. Figure 2.1 lists state-of-practice technologies for building bridges and briefly descriptions follow.

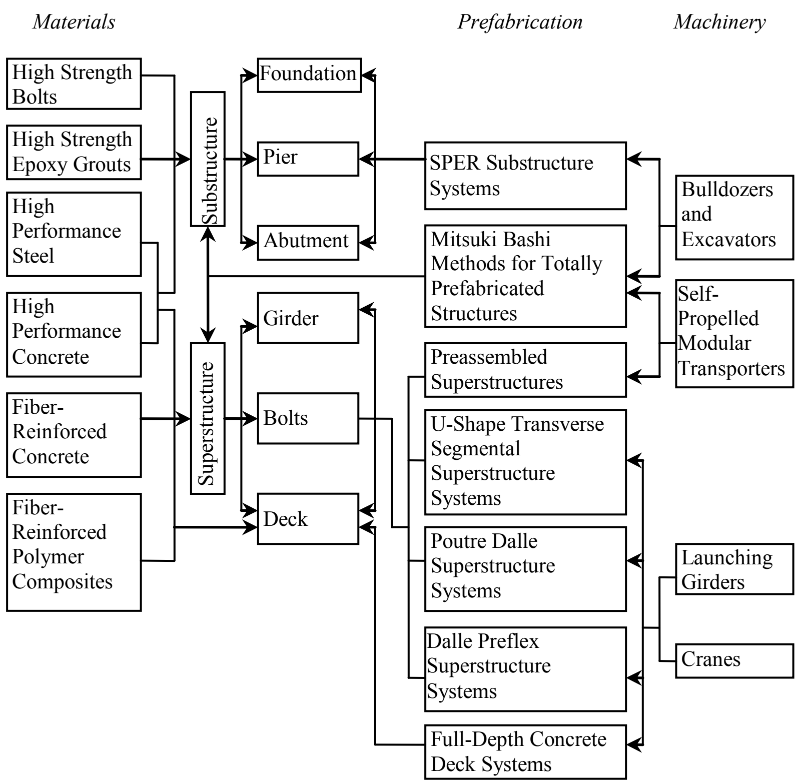

Figure 2.1. Current Practice of Materials, Prefabrication, and Machinery Technologies for Rapid Bridge Replacement/Construction

2.2.1 High Performance Materials

High performance materials, including variations of steel and concrete as well as more exotic materials such as fiber-reinforced polymer composites, have outstanding individual properties (Hooks and Cooper, 2000). When integrated into the design of bridges, these materials will significantly enhance durability, safety, and construction productivity.

<u>High Performance Steel</u>. High performance structural steel is now commercially available for highway bridge construction. Compared to conventional steel, the new steel possesses superior weldability and toughness that will give maximum performance in bridge structures while remaining cost-effective (Barson, 1996; Lwin, 2006; Wright, 2006).

In a cooperative program between the Federal Highway Administration (FHWA), the American Iron and Steel Institute, and the U.S. Navy Carderock Division of the Naval Surface Warfare Center, the new high performance steels (HPS)- HPS 70W, were developed for bridge structures. Compared to traditional 70W steel, the HPS 70W is superior in some important properties, including high strength, high corrosion resistance, low carbon equivalent, high toughness and so on (Yost and Scott, 2002).

<u>High Strength Bolts</u>. High strength bolts are well established as economical and efficient devices for connecting structural steel. The installation of high strength bolts in bridge structures can reduce the risk of improperly manufactured, installed, and poorly inspected fasteners that can contribute to structural failure (FHWA, 1991[1]).

According to Liu and Yang (2007), high-strength bolts of class 8.8 were used for all connections of members and nodes in the Jiangyin Changjiang crossing project. These researchers provided information on the selection of the high-strength bolts, the determination of fastening torque values, quality checking of the bolts, and shear tests of the bolts. Further, Choi et al. (2007) investigated the relationship between axial loading and fatigue life of high-strength bolts. The fatigue limit of bolts was found to increase proportionally along with a higher torque. This finding offers practical guide to the use of high-strength bolts.

<u>High Strength Epoxy Grouts</u>. The sole function of grouting is to prevent the intrusion of contaminants and to surround the steel tendons in an alkaline environment. In recent years, high strength epoxy grouts have been used to join bridge segments (Botelho, 2005). These materials are good for corrosion protection.

<u>Steel-Reinforced High Performance Concrete</u>. Steel-reinforced high performance concrete meets special strength and durability criteria using conventional mixing, placing, and curing practices. It is classified as very early strength, high early strength, very high strength, and fiber-reinforced types that maintain

performance benefits ranging from ease of placement and consolidation without affecting strength, long-term mechanical properties, early high strength, toughness, volume stability, to long-life in severe environment (Goodspeed et al., 1996).

Taylor et al. (2003) investigated the reason that the bridge deck slabs had intrinsic strength, which could be described as compressive membrane action (CMA). Some field experiments suggested that it's possible to design deck slabs with very low percentages of reinforcement to mitigate corrosion problems. Fiber-Reinforced High Performance Concrete. Fiber-reinforced high performance concrete is also known as steel-free high performance concrete because it uses carbon fiber, glass fiber, aramid fiber (trade name Kevlar), or graphite in place of the internal tensile reinforcement. Application of high strength concrete in civil engineering has become more and more popular due to its high compressive strength, durability, lower amounts of creep, and so on. Adding steel fiber into concrete matrix seems to improve the ductility. It has been applied in the casting of bridge decks on a number of highway bridges (FHWA, 1991[2]). Because it does not incorporate reinforcing steel, fiber-reinforced concrete decks are corrosion free. Glass fiber reinforced concrete (GFRC) incorporating fiber reinforced polymer (FRP) is proven to be a potentially ideal composite material for the manufacture of thin structural elements (Kim et al., 2008). The results of field experiments show that the characteristics of GFRP bonds are better than fiber-reinforced concrete.

Steel-Fiber Reinforced High Performance Concrete. Compared to conventional steel and reinforced high performance concrete, steel-fiber reinforced high performance concrete (SFRHPC) is considered to be a favorable material to provide additional ductility (Ozden and Akdag, 2008). It was found that SFRHPC piles with steel fiber reinforcement ratios of 1 percent and 1.5 percent are able to provide more ductility and higher lateral load carrying capacity while taking lower bending moments.

The behaviors of fully and partially prestressed concrete beams made of a mix of high strength and steel fiber reinforced concreted were investigated (Liu et al., 2009). Structural behaviors, such as the deflection of the beam, the formation and development of cracks, and moment redistribution were examined. The results showed that cracking behaviors of fully prestressed high strength concrete can be improved through the use of steel fiber.

Fiber-Reinforced Polymer Composites. Fiber-reinforced polymer composites contain the components of fiber and a resin such as epoxy. A composite with two or more types of fibers is known as hybrid composite. Concrete using fiber-reinforced polymer composites is also non-corrosive and has been used for bridge decks. Such decks can be designed and engineered into non-corrosive, high-strength, light-weight, non-magnetic, and easy-to-install structures (FHWA, 2006).

Although polymer fiber composite has been widely used in the construction area, the elastic-damage behavior of this material is not fully understood. Zairi et al. (2008) investigated the mechanical response of polymer fiber composites. A predictive model based on micromechanical considerations was established. The model's predictions and experimental data agree. To study the machining response of unidirectional carbon fiber reinforced polymer composites, a three dimensional macro-mechanical finite element (FE) model was developed (Rao et al., 2007). These researchers investigated several influential factors, including fiber orientations, depths of cut and rake angles. The field experiment results revealed that the observations of chip formation mechanisms agree with FE simulation.

2.2.2 Prefabrication

The use of prefabrication technologies to produce elements of bridge deck, superstructure, substructure, and abutment components can be a cost- and time-effective solution to bridge construction complexities. These technologies have two major advantages. First, the quality of prefabricated elements is improved as the prefabrication is done in a controlled offline environment circumventing many job-site limitations. Second, prefabricated elements are brought to the site ready for installation, minimizing the need and duration for lane closures, detours, and use of narrow lanes (Verma et al., 2001; Shahawy, 2003). Table 2.1 lists bridge elements typically prefabricated when applying the segmental construction technologies (FHWA, 2006).

Table 2.1. Prefabricated Deck, Superstructure, and Substructure Elements

Bridge Component	Prefabricated Element
Deck	Fiber-reinforced concrete deck panel Full and partial depth concrete deck panel Parapet wall
Superstructure	Beam and girder Pier segment and cap Pile
Substructure	Footing
Miscellaneous	Abutment

Some innovative techniques for prefabricating bridge elements and systems include SPER systems for substructure construction, U-Shaped transverse segmental superstructure systems, Poutre Dalle superstructure systems, Dalle Preflex superstructure systems, preassembled superstructure systems, full-depth concrete deck systems, Mitsuki Bashi methods for constructing totally prefabricated structures, and hybrid steel-concrete deck systems. These systems are briefly discussed as follows:

<u>SPER Systems for Substructure Construction</u>. The SPER substructure system was developed in Japan and uses precast concrete panels as both substructure segments and formwork for cast-in-place concrete piers

(NCHRP, 2004). Short, solid piers have panels for outer formwork, and tall, hollow piers have panels for both the inner and outer formwork. Segments are stacked on top of each other using epoxy joints and filled with cast-in-place concrete to form a composite section. The system has the advantage of a high quality, durable external finish with reduced construction time.

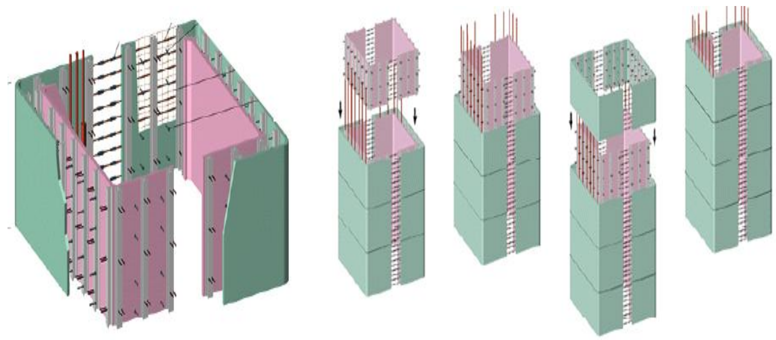

Figure 2.2. Illustration of Substructure Construction Using the SPER System

U-Shaped Transverse Segmental Superstructure Systems. The U-shaped transverse superstructure segmental system reduces the weight of prefabricated superstructure segments (FHWA, 2005). With this system, the traditional top slab is replaced by a transverse concrete rib. After erecting the U-shaped transverse segments, prefabricated partial-depth concrete deck panels are placed longitudinally between the transverse ribs. Cast-in-place concrete is then placed on top of the deck panels and the deck is transversely post-tensioned.

Figure 2.3. U-Shaped Transverse Segmental Systems in Superstructure Construction

Poutre Dalle Superstructure Systems. The patented Poutre Dalle superstructure system is a method for prefabricated partial depth superstructure construction (FHWA, 2004). In this method, shallow, inverted T-beams are placed adjacent to each other and then made composite with cast-in-place concrete placed between the webs of the T-beams and over the tops of the stems to form a solid member. This method eliminates formwork and provides a working surface in superstructure construction.

Figure 2.4. Prefabricated Partial Depth Superstructure Using the Poutre Dalle System

Dalle Preflex Superstructure Systems. The patented Dalle Preflex superstructure system is similar to the Poutre Dalle system, but uses steel I-beams with their bottom flanges precasted in a prestressed concrete slab (FHWA, 2005). The units are placed next to each other. Hooked bars passing through the steel web overlap hooked bars from the adjacent members to provide lateral continuity. Additional stirrups, transverse reinforcement through the hooked bars and stirrups, and longitudinal and transverse reinforcement in the top are used to provide continuity. Cast-in-place concrete is used to complete the system.

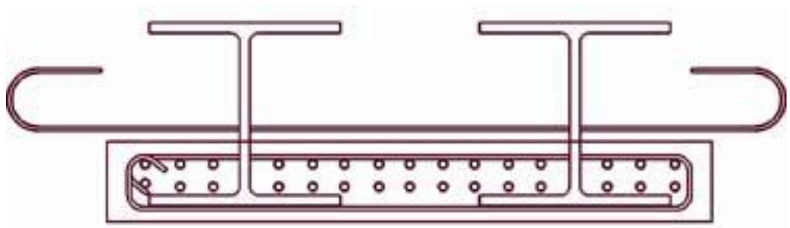

Figure 2.5. Cross-Section of Prefabricated Partial Depth Superstructure Using the Dalle Preflex System

Preassembled Superstructure Systems. Entirely prefabricated, preassembled superstructures offer advantages in terms of constructability and on-site construction time. Pre-constructed units may include steel or concrete girders prefabricated with a composite deck, cast away from the project site, and then lifted into place in one operation. Truss spans can also be preassembled.

Figure 2.6. Preassembled Superstructure Installation

Full-Depth Concrete Deck Systems. The full-depth concrete deck system consists of multiple longitudinal steel beams supporting full-width, full-depth precast concrete deck panels (Issa et al., 1998). The concrete panels are epoxied together and longitudinally post-tensioned. A transverse joint is used between panels. Studs are welded to the steel beams through pockets in the panels. The panels sit on continuous elastomeric pads that also provide a seal for grouting through the stud pockets between panels and steel girders.

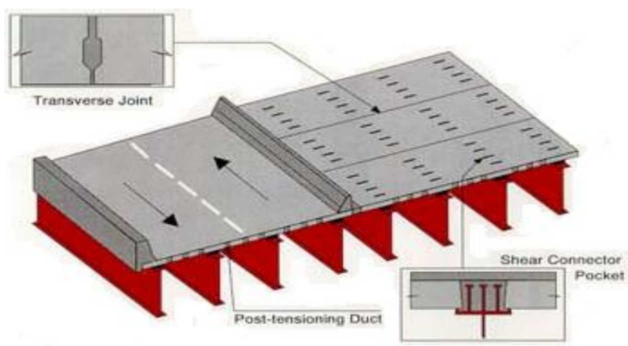

Figure 2.7. Illustration of a Prefabricated Full-Depth Concrete Deck System

Mitsuki Bashi Methods for Totally Prefabricated Structure Construction. Originated from Japan, the patented Mitsuki Bashi method includes a steel hull footing, a steel bridge pier, and a steel box-girder superstructure that claimed to complete bridge construction in three months (FHWA, 2005). First, the steel hull footing is placed in an excavated foundation. The footing has a short stub pier on top and vertical holes through which piles can be driven. The system allows the piles to be placed through the steel footing while the steel pier and pier cap are being erected. The hull can then be filled with concrete to create a composite foundation. Meanwhile, the superstructure can be assembled offsite and be moved into the site for final installation.

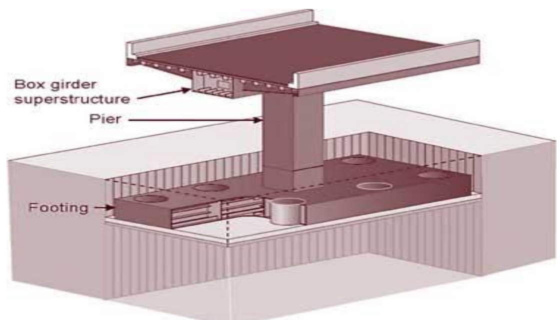

Figure 2.8. Illustration of Totally Prefabricated Bridge Construction Using the Mitsuki Bashi Method

Hybrid Steel-Concrete Deck Systems. The hybrid steel-concrete deck system consists of bottom and side formwork and transverse beams. The system could act as a composite deck system when filled with concrete. It’s possible to carry out rapid replacement with a small capacity crane of a lightweight deck.

Figure 2.9. Hybrid Steel-Concrete Deck System

2.2.3 Machinery

Excavators and Bulldozers. Excavators are used to lift, drop, and dig materials from the site. Bulldozers are ideal for lifting, moving, and dragging materials in sandy and muddy ground and earthwork.

Launching Girders. A Launching girder is a construction system situated above the bridge deck that is slowly advanced along the part of the bridge span that has already been constructed. Riding on the structure itself, a launching girder is used to lift, hang, and adjust cast-in-place concrete, as well as prefabricated elements to their final positions. After individual elements are aligned, the launching girder can then move forward to the next span and repeat the process. It is highly adapted for a wide range of spans and types of superstructure.

Cranes. Technically called “floating cranes,” they are the very same heavy-duty cranes used to build skyscrapers. They are used for loading, unloading, and transporting bridge components during construction. Floating cranes are generally self-propelled, have a lifting capacity exceeding 10,000 tons and can be used to transport entire bridge sections.

Figure 2.10. Launching Girder and Crane Operations in Bridge Construction

Self-Propelled Modular Transporters. The Self-propelled modular transporter is a multi-axle computer-controlled vehicle that can be used to lift and transport large bridge superstructure components or even entire superstructures into precise positions (Ralls, 2005). These vehicles can move in any horizontal direction with equal axle loads while maintaining a horizontal load with undistorted geometry. This allows construction to be completed quickly within the given time restrictions and without cranes, temporary or extensive detours, or traffic delays.

Figure 2.11. Preassembled Superstructure Installation Using Self-Propelled Modular Transporters

CHAPTER 3:
SURVEYS OF CURRENT RAPID BRIDGE REPLACEMENT/CONSTRUCTION PRACTICES

3.1 General

A survey was administered in mid-September of 2010 to collect pertinent information in order to synthesize rapid bridge replacement/construction techniques practiced by all state transportation agencies, including state toll highway authorities in the United States. The survey questionnaire is attached to this report in Appendix A, which consists of five main questions with sub-questions in some inquires. Question one asks about characteristics of agencies' bridge management hierarchy. Question two inquires about the use of rapid bridge replacement/construction techniques, strategies, and technologies in each agency. If rapid bridge replacement/construction is utilized by the agency, sub-questions inquire about the main objectives for using rapid bridge replacement/construction. These include questions about techniques, extent of adoption, restrictions on its application, list of contractors/ vendors for accelerating work, potential benefits, and key factors influencing the selection of rapid bridge construction strategies, techniques, and technologies. Question three asks about the influence on outreach efforts for promoting the use of rapid bridge construction strategies, techniques, and technologies to road users, non-users, local businesses, and communities. If the use of rapid bridge construction and replacement techniques is effective, sub-questions inquire the phase of bridge project delivery in which the efforts are made. Question four asks about types of innovations in rapid bridge replacement/construction strategies, techniques, and technologies that are in practical use. Specific types of innovations are asked about within the sub-questions.

The survey participants were informed of the web address where they could access the online survey. An electronic copy of the questionnaire in an editable Microsoft Word format was also attached to the email to allow more options to participate in the survey. The respondent was allowed to choose to submit the completed survey online, via email, or by fax.

The survey period lasted for 6 weeks. In total, 18 bridge engineers from 16 state transportation agencies responded to the survey, as shown in Figure 3.1. Of these respondents, 14 completed the survey through the Website, while 4 responded by email. The following sections discuss the survey results. Appendix B summarizes the responses in graphs.

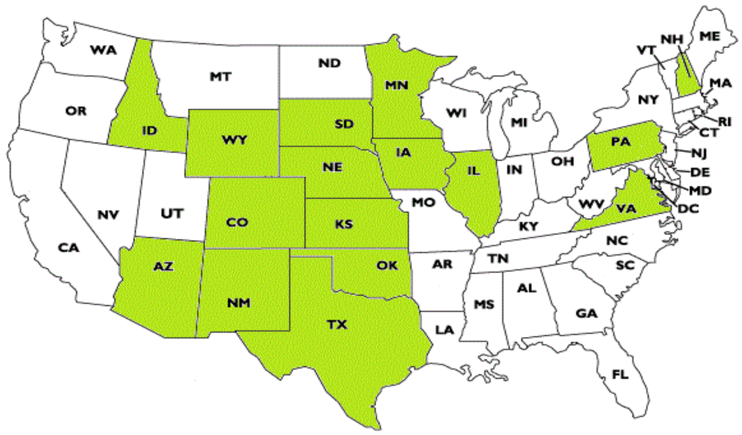

Figure 3.1. States that responded to the Questionnaire Survey

3.2 Survey Results

3.2.1 Characteristics of Bridge Management Team Hierarchy

Table 3.1 summarizes the responses to the question regarding the characteristics of bridge management team hierarchy in state transportation agencies in terms of the overall number and percentage respectively. Most of the agencies that responded to the survey have adopted centralized hierarchies for bridge management (83 percent), while the other agencies adopted decentralized hierarchy.

Table 3.1. Characteristic of Bridge Management Team Hierarchy

Bridge Management Team Hierarchy	Responses	
	No.	%
Centralized	15	83%
Decentralized	3	17%

3.2.2 Use of Rapid Bridge Replacement/Construction Techniques

Table 3.2 presents whether or not rapid bridge replacement/construction techniques are used in state transportation agencies. Two out of 18 respondents are not using rapid bridge replacement/construction strategies (11 percent), while most agencies are using rapid bridge replacement/construction strategies. The reasons that two agencies do not use rapid bridge replacement/construction are as follows. The first agency uses a very restricted definition of rapid bridge construction, where precast boxes and deck panels are not considered as part of rapid construction. In addition, the state is mostly rural and traffic disruption caused by construction is minimal. In this respect, it is difficult to achieve measurable reductions in traffic delays from rapid bridge construction. The second agency is about to begin investigating the possibility of adopting rapid bridge construction techniques in its future bridge projects.

Table 3.2. Use of Rapid Bridge Replacement/Construction Techniques

Rapid Bridge Replacement/Construction Strategies	Responses

	No.	%
Use	16	89%
Not Use	2	11%

3.2.2.1 Main Objective for Using Bridge Replacement/Construction Techniques

As shown in Table 3.3, most state transportation agencies currently using rapid bridge replacement/construction techniques indicated that these techniques could significantly reduce the number of (on-site construction) days with traffic disruption (88 percent), and the others use rapid bridge replacement/construction techniques to reduce the total number of days for bridge construction (12 percent).

Table 3.3. Main Objective for Using Bridge Replacement/Construction Techniques

Main Objective	Responses	
	No.	%
Reducing the total number of days for bridge construction	2	12%
Reducing number of (on-site construction) days with traffic disruption	14	88%

3.2.2.2 Extent of Adopting Rapid Construction Strategies for Bridge Work

As seen in Table 3.4, over 56 percent of state transportation agencies reported adopting rapid bridge construction for less than 10 percent of their bridge work in terms of dollar values. Approximately one-third of the agencies adopt rapid bridge construction in between 10 to 25 percent of their total bridge work. No agency has adopted rapid bridge construction for over 50 percent of their total bridge work. A small portion of respondents answered that they have adopted rapid bridge construction in between 25 to 50 percent of their total projects (13 percent).

Table 3.4. Extent of Adopting Rapid Construction Strategies for Bridge Work

Extent of Adopting	Responses	
	No.	%
< 10%	9	56%
10-25%	5	31%
25-50%	2	13%
50-75%	0	0%
75-100%	0	0%

3.2.2.3 Size Restrictions in Applying Rapid Replacement/Construction

Table 3.5 shows whether state transportation agencies have restrictions in the size of bridges that qualify for rapid construction. In general, agencies adopting rapid replacement/construction technologies have no restrictions regarding the size of the project (94 percent). Only one agency indicated that it only allows using rapid construction techniques for short-span bridges (6 percent).

Table 3.5. Existence of Restriction in Applying Rapid Construction in the Size of Bridge

The Existence of Restriction	Responses	
	No.	%
Only allowed for short-span bridge	1	6%
No restriction	15	94%
Other	0	0%

3.2.2.4 Using Query List of Contractors for Rapid Bridge Replacement/Construction Work

As shown in Table 3.6, eighty-eight percent of respondents do not maintain a list of prequalified query list contractors/vendors for rapid bridge replacement/construction work, only 6 percent query a list of contractors/vendors. The "others" category query lists of contractors as appropriate for specific bridge projects.

Table 3.6. Query List of Contractors for Rapid Bridge Replacement/Construction Work

Using Query List of Contractors/Vendors	Responses	
	No.	%
Yes	1	6%
No	14	88%
Other	1	6%

3.2.2.5 Potential Benefits of Rapid Bridge Replacement/Construction

With reduced construction duration, rapid bridge replacement/construction would significantly improve construction work zone mobility and the safety of high volume roads. Regardless of high or low volume roads, the reduced construction duration could result in benefits of minimized local business and community impacts concerning noise, dust, and disruption experienced by people who live or work next to the road, plus any real estate they are forced to sell to the project. One issue that needs to be taken into consideration is avoiding material supply problems for remote construction sites. In very cold climates, another potential motivation behind rapid bridge construction is to complete the work during a very short construction season.

Table 3.7. Potential Benefits of Rapid Bridge Replacement/Construction

Potential Benefits	Responses	
	No.	%
Improved construction quality	1	6%
Lower bridge life-cycle agency costs	1	6%
Improved work zone safety and mobility	13	81%
Minimized local business and community impacts	14	88%
Minimized environmental impacts	4	25%
Other	3	19%

3.2.2.6 Key Factors Influencing the Selection of Rapid Bridge Construction Strategies

As presented in Table 3.8, the most important factors affecting the selection of rapid bridge construction strategies include criticality of the bridge and construction cost, followed by road user mobility, safety, socioeconomic impacts, and construction worker safety.

Table 3.8. Key Factors Influencing the Selection of Rapid Bridge Construction

Key Factors	Responses	
	No.	%
The rapid bridge construction cost	11	69%
Criticality of the bridge in a dense urban area or a major corridor	12	75%
The need for bridge hyper-fix caused by storm or earthquake	5	31%
Road user mobility	9	56%
Road user safety	9	56%
Construction worker safety	8	50%
Non-road user safety	1	6%
Socioeconomic impacts	9	56%
(local businesses, communities, emergency, special events, etc.)		
Environmental impacts	2	13%
Political influence	4	25%
Other	1	6%

3.2.3 *Outreach efforts for Promoting the Use of Rapid Bridge Construction*

3.2.3.1 Influence of Outreach Efforts in the Promotion of Rapid Bridge Construction Strategies

Based on the survey findings, outreach efforts for promoting the use of rapid bridge construction techniques in a number of bridge projects are generally effective for nearly two-thirds of the states and are ineffective for nearly one-third of the states.

Table 3.9. Influence of Outreach Efforts on Promotion of Rapid Bridge Construction

Influence of Outreach Efforts in Promotion	Responses	
	No.	%
Effective	10	56%
Ineffective	5	28%
Don't know	3	17%

3.2.3.2 Phase of Bridge Project Delivery for Promotion

As shown in Table 3.10, all states have promoted rapid bridge construction techniques in the pre-construction phase. One-third of states further promoted rapid constriction in the construction phase.

Table 3.10. Phase of Bridge Project Delivery for Promotion

Phase of Bridge Project Delivery	Responses	
	No.	%
Pre-construction phase	10	100%
Construction phase	3	30%
Post-construction phase	1	10%

3.2.4 *Type of Innovation in Rapid Bridge Replacement/Construction*

3.2.4.1 Types of Innovation in Rapid Bridge Replacement Strategies

For the states that have adopted rapid bridge construction techniques, innovations are mainly focused on the use of new materials, prefabricating bridge components, and innovative contracts. Relatively few state bridge engineers mentioned the utilization of new machinery for rapid construction and replacement of bridges. This might indicate that state transportation agencies are not directly building the bridges. Most states hire contractors to do the construction, so the machinery selection is the contractor’s responsibility. For the responses choosing the “Other” category, innovations are focused on the full closure of rural low volume roads when bridge work is being done to speed up construction.

Table 3.11. Type of Innovation in Rapid Bridge Replacement/Construction Strategies

Type of Innovation	Responses	
	No.	%

Use of new bridge materials	13	72%
Use of technologies for prefabricating bridge elements in a factory controlled environment	14	78%
Use of new machinery for on-site assembling of prefabricated bridge elements	6	33%
Use of innovative contracting methods	13	72%
Other	1	6%

3.2.4.2 Type of New Bridge Materials Applied in Agency

As shown in Table 3.12, commonly used new material types include high performance concrete and steel. Fiber-reinforcing techniques using materials such as carbon fibers are less popular due to their high costs.

Table 3.12. Type of New Bridge Materials Applied in Agency

Type of New Bridge Materials	Responses	
	No.	%
High performance steel	12	80%
High strength bolts	5	33%
High strength epoxy grouts	7	47%
High performance concrete	13	87%
Fiber-reinforced concrete	4	27%
Fiber-reinforced polymer composites	4	27%
Other (please specify)	0	0%

3.2.4.3 New Technologies Used for Bridge Component Prefabrication

As summarized in Table 3.13, innovative technologies used for prefabrication are mainly concentrated on the bridge superstructure, followed by the bridge deck.

Table 3.13. New Technologies Used for Bridge Component Prefabrication

New Technologies	Responses	
	No.	%
Substructure	4	25%
Superstructure	10	63%
Deck	7	44%
Entire bridge structure	6	38%

3.2.4.4 New Machinery Used by Agency

A low response rate was received regarding the new machinery use section of the survey. This seems to suggest that machinery is not owned by state transportation agencies. Often it is at the contractor's discretion to choose appropriate machinery and the agency is indifferent as to the type of machinery used as long as the construction quality and progress meet the contract stipulations. For those respondents stated to have adopted new machinery for rapid bridge replacement/construction, launching girders and self-propelled modular transporters (SPMT) are more commonly encountered, as shown in Table 3.14.

Table 3.14. New Machinery Used by Agency

New Machinery	Responses	
	No.	%

Piling machinery for foundation work	1	17%
Launching girders and cranes for superstructure and deck construction	4	67%
Self-propelled modular transporters for final positioning of preassembled bridge elements/segments	3	50%
Other	0	0%

3.2.4.5 Innovative Contracting Methods Used by Agency

As presented in Table 3.15, incentive/disincentive contracts are among the most popular form of innovative contract methods used for rapid bridge replacement/construction. A+B contracts, design-build, and lane-rental are also adopted for approximately 50 percent of states that indicated using innovative contracting methods.

Respondents choosing the "Other" category, indicated that some of the listed contracting methods like design-build are prohibited by their respective state legislatures.

Table 3.15. Innovative Contracting Methods Used by Agency

Contracting Method	Responses	
	No.	%
A + B	8	53%
Incentive/ Disincentive	11	73%
A + B + Incentive/ Disincentive	5	33%
Lane rental	6	40%
Design-build	7	47%
Other	2	13%

3.2.5 Additional Comments

The survey respondents provided additional comments on promoting rapid bridge replacement/construction. These comments asked about improving construction cash-flow planning and put the focus on tradeoffs between construction staging and full road closure. The economic benefits of these tradeoffs must be estimated to support or discourage the adoption of rapid bridge replacement/construction technologies.

3.3 Survey Summary

The key findings of the survey are summarized in the text that follows:

- Most of the participating states have adopted centralized hierarchy for bridge management.
- Most of the participating states are using rapid bridge replacement/construction technologies to mitigate traffic disruption during on-site construction. However, the extent of rapid bridge replacement/construction technologies adopted is less than 10 percent of all bridge work.
- Most participating states do not have specific restrictions for adopting rapid replacement/construction technologies for bridge work. Some states limit such technologies to be used only for small-span bridges.
- Most participating states do not maintain a prequalified list of contractors/vendors for rapid bridge replacement/construction work.

- Potential benefits of rapid bridge replacement/construction are derived mostly from mobility improvements, safety enhancements, and mitigation of adverse impacts to local businesses and communities.
- Key factors affecting the selection of rapid bridge replacement/construction strategies include the criticality of the bridge, construction cost, road user mobility and safety, socioeconomic impacts, and construction worker safety.
- Nearly two-thirds of participating states have found that their outreach efforts are effective in promoting the use of rapid bridge construction techniques. Such efforts are usually conducted in the pre-construction phase.
- Types of innovations in rapid bridge replacement/construction include the use of new materials, the prefabrication of bridge components, and innovative contracting. On the new materials side, high performance concrete and steel are commonly used. Prefabrication is concentrated on the bridge superstructure and deck. Innovative contracting methods primarily include incentive/disincentive, A+B, design-build, and lane rental.

CHAPTER 4:
PROPOSED DECISION-MAKING PROCEDURE FOR ADOPTING RAPID BRIDGE REPLACEMENT/CONSTRUCTION

4.1 General

Replacing an existing bridge or constructing a new bridge using conventional methods typically requires traffic crossovers or even full/partial traffic closures for an extended period of time, leading traffic to be diverted via detour routes. This motivates agencies to determine the feasibility of adopting methods for rapid bridge replacement/construction that would minimize on-site construction time to enhance work zone safety, minimize traffic disruption, reduce environmental impacts, improve construction quality, cut-back bridge life-cycle cost, and increase constructability. However, not all bridge replacement and construction projects are suited to rapid construction methods. This chapter contains a framework that describes the factors that need to be considered for determining whether rapid bridge replacement/construction will be feasible along with the framework for a decision support system (DSS) based on Analytical Hierarchy Process (AHP) to rank order/prioritize bridges that are candidates for rapid replacement. The framework for deciding whether rapid replacement is needed along with the decision support system to prioritize the list of bridges will allow for an asset owner to make decisions in an informed and objective manner while allowing to minimize the subjectivity embedded in the process.

4.2 Proposed Decision-Making Framework for Adopting Rapid Bridge Replacement/Construction

The system of rapid bridge replacement/construction is primarily concerned with materials, prefabrication, and machinery. In particular, adequate use of prefabrication to produce bridge elements can be cost-effective and time-effective in a way that will help meet rapid construction requirements. As shown in Figure 4.1, the considerations behind using prefabricated bridge elements and systems for rapid bridge replacement/construction are governed by three categories of factors: rapid on-site construction needs, construction operations management, and construction costs (Russell et al., 2005).

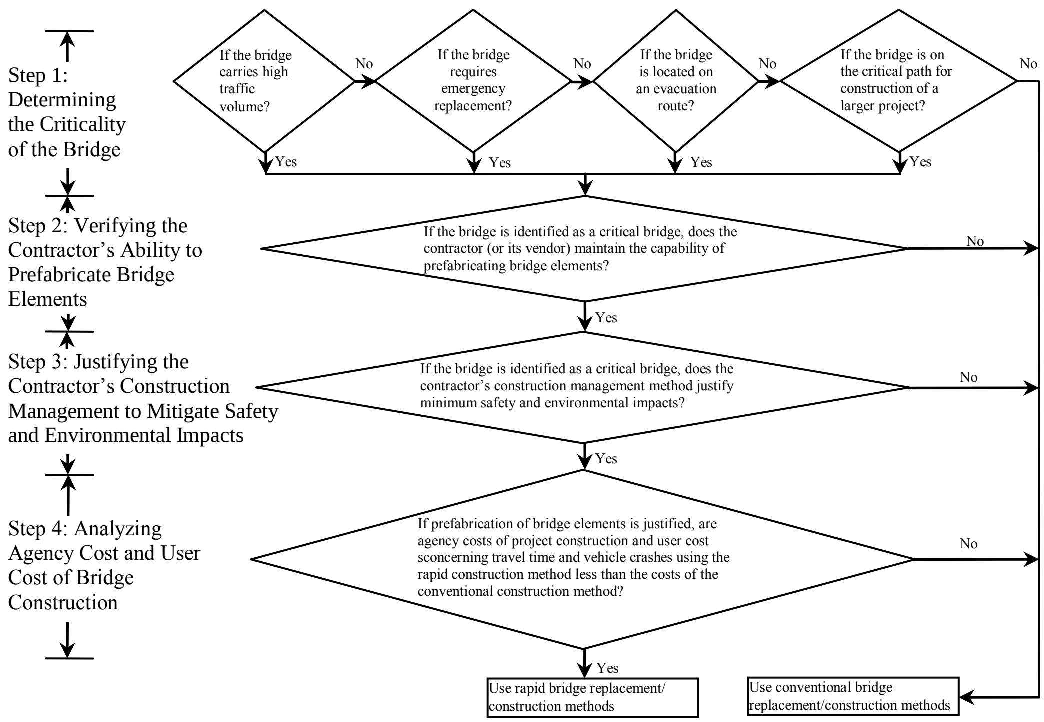

Figure 4.1. Proposed Decision-Making Framework for Adopting Rapid Bridge Replacement/Construction

4.2.1 Determination of the Criticality of a Bridge

The first step to justify the use of rapid bridge replacement/construction is to determine the criticality of the bridge. This is governed by a number of conditions mainly concerned with whether the bridge is accommodating a high traffic volume, involved with emergency recovery, located on an evacuation route, or on the critical path of a larger project that affects the duration of construction. If none of the above conditions apply, the bridge is not regarded as being critical and rapid replacement/construction is not justified. If any of the conditions exist, it confirms the criticality of the bridge and additional assessments in subsequent steps are deemed to be necessary to confirm the possibility of adopting rapid bridge replacement/construction.

Traffic volume is the first condition typically considered for determining the criticality of a bridge. When traffic volume on a bridge is high, keeping most of the lanes open during peak traffic periods could reduce traffic disruption, thus improving traffic mobility and safety during bridge construction. It is a challenging task to effectively divert the traffic to detour routes. This problem can be further magnified in the case where a high-volume road does not have a detour within a reasonable distance. The next two conditions are whether the bridge is in need of emergency replacement and whether it is located on an evacuation route. It may not be possible to close a bridge during construction because of traffic flow for emergency recovery. When a bridge is on an evacuation route,. replacement of the bridge must be completed quickly to ensure that the route is available in the event of an emergency. A bridge that is over a navigation channel must be promptly replaced to avoid impact to port commerce.

With respect to other conditions, a bridge as part of a larger project may be consideredcritical to the entire project. Adopting rapid replacement/construction of the bridge to achieve shortest bridge construction duration could also minimize the construction of the entire project

4.2.2 Verification of Contractor's Prefabrication Ability

After confirming the criticality of a bridge, further assessments could be conducted to determine whether it is feasible to adopt rapid replacement/construction. In this step, the focus will be on verifying whether the contractor (or their qualified vendor) maintains the ability to prefabricate bridge elements typically used in rapid bridge replacement/construction. The prefabrication of bridge elements under a controlled and standardized production environment could ensure better production quality. At a precast plant, formwork is reused for standardized elements that would lead to reduced material costs and result in time and labor savings. In rapid bridge replacement/construction, the use of prefabricated bridge elements for construction could help save tremendous needs for concrete pouring that is needed in the conventional construction of substructure, superstructure, and deck components. Additionally, using prefabricated bridge elements allows for the avoidance of weather impacts on bridge element production and delivery, thus shortening the bridge replacement/construction process. This is a noteworthy advantage resulting from the adoption of rapid bridge replacement/construction, especially in extreme climates. Standardization and stockpiling considerations should be given to bridges that require rapid recovery from natural or manmade hazards or those that require rapid completion of future planned repairs or replacement. Examples include bridges susceptible to damage from hurricanes and barge collisions. If the bridge is located in a very tight work area that limits construction workers, vehicles, and equipment in accessing the construction site, the use of prefabricated bridge elements or even partially assembled bridge components for rapid bridge replacement/construction could significantly shorten construction duration.

4.2.3 Justification of Contractor's Construction Management Strategies for Impacts Mitigation

After confirming the criticality of a bridge and verifying the contractor's prefabrication ability, the next step to assess the feasibility of adopting rapid bridge replacement/construction is to justify whether the contractor's construction management strategies could help control the impacts of rapid replacement/construction on work zone safety and the environment within an acceptable level. At a construction site, construction workers are often exposed to dangerous situations including working close to moving traffic without positive separation, construction vehicles and equipment moving in and out the work activity area, near power lines, or over water. If the contractor could fabricate bridge elements off-site in a safe environment, it would reduce the amount of time workers would be directly exposed to these dangerous situations (Ralls et al., 2002). Another safety related issue is the bridge constructability relevant to shipping and assembling the prefabricated bridge elements or components when a bridge is located at a very tight work area that limits construction workers, vehicles, and equipment from entering and exiting the construction site. In order to justify rapid bridge replacement/construction, the contractor's construction management strategies should be able to effectively handle related work zone safety issues.

Apart from safety concerns, the contractor's construction management strategies need to adequately address adverse impacts of rapid bridge replacement/construction on the environment. Rapid construction techniques often require using shorter bridge spans and thus typically involve extensive piling foundation work. When conducting rapid replacement/construction of a grade separation or an interchange, it seems plausible that using driven piles could produce more noise and vibration than the use of drilled caissons for conventional construction. This could have a negative impact on nearby buildings and their occupants and on adjacent properties.

If a bridge crosses a river, floodplain encroachments could increase due to the placement of more piers in the river. This makes it more difficult to provide sufficient hydraulic capacity to accommodate flooding. In addition, rapid construction may potentially disturb hazardous materials such as heavy metal sediments on the river bottom, disrupt fish and wildlife habitat, compromise erosion control, and affect historic preservation.

As compared with conventional bridge replacement/construction, rapid replacement/construction is likely to increase some environmental impacts while decreasing impacts of traffic mobility and safety of road users and constructor workers. The net effect is highly case-specific in terms of bridge location, design details, and construction management strategies that need to be analyzed on a case by case basis. .

4.2.4 Analysis of Bridge Life-Cycle Agency Costs Using Conventional and Rapid Construction

Having confirmed criticality of the bridge, contractor's prefabrication ability, and contractor's construction management strategies in support of rapid replacement/construction, the next step of analysis is to estimate and compare the life-cycle agency costs of bridge construction using the rapid construction and conventional construction methods, respectively.

4.2.4.1 Bridge Agency Cost Items

Agency costs in the service life-cycle of a bridge are primarily concerned with bridge design and construction, routine maintenance, and deck and superstructure rehabilitation and replacement. Design cost includes all of the costs related to engineering design, field tests and related equipment, and human resources. Construction cost includes the cost of materials, equipment, and labor. Design and construction costs also include all of the administrative costs associated with the intersection overpass project. Routine maintenance costs are a function of the material type, design standard, climatic condition, and the traffic level. Routine maintenance costs are normally estimated for individual structure components. Rehabilitation costs include major repair treatments and require engineering analysis. The cost associated with the replacement of any structure component by the end of its service life is taken as the component replacement cost that is generally estimated as a function of bridge length, deck width, and vertical clearance.

In bridge construction cost estimation, the constituent cost due to the maintenance of traffic varies considerably according to traffic management strategies adopted to cope with different construction work schedules and coordination between operations of the bridge owner agency and the contractor. Issues that should be considered when selecting the appropriate construction work schedule include: i) increases in construction cost typically associated with rapid construction schedules; ii) decreases in user cost and public inconveniences associated with shorter out-of-service periods or with limited-peak traffic closures; iii) the availability of the bridge owner's personnel for inspection and problem solving; iv) the availability of materials and material deliveries; and v) the loss of worker productivity, loss of quality control, and increased worker safety issues typically associated with rapid replacement/construction (Bai and Burkett, 2006). Effective maintenance of traffic could be achieved through smooth collaboration between all parties involved in the bridge replacement/construction.

When comparing agency costs, bridge construction using rapid construction methods is expected to have a higher initial construction cost. The direct benefits of rapid construction include significantly reduced traffic disruption resulting from much shorter on-site construction duration. In addition, the use of prefabricated bridge elements or components with better quality control could result in reduced frequency and magnitude of maintenance and rehabilitation treatments and extended useful service life.

4.2.4.2 Bridge Service Life-Cycle

The bridge service life-cycle can be defined as the time interval between two consecutive bridge replacements and the bridge rehabilitation life-cycle can be defined as the time interval of adjacent bridge construction to rehabilitation, rehabilitation to rehabilitation or rehabilitation to replacement. Maintenance, rehabilitation, and replacement treatments can be applied to a specific substructure, superstructure or deck component or be jointly applied to deck and superstructure components (Gion et al., 1993; Hawk, 2003). Table 4.1 presents typical bridge treatment types.

Table 4.1. Typical Bridge Maintenance, Rehabilitation, and Replacement Treatments

Structure Component	Maintenance	Rehabilitation	Replacement
Deck	-Deck maintenance	-Deck rehabilitation -Deck rehabilitation and widening	-Deck replacement -Deck replacement and widening
Superstructure	-Superstructure maintenance	-Superstructure strengthening -Superstructure strengthening and widening	-Superstructure replacement and widening
Deck and Superstructure	-Deck and superstructure maintenance	-Deck and superstructure rehabilitation -Deck and superstructure rehabilitation and widening	-Deck replacement and superstructure rehabilitation -Deck replacement, superstructure rehabilitation, and widening
Substructure	-Substructure maintenance	-Substructure rehabilitation	-Substructure replacement

4.2.4.3 Bridge Life-Cycle Repair Strategies and Activity Profiles

Of all major treatments in the bridge service life-cycle, deck rehabilitation is the most frequently implemented treatment type. The first deck rehabilitation is implemented t_1 years after the initial construction. Depending on the superstructure type, deck or superstructure replacement is normally scheduled t_2 years after the initial construction. Deck rehabilitation and deck or superstructure replacement will be applied again, with the last major treatment typically being deck rehabilitation, until the end of the bridge life-cycle. In between any two major treatments, annual routine maintenance is applied. Figure 4.2 illustrates the typical bridge life-cycle activity profile.

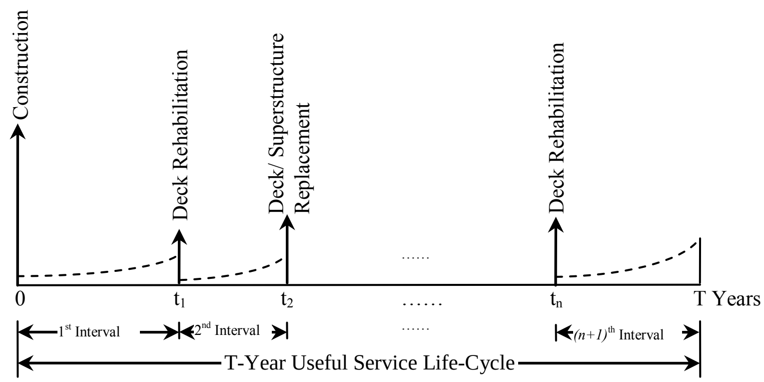

Figure 4.2. Typical Bridge Life-Cycle Activity Profile

4.2.4.4 Bridge Life-Cycle Agency Cost Calculation

The intersection overpass life-cycle agency costs can be quantified on the basis of the typical life-cycle activity profile, reflecting the optimal timing and magnitude of major rehabilitation and replacement treatments, as well as annual routine maintenance. Without a loss of generality, a geometric gradient annual growth rate for the annual routine maintenance cost can be assumed for a time interval between two consecutive major treatments. This will help cope with the increased maintenance need for deteriorating overpass structure conditions over time. Different gradients can be used for different time intervals in the overpass structure service life-cycle.

Denote:

PW_{LCAC} = Present worth of bridge life-cycle agency costs
EUAAC = Equivalent uniform annual agency costs
C_{CON} = Bridge construction cost
$C_{DECK\ REH}$ = Bridge deck rehabilitation cost
$C_{DECK/SUP\ REP}$ = Bridge deck replacement cost
$C_{MAIN(n)}$ = Annual bridge maintenance cost in the first year of the n^{th} interval between two consecutive major treatments
$g_{M(n)}$ = Geometric gradient annual growth rate for annual bridge maintenance cost in the n^{th} interval between two consecutive major treatments
i = Discount rate
t_n = Time of year the n^{th} major treatment is implemented

N_{REH} = Number of deck rehabilitation treatments implemented in the bridge life-cycle
N_{REP} = Number of deck or superstructure replacement treatments implemented in the bridge life-cycle
T = Number of years of service life

The present worth of bridge life-cycle agency costs and the equivalent uniform annual agency costs are computed as follows:

$$PW_{LCAC} = C_{CON} + C_{REH} \times \sum_{n=1}^{N_{REH}} \frac{1}{(1+i)^{t_n}} + C_{REP} \times \sum_{n=1}^{N_{REP}} \frac{1}{(1+i)^{t_n}} + C_{MAIN} \times \sum_{n=0}^{N} \left[\frac{\left(1 - \left(\frac{1+g_{M(n)}}{1+i}\right)^{t_{n+1}-t_n}\right)}{\left(i - g_{M(n)}\right) \times (1+i)^{t_n}} \right] \quad (4\text{-}1)$$

$$EUAAC = PW_{LCAC} \times \left[\frac{i \times (1+i)^T}{(1+i)^T - 1}\right] \quad (4\text{-}2)$$

where $t_0 = 0$ and $t_{n+1} = T$.

4.2.5 Calculation of Work Zone User Costs

The Highway Capacity Manual (HCM) defines a work zone as an area of a highway where preservation activities impinge on the number of lanes available to traffic or affect the operational characteristics of traffic flowing through the area (TRB, 2000). Bridge replacement/construction can significantly reduce the highway capacity and vehicle operating speed, which may result in queue development and consequently travel delays and increased vehicle operating costs. User costs for bridge work zone operations are influenced by a variety of factors such as bridge type, traffic volume and vehicle composition, and work zone characteristics. Recent research showed little impact of bridge work zones on crash rates, which are omitted from work zone user cost computation. Table 4.2 lists individual components of excessive vehicle operating costs and delays caused by bridge work zones.

TABLE 4.2. Components of Excessive Vehicle Operating Costs and Delays Caused by Bridge Work Zones

Flow	Existence of		VOC Components	Delay Components	
Characteristic	Work Zone	Queue	Work Zone Upstream	Work Zone Upstream	Within Work Zone
Uncongested	Yes	No	- Speed change	- Speed change	- WZ reduced speed
Congested	Yes	Yes	- Speed change - Stopping - Queue idling	- Speed change - Stopping - Queue reduced speed	- WZ reduced speed
	No	Yes	- Stopping - Queue idling	- Stopping - Queue reduced speed	None

Table 4.3 provides a systematic methodology for quantifying and costing the additional vehicle operating costs and delay costs resulting from work zones.

TABLE 4.3. Computation of Excessive Bridge Work Zone User Costs

Procedure		Method
Step 0	Determine inputs	- Determine project future-year traffic demand (AADT, directional hourly demand, vehicle composition) - Determine normal operations characteristics (highway capacity, speed) - Determine work zone characteristics (bridge work duration, work zone operation hours and length)
Step 1	Determine future-year traffic demand	- Vehicle class *i* future year $AADT_i$ = (Base year AADT) x(% vehicle class *i*)x((1+class *i* annual growth)$^{(\text{Future year-base year})}$)
Step 2	Calculate work zone directional hourly traffic demand	- Vehicle class *i* directional hourly volume DHV_i = (Future year $AADT_i$)x(Directional distribution *i*) x(Hourly traffic distribution factor *i*)
Step 3	Determine roadway capacity	- Determine roadway normal operations capacity using HCM - Determine work zone capacity using HCM
Step 4	Identify user cost components	- Identify various VOC and delay components for each hour as listed in Table 4.3
Step 5	Quantify traffic affected for each VOC and delay component	- Hourly queue rate = DHV- normal/work zone capacity - Hourly vehicles queued = cumulative hourly queue rates - Vehicles traverse work zone = DHV with work zone - Vehicles traverse queue = normal/WZ capacity with queue - Vehicles stopped for the queue = DHV with queue - Vehicles slowed down = DHV with work zone, no queue
Step 6	Compute queue reduced speed delay	- Hourly volumes through queue and upstream of queue - Hourly speeds through queue and upstream of queue - Hourly densities through queue and upstream of queue - WZ delay = WZ length/WZ speed- WZ length/upstream speed - Queue delay = Queue length/queue speed- queue length/upstream speed - Average hourly vehicles in queue = Arithmetic average of vehicles queued at the beginning and end of each hour - Average hourly queue length = Average hourly vehicles in queue/(density in queue - density upstream of queue) - Average queue delay per vehicle = Average hourly queue length/queue speed
Step 7	Select added VOC rates	- Select added VOC rates due to speed change, stopping, and queue idling by vehicle class
Step 8	Select added delay time and hourly time values	- Select added delay time due to speed change, stopping, queue reduced speed, and work zone reduced speed by vehicle class - Select hourly time values by vehicle class - Compute added delay costs
Step 9	Assign traffic to vehicle classes	- Distribute respective number of vehicles affected by speed change, stopping, queue, and traversing work zone to each vehicle class
Step 10	Compute work zone user costs	- Compute total added VOC costs for the construction duration - Compute total added delay costs for the construction duration

In general, rapid bridge replacement/construction is recommended if the total amount of annualized agency and user costs of rapid construction is lower than that of conventional construction. Table 4.4 lists detailed issues that should be considered in determining the feasibility of adopting rapid bridge replacement/construction.

Table 4.4. Issues to be Considered for Determining the Feasibility of Rapid Bridge Replacement/Construction

Issue Category	Issue Type	Detailed Issue Item
Criticality of the Bridge	Traffic volume	- High annual average daily traffic
	Emergency recovery	Need for emergency bridge replacement
	Part of evacuation route	- The bridge is on an evacuation route, over a railroad or a navigable channel - Requirement of rapid recovery from natural or manmade hazards
	Part of a larger project	- On the critical path of a larger project that affects completion of the overall project
Contractor's Prefabrication Ability	Prefabrication of bridge elements	- Ability of contractor or availability of qualified vendors for prefabrication - Prefabrication of deck, superstructures, substructures, and foundations - Availability of connection details
	Standardization	- Involvement of multiple similar spans at multiple locations - Availability of Federal, state, industry and local prefabricated bridge standards
Contractor's Construction Management in Support of Rapid Construction	Safety concerns	- Road/ truck user safety/ Construction worker safety
	Environmental issues	- Noise and vibration impacts of piling foundation work - Impacts on hydraulic capacity, hazardous materials in river bed, erosion control, historic preservation - Impacts on natural or endangered species
	Site issues	- Accessibility at the construction site - Delivery of prefabricated bridge elements and components to the construction site
Agency and User Costs of Bridge Construction	Agency costs	Bridge construction cost, including cost of maintenance of traffic
	Maintenance of traffic	- Alternative transportation management strategies including transportation system operations, public information, and temporary traffic control strategies to cope with different construction schedules - Acceptable bridge work zone safety and mobility standards targeting users - Acceptable bridge work zone safety standards targeting construction workers
	User costs	Vehicle delays and excessive vehicle operating costs associated with users traversing through the bridge work zone
	Owner agency's operations	- Necessary staffing/ grouping of multiple bridges/ prefabrication time to meet construction duration target
	Contractor's operations	- Innovative contracting strategies, such as A+B, incentive, disincentive - Use of innovative construction machinery, such as launching girders and self-propelled modular transporter - Costs for insurance/bonding

4.3 Decision Support System (DSS) for Prioritization of Bridges

The previous section discussed in detail the framework for exsamining whether rapid replacement/construction was needed for bridges. The decision support system discussed in this section will allow for the asset owner to take the candidate list of bridges screened with the help of the framework in the previous section, and rank order them using the same criteria and with the help of a decision engine. The fact that there are multiple criteria that impact the decision making process make this a typical multi-criteria decision problem. There are numerous methods in the literature that have been identified for dealing with these problems with multiple objectives/criteria.

Analytical Hierarchy Process (AHP) is a systematic method for comparing a list of objectives or alternatives that are likely to inform a multi-criteria decision problem. It helps to structure a problem in a hierarchical manner and a sequence of pair-wise comparison of criteria. The problem needs to be structured in a hierarchical manner (Figure 4.3). The first level denotes the overall goal of this exercise.

The main criteria included in this analysis are: criticality, contractor's ability, safety, environmental impacts, agency cost, and user cost. Amongst these, criticality is defined as the combination of four factors. They are pertaining to whether the bridge is on an evacuation route, whether it is en-route to a large construction project, whether it carries large volumes of traffic, and whether there is a need for emergency replacement of the bridge. The user will complete pair-wise comparison rankings for each of the main criteria. Each DOT or owner of the asset category can complete the pair-wise comparisons in Tables 4.5 and 4.6. In both the tables, the variables being compared (X versus Y) are to be assigned weights on a scale of 1 to 9 (with 1 indicating both variables are equal, to 9 being that one variable is very strongly important compared to the other). In the cases where the sub-criterions cannot be collapsed into a proper index the user will directly apply weights to the sub-criteria. The outcome of the AHP is a prioritized ranking or weighting of each decision alternative. In this instance, the decision alternatives are bridges that are candidates for treatment/replacement.

The overall goal is to rank the bridges that are owned by an agency based on the AHP weights to reflect the agency's priorities with respect to the various criteria.

Table 4.5 Pair-wise comparison matrix for AHP Decision Support System

Compare			**X over Y**				or	**Y over X**			
AS OVERALL SOLUTION											
X	and	**Y**	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
Criticality		Contractor's ability	9	7	5	3	1	3	5	7	9
Safety		Environmental Impacts	9	7	5	3	1	3	5	7	9
Agency cost		User Cost	9	7	5	3	1	3	5	7	9
Criticality		Safety	9	7	5	3	1	3	5	7	9
Criticality		Environmental Impacts	9	7	5	3	1	3	5	7	9
Criticality		Agency cost	9	7	5	3	1	3	5	7	9
Criticality		User Cost	9	7	5	3	1	3	5	7	9
Safety		Contractor's Ability	9	7	5	3	1	3	5	7	9
Safety		Agency Cost	9	7	5	3	1	3	5	7	9
Safety		User Cost	9	7	5	3	1	3	5	7	9
Contractor's ability		Agency Cost									
Contractor's ability		User Cost									
Contractor's ability		Environmental Impacts									
Environmental Impacts		User Cost									
Environmental Impacts		Agency Cost									

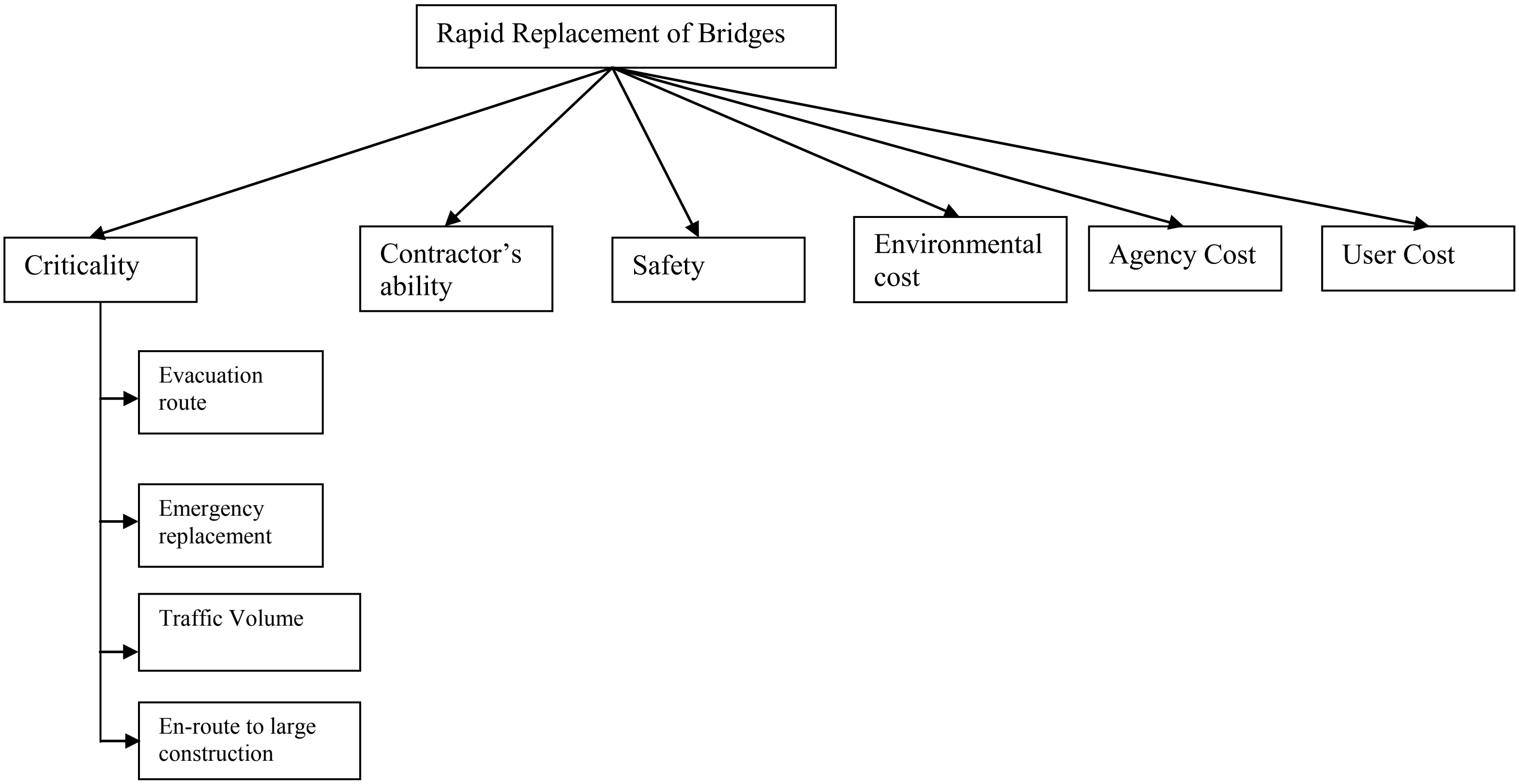

Figure 4.3 AHP Framework for Rapid Replacement/Construction of Bridges

Table 4.6 Pair-wise Comparison Matrix for AHP Sub-criteria

Compare			X over Y				or	Y over X			
AS OVERALL SOLUTION											
X	and	**Y**	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
Traffic Volume		Evacuation route	9	7	5	3	1	3	5	7	9
Traffic Volume		Emergency replacement	9	7	5	3	1	3	5	7	9
Traffic Volume		En-route to large construction project	9	7	5	3	1	3	5	7	9
Evacuation route		Emergency replacement	9	7	5	3	1	3	5	7	9
Evacuation route		En-route to large construction project	9	7	5	3	1	3	5	7	9
Emergency replacement		En-route to large construction project	9	7	5	3	1	3	5	7	9

CHAPTER 5:
EXPLORATORY ANALYSIS OF A CONCEPTUALLY NEW RAPID BRIDGE DESIGN AND CONSTRUCTION SYSTEM

5.1 General

The decision-making framework documented in Chapter 4 could help confirm the feasibility of rapid bridge replacement/construction when compared to conventional construction. The next step is to further determine the best suited rapid bridge replacement/construction method. This Chapter documents an exploratory analysis of a conceptually new rapid bridge design and construction system that may be considered as a candidate for rapid replacement/construction of bridges with similar geometric design standards governed by comparable traffic conditions and site characteristics. This Chapter begins with a brief description of a step-by-step framework of the proposed methodology for exploring an innovative system that supports rapid bridge replacement/reconstruction. It is followed by a preliminary structure analysis and foundation construction considerations. Finally, a conceptual construction method is introduced.

5.2 Proposed Methodology

Figure 5.1 presents key steps of the proposed methodology that include rapid construction considerations, preliminary structure analysis, foundation considerations, and conceptual construction method.

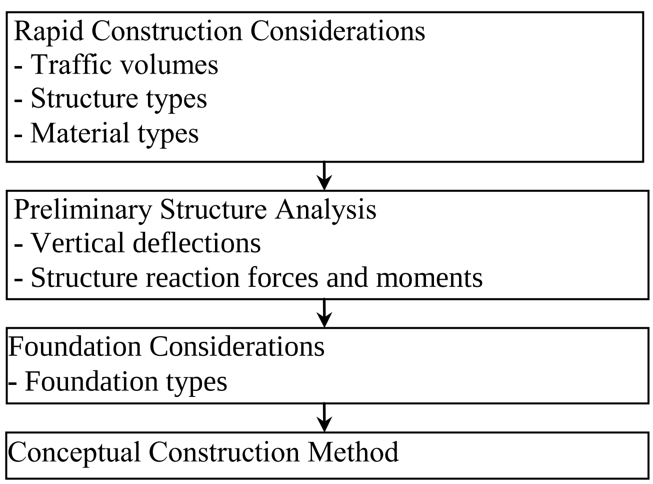

Figure 5.1. Proposed Methodology for the Preliminary Analysis of Rapid Bridge Construction

5.2.1 Rapid Construction Considerations

The criteria considered in regards to identifying a method for replacing or constructing a bridge as innovative include, but are not limited to: i) the total on-site construction duration; ii) minimum traffic disruption with no lane closure; and iii) the use of totally prefabricated structure elements. These criteria will help identify structure and material types that are best suited for rapid replacement/construction of the selected type of bridges.

Typical Structure Types. A bridge is comprised of substructure, superstructure, and deck components. As shown in Table 5.1, four types of superstructure (beam, truss, suspension, and cable-stayed), and two types of substructure (solid stem and piling) are commonly encountered in practice. Partial and full-depth decks are generally used for the deck component. The appropriate combinations of substructure, superstructure, and deck types, as well as material types that meet the innovative criteria could be chosen for preliminary structure analysis.

Table 5.1. Typical Bridge Substructure, Superstructure, and Deck Types

Structure Component	Type			
Substructure	Piling	Spread footing		
Superstructure	Beam	Truss	Suspension	Cable-stayed
Deck	Partial-depth	Full-depth		

Material Types. The material types can be grouped into conventional and non-conventional categories. Conventional materials mainly include high performance steel and concrete. Non-conventional materials include carbon fiber and carbon nanotube-reinforced composites. Carbon fibers are used extensively in both military and civil aircraft structures. As listed in Table 5.2, carbon fibers maintain superior properties compared to those of high performance steel in terms of performance and specific strength, high tensile modulus, low density, good fatigue resistance, and dimensional stability. They are excellent reinforcing materials because of their strength and toughness and appear to be capable of bearing structural loads that would allow for the design of longer spanned bridges than existing technologies allow.

Table 5.2. Comparison of Carbon Fiber and Steel (Kelly, 2006)

Material	Tensile Strength (GPa)	Tensile Modulus (GPa)	Density (g/cm^3)	Specific Strength (GPa)
High Performance Steel	1.3	210.0	7.87	0.17
Carbon Fiber	3.5	230.0	1.75	2.00

5.2.2 Preliminary Bridge Structure Analysis

Method for Bridge Structure Analysis. For the selected type of bridge structure, the finite element (FE) method will be employed to conduct structure analysis. This method models a continuous structure component as a discrete system with a finite number of one, two or three-dimensional elements interconnected at a finite number of nodes. The behavior of individual elements is characterized by the element's stiffness, which altogether leads to the stiffness of the structure component.

The finite element analysis will begin with the main structure that handles the movement of traffic. Alternative deck designs will be considered to examine the sensitivity of structure reactions in terms of force, moment, and vertical deflection of the main structure. This will help identify feasible structure design options. Based on the magnitude of force and moment obtained for the best structure design option, alternative foundation types that meet the criteria of rapid construction could be proposed.

Selection of Bridge Structure Types. The choice of structure type strives to meet the criteria for rapid bridge replacement/construction. The design aims to achieve a high standard of safety, serviceability, constructability, and aesthetics. Specifically, the design must withstand the combined effects of structure dead load and live load for extreme cases and needs to maintain a relatively long service life. The design should ensure that the bridge can be constructed rapidly without significantly affecting road users.

The construction progress of a bridge is greatly affected by the choice of substructure type, particularly the choice of foundation type. The superstructure construction progress is dictated by the substructure construction progress. In order to shorten the total construction duration, the substructure construction duration needs to be minimized. Without compromising the standards of bridge safety and serviceability, the number of foundations to be drilled or excavated must be kept at a minimum. To this end, simple-support structure types that involve massive foundation work may not be suited to rapid construction. Alternatively, it is worthwhile to investigate the cable-stayed bridge that uses two pairs of pylons to support the bridge and balances the number of cables, the weight of the deck, and the supports of the superstructure in order to rapidly complete construction using prefabricated bridge components.

Selection of Geometric Design Parameters. Table 5.3 presents the design standards of geometric design elements proposed by the American Association of State Highway and Transportation Officials (AASHTO) design guide (AASHTO, 2004).

Table 5.3. Summary of AASHTO Highway Geometric Design Standards

Geometric Design Element		Proposed Standard
Stopping sight distance		115 ft for 20 mph design speed 200 ft for 30 mph design speed 305 ft for 40 mph design speed 425 ft for 50 mph design speed
Horizontal curve	Horizontal curve radius	42 ft for 15 mph design speed 86 ft for 20 mph design speed 154 ft for 25 mph design speed 250 ft for 30 mph design speed
	Horizontal clearance	1.5 ft at minimum between the curb face and obstructions such as lighting poles, fire hydrants, etc.
Vertical curve	Vertical curve length	345 ft for 40 mph design speed, 4% longitudinal slope 431 ft for 40 mph design speed, 5% longitudinal slope 517 ft for 40 mph design speed, 6% longitudinal slope 670 ft for 50 mph design speed, 4% longitudinal slope 837 ft for 50 mph design speed, 5% longitudinal slope 1,004 ft for 50 mph design speed, 6% longitudinal slope
	Vertical clearance	16 ft for new or reconstructed structures
Lane width		12 ft
Number of lanes		4-8 lanes for both directions
Median width		4-80 ft or more
Side walks		4-8 ft at the minimum for urban and suburban areas

Bridge Foundation Considerations. The foundation construction of a bridge is critical in minimizing the total on-site construction duration. The selection of a certain type of foundation to support the bridge superstructure is primarily based on three factors: the magnitude of loads, subsurface soil conditions, and the environmental impacts of foundation construction on the area surrounding the project. The values of reaction forces obtained from the structural analysis form the basis of foundation analysis. To cope with varying subsurface soil conditions, three subsurface conditions can be considered for the design of the foundation: shallow rock formation, deep rock formation, and very deep rock formation. For bridges located in dense urban areas, the installation of driven pile foundations is generally accompanied by loud noise from hammer operation and ground vibration.

5.3 Preliminary Structure Analysis

5.3.1 Selection of Bridge Structure Type

As illustrated in Figure 5.2, the cable-stayed bridge that maintains the fewest number of foundation supports was selected as the candidate structure type for preliminary structure analysis. In reference to the 2007 AASHTO Load and Resistance Factor Design (LRFD) Bridge Specifications, the Structure Analysis Software (SAP) Version 2000 that provides linear and nonlinear, and static and dynamic analysis of bridge structure was utilized to construct preliminary models for analyzing a cable-stayed bridge. The pylons were modeled using beam elements and all cables were assumed to be connected at same point on the top of pylons. The pylon bases were treated as fixed connections with bridge foundations. The bases at both ends of the bridge structure were treated as pinned connections with the foundations. Table 5.4 summarizes primary bridge design parameters used for the structure analysis.

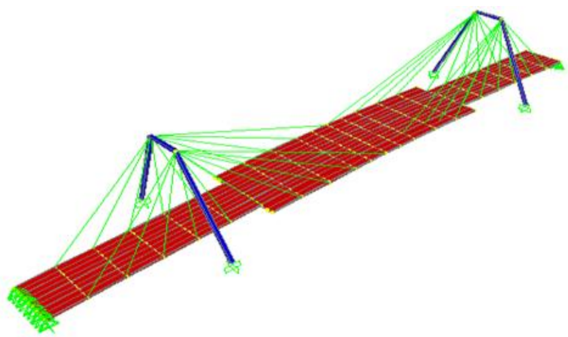

Figure 5.2. Illustration of the Cable-Stayed Bridge Structure

Table 5.4. Bridge Design Parameters Used for Structure Analysis

Geometric Design Element		Design Parameter Value
Design speed		40 mph
Stopping sight distance		305 ft
Horizontal curve	Horizontal clearance	6 ft from obstructions
Vertical curve	Longitudinal slope Vertical curve length Vertical clearance	6% 517 ft 16 ft
No. of lanes per direction	Through	2
Lane, shoulder, and median widths		12, 6, 18 ft
Cross section slope		2%
Bridge dimensions	Total length Deck depth Deck thickness Total width	1,025 ft 4- 7 ft 1.0- 1.5 ft 100 ft
Pylon dimensions	Height Cross section size Cross section thickness	180 ft 5 ft x 5 ft 3- 9 inches
Pylon locations	Relative to bridge ends	205- 295 ft
Cable dimensions	Cross section area	80 inch^2
Cable quantities	Attached to each pylon	10 cables
Material elastic moduli	Concrete Cable steel	3,600 ksi 29,000 ksi

5.3.2 Preliminary Structure Analysis Results

<u>Impacts of Deck Thickness on Bridge Vertical Deflections</u>. Concrete box girders were used in the analysis as illustrated in Figure 5.3. The depths of the main structure deck were varied from 4 to 7 ft, as shown in Table 5.5.

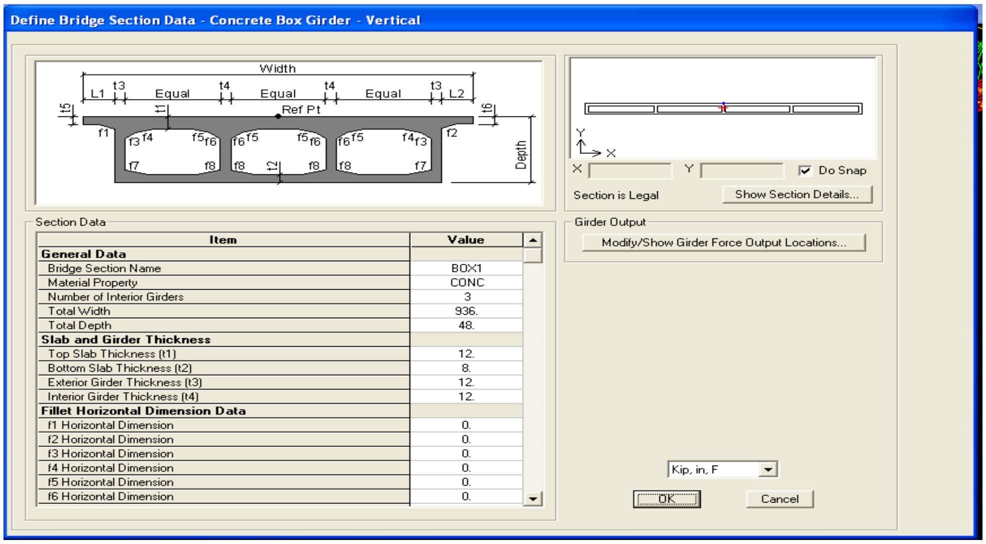

Figure 5.3. Cross Sectional Dimensions of the Concrete Box Girder

Table 5.5. Different Deck Depths Considered for Bridge Structure Analysis

Model	Model 11_4 (Base Model)	Model 11_5	Model 11_6	Model 11_7
Deck Depth (ft)	4	5	6	7

Vertical deflections of the bridge structure under dead load and live load were examined separately. Dead load refers to the weight of the bridge structure itself. Live load refers to the total vehicle load distributed longitudinally along the top length of the bridge and lane load is distributed transversely within the travel lane using AASHTO design truck HS 20-44. Figure 5.4 presents vertical deflections along the edge-line and the central-line of the bridge structure under dead load and live load for different deck depths and thicknesses, respectively.

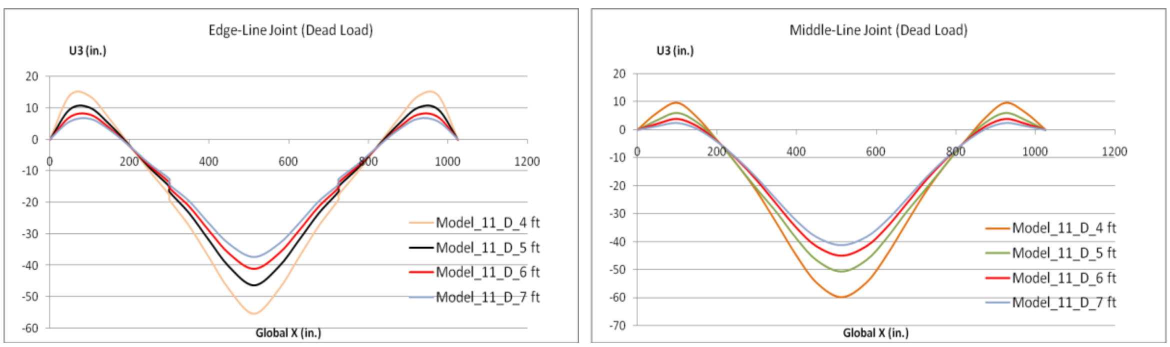

Figure 5.4. Vertical Deflections of the Bridge Structure under Dead Load Using Different Deck Depths

The vertical deflections under dead load and live load were further investigated by increasing the deck thickness from 1 ft to 1.25 ft and then to 1.5 ft. The findings are shown in Figure 5.5.

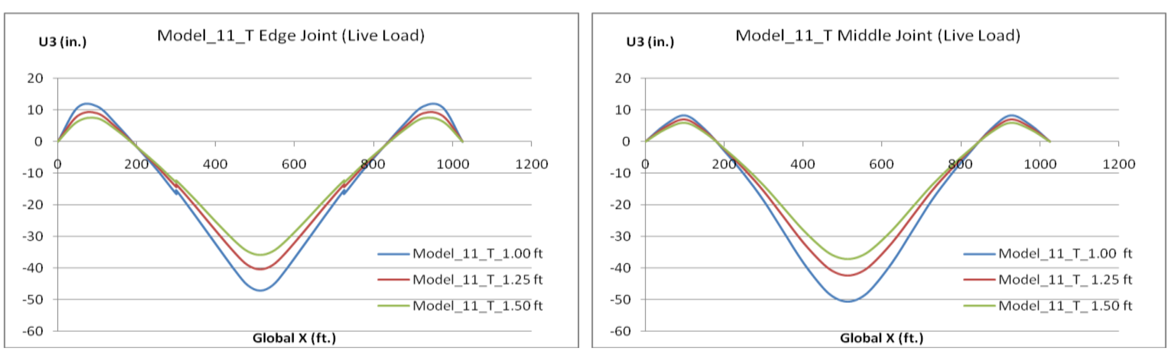

Figure 5.5. Vertical Deflections of the Bridge Structure under Live Load Using Different Deck Thicknesses

Based on the preliminary model runs, it was discovered that increasing the deck depth could reduce vertical deflections. Thicker decks were also associated with smaller vertical deflections.

Impacts of Pylon Location on Vertical Deflections. As Figure 5.6 displays, vertical deflections of the bridge structure were examined by changing the pylon locations relative to their end supports, ranging from 205 ft to 295 ft with 15 ft increments in each step. Figure 5.7 shows the respective vertical deflections along the edge-line and the central-line of the bridge structure under dead load.

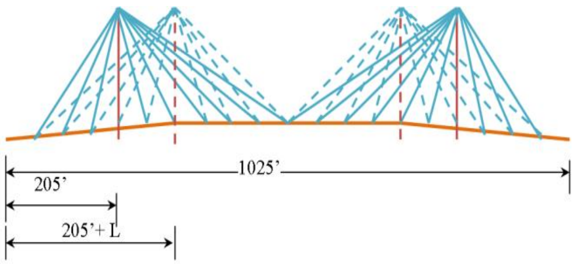

Figure 5.6. Different Pylon Locations Considered for the Analysis

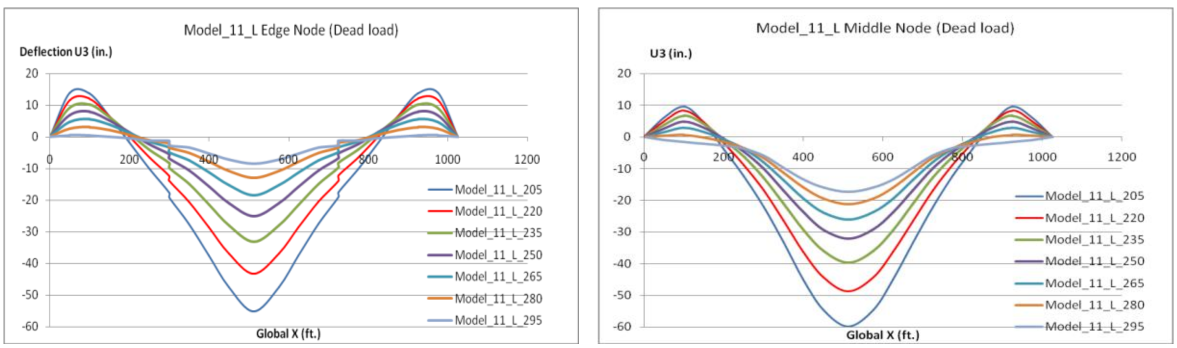

Figure 5.7. Vertical Deflections for Different Pylon Locations under Dead Load

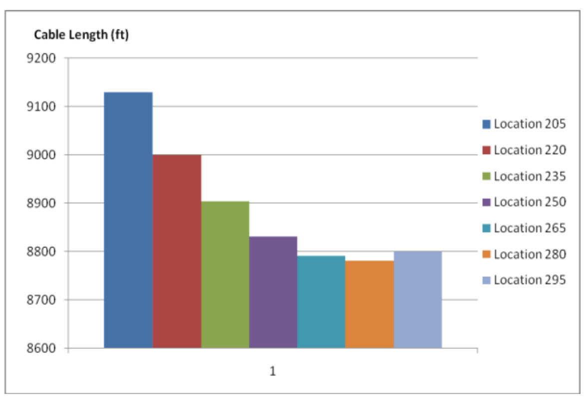

Figure 5.8. Total Cable Lengths for Different Pylon Locations

Moving pylons toward the middle span of the cable-stayed bridge could reduce vertical deflections of the bridge structure. In the process of identifying optimal pylon locations, the pylon location was increased up to 295 ft from the end supports where the total cable length started to increase and the percentage of reductions in vertical deflections of the bridge began to diminish, as seen in Figure 5.8.

Impacts of Pylon Angles on Vertical Deflections. In Figure 5.9, vertical deflections of the bridge were examined by changing the pylon angles relative to the fixed location of 205 ft on the top of the pylons from the bridge end supports, ranging from 15 ft to 90 ft with 15 ft increments in each step. Figure 5.10 shows the respective vertical deflections along the edge-line and the central-line of the bridge under dead load.

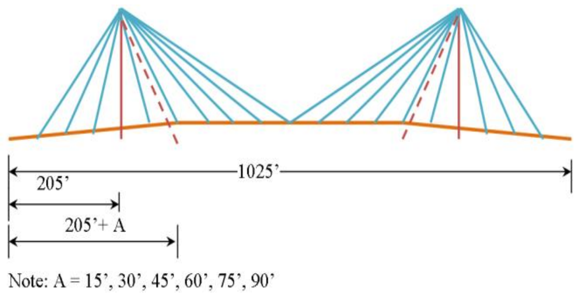

Figure 5.9. Different Pylon Angles Considered in the Analysis

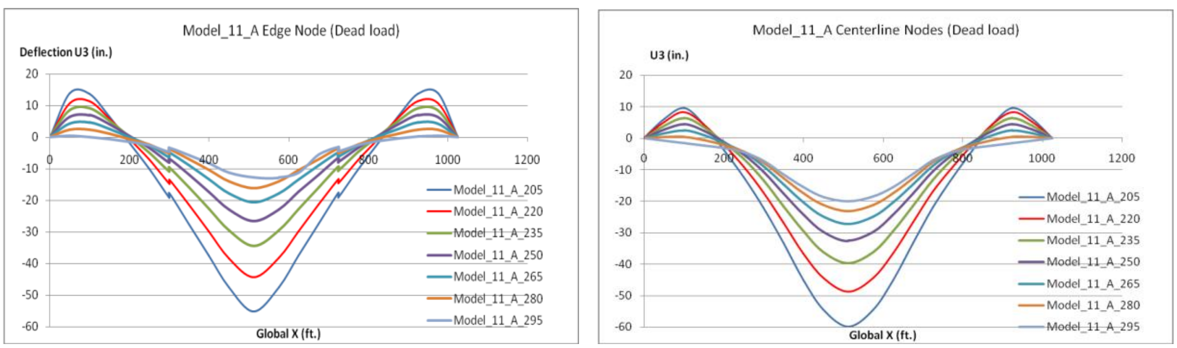

Figure 5.10. Vertical Deflections for Different Pylon Angles under Dead Load

With the same trend as pylon locations, increasing the angle also helped reduce vertical deflections of the bridge. However, larger bending moments at the bases of inclined pylons could potentially require stronger foundations.

Table 5.6. Bridge Vertical Deflections by Deck Depth/Thickness and Pylon Location/Angle

Factor	Model	Center-Line		Edge-Line	
		U_{max}	Percentage	U_{max}	Percentage
Deck Depth	Model_11_D_4 ft	59.8		55.3	
	Model_11_D_5 ft	50.5	-15.6%	46.3	-16.3%
	Model_11_D_6 ft	45.0	-24.7%	41	-25.9%
	Model_11_D_7 ft	41.3	-30.9%	37.3	-32.5%
Deck Thickness	Model_11_T_1.00 ft	50.6		47.2	
	Model_11_T_1.25 ft	42.4	-16.2%	40.5	-14.2%
	Model_11_T_1.50 ft	37.2	-26.5%	35.9	-23.9%
Pylon Location	Model_11_L_205	59.8		55.3	
	Model_11_L_220	48.7	-18.6%	43.2	-21.9%
	Model_11_L_235	39.6	-33.8%	33.2	-40.0%
	Model_11_L_250	32.2	-46.2%	25.1	-54.6%
	Model_11_L_265	26.1	-56.4%	18.4	-66.7%
	Model_11_L_280	21.2	-64.5%	12.9	-76.7%
	Model_11_L_295	17.2	-71.2%	8.5	-84.6%
Pylon Angle	Model_11_A_205	59.8		55.3	
	Model_11_A_220	48.8	-18.4%	44.3	-19.9%
	Model_11_A_235	39.6	-33.8%	34.3	-38.0%
	Model_11_A_250	32.7	-45.3%	26.6	-51.9%
	Model_11_A_265	27.2	-54.5%	20.6	-62.7%
	Model_11_A_280	23.1	-61.4%	16.1	-70.9%
	Model_11_A_295	20.1	-66.4%	12.7	-77.0%

Pylon and End Support Reactions. In Figure 5.11, pylon and end support reactions were measured by forces and moments. Regarding forces, F_1 follows the bridge longitudinal direction, F_2 points to the bridge cross sectional direction. F_3 points to the upward vertical direction. Moments M_1, M_2, and M_3 rotate along the respective directions of F_1, F_2, and F_3 according to the right hand rule.

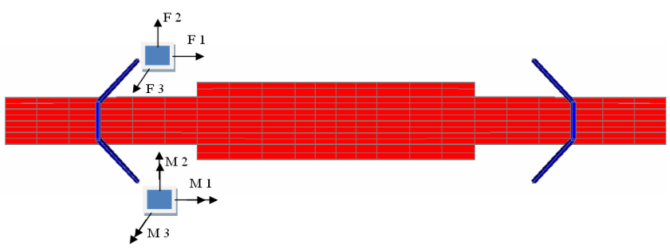

Figure 5.11. Illustration of Bridge Beam Element Forces and Moments

Table 5.7. Summary of Pylon and End Support Reactions

Load Type	Output Case	F_1 (kip)	F_2 (kip)	F_3 (kip)	M_1 (kip-ft)	M_2 (kip-ft)	M_3 (kip-ft)
Dead Load	Pylon	27	4,145	10,345	5,471	4,788	1,324
	End support	9,442	1,616	509			
Live224 (224 lb/ft^2)	Pylon	21	2,968	7,127	186	3,703	1,024
	End support	7,362	1,271	406			
Combination	Pylon	69	10,375	25,404	7,164	12,465	3,446
	End support	24,686	4,244	1,346			

Table 5.8. Summary of Pylon Reaction Forces for Different Models

Output Case	Load Case	Model	F_1		F_2		F_3		M_1		M_2		M_3	
			kips	ratio	kips	ratio	kips	ratio	kips	ratio	kips	ratio	kips	ratio
Maximum Pylons	Dead	Model11_205	27	1.00	4,145	1.00	10,345	1.00	5,471	1.00	4,788	1.00	1,324	1.00
		Model11_250	13	0.47	3,626	0.87	9,099	0.88	5,439	0.99	2,266	0.47	827	0.47
		Model11_275	7	0.26	3,354	0.81	8,445	0.82	5,422	0.99	1,266	0.26	351	0.26
		Model11_295	3	0.13	3,152	0.76	7,962	0.77	5,409	0.99	604	0.13	167	0.13
	Live224	Model11_205	21	1.00	2,968	1.00	7,127	1.00	186	1.00	3,703	1.00	1,024	1.00
		Model11_250	10	0.48	2,579	0.87	6,193	0.87	162	0.87	1,774	0.48	490	0.48
		Model11_275	6	0.27	2,372	0.80	5,696	0.80	148	0.80	1,007	0.27	278	0.27
		Model11_295	3	0.13	2,217	0.75	5,325	0.75	138	0.75	497	0.13	137	0.13
	1.25DL+1.75LL	Model11_205	69	1.00	10,375	1.00	25,404	1.00	7,164	1.00	12,465	1.00	3,446	1.00
		Model11_250	33	0.48	9,045	0.87	22,212	0.87	7,082	0.99	5,940	0.48	1,642	0.48
		Model11_275	19	0.27	8,343	0.80	20,624	0.81	7,037	0.98	3,347	0.27	925	0.27
		Model11_295	9	0.13	7,821	0.75	19,271	0.76	7,004	0.98	1,624	0.13	449	0.13
Maximum Supports	Dead	Model11_205	9,442	1.00	1,616	1.00	509	1.00						
		Model11_250	4,421	0.47	1,101	0.68	495	0.97						
		Model11_275	2,076	0.22	581	0.36	271	0.53						
		Model11_295	776	0.08	525	0.33	213	0.42						
	Live224	Model11_205	7,362	1.00	1,271	1.00	406	1.00						
		Model11_250	3,527	0.48	879	0.69	393	0.98						
		Model11_275	1,733	0.24	480	0.38	224	0.55						
		Model11_295	709	0.10	393	0.31	162	0.40						
	1.25DL+1.77LL	Model11_205	24,686	1.00	4,244	1.00	1,346	1.00						
		Model11_250	11,700	0.47	2,915	0.69	1,311	0.97						
		Model11_275	5,627	0.23	1,567	0.37	731	0.54						
		Model11_295	2,210	0.09	1,344	0.32	549	0.41						

Deck Stresses. Deck stresses and forces were measured along the bridge longitudinal direction S22, cross-sectional direction S11, and upward vertical direction S33, respectively. Figures 5.12-5.15 illustrate deck stresses and forces in response to different pylon locations.

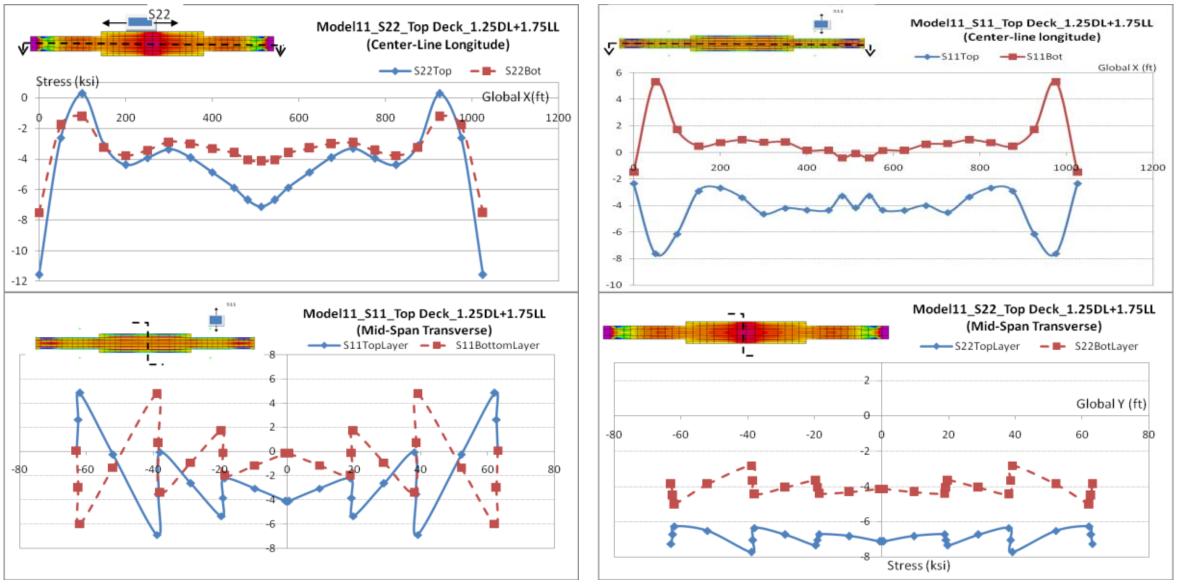

Figure 5.12(a). Deck Stresses along Longitudinal and Transverse Directions under Combined Load (4-ft Deck Depth, Pylons Located 205-ft to End Supports)

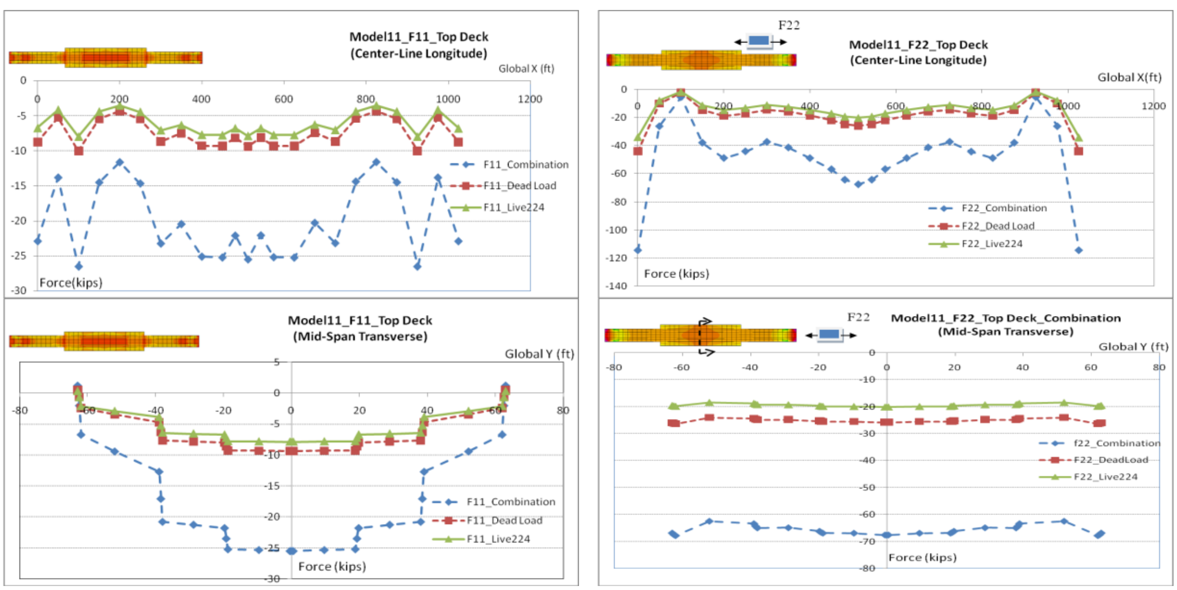

Figure 5.12(b). Deck Forces along Longitudinal and Transverse Directions under Combined Load (4-ft Deck Depth, Pylons Located 205-ft to End Supports)

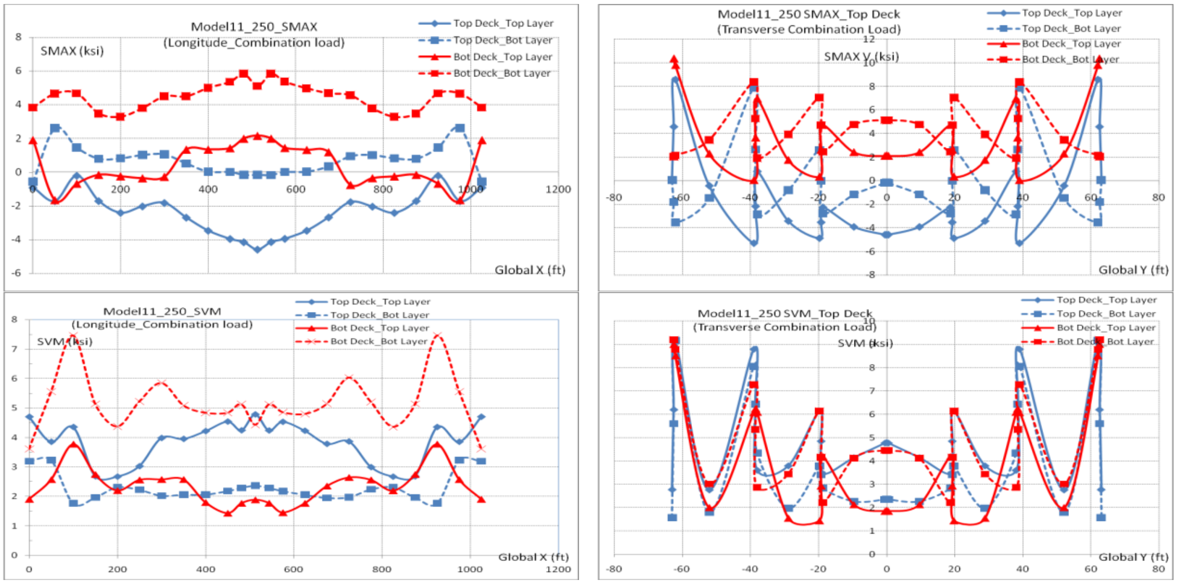

Figure 5.13. Deck Stresses along Longitudinal and Transverse Directions under Combined Load (4-ft Deck Depth, Pylons Located 250-ft to End Supports)

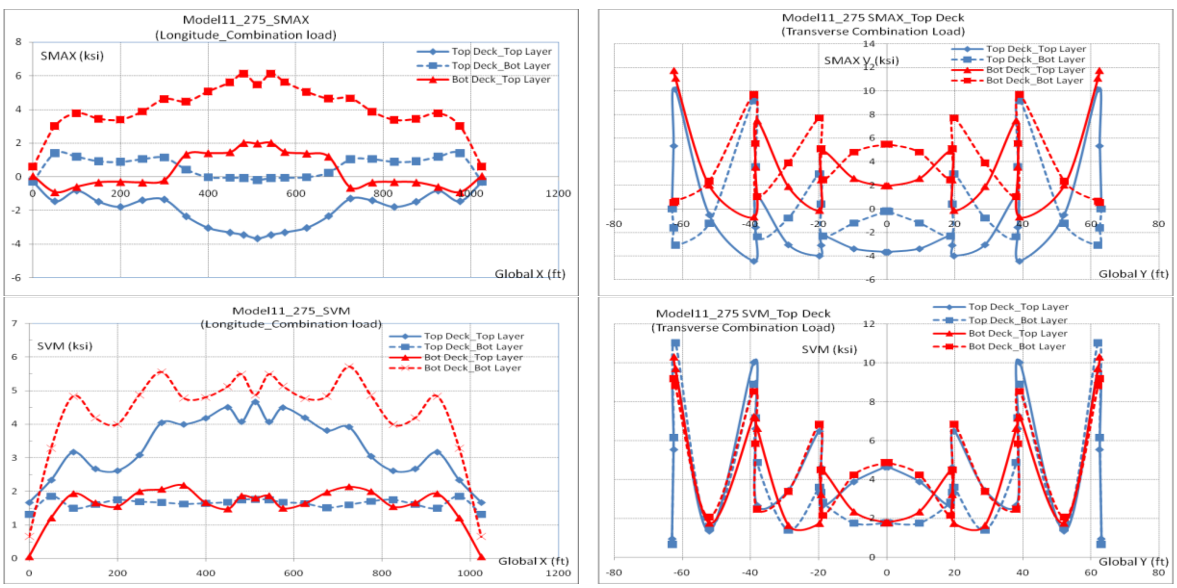

Figure 5.14. Deck Stresses along Longitudinal and Transverse Directions under Combined Load (4-ft Deck Depth, Pylons Located 275-ft to End Supports)

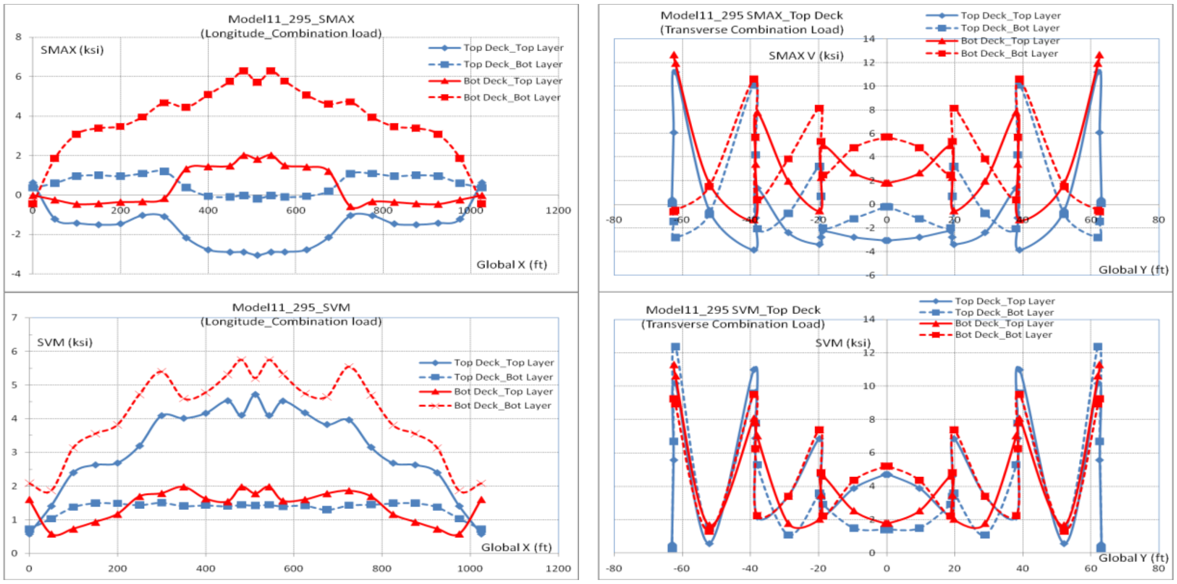

Figure 5.15. Deck Stresses along Longitudinal and Transverse Directions under Combined Load (4-ft Deck Depth, Pylons Located 295-ft to End Supports)

Cable Forces and Displacements. The cable locations and displacements are illustrated in Figure 5.16.

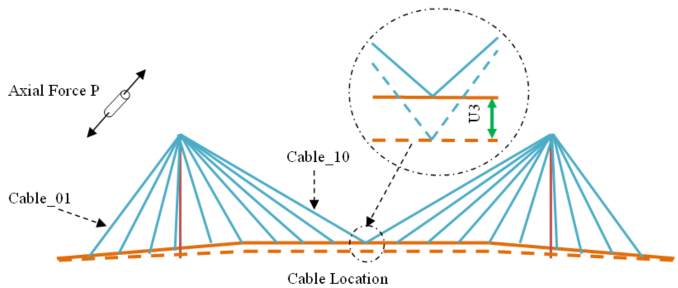

Figure 5.16. Illustration of Cable Locations and Displacements

Table 5.9. Summary of Cable Forces and Displacements for Different Models

Reaction		Load	Model	Cable01	Cable02	Cable03	Cable04	Cable05	Cable06	Cable07	Cable08	Cable09	Cable10
Axial Force P (kips)	Value	Dead	Model11_205	5,183	756	259	458	503	1,116	806	1,390	1,641	309
			Model11_250	2,978	977	518	515	481	1,115	698	1,202	1,526	718
			Model11_275	1,828	967	674	580	492	1,104	661	1,093	1,418	846
			Model11_295	970	896	794	649	514	1,108	633	1,012	1,322	918
		Live224	Model11_205	4,020	577	195	349	379	892	627	1,083	1,265	221
			Model11_250	2,336	747	389	392	362	891	546	944	1,184	540
			Model11_275	1,454	739	507	440	373	879	516	863	1,105	642
			Model11_295	795	684	597	491	389	882	495	802	1,034	698
		1.25DL+ 1.77LL	Model11_205	13,513	1,956	665	1,183	1,292	2,955	2,105	3,632	4,265	771
			Model11_250	7,810	2,527	1,328	1,330	1,236	2,954	1,829	3,154	3,979	1,843
			Model11_275	4,830	2,502	1,729	1,494	1,269	2,919	1,730	2,878	3,707	2,182
			Model11_295	2,605	2,317	2,038	1,671	1,322	2,929	1,657	2,668	3,462	2,371
	Ratio	Dead	Model11_205	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
			Model11_250	0.57	1.29	2.00	1.13	0.96	1.00	0.87	0.86	0.93	2.32
			Model11_275	0.35	1.28	2.60	1.27	0.98	0.99	0.82	0.79	0.86	2.74
			Model11_295	0.19	1.18	3.06	1.42	1.02	0.99	0.79	0.73	0.81	2.97
		Live224	Model11_205	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
			Model11_250	0.58	1.29	2.00	1.12	0.96	1.00	0.87	0.87	0.94	2.44
			Model11_275	0.36	1.28	2.60	1.26	0.98	0.99	0.82	0.80	0.87	2.90
			Model11_295	0.20	1.19	3.06	1.41	1.02	0.99	0.79	0.74	0.82	3.16
		1.25DL+ 1.77LL	Model11_205	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
			Model11_250	0.58	1.29	2.00	1.12	0.96	1.00	0.87	0.87	0.93	2.38
			Model11_275	0.36	1.28	2.60	1.26	0.98	0.99	0.82	0.79	0.87	2.82
			Model11_295	0.19	1.18	3.06	1.41	1.02	0.99	0.79	0.73	0.81	3.06
Displacement at the Cable Location U3 (inch)	Value	Dead	Model11_205	13.9	13.7	6.5	-1.7	-10.0	-19.1	-27.5	-37.5	-47.5	-55.3
			Model11_250	6.9	8.0	5.2	1.5	-2.3	-6.9	-10.7	-15.7	-21.0	-25.1
			Model11_275	3.2	3.9	2.7	0.9	-1.1	-3.8	-5.8	-8.9	-12.1	-14.6
			Model11_295	0.5	0.4	0.1	-0.4	-1.1	-2.7	-3.5	-5.2	-7.1	-8.5
		Live224	Model11_205	10.9	10.7	5.1	-1.2	-7.6	-14.7	-21.1	-28.9	-36.6	-42.5
			Model11_250	5.5	6.4	4.2	1.3	-1.6	-5.2	-8.2	-12.2	-16.3	-19.4
			Model11_275	2.7	3.3	2.4	0.9	-0.7	-2.9	-4.4	-6.9	-9.5	-11.4
			Model11_295	0.7	0.7	0.4	-0.1	-0.7	-2.0	-2.6	-4.0	-5.6	-6.6
		1.25DL+ 1.77LL	Model11_205	36.4	35.9	17.0	-4.3	-25.8	-49.8	-71.3	-97.4	-123.5	-143.5
			Model11_250	18.2	21.3	13.9	4.2	-5.7	-17.8	-27.7	-40.9	-54.7	-65.4
			Model11_275	8.8	10.8	7.5	2.8	-2.5	-9.8	-15.0	-23.1	-31.7	-38.3
			Model11_295	1.8	1.7	0.8	-0.6	-2.7	-6.9	-8.9	-13.5	-18.6	-22.2
	Ratio	Dead	Model11_205	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
			Model11_250	0.49	0.58	0.80	-0.87	0.23	0.36	0.39	0.42	0.44	0.45
			Model11_275	0.23	0.29	0.42	-0.53	0.11	0.20	0.21	0.24	0.26	0.27
			Model11_295	0.04	0.03	0.02	0.23	0.11	0.14	0.13	0.14	0.15	0.15
		Live224	Model11_205	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
			Model11_250	0.51	0.60	0.82	-1.10	0.22	0.36	0.39	0.42	0.44	0.46
			Model11_275	0.25	0.31	0.46	-0.76	0.09	0.20	0.21	0.24	0.26	0.27
			Model11_295	0.06	0.06	0.08	0.06	0.09	0.14	0.12	0.14	0.15	0.16
		1.25DL+ 1.77LL	Model11_205	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
			Model11_250	0.50	0.59	0.81	-0.98	0.22	0.36	0.39	0.42	0.44	0.46
			Model11_275	0.24	0.30	0.44	-0.64	0.10	0.20	0.21	0.24	0.26	0.27
			Model11_295	0.05	0.05	0.05	0.14	0.10	0.14	0.12	0.14	0.15	0.15

5.4 Foundation Type Considerations

For the calculated forces and moments that need to be accommodated by the bridge foundation, shallow, deep or very deep foundations may be designed depending upon subsurface conditions. When the subsurface has rock formations near the surface, a shallow foundation will be suitable considering the high bearing resistance provided by the rock. In this case, the shallow foundation could be treated as a drilled caisson socketed into the bedrock. The socket could provide lateral resistance and stability. To increase the moment resistance, the foundation could be also designed with a cap. Since the foundation is supported by the bedrock, the bearing capacity of the foundation will generally be adequate. The stability of the foundation is the controlling factor in the foundation.

<u>Deep Foundation</u>. When the bedrock is located at moderate depth such as over 100 ft below ground surface, a deep foundation is required. This ground condition reveals that a foundation placed in the soil layer above the rock formation will result in very large settlement. Considering the magnitude of loads and the subsurface conditions, the type of deep foundation required would be a caisson foundation where the tip of the caisson is placed in the rock formation to provide sufficient stability. Since caissons can be designed to carry very heavy load, a single caisson can be used to support the pylon with excellent stability.

In the case of very deep rock formations, utilizing a very long foundation to reach the firm bearing rock layer is not feasible. For this subsurface condition, the design for bearing capacity of the foundation normally depends on the skin resistance or the combination of the shaft resistance and the tip resistance. When shaft resistance is required to support the loads, generally a group of multiple piles such as four piles and nine piles will be needed to provide the load carrying capacity for the foundation.

5.5 Conceptual Cable-Stayed Bridge Design and Rapid Construction

<u>Foundation Design</u>. Depending on the magnitude of loads, subsurface soil conditions, and the environmental impacts of foundation construction, shallow, deep or very deep foundations need to be used as they are appropriate. As a practical matter, rapid bridge construction may be feasible for subsurface conditions that could utilize shallow foundations.

<u>Pylon Design</u>. Prefabricated high performance reinforced concrete segments could be used in basic pylon design. Multiple prefabricated pylon segments can be pre-assembled off-site and further assembled on-site to minimize construction duration.

<u>Cable to Pylon Connections</u>. The top portion of the pylons can be assembled and then be lifted into place by crane. The individual cables could then be connected to each pylon.

Prefabricated Deck Segment Design and Connection. The selection of box shaped cross-sections could facilitate prefabrication of cable-stayed deck girder segments to meet the need for rapid construction. Along both the transverse and longitudinal directions of the deck girder segments, asymptotically reduced deck depths from the central line could be used to balance the dead load and additional torsional resistance from the wider solid web. The adjacent deck girder segments could be designed with overlapping rebar loops, which could be welded together and then grouted using high performance concrete.

Cable to Deck Connections. Another important issue that affects rapid construction is the cable to deck connection. The sockets, as used in the Pasco-Kennewick Bridge in Washington State (Jackson and McCullough, 1988), could serve the purpose of fast and easy erection and construction.

5.6 A Conceptually New Method for Rapid Bridge Construction

Figure 5.17 outlines a new conceptual method for rapid bridge construction. As a convention, the construction of the bridge begins with work on the foundation. Upon the completion of the foundation work, the prefabricated high performance concrete pylon segments that have been partially assembled off-site can be fully assembled on-site. Next, cables can be installed on the high performance steel pylon head that is lifted and connected to the pylon top using a crane. The construction of two pylons can be carried out in parallel to reduce on-site construction time.

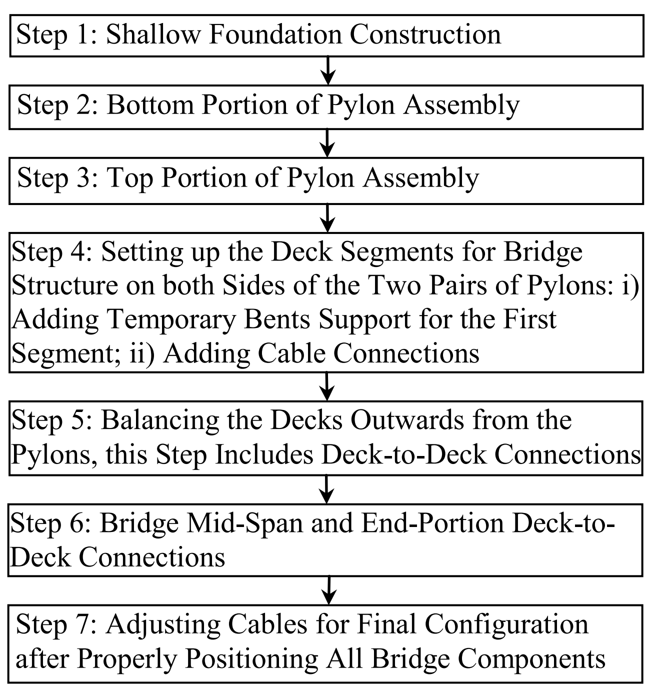

Figure 5.17. A Conceptually New Construction Method for Rapid Bridge Construction

In order to minimize on-site construction duration, a rotatable connection between the foundation and the pylon is proposed. With a rotatable foundation-pylon connection, assembling of the deck segments could progress even with open traffic. The connection of prefabricated deck segments could begin on both sides of the two pairs of pylons by adding temporary bents support for the first segment. Cable connections could follow from the assembled deck segments on both sides of the pylon to keep the balance. After completing deck-to-deck segment connections with the consideration of balancing the decks outward from the pylons and cable installations on the side of the travel way, the partially assembled bridge could be rotated to the correct position.

In the meantime, the deck segments for the remaining portion of the bridge mid-span could be pre-assembled. Next, the three partially assembled deck segments of the bridge could be connected. Further, deck-to-deck connections could be completed for the two ends of the bridge. Cables could be installed in symmetry along the bridge centerline to keep the bridge balanced. Then, cables could be adjusted for final configuration after all bridge components are properly positioned. Finally, welding and grouting of the connections between adjacent deck segments for the main structure and ramps could be completed to finish the entire bridge construction.

CHAPTER 10: SUMMARY AND CONCLUSION

6.1 Summary

Once a bridge reaches its useful designed service life, it needs to be replaced or reconstructed in order to safely and efficiently accommodate traffic. While highways can be repaired relatively quickly, bridge replacement/construction requires special planning, engineering, materials procurement, and an overall longer time period for construction. This report documented the findings of a review of the existing literature on rapid bridge replacement/construction techniques developed worldwide with emphases placed on materials, prefabrication, and machinery techniques. Then, the report summarized findings of a survey aimed to collect pertinent information to synthesize current best practices of rapid bridge replacement/construction in the United States. The key findings of the survey are:

- Most of the participating states have adopted a centralized hierarchy for bridge management.
- Most of the participating states are using rapid bridge replacement/construction technologies to mitigate traffic disruption during on-site construction. However, the extent of rapid bridge replacement/construction technologies adopted is less than 10 percent of all bridge work.
- Most of the participating states do not have specific restrictions for adopting rapid replacement/construction technologies for bridge work. Some states do limit that such technologies be used only for small-span bridges.
- Most of participating states do not query a list of contractors/vendors for rapid bridge replacement/construction work.
- Potential benefits of rapid bridge replacement/construction come from mobility improvements, safety enhancements, and the mitigation of adverse impacts to local businesses and communities.
- Key factors affecting the selection of rapid bridge replacement/construction strategies include criticality of the bridge, construction cost, road user mobility and safety, socioeconomic impacts, and construction worker safety.
- Two-thirds of participating states have found that their outreach efforts are effective in promoting the use of rapid bridge construction techniques. Such efforts are mainly made in the pre-construction phase.
- Types of innovations in rapid bridge replacement/construction include the use of new materials, prefabrication of bridge components, and innovative contracting. On the new materials side, high performance concrete and steel are commonly used. Prefabrication is concentrated on superstructure

and deck. Innovative contracting methods primarily include incentive/disincentive, A+B, design-build, and lane rental.

Next, a rapid bridge replacement/construction decision-making framework was developed to help determine whether rapid bridge construction would be feasible. The system of rapid bridge replacement/construction is governed by a number of factors including: the criticality of the bridge, the contractor's prefabrication ability, the contractor's construction management strategies for mitigating safety and environmental impacts, and the agency costs of the bridge as well as the user costs of bridge. Issues of the criticality of the bridge are mainly associated with whether the bridge is accommodating a high traffic volume, involved with emergency recovery, located on an evacuation route, or affecting the construction duration of a larger project. Issues of the contractor's prefabrication ability are concerned with prefabrication of bridge elements and standardization. Issues related to the contractor's construction management strategies are relevant to safety impacts, environmental impacts, and bridge site conditions. Issues within the category of agency and user costs of bridge construction with respect to bridge construction costs including the cost of traffic maintenance, user costs, the bridge owner agency's operations, and the contractor's operations. Rapid construction is justified after confirming the criticality of the bridge, the contractor's prefabrication ability, the contractor's construction management, and savings in the total of agency and user costs. The use of Analytical Hierarchy Process (AHP) as the enginee that drives the decision support tool/framework needs to be explored further by functionalizing the framework presented in this report for decision making purposes at state DOTs and other asset owners who can benefit from such a framework.

After confirming the feasibility of adopting rapid bridge replacement/construction, an exploratory analysis of a new conceptual rapid bridge design and construction system was conducted to determine the best suited rapid bridge replacement/construction method. Such a rapid bridge replacement/design and construction system may be considered as a candidate for rapid replacement/construction of bridges with similar geometric design standards governed by comparable traffic and site conditions. The analysis covers rapid construction considerations, preliminary structure analysis, foundation type considerations, conceptual cable-stayed bridge design and construction, and a conceptual construction method. Finally, the report discusses implementation issues of the study findings and future research directions.

6.2 Implementation Issues

The products of this research are as follows:

- Findings of a review of existing literature on rapid bridge replacement/construction techniques developed worldwide;

- Findings of a survey of current state-of-practices of rapid bridge replacement/construction in the United States;
- A decision-making framework for determining whether or not to use rapid bridge replacement/construction techniques as opposed to conventional bridge replacement/construction methods; and
- Findings of an exploratory analysis of a conceptually new rapid bridge design and construction system that may be suitable for rapid replacement/construction of some bridges.

Tools needed to facilitate implementation of the research products from this study include the training of bridge engineers and contractors via workshops to demonstrate the usefulness of this research. Possible impediments to successful implementation of the products of this research include skepticism of the conceptual analysis, design, and construction methods proposed the confidence level of construction quality with much shorter construction duration, future inspection of prefabricated structure components, and a lack of funding to promote its broader adoption. However, with close cooperation between concerned stakeholders, the development of new design guidelines and inspection manuals for bridges, and introducing innovative financing mechanisms such as public/private partnerships, the impact of such barriers to the implementation of the research products can be mitigated.

6.3 Directions for Future Research

The findings of this research present a way of conceptually mitigating traffic disruption caused by lengthy bridge construction duration. Future research could be directed towards exploring light-weight, durable new materials to further reduce the dead load of cable-stayed bridges and find the optimal combination of conventional and unconventional materials to ensure safety, serviceability, constructability, and aesthetics in bridges. Consistent to future research products, new design guidelines and inspection manuals can be developed to promote their real-world implementation.

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APPENDICES

APPENDIX A: Questionnaire Survey for Best Practices of Rapid Bridge Replacement/Construction in the United States

Purpose of This Questionnaire

The National Center for Freight and Infrastructure Research and Education (CFIRE) awarded a grant (Award No. DTRT06-G-0020) to a joint research team comprised of the University of Illinois at Chicago and Illinois Institute of Technology to develop a framework that could be used by highway agencies to select appropriate rapid bridge replacement/construction techniques for a variety of situations. Another study objective is to explore innovative methods for rapid bridge replacement/construction. This questionnaire survey is intended to synthesize current best practices of rapid highway bridge construction in the United States.

Please email, fax, or mail the completed survey form by September 30, 2010 to:

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or

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E-mail: lizz@iit.edu

Please spend your valuable time to complete this questionnaire. Your input is very important to minimize impacts of bridge work on road users, local businesses, and communities.

Your General Information (Optional)

Name: ______________________________

Title: ______________________________

Address: ______________________________

____

____

Phone: ______________________________

Fax: ______________________________

E-Mail: ______________________________

Your Employer

- ☐ Federal agency
- ☐ State transportation agency
- ☐ Local government agency
- ☐ Other (please specify)______________________________

1. How will you characterize the bridge management team hierarchy in your agency/employer?

- ☐ Centralized
- ☐ Decentralized

2. Has your agency/employer used rapid bridge replacement/construction techniques, strategies, and technologies?

- ☐ Yes
- ☐ No
- ☐ Don't Know

If "Yes" to Question 2:
Please check the main objectives for using rapid bridge replacement/construction techniques.

- ☐ Reducing the total number of days for bridge construction
- ☐ Reducing number of (on-site construction) days with traffic disruption

To what extent rapid construction strategies, techniques, and technologies have been adopted for bridge work?

- ☐ < 10%
- ☐ 10-25%
- ☐ 25-50%
- ☐ 50-75%
- ☐ 75-100%

Does your organization have restriction in the size of bridges applying rapid replacement/construction work?

- ☐ Only allowed for short-span bridge
- ☐ No restriction
- ☐ Other (please specify) ______________________________

Does your agency/employer query list of contractors/ vendors for rapid bridge replacement/construction work?

- ☐ Yes
- ☐ No
- ☐ Other (please specify) ______________________________

What in your opinion are the potential benefits of rapid bridge replacement/construction?

- ☐ Improved construction quality
- ☐ Lower bridge life-cycle agency costs
- ☐ Improved work zone safety and mobility
- ☐ Minimized local business and community impacts
- ☐ Minimized environmental impacts
- ☐ Other (please specify) ______________________________

Please check key factors influencing the selection of rapid bridge construction strategies, techniques, and technologies.

- ☐ The rapid bridge construction cost
- ☐ Criticality of the bridge being in a dense urban area or a major corridor
- ☐ The need for bridge hyper fix caused by extreme storm or earthquake events
- ☐ Road user mobility
- ☐ Road user safety
- ☐ Construction worker safety
- ☐ Non-road user safety
- ☐ Socioeconomic impacts (local businesses, communities, emergency services, special events, etc.)
- ☐ Environmental impacts
- ☐ Political influence
- ☐ Other (please specify) ____

If "No" to Question 2, please specify the main reason for not using rapid construction strategies, techniques, and technologies?

____

____

____

____

3. Are sufficient outreach efforts made to promote the support of using rapid bridge construction strategies, techniques, and technologies from road users, non-users, local businesses, and communities?

   Influence of outreach efforts in promoting the support of using rapid bridge construction strategies

   - ☐ Effective
   - ☐ Ineffective
   - ☐ Don't Know

   If "Effective", during which phase of the bridge project delivery are the outreach efforts made?

   - ☐ Pre-construction phase
   - ☐ Construction phase
   - ☐ Post-construction phase

4. If your agency/employer is using rapid bridge replacement strategies, techniques, and technologies, please identify the type of innovation (check all that apply).
   - ☐ Use of new bridge materials
   - ☐ Use of technologies for prefabricating bridge elements in a factory controlled environment
   - ☐ Use of new machinary for on-site assembling of prefabricated bridge elements
   - ☐ Use of innovative contracting methods
   - ☐ Other (please specify) ______________________________

a. If new bridge materials are used, please check the specific types of materials applicable to your agency.
   - ☐ High performance steel
   - ☐ High strength bolts
   - ☐ High strength epoxy grouts
   - ☐ High performance concrete
   - ☐ Fiber-reinforced concrete
   - ☐ Fiber-reinforced polymer composites
   - ☐ Other (please specify) ______________________________

b. If new technologies are used for bridge component prefabrication, please specify where they are used:
   - ☐ Substructure
   - ☐ Superstructutre
   - ☐ Deck
   - ☐ Entire bridge structure

c. If new machinery are used by your agency, please specify what they are used for.
   - ☐ Piling machinery for foundation work
   - ☐ Launching girders and cranes for superstructure and deck construction
   - ☐ Self-propelled modular transporters for final positioning of preassembled bridge elements/segments
   - ☐ Other (please specify) ______________________________

d. If innovative contracting methods are used by your agency, please check the specific methods being used.
   - ☐ A + B
   - ☐ Incentive/ Disincentive
   - ☐ A + B + Incentive/ Disincentive
   - ☐ Lane rental
   - ☐ Design-build
   - ☐ Other (please specify) ______________________________

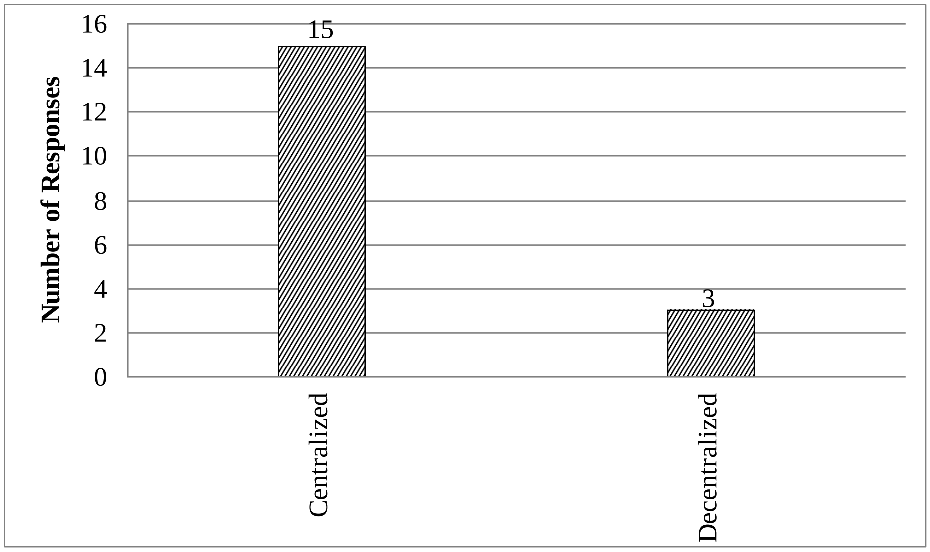
5. Additional comments for implementing rapid bridge replacement/construction techniques, strategies, and technologies:

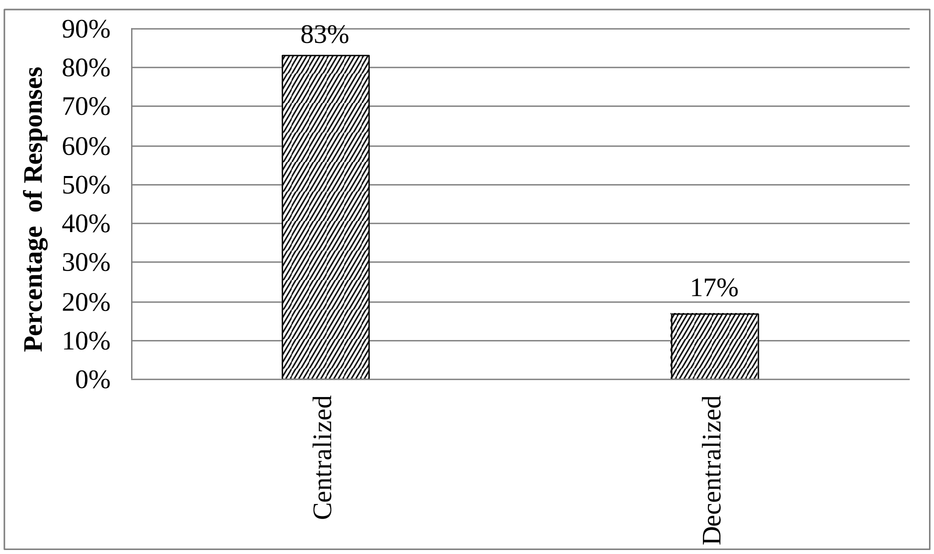
____

____

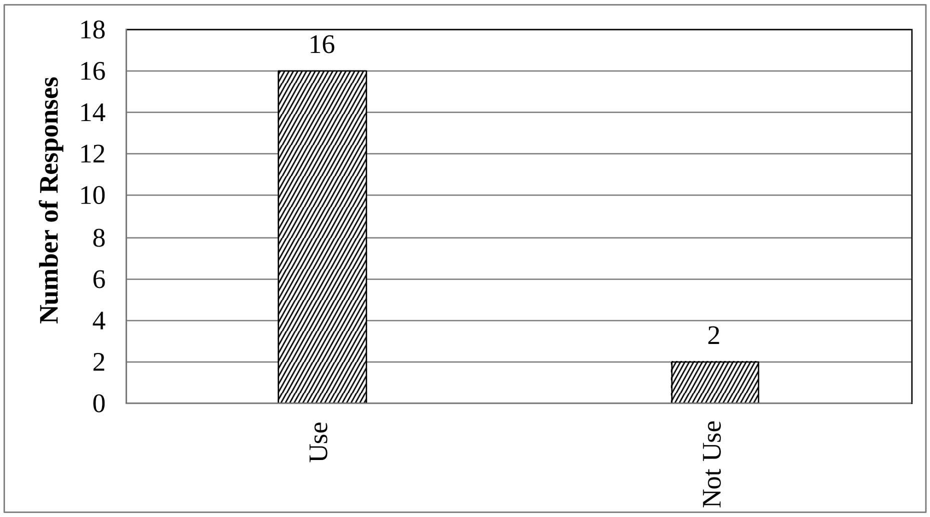
Thank You for the Participation!

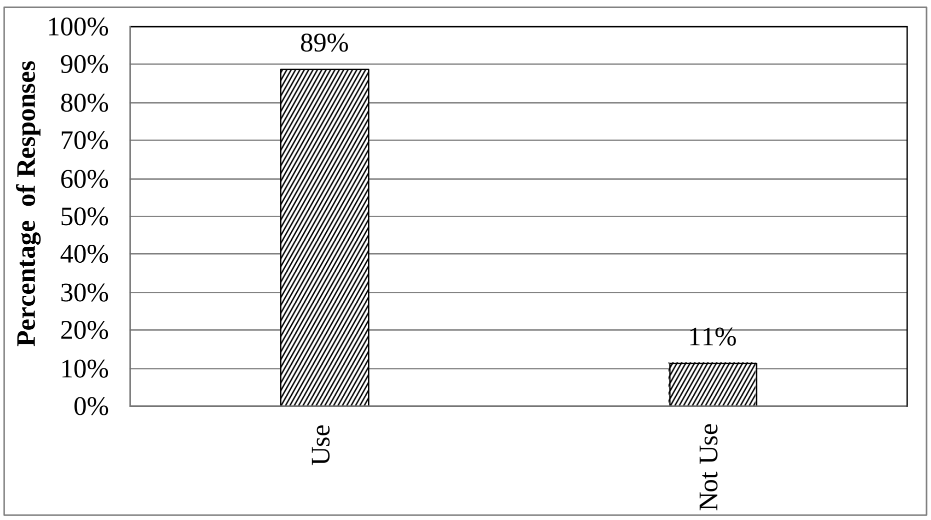
APPENDIX B: Graphic Presentations of Survey Results



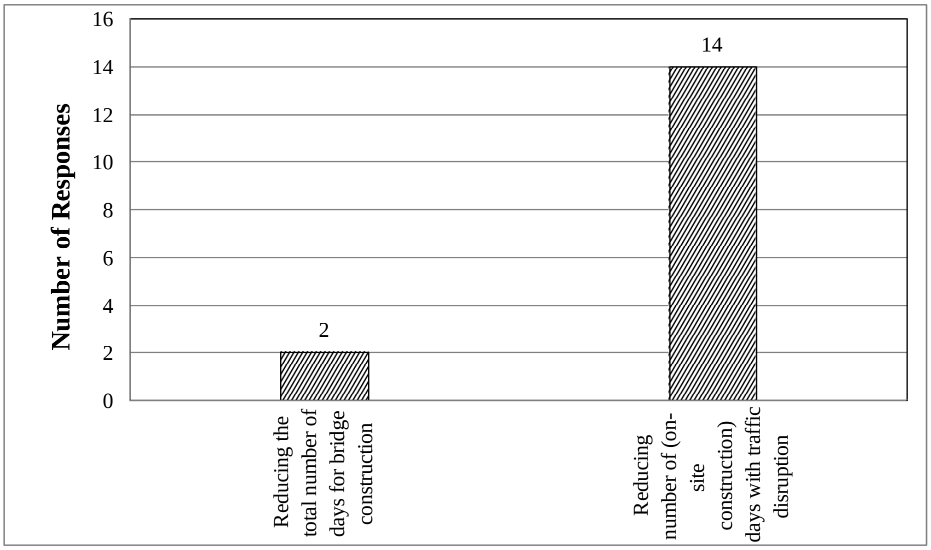


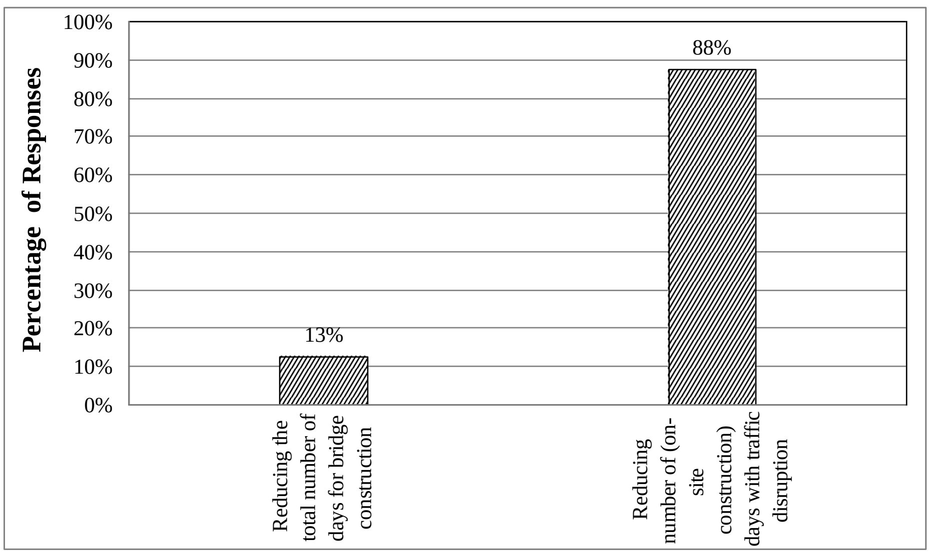
B-2-1. Use of Rapid Bridge Replacement/Construction Techniques



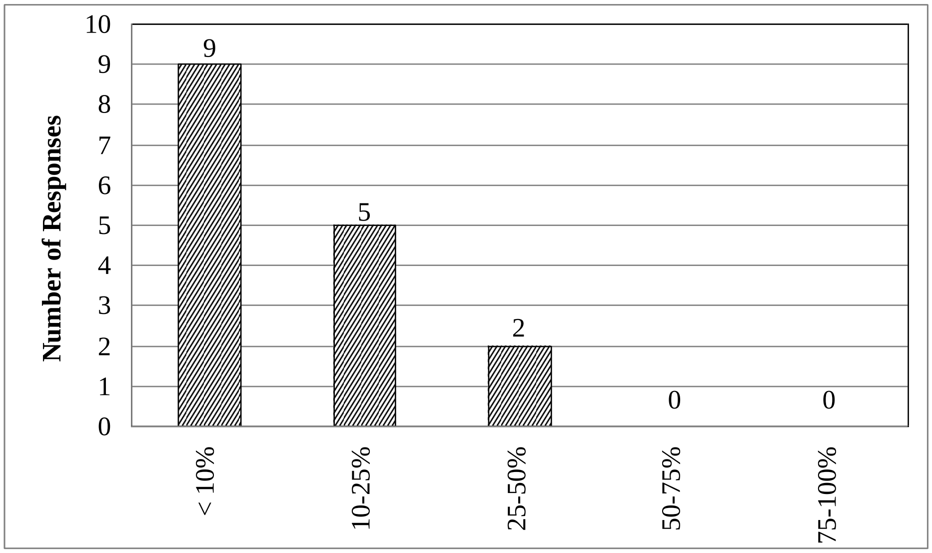


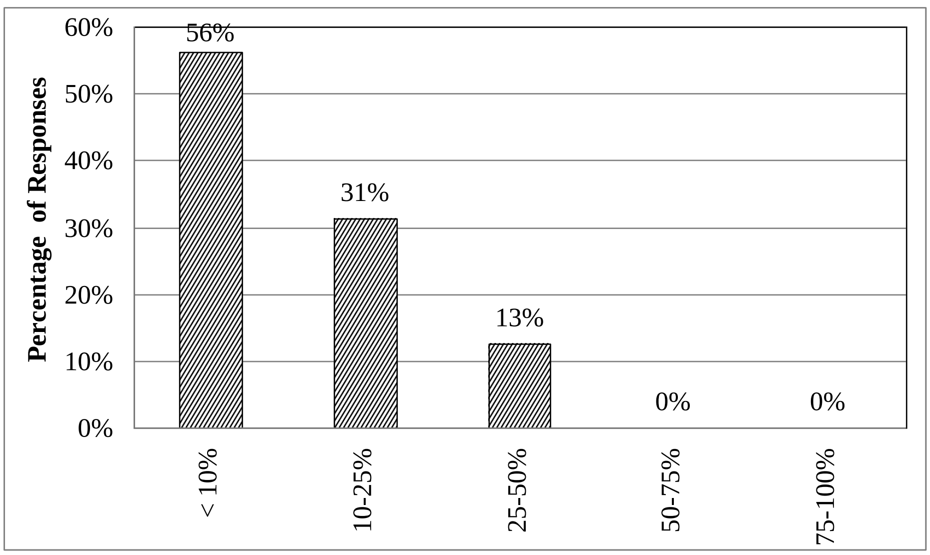
B-2-2. Main Objective for Using Bridge Replacement/Construction Techniques



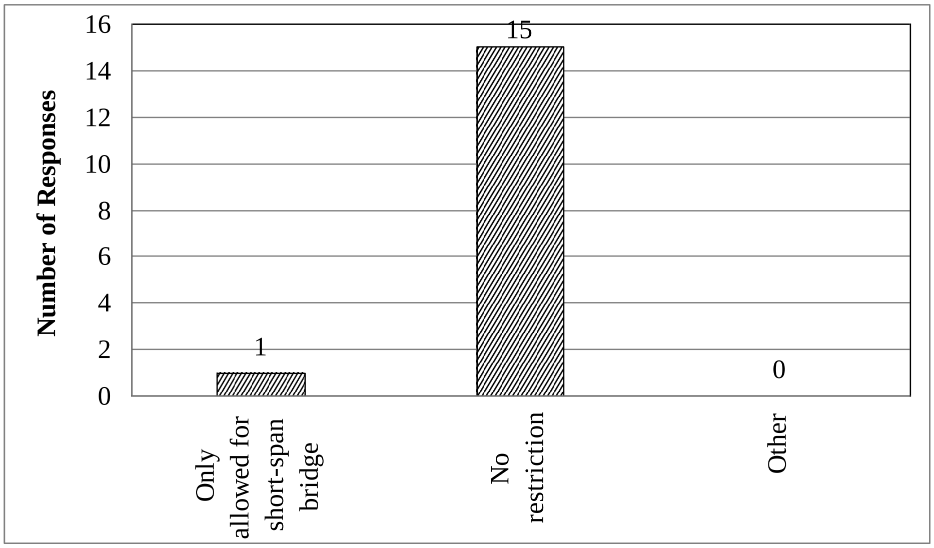


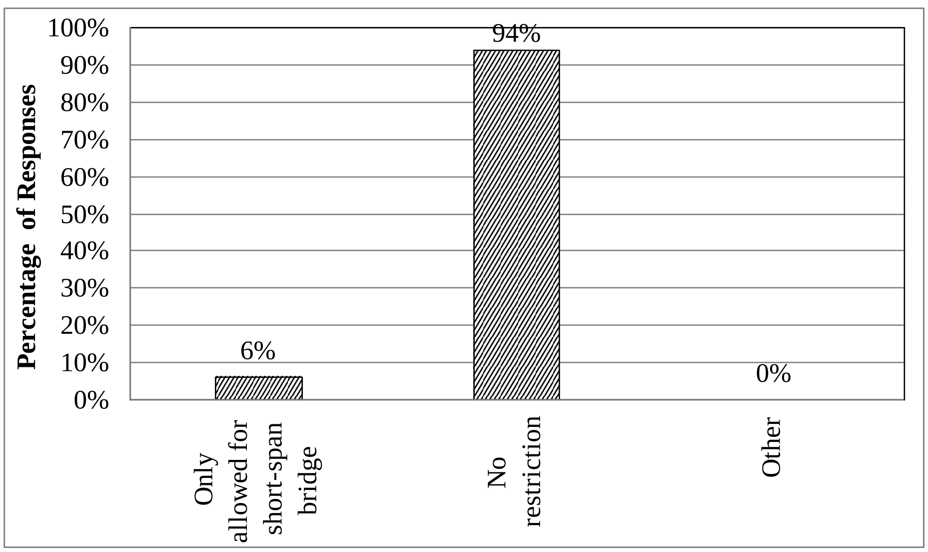
B-2-3a. Extent of Adopting Rapid Construction Strategies for Bridge Work



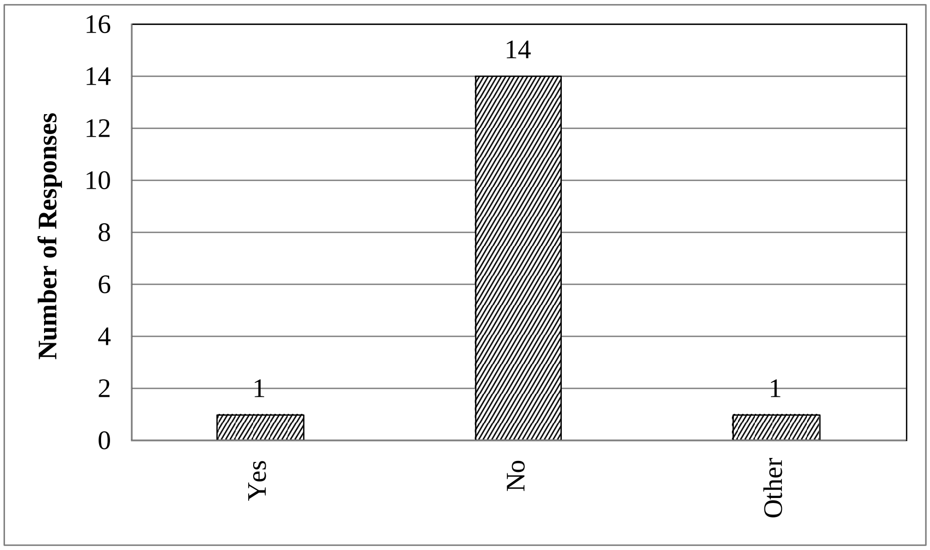


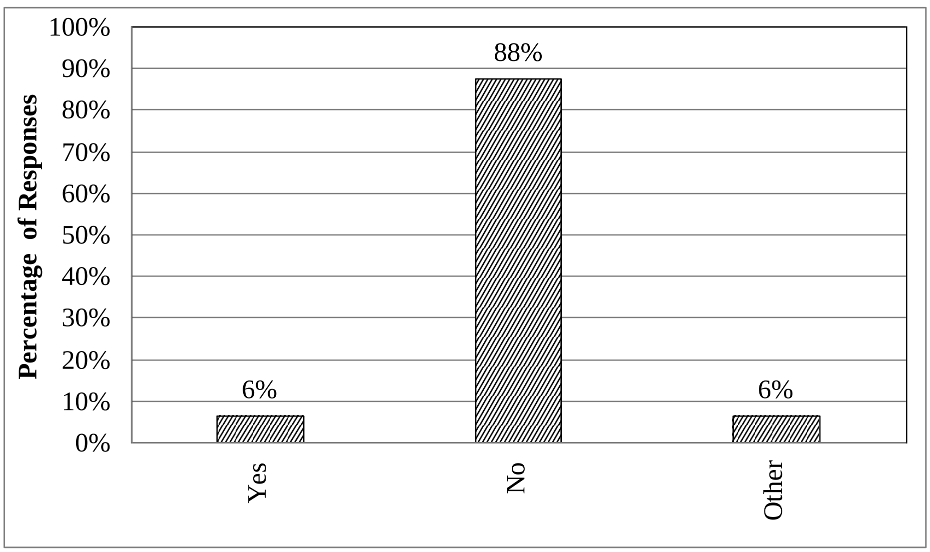
B-2-3b. Existence of Restriction in Applying Rapid Construction in the Size of Bridge



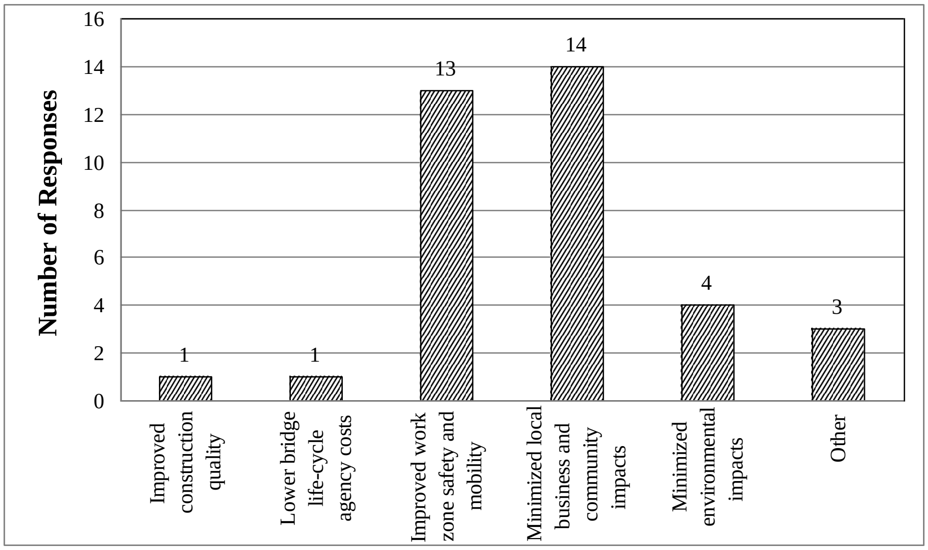


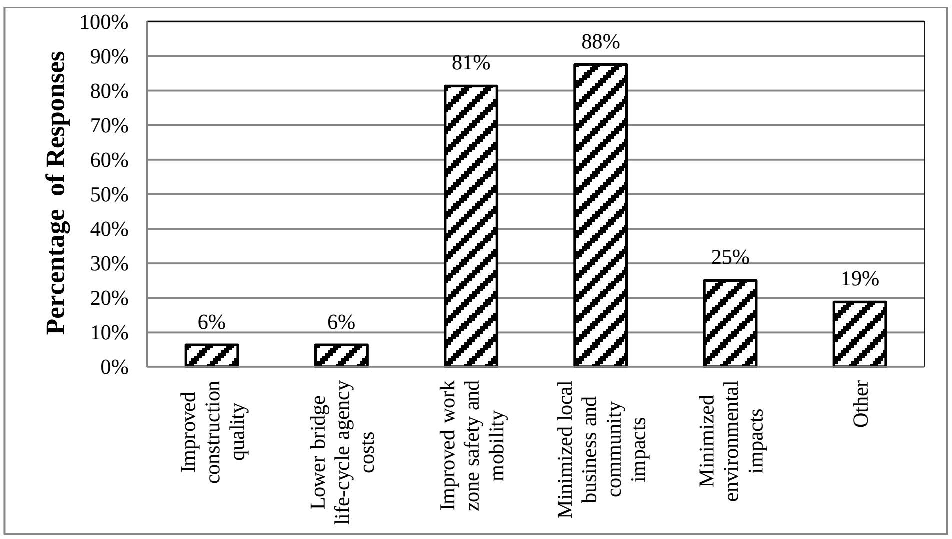
B-2-3c. Query List of Contractors for Rapid Bridge Replacement/Construction Work



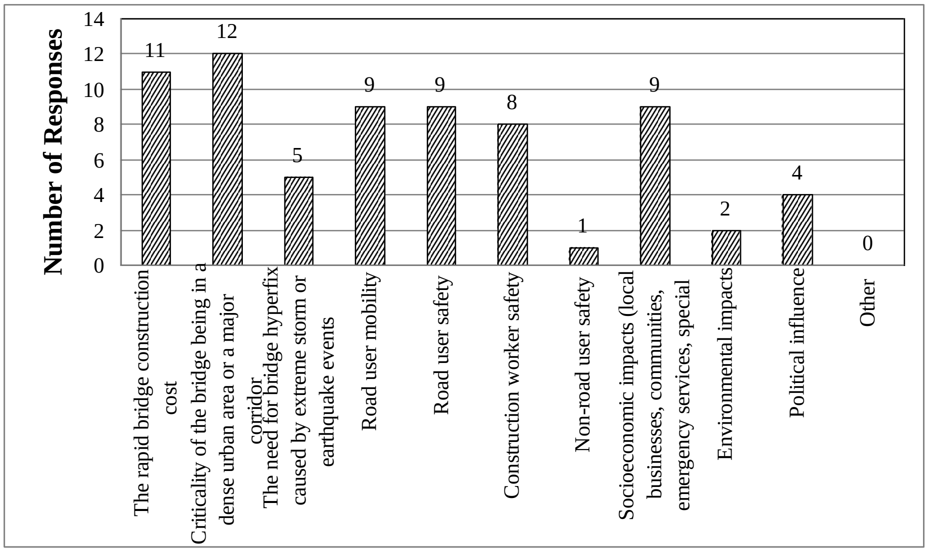


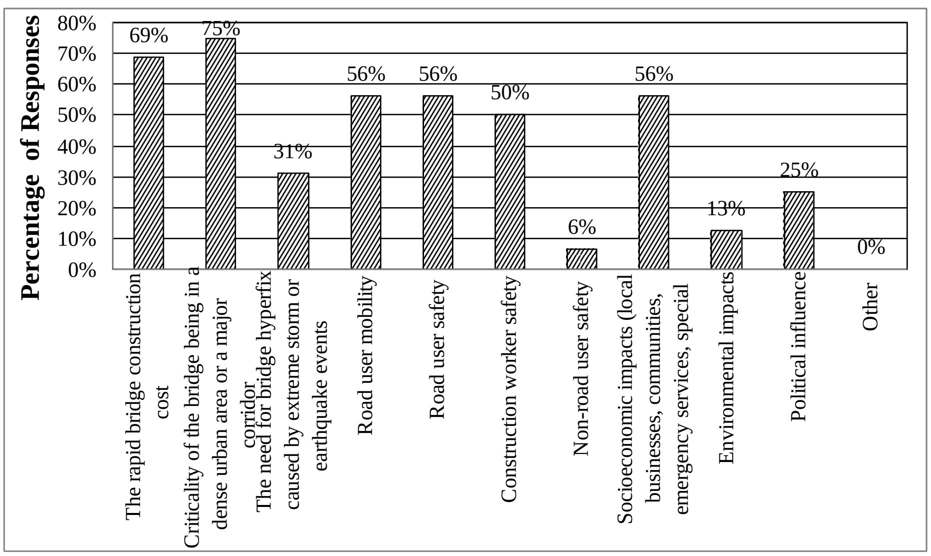
B-2-3d. Potential Benefits of Rapid Bridge Replacement/Construction



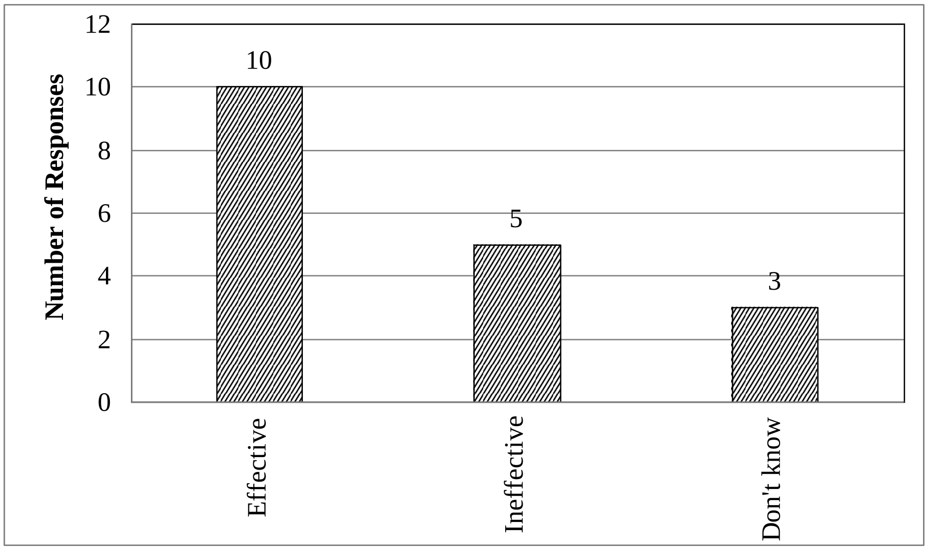


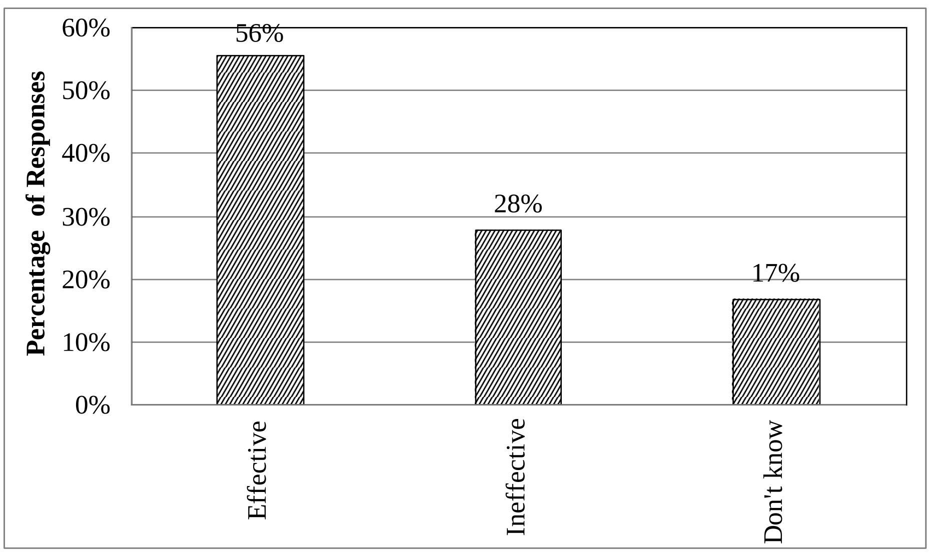
B-2-3e. Key Factors Influencing the Selection of Rapid Bridge Construction



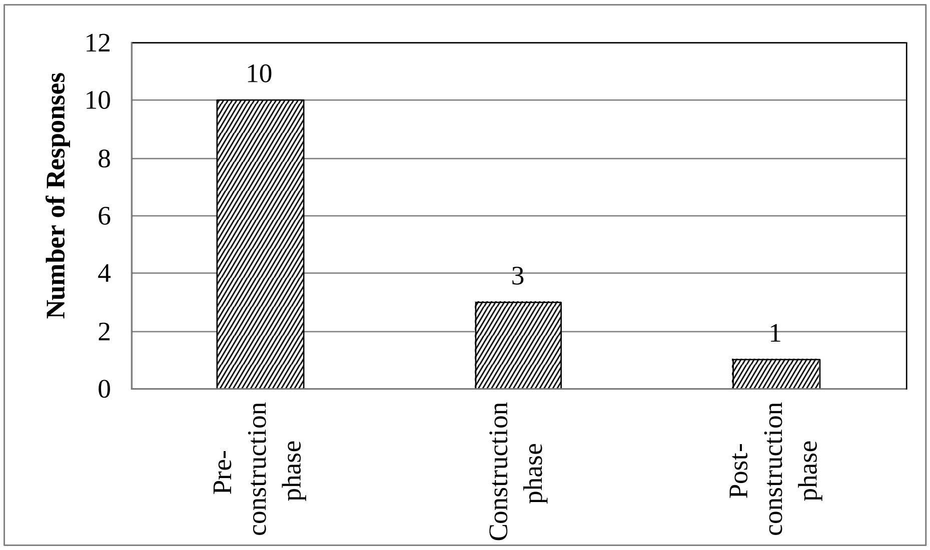


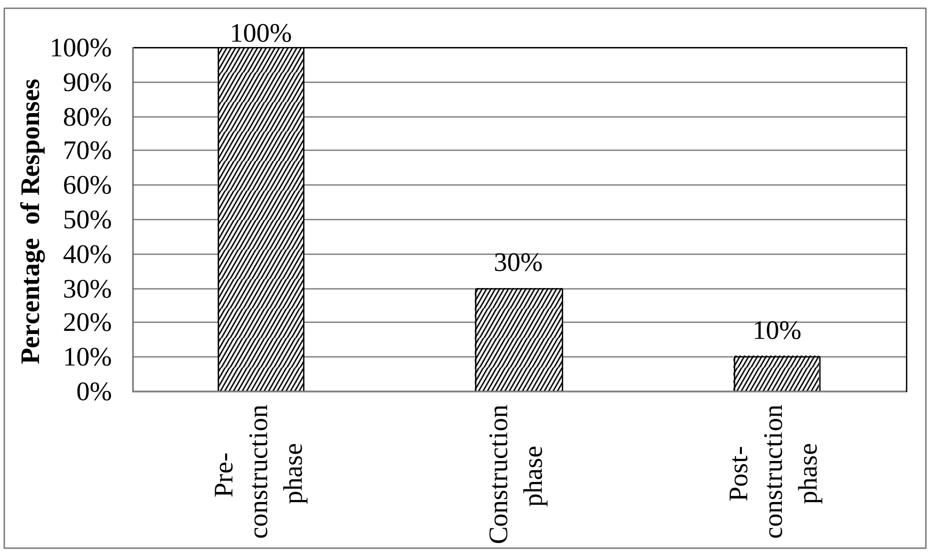
B-3a. Influence of Outreach Effort on Promotion of Using Rapid Bridge Construction



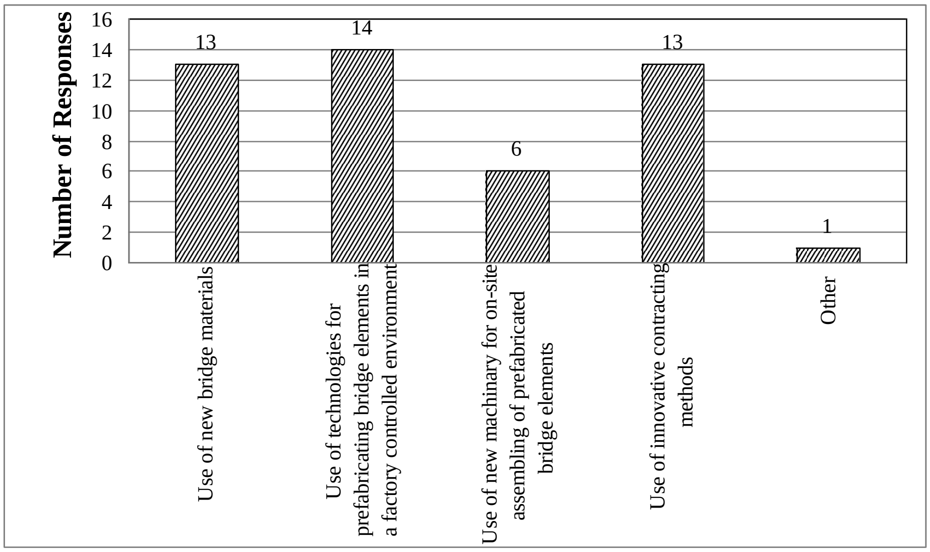


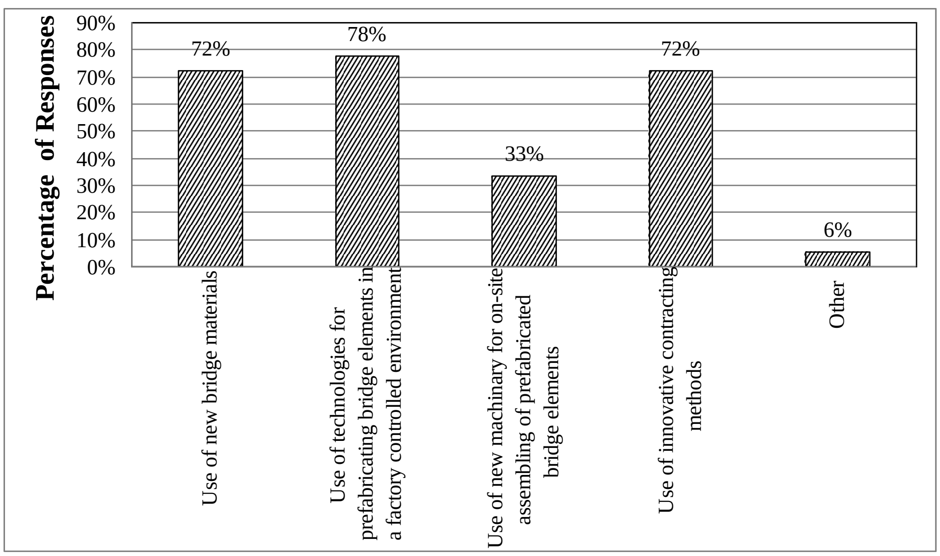
B-3b. Phase of Bridge Project Delivery for Promotion



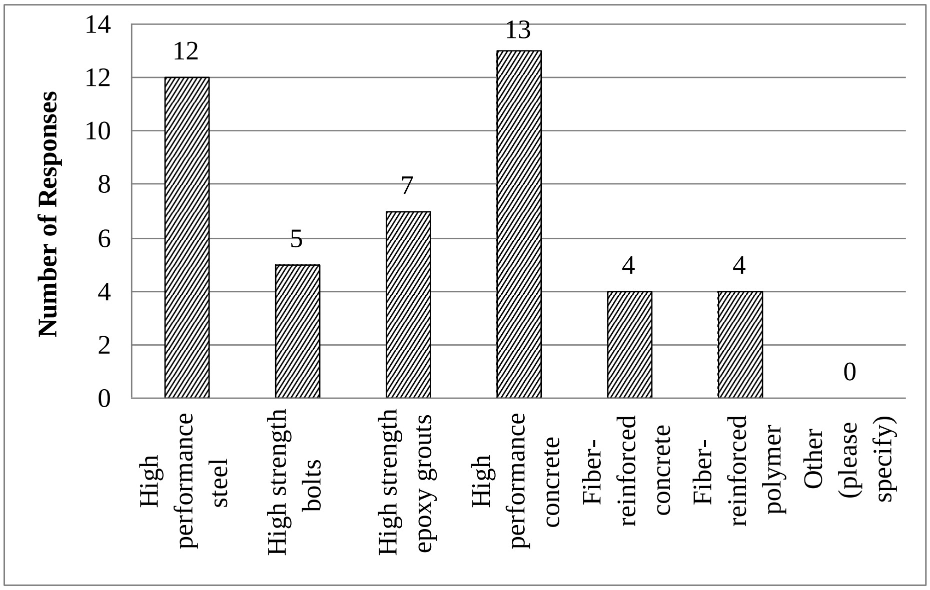


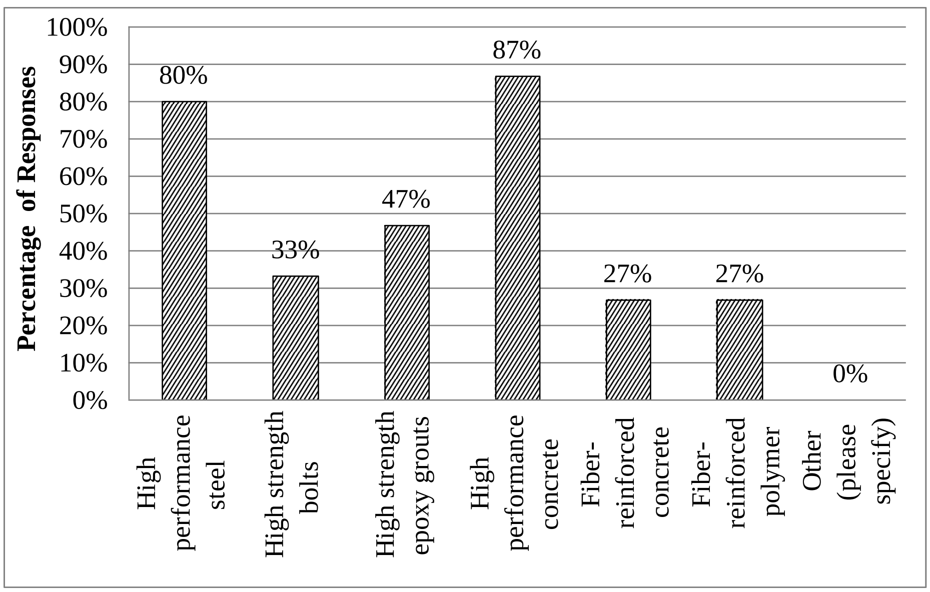
B-4-1. Type of Innovation in Rapid Bridge Replacement Strategies



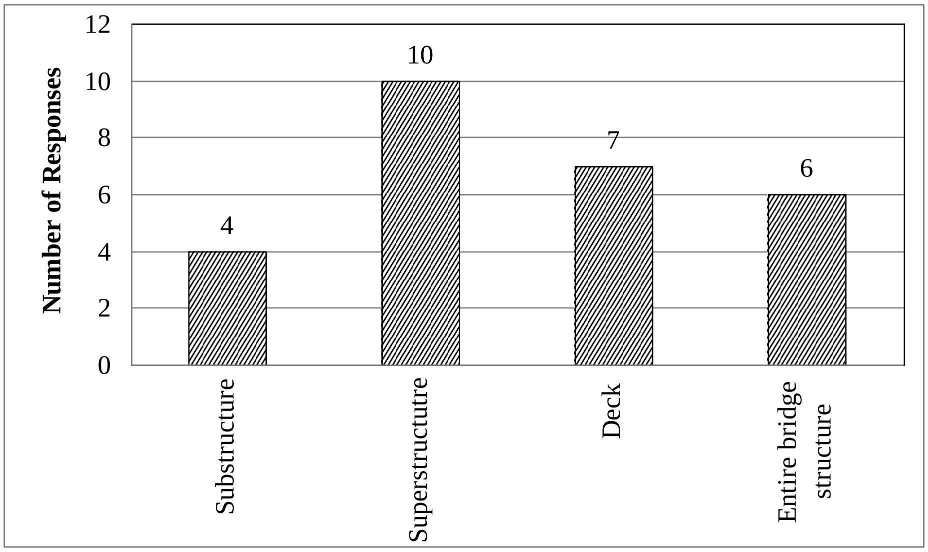


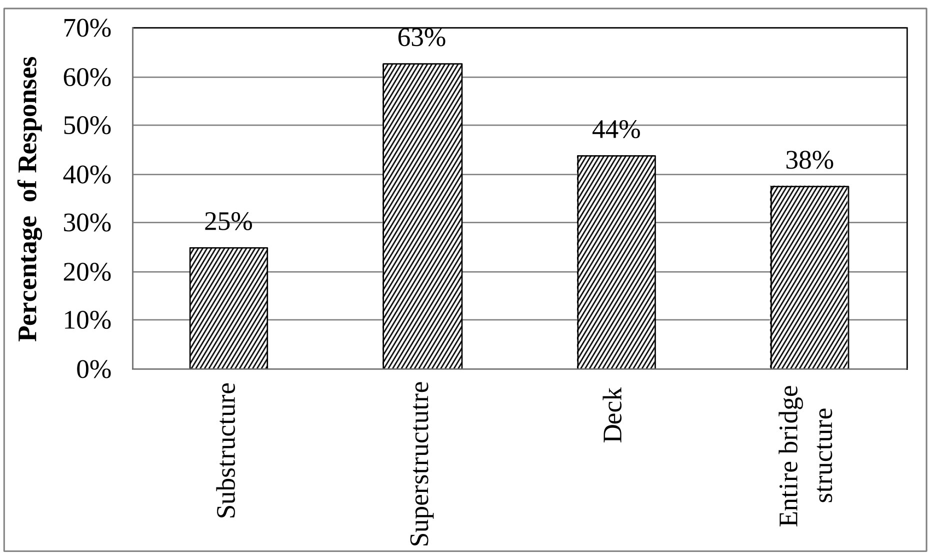
B-4-2a. Type of New Bridge Materials Applied in Agency



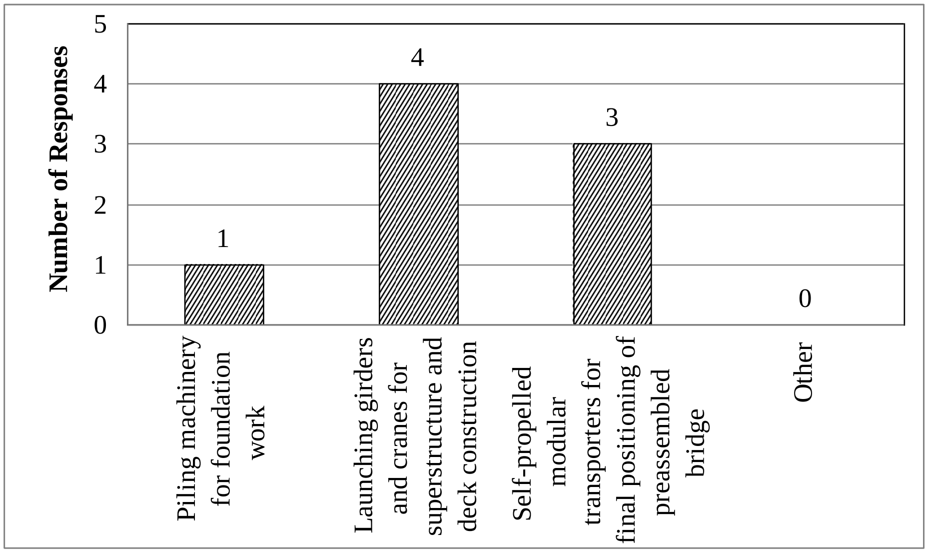


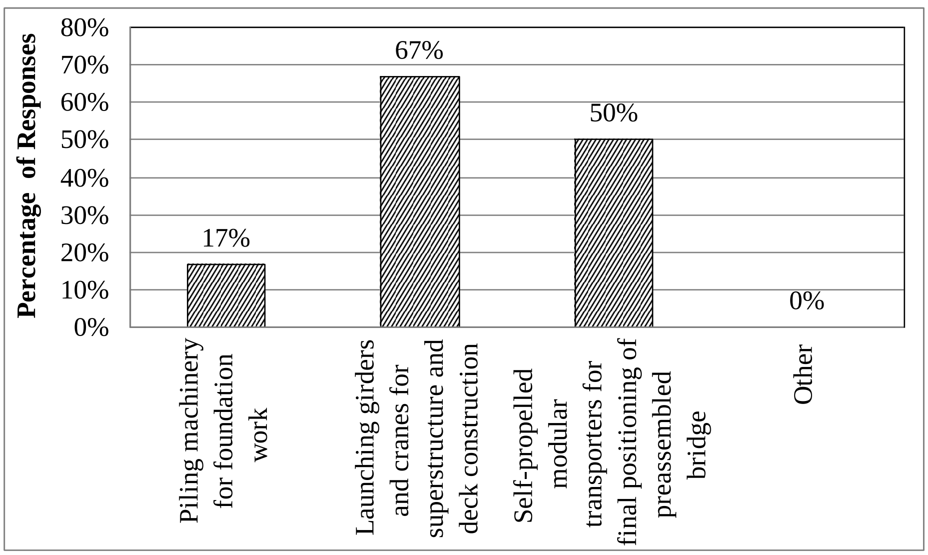
B-4-2b. New Technologies Used for Bridge Component Prefabrication



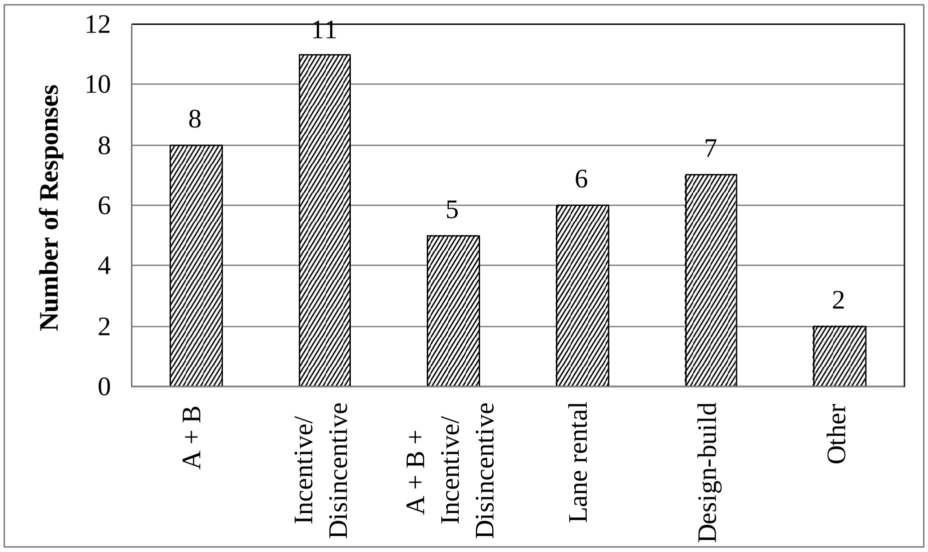


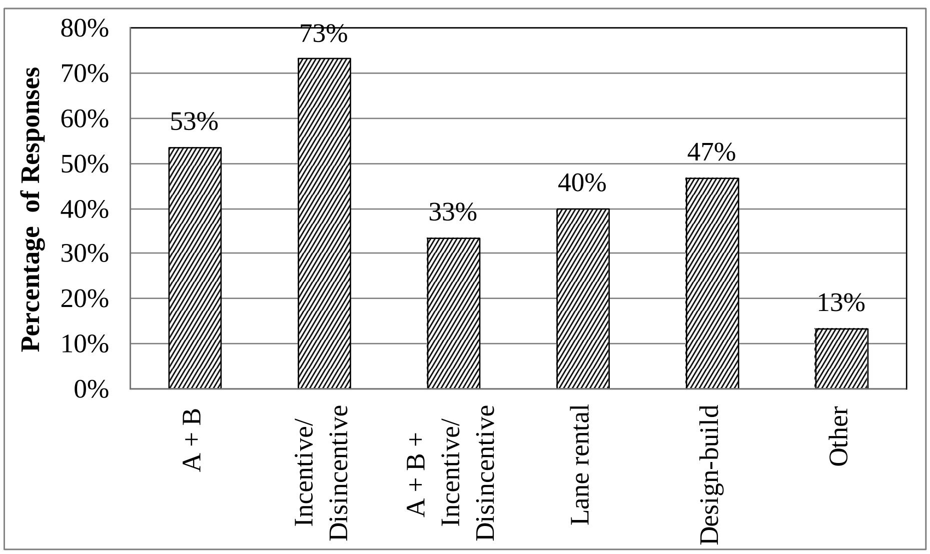
B-4-2c. New Machineries Being Used by Agency





B-4-2d. Innovative Contracting Methods Used by Agency





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