2014

Methods for removing concrete decks from steel girder bridges

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Methods for removing concrete decks from steel girder bridges

by

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A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Civil Engineering (Structural Engineering)

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2014

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ACRONYMS AND ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ACEC	American Council of Engineering Companies
AISC	American Institute of Steel Construction
ASCE	American Society of Civil Engineering
AWS	American Welding Society
BE^{2}ST-in-Highways	Building Environmentally and Economically Sustainable Transportation Infrastructure-Highways
CaGBC	Canada Green Building Council
CEEQUAL	Civil Engineering Environmental Quality Assessment & Award Scheme
CFRP	Carbon Fiber Reinforced Polymer
CMAA	Construction Management Association of America
DOT	Department of Transportation
ENV SP	Envision™ Sustainability Professional
EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
FMI	Fails Management Institute
GreenLITES	Green Leadership in Transportation and Environmental Sustainability
ICE	Institute of Civil Engineering
IHRB	Iowa Highway Research Board
I-LAST	Illinois-Livable and Sustainable Transportation Rating System and Guide
INVEST	Infrastructure Voluntary Evaluation Sustainability Tool
IRTBA	Illinois Road and Transportation Builders Association
IS	Infrastructure Sustainability

ISCA	Infrastructure Sustainability Council of Australia
ISI	Institute for Sustainable Infrastructure
MATC	Mid-America Transportation Center
MOT	Ministry of Transportation
MPO	Metropolitan Planning Organizations
NCHRP	National Cooperative Highway Research Program
NY	New York
NYSDOT	New York State Department of Transportation
NMP	Noise Mitigation Plan
PANYNJ	Port Authority of New York & New Jersey
PEACH	Preserving Environment And Community Heritage
PB	Parson-Brinckerhoff
SITES™	Sustainable Sites Initiatives™
SMAW	Shielded Metal Arc Welding
STARS	Sustainable Transportation Analysis and Rating System
STEED	Sustainable Transportation Engineering and Environmental Design
STC	Sustainable Transportation Council
UK	United Kingdom
UNL	University of Nebraska-Lincoln
U.S.	United States
WCED	World Commission on Environment and Development

ACKNOWLEDGEMENTS

I thank Drs. Terry Wipf, Brent Phares, and Jennifer Shane for their patience, motivation, enthusiasm, and knowledge. Their advice had always been inspiring and enlightening throughout my study. I learned a tremendous amount of engineering skills over the past two years from my committee members, professors, faculty, staff, and students at Iowa State University.

I am grateful to Justin Dahlberg for his efforts in experimental tests in this study. I thank Douglas Wood for managing the lab space and helping with testing setups.

Family is always my greatest source of support. I would like to thank the best parents in the world, who raised and supported me while studying abroad. I am also grateful to my sister, who has taken excellent care of my parents while I was not around to help. Nothing is impossible with their unconditional love. My graduate experience was wonderful with many friends. I thank Beth Hartmann for being a great role model, friend, mentor, lecturer, and supervisor. I would like to extend my appreciation to Dr. Christianna White for coaching my writing skills.

Finally, I thank the Iowa Highway Research Board (IHRB), Mid-America Transportation Center (MATC), and Iowa DOT for sponsoring this research.

ABSTRACT

Infrastructure in the U.S. transportation systems is at or beyond its current useful life (D'Agostino 2007), and many deteriorated concrete bridge decks need to be replaced. Removing these decks without damaging the bridge superstructure is a tedious and expensive task that often controls the deck replacement timeline. With ever tightening budgets and limitations of demolition equipment, states are looking for cost-effective, reliable, and sustainable methods for removing concrete decks from steel girder bridges. The goal of this research is to explore such methods. The research team conducted qualitative studies through a literature review, interviews, surveys, and workshops and performed small-scale trials and push-out tests (shear strength evaluations). Interviews with bridge owners and contractors indicated that concrete deck replacement was more economical than replacing an entire superstructure under the assumption that salvaged superstructures have adequate remaining service life and capacity. Surveys and workshops provided insight into advantages and disadvantages of deck removal methods, information that was used to guide testing. Small-scale trials explored three promising deck removal methods: hydrodemolition, chemical splitting, and peeling. Hydrodemolition is suitable for both partial and full-depth concrete removal, but containing and treating the water is expensive. Chemical splitting did not sufficiently break the reinforcing concrete. Peeling seems to be effective, but more testing is needed. Shear strength evaluations suggested that shear strength is not sensitive to the quantity of concrete removal and that it is not necessary to remove all of the concrete around shear connectors. Finally, a sustainability scorecard for bridge deck removal is proposed to incorporate sustainable practices into bridge deck replacement projects.

CHAPTER 1. INTRODUCTION

In a recent survey of owners conducted by FMI and CMAA for facility construction and maintenance, seven challenges were outlined. The first challenge was "Aging infrastructure in nearly every market segment is at or beyond its current useful life. The highway, street, bridge, marine port, airport, inter-modal, rail, K-12 and higher education facilities, water, sewer/waste disposal, electric transmission, and electric/gas distribution markets represent trillions of dollars in necessary spending over the next 10 to 20 years to upgrade and replace those assets" (D'Agostino et al. 2007). According to the American Society of Civil Engineering's 2013 report card for America's infrastructure, the average age of the nation's 607,380 bridges is 42 years, and the decks of one-third of these bridges need maintenance, repair, or replacement (ASCE 2013). This sequence is increasingly expensive. Although bridges are typically designed to last for 75 years (AASHTO 2012), bridge decks deteriorate at a faster rate (Flowers et al. 2010). In the past, this has often meant that entire bridges were replaced at great cost. However, full-depth replacement of bridge decks that can be performed without replacing the bridge superstructures and substructures is one way of extending service life.

Problem Statement

Bridges typical undergo major deck replacement after about 40 years of service life (Tadros et al. 1998). Much previous research has focused on the design and construction of new concrete decks (Bettigole et al. 1997, Tadros et al. 1998, Fu et al. 2013, and Holden et al. 2014), but less research has been conducted on methods for removing existing concrete decks. Current deck removal methods (e.g., saw cutting, jackhammering, and blasting) often damage bridge superstructures. Sometimes a lack of information on the as-built condition increases the possibility of damaging existing superstructures thereby increasing the cost of deck replacement and delaying construction progress. Also, noise, vibration, dust, and falling materials are environmental and public safety concerns. Consequently, bridge owners and contractors need economic, efficient, reliable, and green methods for concrete deck removal that do not damage existing superstructures.

Research Goal and Objectives

The overall goal of this research is to identify more efficient and reliable methods for concrete deck removal that preserve bridge superstructures and substructures. The preserved structures are assumed to have adequate strength and remaining life.

The tasks completed to meet the project objectives are as follows.

Task 1. Review literature about removing concrete decks from concrete and steel girders. This literature review covers five topics: deck removal methods and equipment, steel girder damage and repair, research methods, and sustainable infrastructure rating systems.

Task 2. Interview bridge owners and contractors to determine cost effective replacement alternatives.

Task 3. Survey state DOTs to assess their experience with deck removal methods and identify current deck removal practices.

Task 4. Conduct meetings with Iowa and Nebraska bridge owners and contractors to discuss deck removal methods from steel girders and concrete girders.

Task 5. Conduct small-scale trials on promising deck removal methods on steel girders.

Task 6. Evaluate the performance of various shear connectors with partial concrete removal on steel girders.

Task 7. Propose a sustainability scorecard and criteria for deck removal projects

Research Approach

This study involved a literature review, three interviews, two surveys, two workshops, and two experimental studies. The literature review presents information on the state-of-the-art of deck removal methods, steel girder damage repair, qualitative and experimental research methods, and sustainable infrastructure rating systems. The interviews with both bridge owners and contractors focused on identifying cost-effective bridge deck replacement methods. A nationwide survey of state DOTs was conducted to identify current deck removal practices. Both bridge owners and contractors were invited to two workshops to discuss the advantages and disadvantages of deck removal methods.

The research team conducted two experimental studies. Small-scale trials of three promising deck removal methods that were identified through the surveys and workshops—hydrodemolition, chemical splitting, and peeling—were conducted to evaluate their effectiveness. Push-out tests were conducted to evaluate the shear strength when only partial concrete was removed from around shear connectors. After identifying related sustainable practices to bridge deck replacement projects, a section of scorecard was proposed to incorporate these practices into deck removal projects.

Significance of the Research

The results of this study address two of the United States Department of Transportation (U.S. DOT) strategic goals: state of good repair and environmental sustainability (U.S. DOT 2012). Successful implementation of cost-effective deck removal methods maintains a state of good repair of U.S. transportation system. Efficient deck removal methods enhance a timely bridge deck replacement and avoid undesirable public inconvenience, travel delay, and economic hardship. These methods can preserve the superstructure resulting in improving the environmental sustainability of the U.S. transportation system.

Organization of the Thesis

Following this introduction chapter, this thesis is organized into seven additional chapters. Chapter 2 reviews pertinent literature and provides background information important to this study. Chapter 3 presents the results of interviews that focused on the cost-effectiveness of bridge replacement methods. Chapter 4 describes and reports the results of two surveys and two workshops that focused on deck removal methods. Chapter 5 describes the small-scale trials of three deck removal methods. Chapter 6 documents the shear strength evaluation for partial concrete removal around shear connectors. Chapter 7 focuses on sustainable infrastructure rating systems and proposes a sustainability scorecard and criteria for bridge deck removal projects. Chapter 8 provides conclusions and recommendations based on this research.

CHAPTER 2. BACKGROUND AND LITERATURE REVIEW

This chapter has four sections. The first section reviews eight deck removal methods. The second section discusses steel girder damage and repair. The third section introduces research methods used in this study. The final section reviews five sustainable infrastructure rating systems.

Deck Removal Methods

Depending upon the project requirements, a bridge deck demolition might use one method or a combination of methods. Manning (1991) reported that sawing, drilling, use of rig-mounted percussive tools, splitting, crushers, water jet cutting, ball and crane, and blasting are methods used to completely remove concrete from bridges. Abudayyeh et al. (1998) stated that machine-mounted demolition attachments, hydrodemolition, blasting and miniblasting, sawing and cutting, splitting, jackhammers, and thermal demolition are demolition methods and equipment for full and partial removal of reinforced concrete. This section describes the deck removal methods—sawing, breaking, hydrodemolition, drilling, splitting, crushing, blasting, and peeling—that participants in a survey and workshops conducted as part of this research indicated were the most commonly used demolition methods. These are presented in the order from most to least frequently used methods.

Sawing

Saws are commonly used in bridge deck removal. Bridge decks are typically saw cut into manageable sections and then removed by an overhead crane or other vertical lift equipment. In general, there are two types of saws: the diamond blade saw and the diamond wire saw (Manning 1991).

Diamond blade saws are available in different sizes, blade types, operating speeds, cooling systems, and power sources. The blades are steel disks with diamond segments welded around the rims and can cost anywhere from $100 to $1,500. The quality of the blade depends on the composition of the metal bond, type, size, and concentration of diamonds. Diamond blade saws can either be dry- or wet-cutting. Dry-cutting blades can operate at temperatures between 400° and 550° F (204° and 288° C) (Manning 1991). Wet-cutting saws operate at temperatures around 212° F (100° C) by using water to cool the blades and reduce dust (Manning 1991).

Diamond blade rims are continuous, serrated, or segmented and the geometry determines the cutting characteristics. Continuous rim blades typically create the smoothest cuts while serrated blades provide smooth cuts and faster cutting speeds. Segmented blades result in the smoothest cuts and the fastest cutting speeds and a long blade life. The segmented blade is typically used in cutting concrete decks (Manning 1991).

Diamond wire saws are made of steel beads with electroplated diamonds that are strung on a wire rope (Abudayyeh et al. 1998). Diamond wires are typically mounted on a drive wheel, which can slide to maintain tension in the wire by using either hydraulic or electric power. Hydraulic power is generally preferred because it is more portable. The drive speed is adjustable and the drive direction is reversible. Diamond-wire saws operate by threading the wire through two small holes, which determine the cut angle and length. Diamond wire cutting usually uses water to cool and clean the wire rope. Typical production rates for wire saws, usually between 5 and 40 ft^2/h (0.5 to 4 m^2/h), depend on the type of wire used, the aggregate properties, and the amount of reinforcement (Hulick et al. 1989). However, the life of diamond wires is relatively short compared with saw blades.

Sawing is a relatively rapid removal method that can cut concrete at any angle with negligible vibration and no falling materials. Wet-cutting can further reduce dust and noise. Wet-cutting can also avoid overheat during cutting and, compared to dry-cutting, prolong the useful life of the saw blades or cutting wires. Other factors that determine the cutting speed and blade life are the hardness of the concrete aggregate and the amount of reinforcement (Johnston 1994). It is important to note that personnel training are essential for both the safety and economics of employing this method, due to the costs associated with replacing blades (Abudayyeh et al. 1998).

Breaking

A pneumatic breaker, also known as a jackhammer or a paving breaker, is a common tool used for bridge concrete removal (Vorster et al. 1992). This pneumatic breaker breaks concrete into small, manageable pieces that can be removed by a loader bucket or other small, mobile construction equipment. Breakers are available in both hand-held and machine-mounted types.

Pneumatic breakers are typically classified by weight and power source. Jackhammers, a typical hand-held breaker, are powered by an air compressor, electricity, or gasoline engines (Abudayyeh et al. 1998). The internal hammer is iteratively driven down and then returns to the original position via a spring. These repeated cycles create a percussive impact on the concrete that breaks it into small pieces. A whiphammer is a hydraulically operated hammer, truck mounted, and attached to the end of a heavily restrained leaf spring arm. This type of hammer produces up to 42 blows per minute with the normal operation producing 35 to 40 blows per minute (Manning 1991). Large hydraulic breakers are typically mounted on an excavator. They are powered by hydraulic power provided by the excavator resulting in a production rate that exceeds both the whiphammer and jackhammer.

The production rate of a hand-held breaker depends on the operator's skill and the breaker's weight. The typical hand-held hammer ranges in weight between 20 to 90 lb (Manning 1991). A typical production rate for a 30 lb jackhammer operated on a horizontal surface is 1 ft^3/h

(Manning 1991). In comparison, the production rate for a whiphammer ranges from 200 to 600 ft^3/h for a 6 in. thick deck.

Regardless of the specific piece of equipment used, breaking creates a significant amount of vibration, noise, falling materials, and dust. Using a hand-held hammer is both labor-intensive and time-consuming. Percussive hammers can create high-level damage to the girder remaining in place, if the operator does not exercise care. Typically, state highway agencies limit the power and weight of the breaker to reduce the risk of damage (Weyers et al. 1993).

Hydrodemolition

Hydrodemolition, also called water jetting, breaks concrete by using high-pressure water (Weyers et al. 1993). Both hand-held and machine-mounted hydrodemolition equipment are available. Hand-held equipment can shoot water at any angle. However, hand-held hydrodemolition has a very limited production rate and induces operator fatigue and places the operator at risk. Machine-mounted hydrodemolition can remove deteriorated concrete or reasonable depths of sound concrete by applying a combination of different water pressures, frequencies, lance angles, and nozzle types (Weyers et al. 1993).

Hydrodemolition equipment consists of a power unit and a demolishing unit. The power unit is comprised of a drive engine, a high-pressure pump, water filters, a water tank, and other accessory equipment (Vorster et al. 1992). This unit is typically housed in a large truck or a flatbed tractor-trailer. The demolishing unit is a wirelessly controlled robotic vehicle with an oscillating nozzle connected by a high-pressure flexible hose.

Abrasive water used in hydrodemolition is specifically for cutting the reinforcing steel in concrete (along with removing concrete as well). There are three types of abrasives typically used, including minerals, metals, and artificial. These abrasives are typically stored in a hopper and metered to the nozzle during water jetting.

The production rates estimated for a typical 4,000 psi concrete and 3 in. removal depth are between 10 to 25 ft^3/h for single-pump systems and from 20 to 35 ft^3/h for dual-pump systems (Vorster et al. 1992).

Hydrodemolition produces no dust or vibration. This method protects steel elements from damage (VanOcker et al. 2010). Track-mounted hydrodemolition equipment is safe, but the power units can be noisy unless muffled.

Drilling

Drilling is typically not a sole removal method but is very important to the success of other removal methods. Drilling is typically the first step of preparing a bridge deck for removal when other methods, such as splitting, blasting, or saw cutting, will be used to perform the bulk of the removal process (Manning 1991). The resulting holes can be used in various ways during bridge deck demolition. For example, drilling creates voids where splitting or blasting agents may be placed. Drilling can also be used to define cutting directions or to weaken a component. Stitch-drilling creates overlapping small holes around the perimeter of a specific area of concrete and removes concrete at any depth or angle (Chynoweth et al. 2001). However, this method is practical only when removing concrete more than 18 in. deep, uncommon in bridge work (Manning 1991).

A typical drill includes the drill bit, chuck, torque selection ring, side handle, on and off trigger, forward and reverse switch, and a grip. Smaller drills are electronically powered and larger drills are hydraulically or pneumatically powered. Most drills used in deck removal operations have core bits made with low carbon steel, high carbon steel, carbide, or brazing diamond segments on steel shanks. The steel bits are usually coated with black oxide, titanium nitride, titanium aluminum nitride, titanium carbon nitride, diamond powder, or zirconium nitride to extend the cutting life of the bits.

Drilling is reasonably quiet and relatively inexpensive and produces little vibration and dust. However, operators should be aware that drill bits might damage steel girder flanges or blowout the bottom of the deck.

Splitting

Splitting involves applying tension on a pre-defined path within the concrete to fragment it in a controlled way. Two primary types of splitting are mechanical splitting and chemical splitting. Before splitting can be applied, holes must be drilled to accommodate the mechanical splitting equipment or the chemical splitting agent. The diameters, depths, spacing of holes, also collectively called the hole pattern, are all critical to the effectiveness of any concrete splitting operation. Hole patterns control the break orientation and protect some areas from unintended damage.

Mechanical splitting means that the concrete is placed in tension by inserting a mechanical splitter in a predrilled hole. Mechanical splitters are usually hand-held tools powered by hydraulic pressure. The splitter consists of a steel wedge placed between two hardened steel feathers in the lower cylinder and a piston in the upper valve cylinder. When the piston is pressurized, it pushes the wedge forward and applies forces on the feathers and thus against the sides of the hole. These feathers can exert a force of 125 to 410 tons (Abudayyeh et al. 1998).

Chemical splitting creates pressure in holes by using expansive chemical agents. The main component in chemical splitting agents is calcium oxide, which expands to about three times its original volume when hydrated with water. During use, the chemical powder is mixed with cold water to form slurry, which is then placed into pre-drilled holes. As the slurry hydrates, it expands over a period of approximately 48 hours, first cracking the concrete and then causing the cracks to propagate and widen. Typical pressures of 3000 psi (20MPa) after 12 hours and 9000 psi (62MPa) after 48 hours have been reported (Manning 1991).

Crushing

Crushing basically applies opposing forces on both sides of the concrete element to cut the internal reinforcement and break the concrete simultaneously. Using this method, both materials can be recycled.

Crushing tools, typically a jaw-like attachment mounted on an excavator, can produce crushing forces that break both the concrete and reinforcing steel. Three types of jaws are available including concrete cracking jaws, shearing jaws, and pulverizing jaws (Manning 1991). Concrete cracking jaws are designed for removing large sections of concrete. Shear jaws are used in cutting both concrete and reinforcement. Pulverizers are used to separate concrete from reinforcing steel. During demolition, crushers can be either fixed or flexible in the snapping direction and can be articulated with a rotator to adjust the snapping directions (Manning 1991).

The crushing method is relatively rapid and has minimal vibration and noise. Falling materials and debris must be collected and removed. This method is difficult to use over beams and the concrete above the girders will still require hand removal.

Blasting

Blasting, placing explosives in a certain pattern of holes to fracture concrete in a controlled way, is sometimes used in bridge demolition. Explosives produce shock waves and expanding gases in pre-drilled holes to form and widen cracks and fracture the concrete (Manning 1991). The effectiveness of blasting is controlled by the hole pattern, size of the blasting charge, and concrete properties, such as thickness, strength, quality of the concrete, and location of reinforcement.

There are four major classes of explosive: dynamite; mixtures of ammonium nitrate and fuel oil (ANFO); slurries; and blends of ANFO and emulsions (Manning 1991). Nitroglycerin-based dynamites are available in a wide range of small- and medium-diameter cartridges of different lengths. Dynamite has good water resistance, and is relatively reliable and predictable. ANFO, a combination of ammonium and fuel oil, is very economical and effective for large projects. It is best suited to dry conditions, but wet-use is also possible. Slurries are water gels or emulsions formed by mixing explosive chemicals with water. Water gels are explosive chemicals dissolved in water, while emulsions are explosive chemicals surrounded by a fuel mixture of wax and oil in water. Both can be either sensitive or insensitive to initiation by different formulations. Slurries are available in small- and medium-diameter cartridges or in bulk form. Emulsions and ANFO blends, a mix of high-velocity explosives in various percentages, are formulated to achieve varying degrees of water resistance, oxygen balance, density, velocity, pressure, environmental impacts, and cost (Manning 1991).

Blasting is a rapid removal method for large areas, if achieved correctly. This method is more suitable for removing an entire bridge than for deck removal only. Handling explosives is inherently dangerous. Therefore, this requires significant expertise to control the site, and maintain the safety of workers and the general public (Chynoweth 2011). Blasting creates significant noise, dust, vibration, and falling materials in a short time.

Peeling

Removing a concrete bridge deck by peeling off the concrete by applying vertical forces on the deck to break the concrete free from the girder is a relatively new deck removal method. The method uses an excavator, a slab crab, and machine mounted bucket attachments (Morcous et al. 2013). Individuals have expressed concern that peeling might weaken shear connectors, but there is no published literature supporting or refuting this concern.

Peeling is a relatively rapid removal method, but results in notable vibration, noise, dust, and falling materials. It has not been used in deck removal projects in Iowa. This method was investigated as part of the study reported here.

Steel Girder Damage Repair

Cuts, dents, and bends are typical steel girder damage types that are caused by deck removal operations. Cuts and dents are typically repaired by grinding. Bends can be repaired by heat-straightening. Carrato (2013) discussed welding repair on structural members and pointed out that methods for repairing cracks are applicable to repairing cuts. This section reviews methods for repairing damaged steel girders.

Grinding

Grinding repairs minor damage such as cuts, gouges, nicks, and dents that are typically less than 0.25 in. deep (NY DOT 2009). This repair method prevents cracks, particularly at surfaces of flanges, by grinding sharp edges to smooth surfaces. Bhatt et al. (2012) provided a two-step repair procedure for shallow nicks and gouges in steel members: (1) grind out the defect and blend the edges of the defect into the surface of the surrounding material at a 1:12 maximum slope and (2) prime and paint the exposed surfaces. Alberta Transportation (2004) specified that nicks and gouges shall be removed by grinding provided that the repaired cross-sectional area is at least 98% of the original cross-section. This repair should be accomplished by fairing to the edge of the material with a 1:10 maximum slope. Grinding marks should be parallel to the rolling direction. Specific requirements for grinding are based on the location and depth of the damage.

For example, damage at the negative moment region of a bridge girder has a higher potential for crack propagation and typically has more stringent repair requirements.

Welding

Welding corrects cuts and cracks in steel girders. This method typically requires specific welding procedures and certified welders to produce high quality welds (Carrato 2013).

A typical welding repair includes damage removal, edge preparation, root placement, weld passes, grinding welds to a smooth surface, and inspection of the completed weld (Carrato 2013). A specific welding repair procedure for full-depth cracks is outlined in “Welded Repair of Cracks in Steel Bridge Members” (Gregory et al. 1989). Carrato (2013) reported that this procedure can also be used to repair cuts.

1. The base metal was preheated to 150° F.
2. The crack was cut out from one side by air carbon arc gouging to approximately half-plate thickness.
3. The groove was cleaned by rotary disc grinding, completing the required groove radius of 0.375 in. and angle of 20°.
4. After cooling, visual and magnetic particle testing were performed on the grove and groove edges.
5. The base metal in the crack area was preheated to 250° F for welding.
6. The root, intermediate and final weld passes were completed, with visual inspection performed upon completion of each pass.
7. Slag inclusions were removed and weld underfill repaired.
8. Weld reinforcement was ground flush with the base metal.

9. The area was post-heated to 400° F for one hour and covered by 6.25 in. thick Owens-Corning Fiberglass R-19 insulation for slow cooling.
10. This process was then repeated for the other side of the web.
11. Ultrasonic testing was performed in compliance with American Welding Society (AWS) Bridge Welding code AWS D1.5-88. The tension member requirements were used.
12. Unsatisfactory repairs were gouged out and rewelded. (Gregory et al. 1989)

New York DOT (2009) recommended that impact damage be repaired for any of the following:

(1) Any damage that extends less than 0.25 in. into the base metal of the structure may be repaired by grinding. The base metal shall be made smooth and flush and shall be faired-out to a slope no less than 1:10 by grinding;

(2) Dents and gouges greater than 0.25 in. deep shall be repaired by welding using the shielded metal arc welding (SMAW) process;

(3) If cracks present at the impact locations, grind and remove cracks and then continue with welding repair.

Other repair methods

Other repair methods (e.g., heat-straightening, strengthening, or replacing damaged structure members) are rarely used in deck removal projects, but deserve some mention here. Heat-straightening damaged steel is accomplished by gradually applying controlled heat in specific patterns on plastically deformed regions. The FHWA Guide for Heating-Straightening of Damaged Steel Bridge Members (2013) covers these topics: (1) heat straightening basics; (2) assessing, planning, and conducting successful repairs; (3) the effects of heat straightening on the material properties of steel; (4) the heat straightening of flat plates; (5) the heat straightening rolled shapes; and (6) heat straightening repair of localized damage.

Strengthening restores structural functionality by retrofitting existing structures or adding new structural elements such as cover plates, post-tensioning systems, or carbon fiber reinforced polymer (CFRP) strips. Sectioning and replacing portions of damaged structures or replacing whole structure members can be used to repair severe damage.

Research Methods

This research used qualitative methods to collect information prior to employing experimental methods. The former methods include interviews, surveys, and workshops (considered as group interviews). The latter methods include small-scale trials and laboratory tests. This section reveals previous literature on those methods.

Interviews, workshops, and surveys

Koro-Ljungberg et al. (2008) stated that individual interviews, focus group interviews, and surveys and questionnaires are common data collection methods in qualitative research. Workshops are equivalent to focus group interviews in this study. Interviews are the most appropriate methods to get experience of interest, perceptions of selected participants, and answers to specific questions (Chrism et al. 2008). Interviews are generally classified into three types including structured, semi-structured, and unstructured interviews. Structured and semi-structured interviews are guided by pre-determined, open-ended questions. Semi-structured interviews have flexibility in exploring addition question during interview process. Unstructured interviews provide the most flexibility and can be formal or informal (Chrism et al. 2008).

Surveys are another non-experimental, descriptive research method that can use either qualitative or quantitative measures. There are two basic types of surveys: cross-section surveys and longitudinal surveys (Babbie 1973). Cross-section surveys collect data at a single point in time. Longitudinal surveys gather information over a period of time. Both Manning (1991) and Tadros et al. (1998) used a cross-section survey "(1) to investigate the current practices for replacement of existing concrete decks and the possible improvements of the deck replacement procedures and (2) to solicit recommendations for new bridge superstructure designs to enhance future rapid deck replacement".

Experimental research

The two experimental research methods used in this study are small-scale trials and laboratory tests. Small-scale trials are preferred to explore and validate new methods when field trials are expensive. Laboratory tests, or true experiments, have at least two groups: control group(s) and experimental group(s). Control groups provide baseline data for comparison. Experimental groups are defined by the variables under study. The specific methods used in the experimental research conducted for this study are discussed in the methods chapter.

Sustainable Infrastructure Rating Systems

Sustainable development is defined as "development that meets the needs of the present without compromising the ability of future generation to meet their own needs" (WCED 1987). The efforts of sustainable infrastructure development have undertaken in the U.S. and worldwide. For example, New Zealand, the United Kingdom, and the European Union have developed national strategies to improve the sustainability of their infrastructure systems (Barrella 2010). The U.S. Federal Government and 14 state DOTs have included sustainability in their mission statements (Jeon and Amekudzi 2005). Bahrevar (2013) identified 17 infrastructure sustainability tools that were created after 2003. This study first focused on 16 infrastructure sustainability tools in Table 1.

Table 1. Infrastructure sustainability tools

Infrastructure Sustainability Tools	Developed By	Year
CEEQUAL	ICE (The UK)	2003
PB Highway Sustainability Checklist	PB	2005
Greenroads™ Rating System	Söderlund et al.	2006, 2007, 2010
STARS	North American STC	2007
GreenLITES	NYSDOT	2008
GreenPave	MTO (Canada)	2008
STEED	H.W. Lochner, Inc.	2008, 2010
Guidelines and Performance Benchmarks	SITES™	2009, 2014
Green Guide for Road	CaGBC and Stantec	2009
I-LAST	IDOT, IRTBA, ACEC-IL	2009
BE^2ST-in-Highways	Wisconsin DOT	2010
Sustainable Infrastructure Guidelines	PANYNJ	2010
Envision™ Rating System	ISI	2011
PEACH Roads	Cobb County	2011
INVEST	FHWA	2012
IS rating scheme	ISCA (Australia)	2012

These tools typically consist of a rating scorecard and a reference guide that defines categories, criteria, points, and weights (Table 2) of sustainability goals. The sustainable practices are typically summarized in criteria format and grouped in categories. Depending on the focus of the rating system, each criterion or category may weigh differently by assigning points. Note that the word "credits" has been defined in some sustainability tools to mean either criteria or points.

Table 2. Word usage in sustainability tools

Word	Usage
Categories	Define a group of sustainability criteria
Criteria	Express sustainability goals
Points	Assigned to criteria and added to compute the final score or rating
Weights	Reflect the importance of criteria relative to the total possible score

Infrastructure sustainability tools were developed by independent authors to meet their sustainability goals and project types (Table 3). For example, Envision™ was used for most infrastructure projects. I-LAST was used for Illinois highway projects.

Table 3. Applicable project types of infrastructure sustainability tools

Project Type	Infrastructure Sustainability Tools
Infrastructure	CEEQUAL, STEED, the PANYNJ Sustainable Infrastructure Guidelines, Envision™, IS rating scheme
Highways	PB Checklist, STARS, GreenLITES, I-LAST, INVEST
Roads	Greenroads™, Green Guide for Road, PEACH Roads
Pavement	GreenPave, BE^{2}ST-in-Highways
Landscape	Guidelines and Performance Benchmarks

Among those 16 tools, GreenLITES, I-LAST, the PANYNJ Sustainable Infrastructure Guidelines, Envision™, and INVEST were used in the United States and included bridges in their project rating. These five tools were selected for further review to explore possibilities of improving sustainability of deck removal projects.

GreenLITES

The New York State Department of Transportation (NYSDOT) developed GreenLITES (Green Leadership in Transportation and Environmental Sustainability) in 2008 to improve their transportation sustainability (NYSDOT 2008). This rating system is a mandatory tool for all NYSDOT highway projects. The GreenLITES rating system promotes the best sustainable practices in the planning, design, construction, and operations and maintenance phases (McVoy et al. 2010).

GreenLITES summaries a total of 175 (excluding 3 for innovation/unlisted) sustainable practices into five categories in Table 4. An additional of 22 sustainable practices has been added to the rating system in 2010 comparing to the original version in 2008. Percentages of point weight indicate that sustainable sites, material and resources, energy and atmospheres are three main focuses of the GreenLITES sustainability rating system. Four levels are assigned based on points earned in each category. The GreenLITES levels are: Certified (15-29 points), Silver (30-44), Gold (45-59), or Evergreen (60 points or more).

Table 4. GreenLITES sustainability rating system categories (v 2.1.0) (NYSDOT 2010)

Categories	Criteria	Possible Points	Point Weight (%)
Sustainable Sites	55	81	29
Water Quality	12	20	7
Material & Resources	39	66	24
Energy & Atmosphere	69	104	37
Innovation/Unlisted	3	7+	3
Total:	178	278+	100

GreenLITES is an internal management tool for NYSDOT to measure sustainable practices and identify potential improvements (McVoy et al. 2010). This rating system has been used to evaluate 326 projects by 90 operation groups between 2008 and 2011 (Krekeler 2011).

I-LAST

The joint sustainability group that formed by IDOT, the IRTBA, and the ACEC-Illinois developed Illinois Livable and Sustainable Transportation (I-LAST) rating system in 2009 (IDOT et al. 2010). This is a voluntary tool to encourage sustainable practices and evaluate sustainability improvement in highway projects regardless of complexity and size (Clevenger et al. 2013). I-LAST includes sustainability improvements in planning, design, and construction phases (Knuth et al. 2013).

I-LAST consists of 153 (excluding 1 for innovation) sustainable or livable practices in eight categories to advance sustainability in highway projects (FHWA 2012). These sustainable or livable practices, recognized as criteria, have a hierarchic scoring system from 1 to 3 points per criteria (Clevenger et al. 2013) The self-evaluator can simply select yes or no to identify applicable criteria and scores for their projects. A total of 233 points are achievable in I-LAST rating system. The distribution of these points indicates that I-LAST weighs environmental, transportation, materials, and design slightly higher than planning and lighting. I-LAST does not provide an awards system. The evaluation is based on a ratio of acquired points over achievable points. Further development of an awards system depends on future feedback (Clevenger et al. 2013).

Table 5. I-LAST sustainability rating system categories (IDOT et al. 2009)

Categories	Criteria	Possible Points	Point Weight (%)
Planning	10	19	8
Design	18	27	12
Environmental	30	51	22
Water Quality	23	35	15
Transportation	31	42	18
Lighting	9	16	7
Materials	32	40	17
Innovation	1	3	1
Total:	154	233	100

I-LAST is primarily used by IDOT and engineering firms as a guide book for highway projects in Illinois (Knuth et al. 2010). For example, the I-55 at arsenl road interchange project achieved 87 out of 165 possible points. The budget of this project is $60 million. The project used recycle asphalt, native plants, and more than 60 percent of regional materials.

The PANYNJ Sustainable Infrastructure Guidelines

The Port Authority of New York and New Jersey (PANYNJ) created the PANYNJ Sustainable Infrastructure Guidelines as a section of their Sustainable Design Guidelines to meet the Administrative Instruction 45-2 (AI 45-2 issued on July 13, 2006) "*to reduce adverse environmental impacts of the design, construction, operation and maintenances and occupancy or leasing of new of substantially renovated buildings and facilities, reconstruction projects, and programs*" (PANYNJ 2011). The goals of the guidelines are to reduce operational costs, extend project lifecycle, and optimize infrastructure project design by implementing sustainable engineering practices (PANYNJ 2011).

The PANYNJ Sustainable Infrastructure Guidelines include 50 criteria (referred to as credits) and 7 categories (Table 6). These criteria have points values that range from 1 to 3 and add up to a total of 100 points. Percentages of point weight show that the PANYNJ Sustainable Infrastructure Guidelines primarily focus on site sustainability. The guidelines offer three levels of awards: Certified (29–38 points), Gold (38–48), and Platinum (49–65).

Table 6. The PANYNJ Sustainable Infrastructure Guidelines categories (PANYNJ 2011)

Categories (or Sections)	Criteria	Possible Points	Point Weight (%)
Site	21	43	43
Water	4	10	10
Energy	6	17	17
Material	9	14	14
Construction	7	10	10
Operations and Maintenance	2	4	4
Innovation	1	2	2
Total:	50	100	100

The PANYNJ Sustainable Infrastructure Guidelines are required for Port Authority capital projects (PANYNJ 2011). DesRoches et al. (2011) reported that four projects applied the PANYNJ Sustainable Infrastructure Guidelines. For example, the runway 13R-31L (the Bay Runway) at John F. Kennedy International Airport was rehabilitated by using the guidelines. This project achieved $2 million cost savings and 30,000 cubic yards of waste reduction (DesRoches et al. 2011).

Envision™

The ISI and the Zofnass Program for Sustainable Infrastructure at Harvard University collaboratively developed the Envision™ Rating System (Envision™) in 2011. The system focuses on civil infrastructure, such as roads, bridges, pipelines, railways, airports, dams, levees, landfills, and water treatment systems (ISI and Zofnass 2012).

The Envision™ sustainability rating system has 60 criteria (refer as credits) divided into 5 categories (Table 7). Each criterion is evaluated by five possible levels of achievement: improved, enhanced, superior, conserving, and restorative. A point value is also assigned with a level of achievement in a criterion. Evaluation is based on a percentage ratio of acquired points over applicable points. This system recognizes four levels of award including Bronze (20%), Silver (30%), Gold (40%), and Platinum (50%). These awards require that at least one person on the project team must be an Envision™ sustainability professional (ENV SP) and the project must be verified by an Envision™ project verifier to obtain third-party verification and public recognition (Clevenger et al. 2012, ISI and Zofnass 2012).

Table 7.The Envision™ sustainability rating system categories (ISI Zofnass 2012)

Categories	Criteria	Possible Points	Point Weight (%)
Quality of Life	13	181	22
Leadership	10	121	15
Resource Allocation	14	182	22
Natural World	15	203	25
Climate and Risk	8	122	15
Total:	60	809	100

The Envision™ rating system is an overarching assess tool for infrastructure sustainability. Hirsch (2012) reported that Envision™ pilot tested four Colorado projects. HDR, Inc. (2013) completed the William Jack Hernandez Sport Fish Hatchery in Anchorage, Alaska by using Envision™. The project teams reduced 95% of water and energy comparing to conventional hatcheries. This project received an Envision™ Gold award.

INVEST

Infrastructure Voluntary Evaluation Sustainability Tool (INVEST) is a web-based, self-directed, free tool created by the Federal Highway Administration (FHWA) in 2012. This tool facilitates state DOTs, MPOs, and local transportation agencies to assess and improve the sustainability of transportation projects and programs (Bevan et al. 2012). INVEST applies to three project stages including system planning, project development, and operations and maintenance (Bevan et al. 2012).

INVEST has 60 criteria divided into three categories (refer as modulus) in Table 8. This system provides a specific pre-defined scorecard for project development base on six types of projects: paving (12 applicable criteria), urban basic (24), urban extended (29), rural basic (21), rural extended (25), and custom core criteria (minimum 19 criteria). Criteria are equally weighted at 15 points maximum in system planning and operation and maintenance categories except 10 points maximum for bonus credits. Criteria in project development are weighted in a range from 1 to 10 points. A total of 586 points are distributed into the 60 criteria. Percentages of point weight indicate that INVEST concentrates on system planning slightly more than operation and maintenance followed by project development. Similar to Envision™, this system evaluates achievements by the percentage ratio of achieved points over applicable points and offers four levels of awards: bronze (30%), silver (40%), gold (50%), and platinum (60%).

Table 8. The INVEST sustainable rating system categories (FHWA 2012)

Categories	Criteria	Possible Points	Point Weight (%)
System Planning	17	250	43
Project Development	29	126	22
Operation and Maintenance	14	210	36
Total:	60	586	100

Many state DOTs used this tool to improve sustainability of their transportation systems. For example, The Ohio DOT used the INVEST to evaluate the sustainable performance of Cleveland Innerbelt (George V. Voinovich) bridge (Clevenger et al. 2013). Transportation agencies reported a total of 27 projects that using INVEST (FHWA 2013).

CHAPTER 3. INTERVIEWS ON COST-EFFECTIVE ALTERNATIVES

Concrete deck removals requiring very cautious operations are expensive and time consuming. Individuals have been known to be concerned with costs associated with carefully remove concrete decks because they fear that costs may exceed the costs to replace the entire superstructure or bridge. This is especially true when damage occurs which results in construction delays and extra costs for repair which may result in cost overruns. This chapter describes three interviews conducted to seek information on cost-effective bridge replacement alternatives (e.g., deck, superstructure, or entire bridge replacements).

Methods

Researchers at Iowa State University conducted three semi-structured telephone interviews to explore the cost of bridge replacement alternatives from a Midwest DOT estimator and two bridge contractors. Each interview took approximately 1.5 hours. A questionnaire (Appendix B) was used to guide the interview process. The DOT estimator has more than 30 years of bridge engineering and cost estimating experience. One of the contractors has 24 years estimating experience, including a 10-year experience as chief estimator in Texas and has performed a number of bridge deck replacement projects using different deck removal methods. The other contractor is a project director and has 16 years of experience with approximately eight years in steel girder bridge projects in Arkansas.

Interview Findings

Three telephone interviews were conducted at the Institute for Transportation on October 15, 2013, November 19, 2013, and December 12, 2013. The interviews were structured to obtain information in three main topical areas: (1) removal methods and damage, (2) cost and duration, and (3) salvage or replacement.

Removal methods and damage

The interview participants confirmed that sawing and jackhammering are conventional methods for removing concrete decks from steel girders. These methods are commonly used by both state DOTs and contractors. The typical procedure to remove concrete between steel girders is sawing the deck into sections and then lifting these sections by cranes. The concrete on top of the steel girders is typically removed by a handheld jackhammer or a backhoe.

The consequence of damage is generally not considered in cost estimating or decision-making by either the DOTs or contractors. Most DOTs require contractors to submit a demolition plan that meets their specifications and special provisions. Special provisions typically specify that the contractor is responsible for repairing any damage (e.g., dents, cuts) to the structure that is planned to remain in place. In most cases, the interviewees indicated that damage is typically minimal and requires only insignificant repairs. If unexpected damage occurs, the designer of record or the DOT would be responsible to estimate the damage, recommend repair methods, and evaluate the condition of the resulting repair.

Cost and duration

The Midwest DOT uses cost-based estimates for major items and historical pricing for minor items. Deck replacements are considered renovations that should not exceed 70% of the cost of the entire bridge replacement. For estimating purposes, contractors typically keep historical cost data for preparing new estimates. Estimates begin with the quantity takeoff, and then that quantity is converted to man hours by dividing by typical production rates. The required duration is then calculated by adding the total man hours. Meanwhile, equipment, operation costs, rental costs, and small tool supplies are considered in the estimate.

Salvage or replacement

Salvaging steel girders is desirable when the girders have adequate remaining service life and capacity. Fortunately, most damage caused by deck removal methods and equipment is typically minimal and not a factor when considering to either just replace the deck or to replace the entire structure.

State DOTs typically decide whether to salvage or replace existing bridge decks or superstructures and dictate demolition work in contract terms and plans. In design-build projects, the contractor might decide to either salvage or replace steel girders. In other cases, such as public private partnerships, the contractor will own, maintain, and operate the project for more than 30 years. The contractor will perform a cost analysis to determine the most economical strategy.

CHAPTER 4 SURVEYS AND WORKSHOPS ON CURRENT PRACTICE

Because there was limited literature available on current deck removal practices, the research team at Iowa State University conducted a survey and a workshop to investigate the state-of-the-art deck removal practices on steel girders. A parallel study of deck removal methods for concrete girders was undertaken in University of Nebraska-Lincoln (UNL). The research team at UNL conducted a survey and a workshop for deck removal methods on concrete girders. These surveys and workshops were designed to determine methods that state DOTs currently accept and to develop ideas for methods worth further exploration.

Methods

A survey questionnaire (Appendix A) was sent to the 50 state DOTs to collect information on full-depth concrete deck removal methods from steel girders. This questionnaire focused on eight deck removal methods: sawing, use of percussive tools, hydrodemolition, drilling, crushing, splitting, ball and crane, and blasting. Evaluations of these methods were based on cost, duration, noise, safety, and damage to the superstructure. The survey questionnaire addressed four main topics: (1) available special provisions and allowed methods for concrete deck removal; (2) relative cost, duration, noise, safety, and damage related to each method; (3) typical repair methods of damage, and (4) innovative deck removal ideas.

A workshop that focused on methods for removing concrete decks from steel girders was held at the Bridge Engineering Center at Iowa State University. Eighteen workshop participants (8 bridge owners, 6 contractors, and 4 researchers) identified and discussed currently used deck removal methods (e.g., sawing, drilling, splitting, crushing, and hydrodemolition). The strengths and weaknesses of each method were discussed at length with the goal of identifying methods that might be the most promising for future development and usage. For the most part, the opinions expressed by the workshop participants were very similar to those obtained from the literature review.

Methods for removing concrete decks from concrete girders were investigated via a survey conducted by the University of Nebraska–Lincoln. Also, researchers from the University of Nebraska–Lincoln held a workshop focused on the removal of decks from concrete girders. Thirty-six workshop participants discussed current practices and brainstormed new, innovative removal approaches.

Survey of State DOTs on Methods for Removing Concrete Decks from Steel Girders

The research team received 28 responses from 50 state DOTs, a 56% response rate. The following states responded.

Delaware	Florida	Georgia	Hawaii
Illinois	Kansas	Maine	Maryland
Michigan	Minnesota	Mississippi	Missouri
Nebraska	Nevada	New Hampshire	New Mexico
New York	North Dakota	Oklahoma	South Dakota
Tennessee	Texas	Utah	Vermont
Virginia	West Virginia	Wisconsin	Wyoming

Deck removal methods

Ten states reported that they have special provisions for full-depth concrete deck removal. For example, New York State DOT has a special specification for removing slabs from steel girders that requires saw cutting 6 in. outside of the edge of the beams and removing the rest of the slab over the beams by hydrodemolition. This special provision has only been used 4 times in the last 10 years. Tennessee DOT limits the maximum pneumatic hammer sizes to 90 lb for full-depth concrete removal except over beams and 60 lb for removal over beams. Most state

DOTs require the submission of the deck removal plan outlining the methods to be used including descriptions of the proposed equipment for prior approval.

Respondent states indicated that the top three most commonly used deck removal methods are saw cutting, use of percussive tools, and hydrodemolition as shown in Figure 2. Missouri and Minnesota DOTs commented that sawing and the use of percussive tools are the primary methods used in their states. Mississippi and New Mexico DOTs indicated that they have successfully used hydrodemolition to remove deteriorated concrete for deck repair.

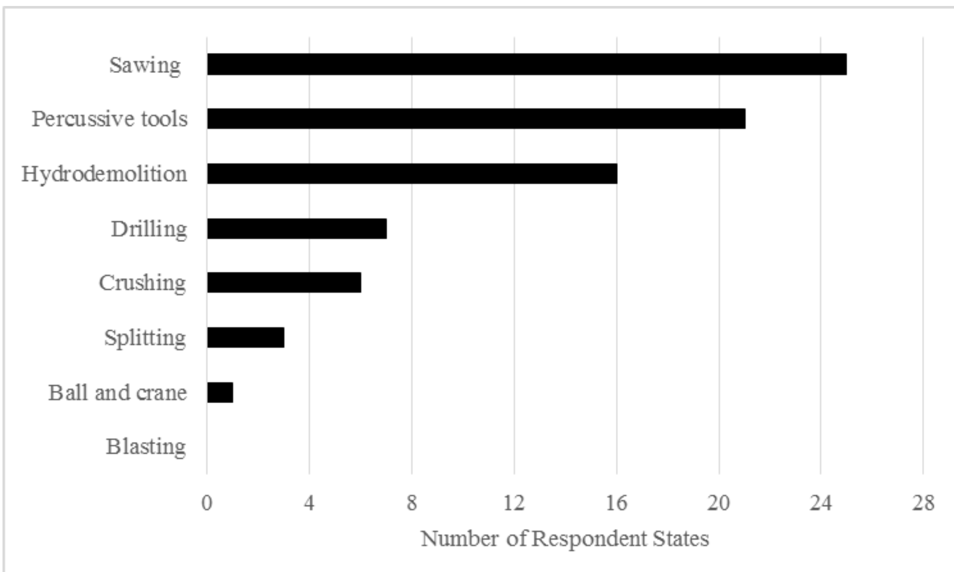

Figure 1. Currently allowed deck removal methods for steel I-girders

Relative cost, duration, noise, safety, and damage

The relative cost, duration, noise, safety, and damage for sawing, use of percussive tools, and hydrodemolition are presented in Table 9. Sawing and use of percussive tools appear to be relatively cost-effective methods. However, these methods are noisy and may damage superstructure elements. Twelve states specifically indicated that sawing could damage the shear connectors. Four states reported rig-mounted percussive tools have a good chance of damaging the steel girders. Eighteen States reported that rig-mounted percussive tools could damage the shear connectors. Oklahoma DOT commented that saw cuts that extended into the top flanges of steel beams require expensive welding repair. A total of nineteen states indicated that use of percussive tools is extremely noisy and sawing is moderately noisy. Hydrodemolition is expensive and noisy. Ten states indicated that hydrodemolition has no chance of damaging steel girders. New Mexico DOT suggested that hydrodemolition produced minimal damage to bridge girders when the water pressure was adjusted correctly. On the other hand, Tennessee DOT recommended hydrodemolition for only partial concrete deck removal.

Table 9. Survey results of relative cost, duration, noise, safety, and damage

Evaluation Criteria	Sawing	Percussive Tools	Hydrodemolition
Cost	Moderate	Moderate to Low	High
Duration	Moderate to Low	Moderate to Low	Moderate
Noise	Moderate	High	High
Safety	Moderate to High	Moderate to High	Moderate
Damage	Moderate	Moderate to High	Low

Typical repair methods of damage

According to the survey responses, actions taken to repair a damaged steel girder's top flange depends on the level of damage. Small damage levels can be repaired by grinding or heat straightening. More significant damage tends to need welding, and severe damage requires full girder replacement. Most states require that contractors prepare a repair plan for approval in their bid document.

State DOTs were also asked about their experience with repair methods such as grinding, welding, heat-straightening, flange build-up, or replacing. Virginia DOT suggested grinding for nicks and gouges and full penetration groove welds for saw cut damage. Wyoming DOT recommended grinding, welding, and adding a cover plate for flange cuts depending on the cut depth.

Workshop on Methods for Removing Concrete Decks from Steel Girders

The previously mentioned workshop discussed and brainstormed the eight deck removal methods mentioned in the previously described survey. The workshop participant identified advantages and disadvantages associated with those removal methods and discussed innovative ideas and interest.

Sawing

Sawing is a relatively rapid removal method that can result in cuts at any angle with negligible vibration and no falling materials. This method generates little dust when wet-cutting is used. However, saw blades or cutting wires can possibly overheat during operation.

Breaking

Breaking (use of percussive tools) is relatively safe and rapid, but noisy, dusty and has significant associated vibration. This method requires a skilled, careful operator to avoid damaging structural elements left in place. Limiting the power and size of breaking equipment can also reduce the risk of damage.

Hydrodemolition

Hydrodemolition produces no dust. The pressure controlled cuts protect the steel beams and, when desired, the reinforcing steel from damage. However, the power units can be noisy unless muffled. Hand-held units induce operator fatigue and place the operator at risk.

Drilling

Drilling is typically combined with another method. It is reasonably quiet and relatively inexpensive. However, it was noted the drill bit might damage the steel girder flange or blowout the deck on the bottom.

Crushing

Crushing is relatively rapid, but produces noise, dust and vibrations. Falling materials are notable safety concerns. This method is difficult to use over beams and the concrete above girders will most likely still require hand removal.

Splitting

Splitting produces no vibration, little dust, and little noise. The remaining members are typically left undamaged. The splitting method is relatively safe and inexpensive for mechanical splitting. However, chemical splitting could be expensive.

Ball and crane

The Ball and crane method is relatively safe and rapid. However, the process is very dusty and noisy. This method has the least control and results in substantial vibrations.

Blasting

Blasting is a rapid removal method for large areas, if done correctly. This method is more suitable for removing an entire bridge than portion(s) of the bridge. Handling explosives is inherently dangerous. Therefore, it requires significant expertise to control the site, and maintain the safety of workers and the general public.

CHAPTER 5. SMALL-SCALE TRIALS

Three deck removal methods—hydrodemolition, chemical splitting, and peeling—were selected for small-scale, controlled, laboratory trials based on the literature review and findings from the surveys and workshops. These methods have not been frequently used to remove bridge decks, but were thought to have the potential to change and positively impact the state-of-the-art of deck removal practices.

Methods

The research team constructed three specimens for the hydrodemolition, chemical splitting, and peeling trials at the Iowa State University Structural Engineering Laboratory. Specimens were fabricated to simulate actual bridge deck conditions by using standard Iowa DOT C-4RW concrete mix (minimum compressive strength of 4500 psi or greater per Iowa DOT specifications). Grade 60 black reinforcing steel #6 bars were used at a typical 10 in. spacing for both the top and bottom layers of reinforcement. Materials, equipment, and testing procedures for each trial are documented in the following sections.

Hydrodemolition

A Midwest company specializing in hydrodemolition was invited to conduct the small-scale hydrodemolition trial at Iowa State University on October 17, 2013. The overall on-site time of this trial was approximately nine hours. The actual hydrodemolition time was approximately two hours.

Materials and equipment

The hydrodemolition specimen was a 20 ft long, 58 in. wide, and 8 in. thick reinforced concrete slab built on a 20 ft long, 10 in. wide and 0.25 in. thick steel plate. Two shear studs were installed 4 in. apart at typical 10 in. spacing on the steel plate. A plan and a cross-section views of the hydrodemolition specimen are shown in Figure 2 and Figure 3, respectively.

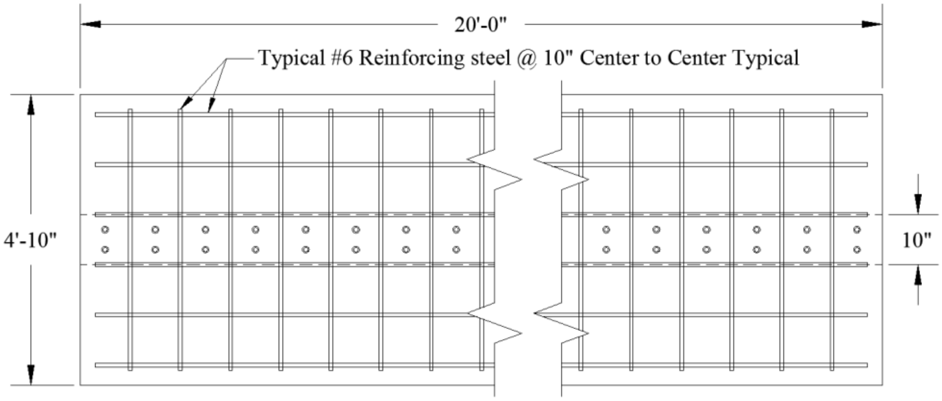

Figure 2. Plan view of the hydrodemolition specimen

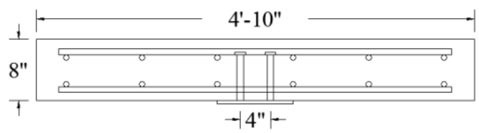

Figure 3. Cross-section view of the hydrodemolition specimen

Hydrodemolition equipment used in this trial has two primary units, a power unit and a demolition unit. The demolition unit, Aqua cutter 710V classic, was used to perform the demolition tasks (Figure 4). Technical details for the demolition unit are provided in Table 10. The demolition unit can perform horizontal, vertical, overhead, or circular demolition with a wide range of removal widths.

Table 10. Technical specifications of the demolition unit (AQUAJET SYSTEMS AB 2013)

Specification	Metric	Imperial
Length minimum	2.65 m	8.69 ft
Length maximum	2.85 m	9.35 ft
Total width	2.00 m	6.56 ft
Minimum width	1.04 m	3.41 ft
Work width range standard	0-2.14 m	0 – 7.02 ft
Working width extended	4.00 m	13.12 ft
Width of track	1.04 – 1.64 m	3.41 – 5.38 ft
Weight	2300 kg	2.54 tons
Height standard	1.6 m (@ 2 m width)	5.25 ft (@ 6.56 ft width)
Height minimum	1.42 m (hood only 1.3 m)	4.66 ft (hood only 4.27)
Max working height standard	7 m	22.97 ft
Drive Source	Diesel engine (Possibility for Hybrid (electric) drive - option)	

Figure 4. A photograph of the demolition unit (Dang 2013)

The front portion of the demolition unit contains several mechanical systems. The first mechanism is a front roller beam with mechanical stoppers. The demolition attachment moves back and forth transversely along the roller beam within the finite distance between the mechanical stoppers which determine the demolition width. The second mechanism is a roller beam mechanical system that is attached to the nozzle. The nozzle can rotate in both the longitudinal and transverse directions to form multiple angles with the concrete surface. The longitudinal angle is called the oscillating angle and the transverse angle is called the lance attack angle. Both the angle size and operation speed can be manually controlled or preprogrammed. A photograph showing the components of the hydrodemolition mechanism is given in Figure 5.

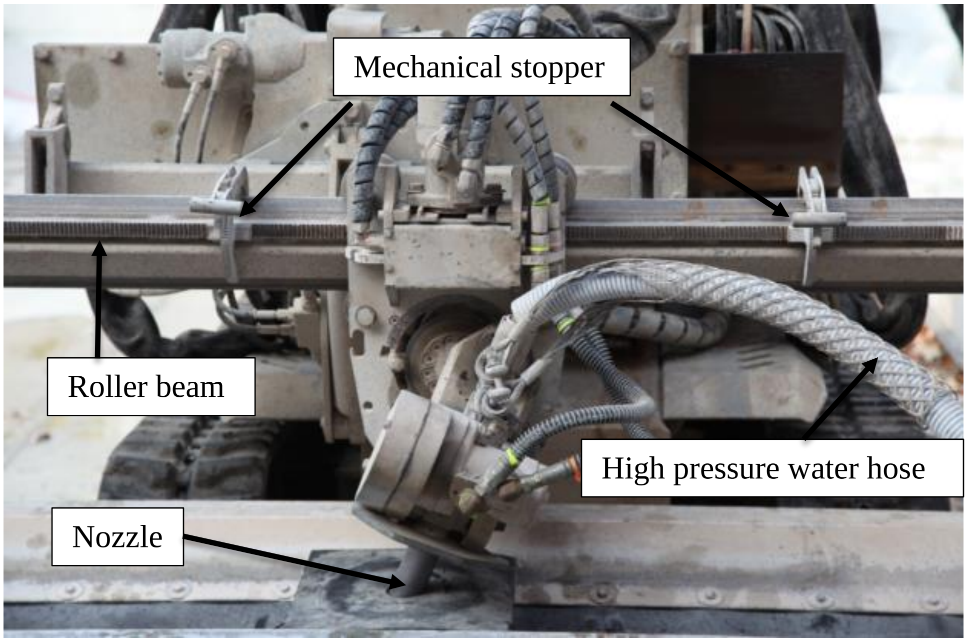

Figure 5. A photograph showing the components of the hydrodemolition mechanism (Dang 2013)

The nozzle is designed to maintain a set distance from the nozzle tip to the concrete surface regardless of the lance attack angle. The effectiveness at breaking concrete is the reciprocal of the lance attack angle; whereas, the effectiveness at removing concrete from the reinforcing steel is proportional to the lance attack angle. For example, a zero lance attack angle is more effective at breaking concrete and a 30° inclination is more effective at cleaning the reinforcing steel. A front close-up view of the hydrodemolition nozzle is shown in Figure 6.

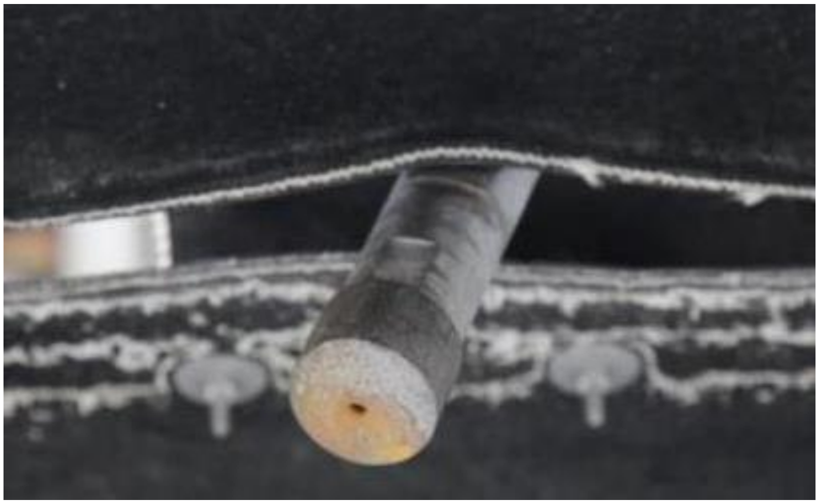

Figure 6. A photograph of front close-up view of the nozzle (Dang 2013)

The power unit used in this trial was a diesel-based 600 horsepower engine that could generate 20,000 psi pressure water and pump up to 50 gallons of water per minute. During the hydrodemolition demonstration, the pressure was set to a range of 18,500 to 19,000 psi and consumed 42 gallons of water per minute. A photograph of the power unit is shown in Figure 7.

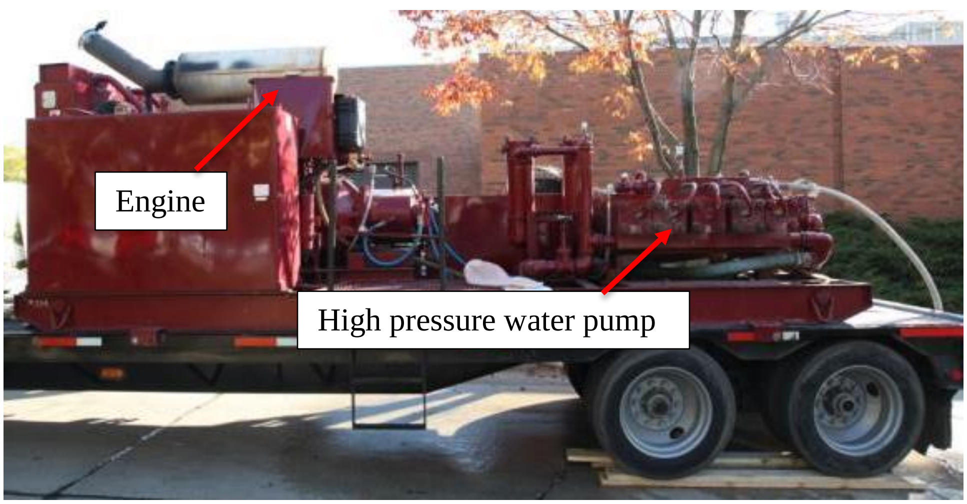

Figure 7. A photograph of the power unit (Dang 2013)

Testing procedures

To conduct the hydrodemolition trial, the operator located the demolition unit on top of the small-scale specimen and then calibrated the demolition unit. A photograph of hydrodemolition site is shown in Figure 8.

Figure 8. A photograph of the hydrodemolition site (Dang 2013)

The first hydrodemolition test demonstrated the removal of just the top layer concrete. The demolition unit was preprogrammed to perform a 2 ft wide, 4 in. deep, and approximately 18 in. long concrete removal. A photograph taken during the first hydrodemolition test is shown in Figure 9. The results of the first hydrodemolition are illustrated in Figure 10.

Figure 9. A photograph of the hydrodemolition trial (Dang 2013)

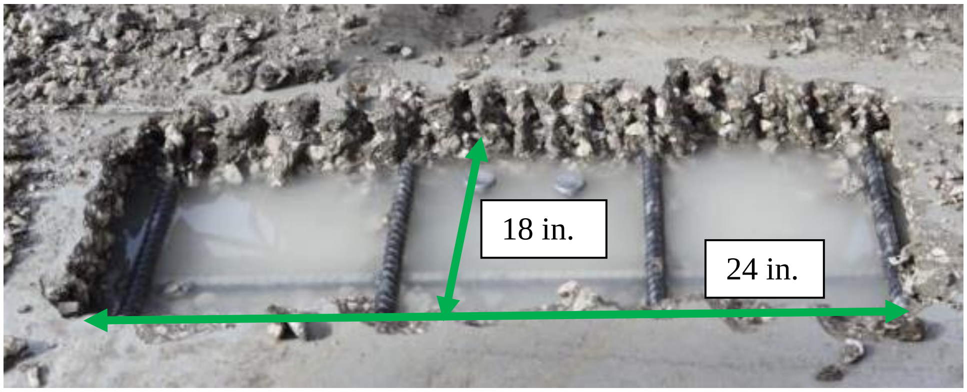

Figure 10. A photograph of the first hydrodemolition test result (Dang 2013)

The second hydrodemolition test demonstrated full-depth concrete removal. The demolition unit performed a 33 in. wide, 8 in. deep (full-depth), and approximately 13 ft long concrete removal. This demolition task took approximately an hour. A photograph of the second hydrodemolition test results is shown in Figure 11. The reinforcing steel, steel plate, and shear studs were left clean and undamaged.

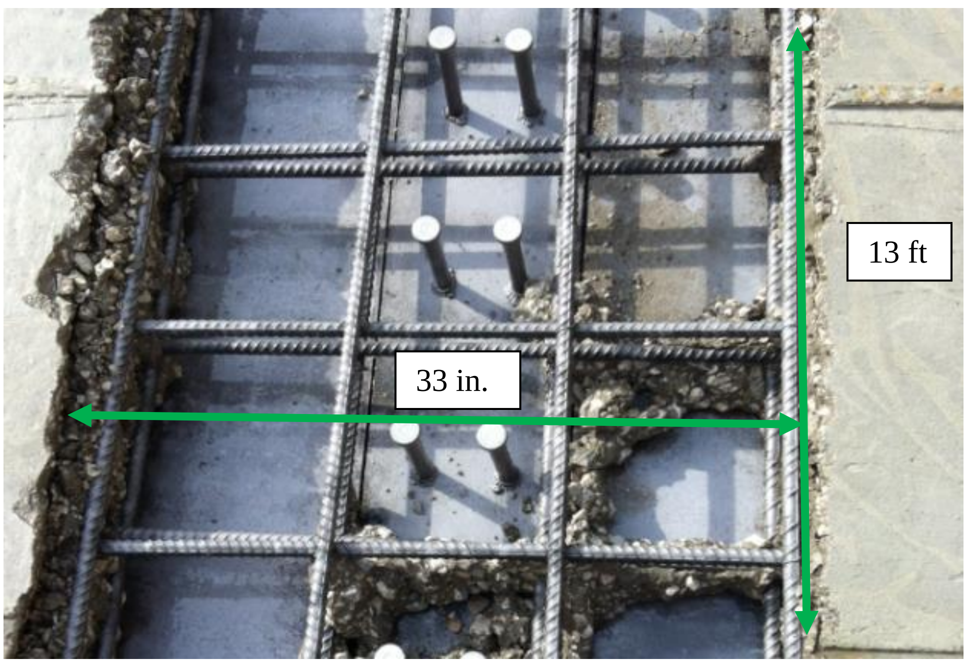

Figure 11. A photograph of the second hydrodemolition test result (Dang 2013)

Chemical splitting

The chemical splitting demonstration was performed in October 2013 near the Iowa State University Structural Laboratory. The entire chemical splitting process took approximately one week. Photographs during the splitting process were acquired from a networked camera and were time and date stamped to document the process and effectiveness.

Materials and equipment

The chemical splitting specimen was a 20 ft long, 26 in. wide, and 8 in. thick reinforced concrete slab built on a 20 ft long, 10 in. wide, and 0.25 in. thick steel plate. Two shear studs were installed 4 in. apart at a typical 10 in. spacing on the steel plate. A plan view and a cross-section view of the chemical splitting specimen are shown in Figure 12 and Figure 13, respectively.

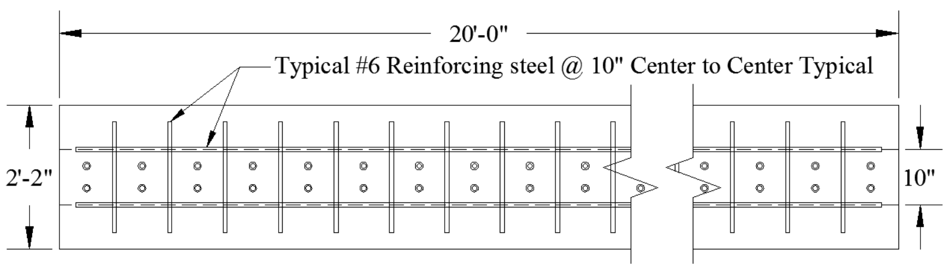

Figure 12. Plan view of the chemical splitting specimen

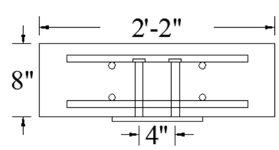

Figure 13. Cross-section view of the chemical splitting specimen

The chemical splitting agent used in this trial is comprised of lime, calcium fluoride, and calcium oxide. This general class of material produces an expansive pressure after hydration. This hydrated mixture is typically placed into predrilled holes arranged in an engineered pattern. For this trial, the chemical splitting specimen was constructed with the hole pattern shown in

Figure 14. The holes were spaced 10 in. apart longitudinally and 9 in. apart transversely, except near the end of the specimen where these holes were spaced 7 in. from the inner holes and 3 in. from the edge of the specimen. All holes were 7.75 in. deep and 1 in. diameter. In addition to observing the effectiveness of chemical splitting on the simulated bridge deck, a standard concrete cylinder with a predrilled hole in the center was also documented.

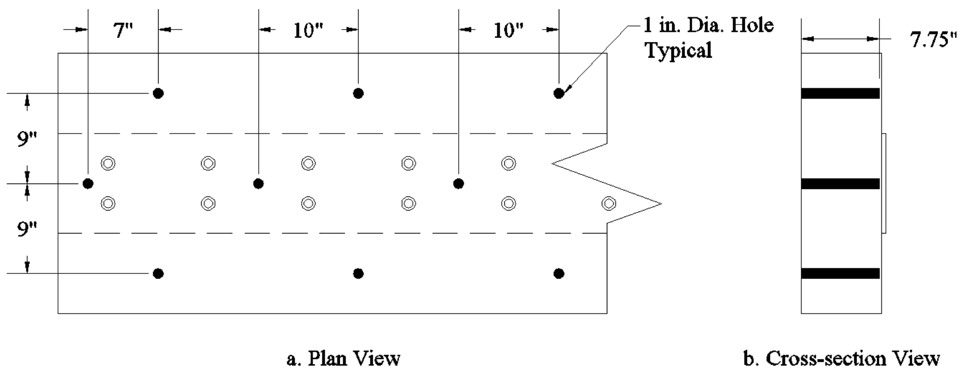

Figure 14. The hole pattern for the chemical splitting specimen

Testing procedures

To prepare the chemical splitting agent, three liters of cool, clean water were poured into a clean bucket, and 22 lb of chemical splitting agent was mixed with the water for three minutes. Then the holes were filled within 5 minutes of mixing. All holes filled with the expansive grout were then capped. A photograph during the hole drilling process is shown in Figure 15.

Figure 15. A photograph of drilling and cleaning holes taken by the networked camera

The chemical splitting process was monitored via a networked camera for six days following placement of the expansive grout in the preformed holes as shown in Figure 16. Photographs were taken every 12 minutes after grout placement.

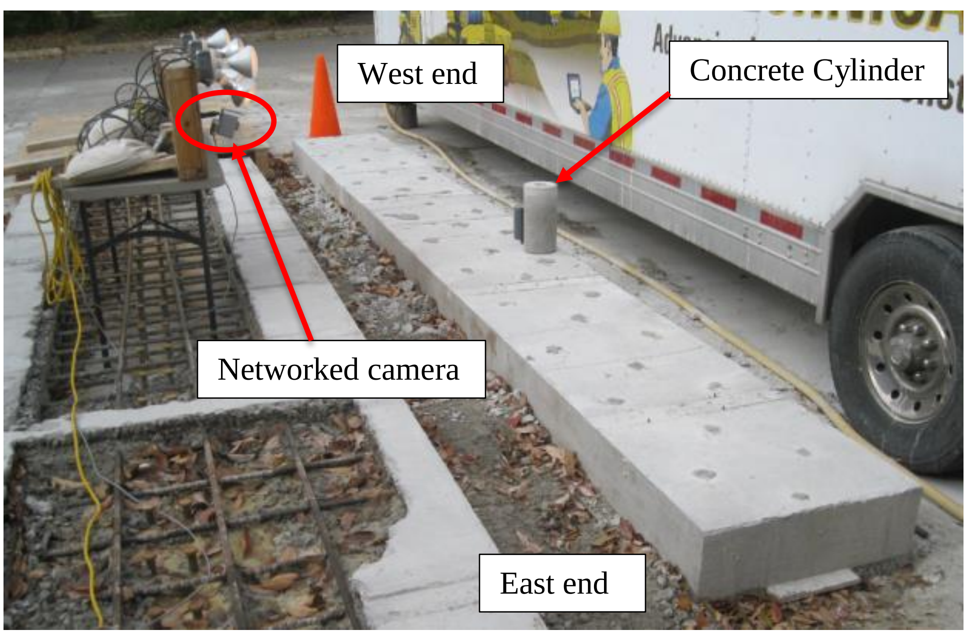

Figure 16. A photograph of the networked camera and the chemical splitting specimen (Dang 2013)

A photograph of the chemical splitting specimen after placement of the expansive grout is shown in Figure 17.

Figure 17. A photograph of the chemical splitting specimen and the grout

One day after placing the chemical splitting agent, the chemical splitting specimen was observed to be sound (Figure 18). Although it is possible that micro cracks might have developed, the research team observed no signs of cracks.

Figure 18. A photograph of the chemical splitting on day one (after 24 hours)

On day two, three major cracks developed on the top of the concrete cylinder (Figure 19). Small cracks initiated on the surface of the concrete slab, and two major cracks formed at the ends of the specimen.

Figure 19. A photograph of the chemical splitting on day two (after 48 hours)

On days three and four, the cracks initially observed on day two grew and propagated (Figure 20 and Figure 21). Additionally, new cracks developed on the surface of chemical splitting specimen.

Figure 20. A photograph of the chemical splitting on day three (after 72 hours)

Figure 21. A photograph of the chemical splitting on day four (after 96 hours)

On day five, a 25-minute rainfall occurred at 1:00 a.m. and another three-hour rainfall started at 9:00 a.m. (Figure 22). As a result, it is possible that the expansive grout absorbed additional water and may have been rehydrated.

Figure 22. A photograph of the chemical splitting on day five (after 120 hours)

On day six, the concrete slab remained as one piece (Figure 23). Large cracks were observed at both ends of the specimen and small cracks were presented in the middle of the specimen.

Figure 23. A photograph of the chemical splitting on day six (after 144 hours)

After day six, there were no further observable changes in any of the previous cracks and no new cracks developed. It was assumed that the expansive capacity of the grout had been reached and the chemical splitting trial was terminated.

Peeling

The peeling deck removal method was simulated by restraining the peeling specimen and applying uplift forces using two hydraulic jacks on each side of the steel girder under the concrete deck. The peeling trial was performed for two types of shear connectors at different times. The test was performed on the three shear stud connector section on December 11, 2013 and on the two shear stud section on January 8, 2014.

Materials and equipment

The peeling specimen was a 20 ft long, 26in. wide, and 8 in. thick reinforced concrete slab built on a 23 ft long steel H-pile (HP 10 x 57). A plan view and a cross-section view of the peeling specimen are shown in Figure 24 and Figure 25. The peeling specimen included two equal sections (Section A and B in Figure 24). Section A was fabricated with three shear studs at

3 in. spacing transversely. Section B was constructed with two shear studs at 6 in. spacing transversely. All of the shear studs were welded at a typical 10 in. spacing longitudinally on the steel HP-section.

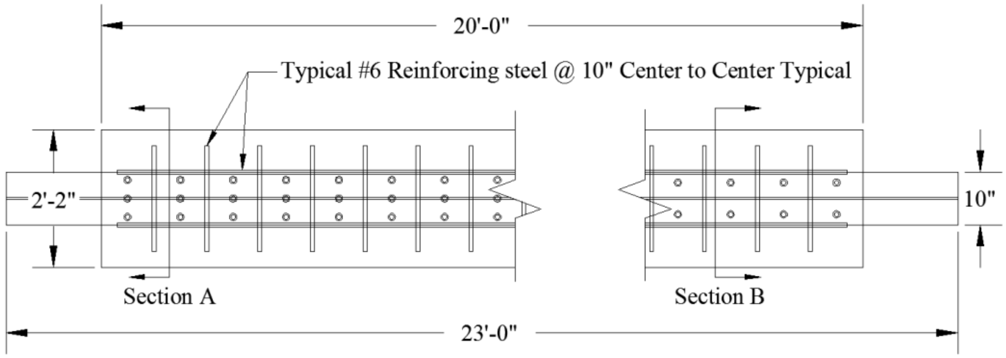

Figure 24. Plan view of the peeling specimen

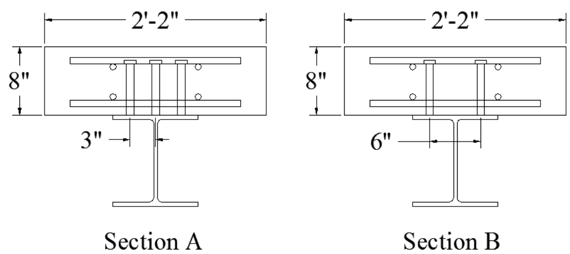

Figure 25. Two cross-section views of the peeling specimen

Testing procedures

During each trial, the concrete deck was removed from one “free” end and progressed towards the middle of the specimen. The peeling simulation consisted of a series of repeated loading steps which would represent repeated placement of the peeling equipment. During each loading step the same series of basic steps were followed. First, the specimen was securely tied to the ground. Second, two hydraulic jacks were placed under the concrete slab on each side of the steel girder (Figure 26). Third, vertical loads were slowly applied until failure occurred. Fourth, the failure mode and peak load were documented and the loading apparatus moved to the next location.

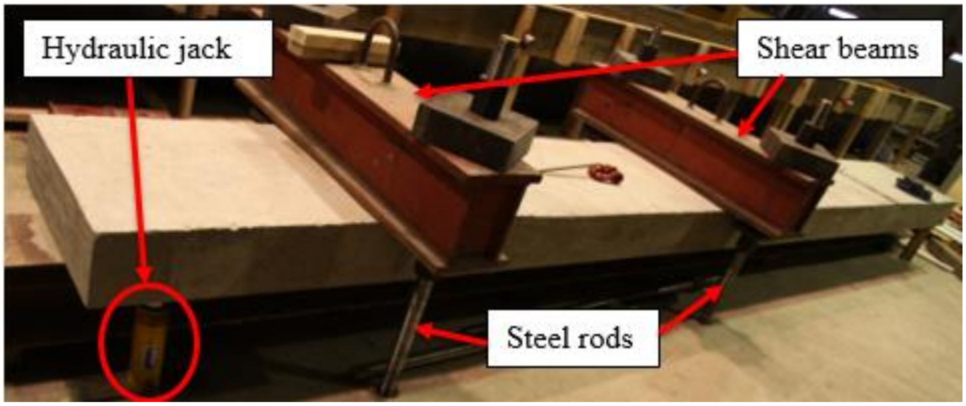

Figure 26. A Photograph of peeling trial setup

Peeling of section A (3 shear studs)

The first peeling test result is illustrated in Figure 27 and Figure 28. The failure appeared to be relatively symmetric about the longitudinal centerline of the steel girder. The peak load for this test was 21.1 kips.

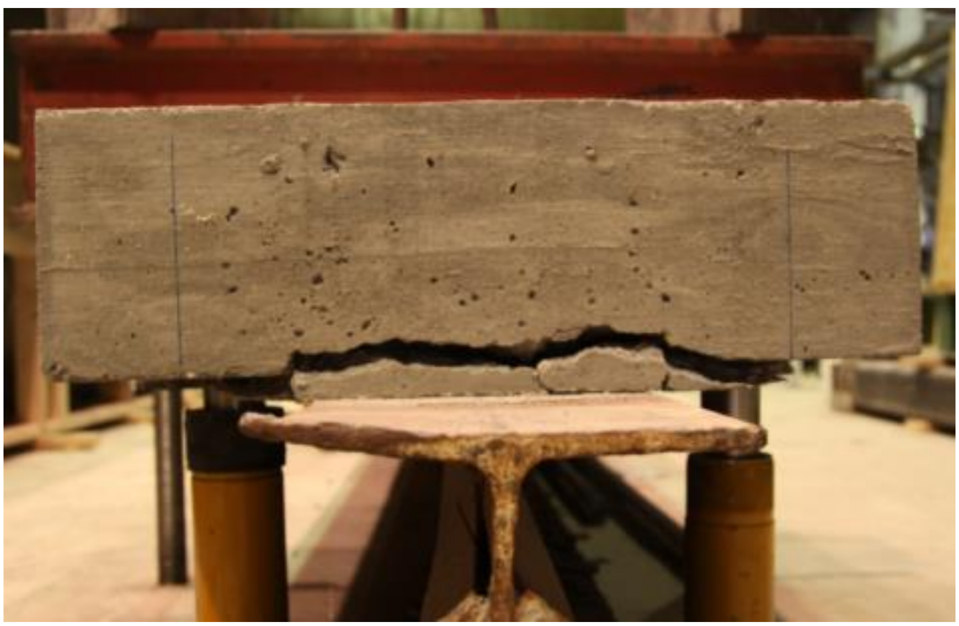

Figure 27. A photograph of the front view of the first peeling test (3 shear studs) (Dang 2013)

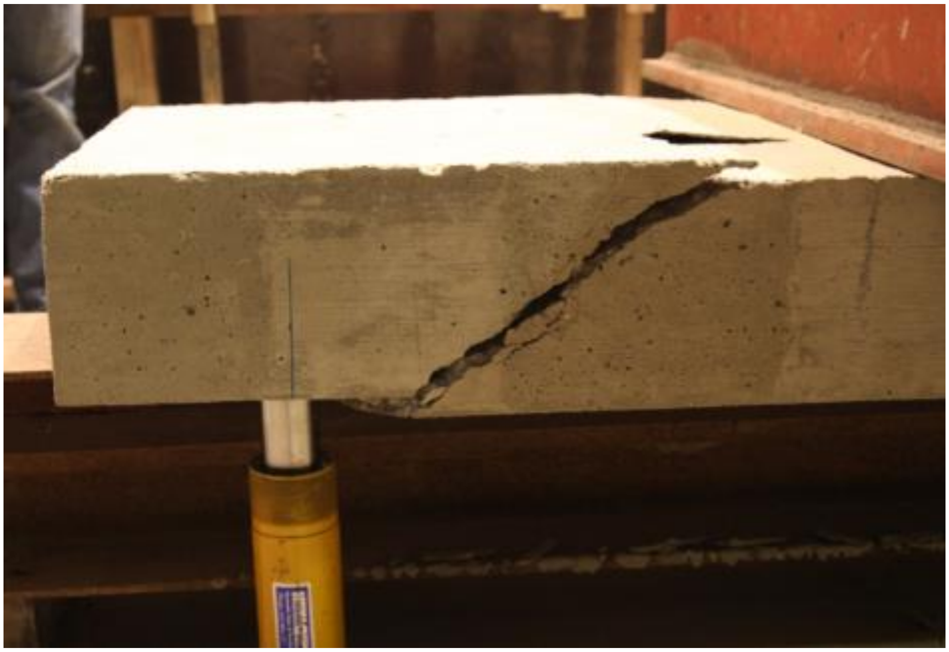

Figure 28. A photograph of the side view of the first peeling test (3 shear studs) (Dang 2013)

The second test apparatus was modified by adding a steel plate to distribute the hydraulic jack load over a larger area. Photographs of the second peeling test are shown in Figure 29. Only one side of the concrete slab failed and broke into two large pieces. The peak load for this test was 41.8 kips.

Figure 29. A photograph of the second peeling test (3 shear studs) (Dang 2013)

The third peeling test resulted in only one side failing since the concrete on the opposite side had been damaged during the second test. The peak load for this test was 36.1 kips. A photograph of the third peeling test result is shown in Figure 30.

Figure 30. A photograph of the third peeling test (3 shear studs) (Dang 2013)

The fourth peeling test was a punching shear failure on one side of the specimen. The peak load for this test was 30.0 kips. A photograph of the fourth peeling test result is shown in Figure 31.

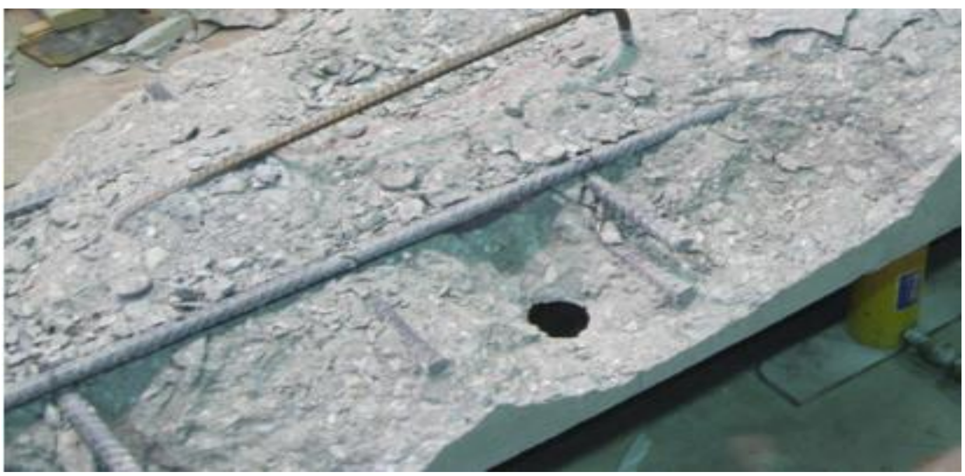

Figure 31. A photograph of the fourth peeling test (3 shear studs) (Dang 2013)

The fifth peeling test resulted in two pieces of concrete being broken off the concrete slab with the failure pattern similar to previous failures. The peak load for this test was 26.7 kips. A photograph of the fifth peeling test is shown in Figure 32.

Figure 32. A photograph of fifth peeling test (3 shear studs) (Dang 2013)

Peeling of section B (2 shear studs)

The peeling trial for section B (2 shear studs) had similar failures. Compared to the loads applied to section A, the loads were applied more consistently from the end of the specimen to the middle of the specimen. The testing ensured every peeling test was loaded from a free end. The first test failed in shear as shown in Figure 33 and Figure 34. The peak load for this test was 15.8 kips.

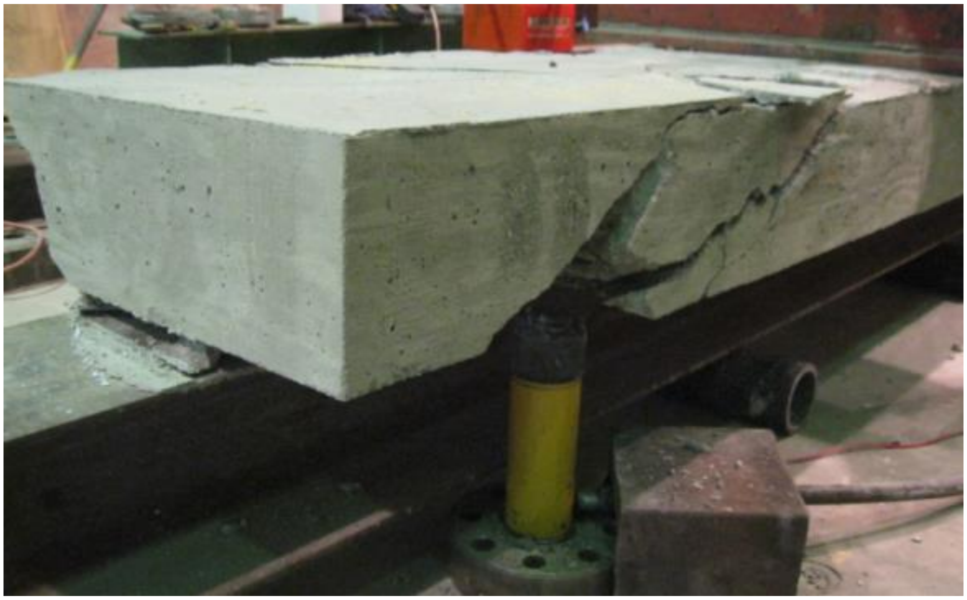

Figure 33. A photograph of the side view of the first peeling test (2 shear studs) (Dahlberg 2014)

Figure 34. A photograph of the top view of the first peeling test (2 shear studs) (Dahlberg 2014)

The section B peeling trial removed most of the concrete by multiple peeling tests conducted one after the other. A photograph of the section B peeling trial is shown in Figure 35. The peak loads were summarized in following result section.

Figure 35. A photograph of the second peeling test (2 shear studs) (Dahlberg 2014)

Results and Discussion

This section discusses the results of the small-scale trials of bridge deck removal by hydrodemolition, chemical splitting, and peeling methods.

Hydrodemolition

Hydrodemolition is well suited to both partial and full-depth removals. The pressure controlled demolition protects the steel girders, shear connectors, and reinforcing steel from unintended damage. This method produces no dust and induces no vibration.

Though hydrodemolition yields a high quality deck removal, this method has several drawbacks. Hydrodemolition produces at least an equal amount of wastewater which needs to be contained and treated. The power unit is noisy (range 90 to 100 dB). Shadowing might occur when steel elements shield the concrete beneath them.

Chemical splitting

Chemical splitting produces no noise, dust, or vibration, but even in the best cases requires a long time to break the concrete deck and needs a method to catch falling materials. This method is not an effective deck removal method in this study. The result of chemical splitting after six days (144 hours) is illustrated in Figure 36. The cracks caused by chemical splitting were not sufficient to remove the concrete deck from the steel girders.

Figure 36. A photograph of chemical splitting on day six (Dang 2013)

Peeling

The peak loads measured during the peeling trials for section A (three shear studs) are ranging from 11.8 kips to 41.8 kips in Table 11.

Table 11 Peeling loads for section A

Load Number	1	2	3	4	5	6	7	8	9
Peak Load (kips)	21.1	41.8	36.1	30.0	26.7	31.2	13.6	12.2	11.8

The peak loads recorded during the peeling trial for section B (two shear studs) are between 9.2 kips and 38.3 kips in Table 12.

Table 12 Peeling loads for section B

Load Number	1	2	3	4	5	6	7	8	9	10	11
Peak Load (kips)	15.8	9.3	22.0	21.4	9.9	19.4	25.4	31.0	9.4	38.3	9.2

Peeling method may offer contractor some advantages such as high production rate, low cost, and simplified operation. Peeling does not damage steel elements in this trial. However, concrete on top of steel girders and around shear connectors may need additional removals by using other methods such as jackhammering. This method yields dust, noise, and falling materials. Large loads in peeling might cause undesirable vibrations or deformations. Safety and structural adequacy and stability are other concerns when equipment is working on bridges.

CHAPTER 6. SHEAR STRENGTH EVALUATION FOR PARTIAL CONCRETE REMOVAL AROUND SHEAR CONNECTORS

Chapter 6 describes laboratory testing completed to understand how shear strength is impacted when variable amounts of concrete are removed from around shear connectors. This evaluation focuses solely on the shear connector strength with respect to the extent and quality of concrete removal; no consideration was given to the quality of the concrete left in place. This study assesses whether it is necessary to remove 100% of the concrete during a deck replacement.

Methods

Three different concrete removal levels were evaluated as shown in Table 13. Specimens were prepared in three steps. First, concrete was placed around the shear connectors. Second, the concrete was removed to the desired levels (i.e., 100, 75, and 50% concrete removed). Third, the complete specimens were fabricated by placing new concrete around the entire assembly. The control group specimens skipped the first and second steps to simplify the fabrication process.

Table 13. Concrete removal group for shear strength evaluation

Group	Specimen Description
Control	100% concrete removal (100% new concrete)
Experiment A	75% concrete removal (25% old concrete and 75% new concrete)
Experiment B	50% concrete removal (50% old concrete and 50% new concrete)

A total of 27 specimens were fabricated. These specimens had three types of shear connector: stud (7/8 in. diameter), channel (C5×6.7), and angle-plus-bar (6×6×3/8 angle and 1 1/4×3/4 bar). Each type of shear connector was further subdivided into three groups based upon the amount of concrete removed, including three specimens in the control group (100% removal), three specimens in the experiment A group (75% removal), and three specimens in the experiment B group (50% removal).

Specimen preparation

Specimen preparation consisted of steel fabrication, initial concrete placement, concrete removal, and final specimen fabrication. The steel specimen fabrication consisted of welding shear connectors on both flanges of 1.5 ft long steel girder (W10×60) section. Each shear connector was welded 6 in. from one end of the steel girder to the geometric center of the shear connector. Three-dimensional renderings of the steel specimens are shown in Figure 37.

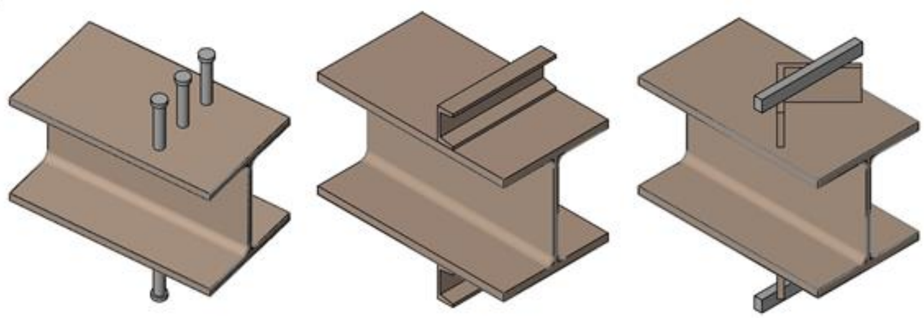

Figure 37. Shear connector (from left to right: shear studs, channel, and angle-plus-bar)

After all shear connectors were welded to the steel girders, concrete formwork was constructed for the initial concrete placement (Figure 38). The formwork was designed to allow for a concrete cover of 6 in. on both sides of the shear connector, simulating a concrete deck with a thickness of 8.75 in.

Initially, eighteen specimens were fabricated using Iowa DOT standard C-4WR concrete mix and then cured for 28 days (Figure 41). The eighteen specimens consisted of six specimens with each type of shear connector. The concrete around these specimens was then removed to the 50% and 75% levels. The control group (100% removal) was constructed by casting concrete on new steel specimens and thus simulating the case where 100% of the concrete was removed and then replaced.

Figure 38. A photograph of constructed steel specimens and concrete formwork (Dang 2013)

Figure 39. Eighteen specimens after initial concrete placement (Dang 2013)

After curing the concrete for 28 days, a rotary hammer was used to remove the concrete to the desired level. The level of concrete removal was controlled by weighing the removed concrete. Figure 40 shows a photograph when the left side has reached 75% removal and the right side has reached 50% removal. Note that the right side will have additional materials removed until it closely matches the 75% removal shown on the left side.

Figure 40. A photograph of a specimen with partially concrete removed (Dang 2013)

The 27 specimens (9 with 50% removal, 9 with 75% removal, and 9 original steel specimens) were then placed in new concrete formwork. The new concrete placement encapsulated the old concrete to represent a replaced deck. The final specimen configuration is schematically illustrated in Figure 41. Figure 42 and Figure 43 show the specimens in the formwork. All specimens were then cured for 28 days before testing.

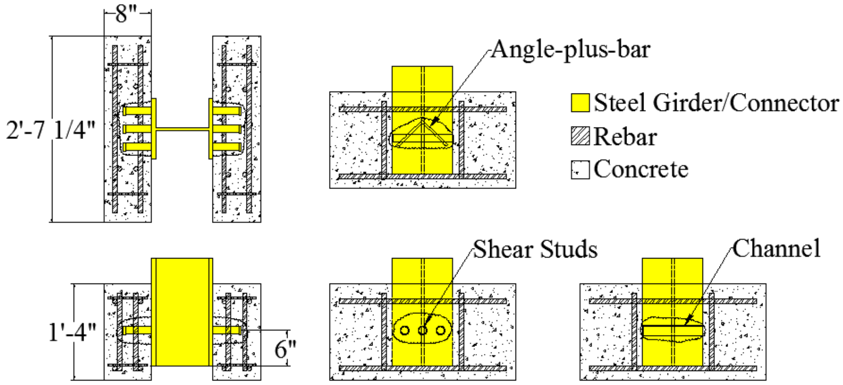

Figure 41. Schematic dimensions of specimens

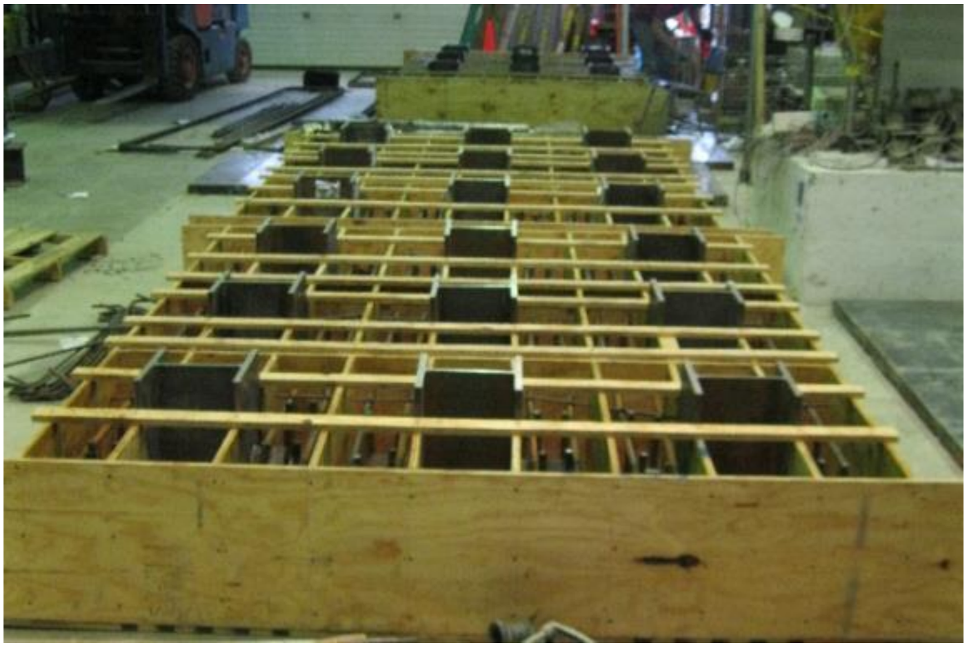

Figure 42. A photograph of partially removed concrete specimens and formwork (Dang 2013)

Figure 43. A photograph of specimens, reinforcing steel, and formwork (Dang 2013)

Testing procedures

The steel frame used to load the specimens consisted of four hollow steel columns, four rectangular tubes, and a wide flange steel girder as shown in Figure 44. Displacement transducers were used to measure the relative displacement between the concrete deck and the steel girder at the four corners of the specimen. Next, loads were gradually applied to each specimen with a hydraulic load actuator. Testing was conducted until each specimen failed. The load and displacement were monitored with a computerized data acquisition system.

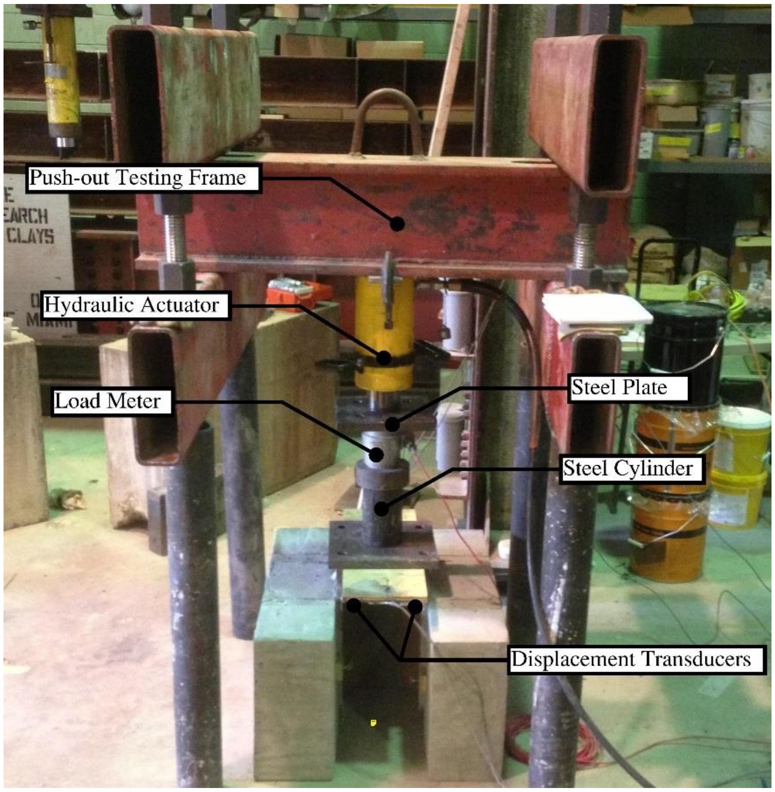

Figure 44. A photograph of shear capacity testing setup (Dang 2013)

Two types of failures, including shear connector failure and concrete failure, were observed during testing. An example of a specimen with a shear connector failure is shown in Figure 45. The shear connector failure results either one or both sides of the specimen breaking apart. An example of a specimen with a concrete failure is shown in Figure 46. This type of failure is exemplified by concrete cracks that initiate on the bottom of the specimen and then propagate quickly as loads are gradually applied.

Figure 45. A photograph of shear connector failure (Dang 2013)

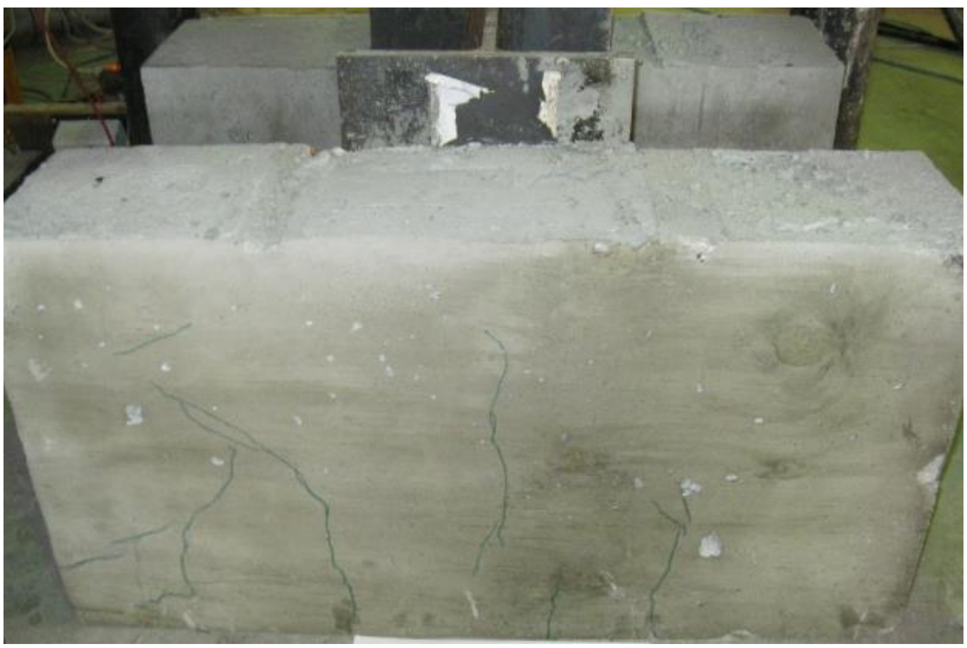

Figure 46. A photograph of concrete failure (Dang 2013)

Results and Discussion

The two principal metrics for evaluating the impact of concrete removal on shear strength were: (1) the applied loads and (2) the relative displacement between the concrete and steel. The load per connector was calculated as one-half of the total applied load. The relative displacements at the four corners of the specimen were averaged to produce a single load displacement relationship.

Stud shear connectors

The load versus the average displacement for stud shear connectors is illustrated in Figure 47. The shear strength is slightly higher in the 50% removal and the 75% removal when compared with the control group. Also, the stiffness appears to be slightly increased when less concrete is removed.

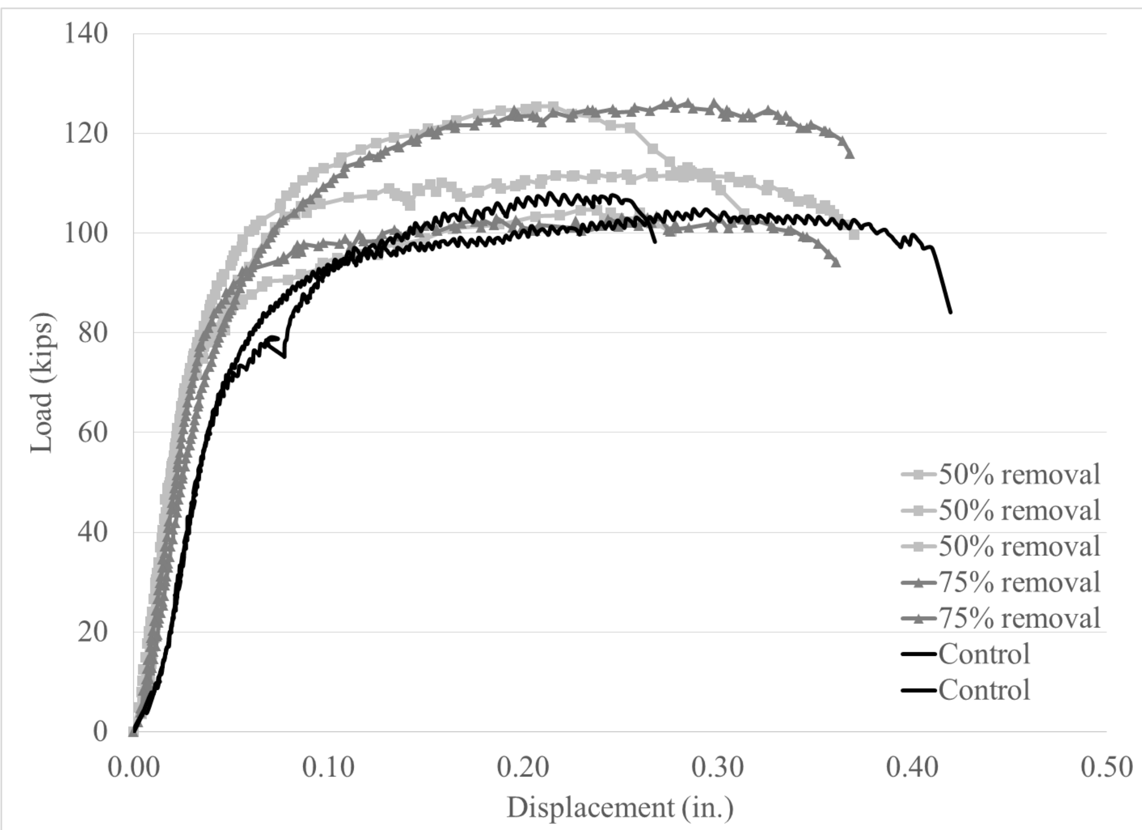

Figure 47. The load verse the average displacement for stud shear connectors

The experimental loads for the stud shear connectors are shown in Table 14. The measured peak load for the stud shear connectors ranged from 104 to 126 kips. The average control peak load was 106.5 kips. The ratio load for the partial removal to the control stud shear connectors ranged from 0.98 to 1.18.

Table 14. Predicted and experimental loads for the stud shear connectors

Specimen	Experimental load (kips)
50% removal	105
50% removal	126
50% removal	112
75% removal	126
75% removal	104
75% removal	108
Control	108
Control	105

Overall, Table 14 shows insignificant differences between partial and complete concrete removals for the ultimate shear strength. The testing results indicate the ultimate shear strength of stud shear connectors is basically insensitive to the quantity of concrete removed.

Channel shear connectors

The load versus the average displacement for the channel shear connectors show similar behaviors between the 50% removals and the control group, as shown in Figure 48. Full data for the 75% removal specimens were not retrieved because of technical issues (e.g., only peak load was obtained). One of the 50% removals had lower shear strength than the other two and was attributed to poor specimen construction.

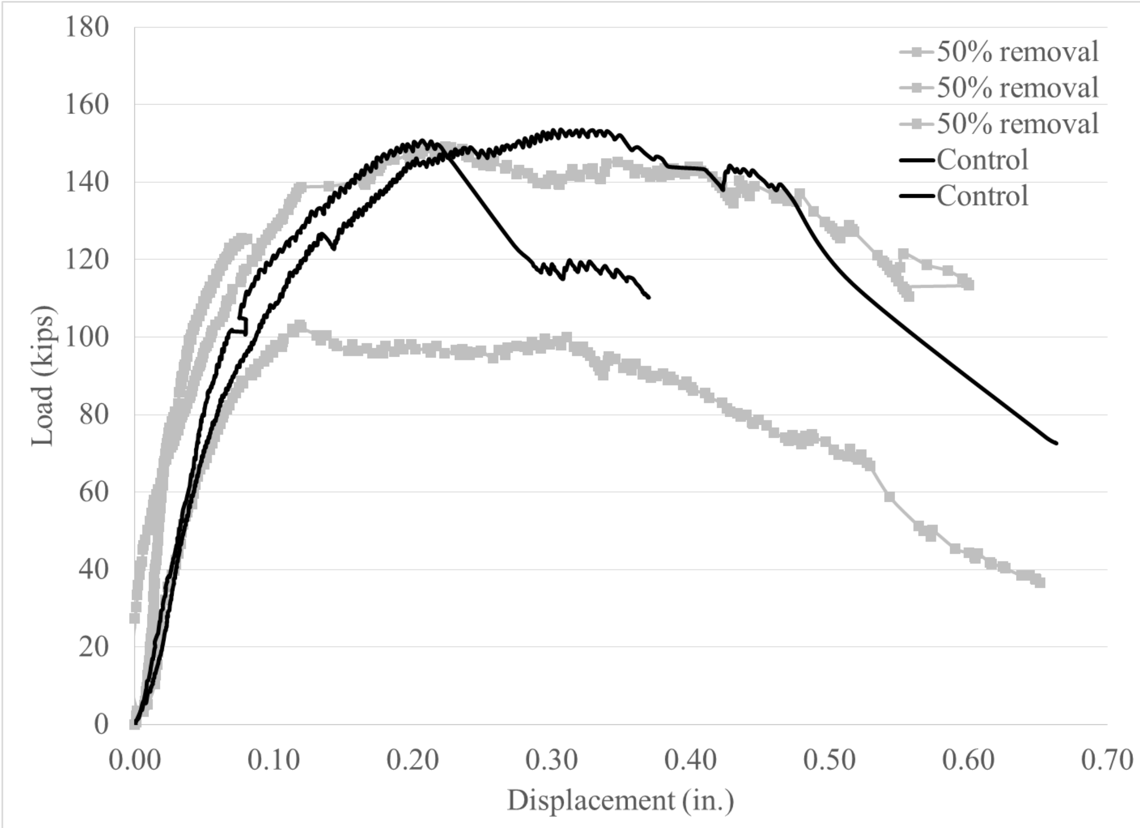

Figure 48. The load versus the average displacement for channel shear connectors

The experimental loads for the channel shear connectors are shown in Table 15. The loads vary from 103 to 154 kips. Seven of the channel connector specimens had concrete crushing-splitting failure modes. One had a channel fracture on one side of the specimen. The ratios of load for the partial removal to full removal vary between 0.68 and 0.98. These results indicated that the channel shear connector is sensitive to the amount of concrete removal.

Table 15. Predicted and experimental loads for channel shear connectors

Specimen label	Experimental load (kips)
50% removal	149
50% removal	126
50% removal	103
75% removal	150
75% removal	125
75% removal	130
Control	154
Control	151

Angle-plus-bar

The load versus the average displacement for the angle-plus-bar shear connectors is shown in Figure 49. The slopes are approximately the same in the elastic region. Variations within one particular concrete removal level are similar to the variations within the control group.

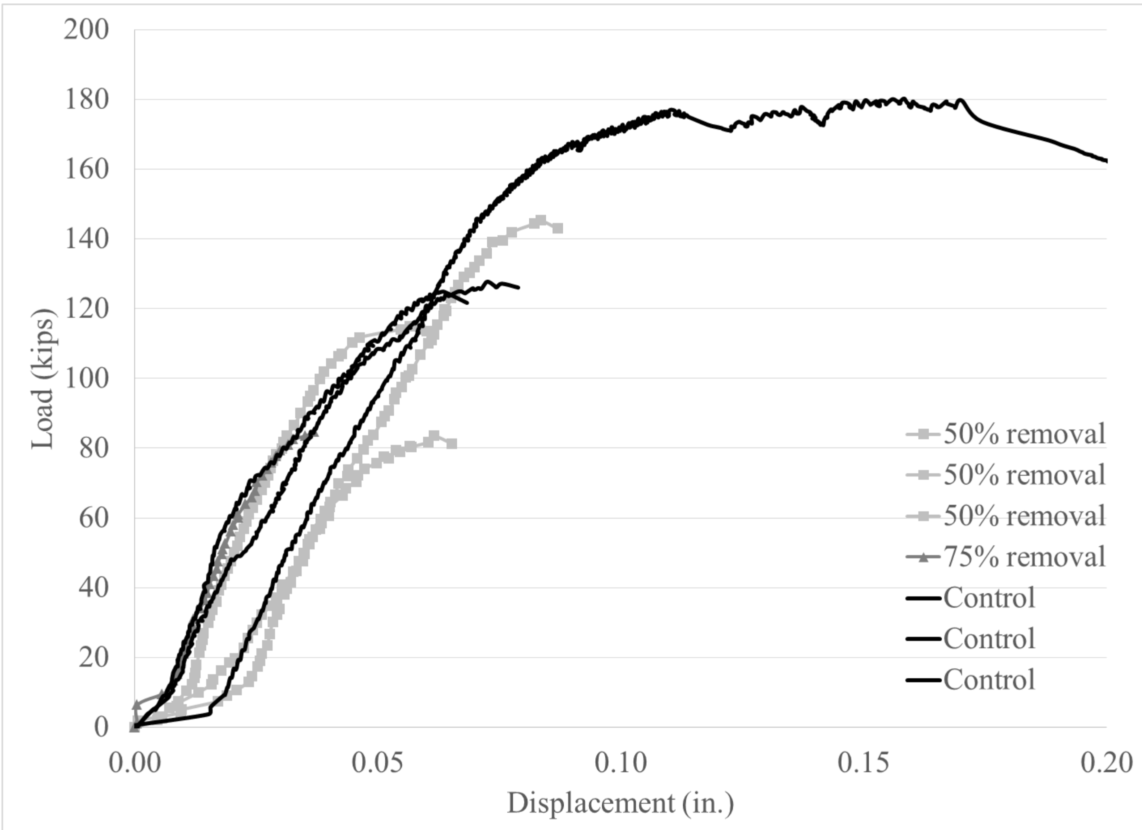

Figure 49. Load versus average displacement of the angle-plus-bar shear connectors

The experimental peak loads for the angle-plus-bar shear connector specimens are shown in Table 16. The experimental loads are scattered between 84 and 180 kips with the control having an average peak load of 144 kips. Four specimens had angle fractures on one side; three specimens had angle fractures on both sides; and one specimen had a concrete crushing-splitting failure. As with the angle-plus-bar shear connector, some difference in peak load was observed with a lower percentage of concrete removed.

Table 16. Predicted and experimental loads for angle-plus-bar shear connectors

Specimen label	Experimental load (kips)
50% Removal	115
50% Removal	84
50% Removal	146
75% Removal	85
75% Removal	143
Control	125
Control	180
Control	128

CHAPTER 7. A SUSTAINABILITY SCORECARD FOR BRIDGE DECK REMOVAL

This chapter discusses deck removal related criteria based on previous literature reviews and proposes a scorecard and criteria to address sustainability concerns in bridge deck removal projects.

Introduction

After the Leadership in Energy and Environmental Design (LEED) successfully entered in building industrial in 1998 (USGBC 2013), the impact such as reductions in energy and water usages, wastes, and emissions has stimulated the development of sustainable infrastructure tools and adoption of sustainable practices. The first sustainable infrastructure rating system (i.e., CEEQUAL) was developed by the Institute of Civil Engineers (ICE) in the United Kingdom in 2003. Then, other sustainability (e.g., Greenroads, I-LAST, and INVEST) tools were developed by different authors and organizations to accomplish their sustainability goals. Sixteen rating and checklist systems (Figure 50) have been developed to improve the sustainability of infrastructure projects since 2003.

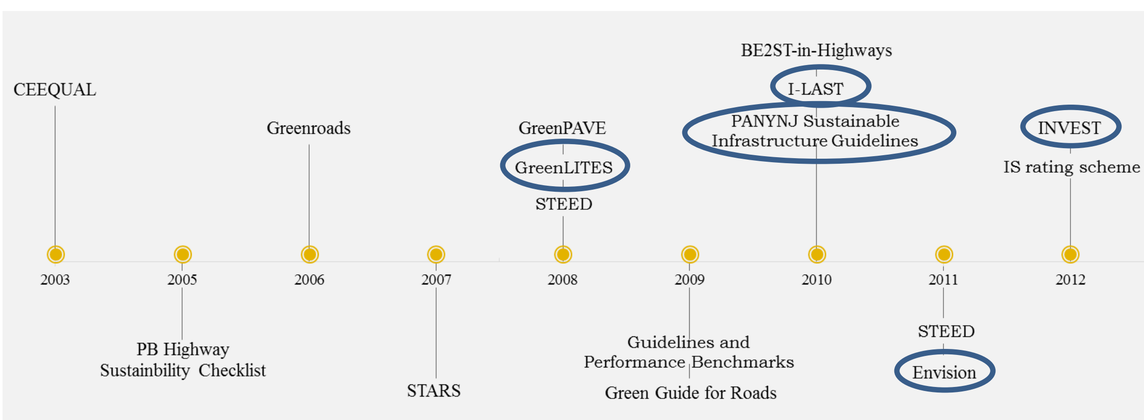

Figure 50. Timeline of the development of infrastructure sustainability tools

In general, sustainable infrastructure rating systems are committed to protect and enhance the environment and community life, conserve energy and natural resources, encourage public involvement and usage of innovative sustainable design, and preserve the historic, scenic, and aesthetic context of highway projects. The Envision™ sustainable infrastructure rating system encourages the use of additional sustainability rating systems that may address in-depth specific or specialized aspects of a project (ISI and Zofnass 2012). However, there are no tools that specifically address sustainability in bridge deck removal projects. After reviewing five rating systems (Figure 50, highlighted in circles) that are related to bridge projects in the literature review, the author identified related criteria for deck removal projects. They proposed a scorecard with criteria to specifically address sustainability concerns in bridge deck removal projects.

Deck Removal Related Criteria

The evaluation of deck removal methods and projects are based on, noise, vibration, dust, falling materials, and superstructure damage. These evaluation criteria form a basic sustainability metric for bridge deck removal projects. Additional criteria (e.g., fuel efficiency and emission reduction) were identified from the reviewed five rating systems: (1) Envision™, (2) INVEST, (3) the PANYNJ sustainable infrastructure guidelines, (4) I-LAST, and (5) GreenLITES. This section presents some examples of the noise and vibration criteria in Envision™ and INVEST; the dust and falling material criteria in the PANYNJ Sustainable Infrastructure Guidelines and I-LAST; and the overall bridge deck removal criteria in the reviewed five systems.

Noise and vibration

The Envision™ rating system has criteria (criteria ID: QL 2.2) that improve quality of life by minimizing noise and vibrations duration construction and operation. This criterion has three levels of achievement with assigned point values: improved (1 point), conserving (8 points), and restorative (11 points). These levels can be achieved by following questions provided from Envision™ reference book (ISI and Zofnass 2012).

A. Have appropriate studies have been carried out to predict the levels of air-borne, ground-borne, and structure-borne noise and vibrations that will be present during construction and when the completed works is in operation?
   1. *Noise and vibration studies and field monitoring providing adequate baseline information and predictions of ambient noise and vibration levels during construction and operation.*
   2. *Acceptability of the credentials and qualifications of the person(s) conducting the baselines studies and predictions and developing the mitigation proposals.*
B. Have proposals for ambient noise and vibration mitigation and monitoring been made and incorporated into the project design to reduce noise and vibration to accepted standard target levels?
   1. *Proposals for ambient noise and vibration mitigation and monitoring submitted*
   2. *Comprehensiveness of proposals in terms of coverage, detail and the flowdown of requirements to the construction contractor.*
C. Has the project been designed to markedly reduce ambient noise and vibration down to levels that substantially improve community livability?
   1. *Analyses and documentation of estimates of ambient noise and vibration levels and comparisons to community needs and goals for livability.*

The INVEST rating system proposes construction noise mitigation (Criteria ID: PD-27) in project development category for urban transportation projects. These criteria contain two points with separate requirements as follows (FHWA 2012).

A. Require contractors to establish, implement, and maintain a form noise mitigation plan (NMP) during roadway construction by including the following information at minimum. (1 point)

1. Responsible party for noise mitigation activities, contact information, their responsibilities, and qualifications. Include information for the NMP preparer, if applicable, or if completed by an outside party.
2. Project location and distance to closest receptor of noise. Include a description of the surrounding zoning and parcel information (i.e., commercial, residential, hospitals, schools, parks, sensitive habitat).
3. A list of proposed construction activities (e.g., demolition, excavations, paving, bride foundations, finishing).
4. Dates and working hours of proposed construction activities.
5. A list of noise-generating devices used during each construction activity listed in #3.
6. A list of noise-mitigating devices used during each construction activity used in #3, including personal safety equipment requirements for all site employees.
7. Noise permit numbers, agency, or local authority policies associated with construction work, as applicable.
8. Description of noise monitoring standards, methods, and acceptable levels.
9. Descriptions of correction procedures for non-compliant noise levels.
10. Description of complaint or feedback mechanism for public use.
11. Signature of responsible party.

B. Require contractors to monitor noise and the effectiveness of mitigation measures at the receptors throughout construction to ensure compliance with the NMP. Provide one or more of the following documentation sources. (1 point)

    1. Contract documents requiring contractor to develop a noise mitigation plan and monitor noise during construction.
    2. Noise mitigation plan
    3. Applicable noise permits, or agency or local authority noise polices.

Dust and falling materials

Sustainable infrastructure rating systems include dust concerns in environmental criteria. One example, such as minimize pollution from construction activity (criterion ID: IC-1), is found in the PANYNJ Sustainable Infrastructure Guidelines. Another example is I-LAST, which promotes protection from materials entering waterways on bridge demolitions and construction (criterion ID: W-3h). One point is awarded for this criterion in the water quality category of I-LAST rating system. The requirement of each criterion is listed as following.

The PANYNJ Sustainable Infrastructure Guidelines IC-1: Minimize pollution from construction activity.

- Required: Prepare a simplified construction stormwater pollution prevention plan as detailed below and reflect on contract drawings for any project over 1/2 acre of soil disturbance (in both NJ and NY) to minimize pollution during construction. This applies to minimizing pollution in stormwater as well as air pollution from dust and particulate matter at the construction site. This plan should include the following components:
    - On a drawing titled pollution control plan, indicate the location of the controls on the site map.

- Identify dust mitigation measures:
  - Utilize sprayed suppression agents (nonhazardous and biodegradable) for containment of fugitive dust; adjust strategies for meteorological conditions.
- Identify structural erosion and sediment control measures; can include, but are not limited to:
  - Silt fencing (straw bales and hay bales are not recommended for storm drain inlet protection in EPA document 832/R-92-005[50]).
  - Use of geotextiles and gravel and stone filter berms around construction areas to minimize sedimentation.
- Identify Opportunities to collect and utilize stormwater for construction activities such as wetting dust for suppression and washing vehicle tires.
- Proper disposal of construction site waste (i.e., spoils from concrete truck wash-out).
- Control offsite vehicle tracking with typical details for stone pads at construction exits.
- Prepare an inspection and maintenance plan; include stand forms to document installation and repair of pollution control measures.
- Follow standard procedure when an unexpected environmental condition or contamination is encountered.

- Required: Inspect and maintain controls – inspect every 7 days or within 24 hours of a rainfall of more than 1/2 in.; maintain records of construction activity.
- Required: Groundwater dewatering discharges to surface water or storm sewer must be in compliance with the appropriate state’s discharge general permit requirements.

I-LAST W-3: Construction practices to protect water quality. One of the sustainable practices is W-3h protection from materials entering waterway on bridge demolition and construction. The criteria requirement states that one point will be awarded to projects that include requirements for capture of bridge demolition or construction materials before entering waterways.

Overall bridge deck removal criteria

Bridge deck removal sustainable metrics were developed, based on evaluation criteria of selecting cost-effective deck removal methods for this study and related sustainable practices from the reviewed five systems. Table 17 lists sustainability criteria that are related to bridge deck removal. These criteria include recycle materials (divert waste), reduce emissions (increase fuel efficiency), protect waterways, and a prepare quality control plan (removal plan).

Table 17. Deck removal related sustainability criteria

Sustainability tools	Criteria Identifications, Numbers and titles
Envision™	QL2.2 Minimize Noise and Vibration LD1.4 Provide for Stakeholder Involvement RA1.3 Use Recycled Materials RA1.4 Use Regional Materials RA1.5 Divert Waste from Landfills RA2.1 Reduce Energy Consumption NW1.2 Protect Wetlands & Surface Water CR1.1 Reduce Greenhouse Gas Emissions CR1.2 Reduce Air Pollutant Emissions
INVEST	PD-19 Reduce and Reuse Materials PD-20 Recycle Materials PD-26 Construction Equipment Emission Reduction PD-27 Construction Noise Mitigation PD-28 Construction Quality Control Plan PD-29 Construction Waste Management
PANYNJ sustainable infrastructure guidelines	IC-1 Minimize Pollution from Construction Activity IC-2 Protect Existing Natural Systems IC-3 Utilize Transportation Management During Construction IC-4 Utilize Green Construction Equipment IC-5 Reduce Noise and Vibration During Construction IC-6 Implement Construction Waste Management
I-LAST	D-2b Incorporate locally produced or native materials W-3h Protection from materials entering waterway on bridge demolition and construction

Table 17. Deck removal related sustainability criteria (Continued)

Sustainability tools	Criteria Identifications, Numbers and titles
GreenLITES	M-1g Specify the processing of demolished concrete to reclaim scrap metals and to create a usable aggregate material

The identified criteria form the foundation of developing a sustainability tool for bridge deck removal projects. These criteria provide the best possible sustainable practices that can implement in the bridge deck removal projects. Those criteria include a bridge deck removal plan, preservation of existing superstructures, noise abatement, vibration mitigation, dust control, protection of waterways, roadways, or railways below bridges, fuel efficiency and emission reduction, and demolition waste diversion.

Proposed Sustainability Scorecard

A sustainability scorecard for deck removal will assist both bridge owners and contractors implement sustainable practices in bridge deck removal projects. This is a voluntary tool and does not supersede local regulations, specifications, laws, and contract documents. The deck removal scorecard proposed here could be included as a sustainability tool for bridge deck replacement. This deck removal section could be integrated with a section that covers the entire project with a deck reconstruction section.

This sustainability tool features two main parts, a scorecard and criteria. The criteria describe the activities that must be achieved to receive points at each of four levels. The basic level, called the conventional level, describes the minimum requirements for deck removal projects. The next three levels describe activities that potentially improve the sustainability of the process (Table 18). The improved level is evaluated based on performance that achieved to be above the conventional, minimal requirements. The advanced level encourages minimum negative impacts to the natural, social, and economic worlds. Exceptional level focus on improve and restore the natural, social, and economic worlds.

Table 18. Descriptions of achievement levels for each criterion

Level	Description
Conventional	Performance meets typical, minimum requirements
Improved	Performance above conventional
Advanced	Sustainable performance with minimum negative impacts
Exceptional	Sustainable performance achieves zero impact or restores natural or social systems

The scorecard (shown in Table 19) contains eight criteria and a total of 32 possible points. The points are simply assigned as 1, 2, 3, 4, for conventional, improved, advanced, and exceptional, respectively.

Table 19. Sustainability scorecard for deck removal

Deck removal	Awarded points
Bridge deck removal plan	
Preservation of existing superstructures	
Noise abatement	
Vibration mitigation	
Dust control	
Protection of waterways, roadways, or railways below bridges	
Fuel efficiency and emission reduction	
Demolition waste diversion	
Total:	

Deck Removal Sustainability Criteria

The previous section described the development of the scorecard and descriptions for each criterion. This section describes how to navigate these criteria in-depth to assist users in sustainable deck removal and preservation of existing superstructures. The six main criteria, (1) noise abatement, (2) vibration mitigation, (3)dust control, (4) protection of waterways, roadways, or railways below bridges, (5) fuel efficiency and emission reduction, and (6) divert demolition waste from landfills, are discussed in detail to ensure the Deck Removal Plan's user understands their targets, descriptions, and levels of achievement.

Navigating the criteria

Explanations for the criterion layout are illustrated in Figure 51. Each criterion includes a title, target, description, requirements for each level of achievement, and related criteria. The levels are achieved by completing all of the described activities. The example for a deck removal plan follows, with step-by-step instructions for successful completion by carefully following Figure 53.

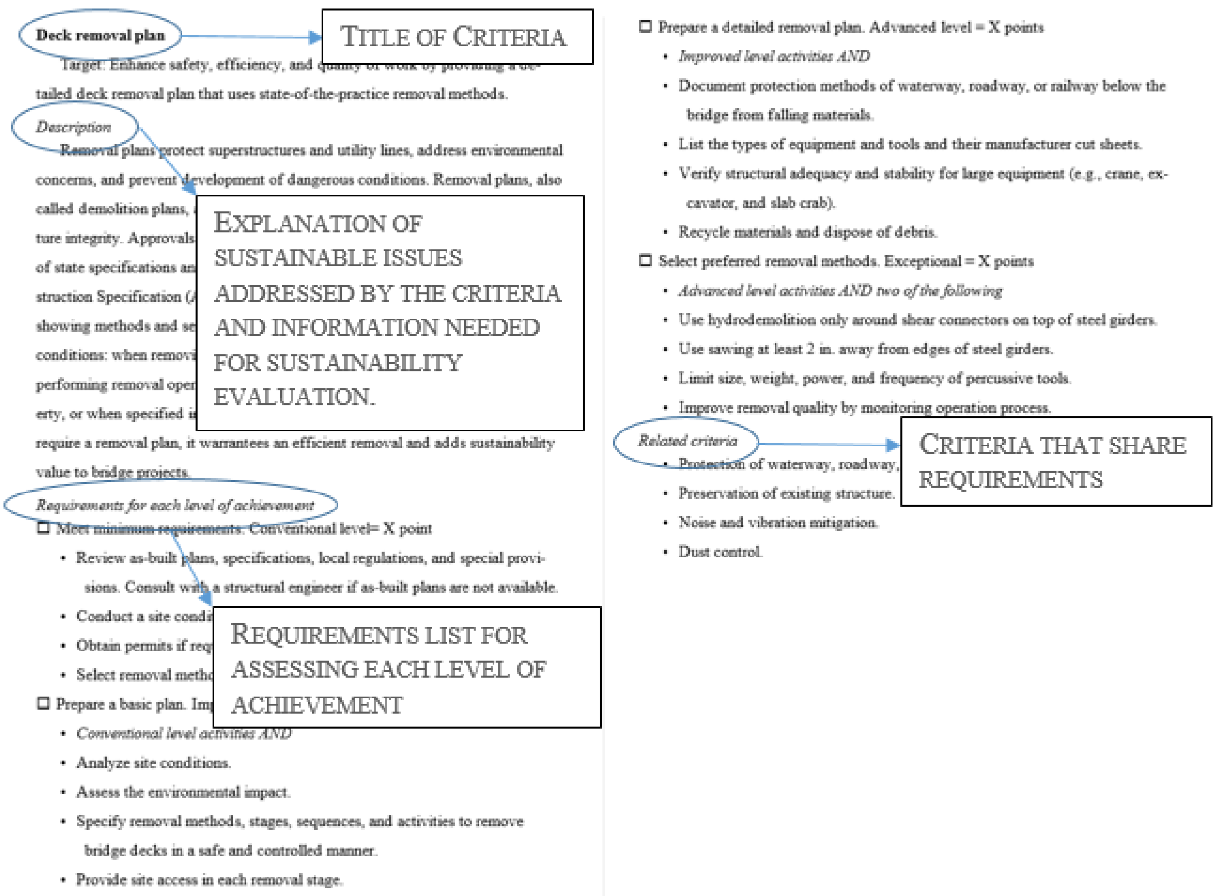

Figure 51. Navigating the deck removal sustainability criteria

Bridge deck removal plan

Target: Enhance safety, efficiency, and quality of work by providing a detailed bridge deck removal plan that uses state-of-the-practice removal methods.

Description

Bridge deck removal plans protect superstructures and utility lines, address environmental concerns, and prevent development of dangerous conditions. Bridge deck removal plans are crucial to the quality of removal and superstructure integrity. Approvals of deck removal methods and equipment are specified in half of the 50 state specifications and national guidance. For example, LRFD Bridge Construction Specification (AASHTO 2010) recommends working drawings that show methods and sequence of removal should be prepared under one of three conditions: (1) removing or salvaging structures or portions of structures, (2) performing removal operations over or adjacent to public traffic or railroad property, or (3) specified in the contract documents. Although bridge owners may not require a bridge deck removal plan, the plan warrants an efficient deck removal and adds sustainability value to bridge projects.

Requirements for each level of achievement

☐ Meet minimum requirements. Conventional level= 1 point

- Review as-built plans, specifications, local regulations, and special provisions. Consult with a structural engineer if as-built plans are unavailable.
- Conduct a site condition investigation.
- Obtain permits if required.
- Select removal methods.

☐ Prepare a basic bridge deck removal plan. Improved level = 2 points

- *Conventional level activities AND*
- Analyze site conditions.
- Assess the environmental impact.

- Specify removal methods, stages, sequences, and activities to remove bridge decks in a safe and controlled manner.
- Provide site access during each removal stage.

☐ Prepare a detailed bridge deck removal plan. Advanced level = 3 points

- *Improved level activities AND*
- Document protection methods for waterway, roadway, or railway below the bridge from falling materials.
- List types of equipment and tools, and provide their manufacturer cut sheets.
- Verify structural adequacy and stability for large equipment (e.g., crane, excavator, and slab crab).
- Recycle materials and dispose of debris.

☐ Select preferred removal methods. Exceptional = 4 points

- *Advanced level activities AND two of the following*
- Use hydrodemolition only around shear connectors on top of steel girders.
- Use sawing at least 2 in. from edges of steel girders.
- Limit size, weight, power, and frequency of percussive tools.
- Improve removal quality by monitoring operation process.

Related criteria

- Protection of waterway, roadway, or railway below bridge.
- Preservation of existing structure.
- Noise and vibration mitigation.
- Dust control.

Preservation of existing superstructures

Target: Avoid damage to superstructures, while removing concrete bridge decks.

Description

Preservation of existing, sound superstructures improves environmental sustainability by minimizing unnecessary consumption of new materials. Superstructures are exposed to potential damage during the deck removal process. These damages should be avoided or minimized to ensure sufficient capacity, remaining life, and structural integrity of salvaged superstructures.

Requirements for each level of achievement

☐ Meet minimum requirements. Conventional level = 1 point.

- Exercise care during equipment operations.
- Calculate structural adequacy and stability for doubtful operation steps.

☐ Review as-built plans of the superstructure. Improved level = 2 points.

- *Conventional level activities AND*
- Identify bridge girder sizes and taper zone of top flanges.
- Pinpoint cover plates, bolts, and shear connector locations.
- Monitor operation process.

☐ Prepare repair plans. Advanced level = 3 points.

- *Improved level activities AND*
- Typical repair for deck removal damage (e.g., dents, minor cuts).
- Collect repair methods for specific damage from previous projects.

☐ Use removal methods that preserve the existing structure. Exceptional level = 4 points.

- *Advanced level activities AND*
- Use hydrodemolition on top of steel girders.

- Implement innovative demolition method(s) that do not damage superstructure.

Related criteria

- Bridge deck removal plan.

Noise abatement

Target: Minimize noise during construction and operation of the constructed works.

Description

Noise mitigation improves the construction working environment and community livability. According to the FHWA, noise is “unwanted sound” (1995). The noise measurement used in this criterion is A-weighting of the sound level, short dBA. This measurement begins with the threshold for human hearing to the threshold of pain for human hearing. For example, the specified noise level of a food blender at 3 ft is 90 dBA, while a library, quiet bedroom, or nighttime concert hall background is 30 dBA.

Noise above 75 dBA can cause hearing loss. A noise level at 67 dBA, as reported by the FHWA (2010), is the exterior criterion in residential areas. Generic target noise levels are provided in Table 20 from the state of Oregon. Noise measurements are taken to the nearest property boundary of the affected land use for a cumulative period of 30 minutes or more.

Table 20. Target noise levels (Source: City of Portland, Oregon 2010)

Permissible Sound Levels, dBA (7 AM – 10 PM, otherwise minus 5 dBA)					
Zone Categories of Source	Zone Categories of Receiver (measured at property line)				
		Residential	Open Space	Commercial	Industrial
	Residential	55	55	60	65
	Open Space	55	55	60	65
	Commercial	60	60	70	70
	Industrial	65	65	70	75
During all hours, the sound levels shall be decreased 5 dBA for narrow band or steady sound.					

Requirements for each level of achievement

☐ Meet minimum requirements. Conventional level = 1 point

- Comply with local regulations, specifications, and laws.
- Identify activities that may be affected by noise from construction.
- Implement noise reduction methods.

☐ Mitigate noise. Improved level = 2 points

- *Conventional level activities AND*
- Use quiet removal methods and equipment.
- Install noise screens to isolate sounds for schools, hospitals, and churches.

☐ Meet target noise levels. Advanced level = 3 points

- *Improved level activities AND*
- Determine measurements of noise levels.
- Reduce noise levels to target noise level indicated in Table 1.
- Construct new barriers, if necessary.

☐ Create the quietest possible environment. Exceptional level = 4 points

- *Advanced level activities AND*
- Reduce noise levels below the target noise level shown in Table 1.

Related criteria

- Bridge deck removal plan.
- Vibration mitigation.

Vibration mitigation

Target: Minimize vibrations to equipment operators and existing superstructures.

Description

Vibration mitigation contributes to both health of construction workers and integrity of existing superstructures. Individuals experiencing prolonged vibrations (e.g., whole-body vibration, segmental vibration) may have multiple negative effects, such as motion sickness, control errors, vibration-induced white finger, and hand-arm vibration syndrome (Hedge 2013). Vibrations can develop damage (e.g., fatigue) in the existing superstructure, too.

Requirements for each level of achievement

☐ Meet minimum requirements. Conventional level = 1 point

- Comply with local regulation, specifications, and laws.

☐ Reduce vibrations to operators and superstructures. Improved level = 2 points

- *Conventional level activities AND*
- Minimize use of methods and equipment that cause vibrations to operators and fatigue damage to superstructures.

☐ Minimize vibrations to operator. Advanced level = 3 points

- *Improved level activities AND*
- Minimize vibrations to operators (machine-mounted equipment and robotic machines).

☐ Use removal methods with minimum vibrations. Exceptional level = 4 points

- *Advanced level activities AND*
- Use removal methods with minimum vibrations (e.g., mechanical and chemical splitting).

Related criteria

- Noise abatement.

Dust control

Target: Minimize dust generation and air-borne particle pollutants.

Description

Dust control promotes clean air in both the construction site and the local community. Dust is hazardous to both human health and the natural environment. For example, long-term exposure to dust can cause asthma, chronic lung disease, and even tuberculosis.

Requirements for each level of achievement

☐ Meet minimum requirements. Conventional level = 1 point

- Comply with local regulations, specifications, and laws.

☐ Improved level = 2 points

- *Conventional level activities AND*
- Determine the baseline dust level and set a dust reduction goal beyond the baseline.
- Ensure all workers are aware and follow specific OSHA requirements (e.g., wear mouth muffles or respirators).

☐ Implement dust control methods. Advanced level = 3 point

- *Improved level activities AND*
- Monitor dust levels and calculate percentages of dust reduction throughout the removal process.
- Use wet-cutting methods.
- Pre-wet surfaces before operations.

☐ Attain dust reduction goals. Exceptional level = 4 points

- *Advanced level activities AND*
- Use advanced dust suppression tools (e.g., water hose and dust extraction vacuums).

Related criteria

- Vibration mitigation.

- Protection of waterways, roadways, or railways below bridges.

Protection of waterways, roadways, or railways below bridges

Target: Protect waterways, roadways, or railways below bridges from falling materials.

Description

Falling materials are both safety and environmental concerns. Materials that fall during bridge deck removal may injure the public or workers, damage roadways or railways, and pollute waterways and the natural environment.

Requirements for each level of achievement

☐ Meet minimum requirements. Conventional level = 1 point

- Comply with local regulations, specifications, and laws.

☐ Improved level = 2 points

- *Conventional level activities AND one of following*
- Build a false deck that covers the critical areas below the bridge.
- Use methods (e.g., sawing) that remove decks in large pieces.

☐ Advanced level = 3 points

- *Improved level activities AND*
- Build a false deck that covers the entire area below the bridge.

☐ Exceptional level = 4 points

- *Advanced level activities AND*
- Implement treatment to restore or improve waterways, roadways, or railway conditions.

Related criteria

- Dust control.

Fuel efficiency and emission reduction

Target: Reduce fossil fuel use and emission during construction.

Description

Reducing emissions from construction equipment supports environmental and social principles by lessening impacts to air quality and reducing fossil fuel consumption. The EPA has adopted emission standards for all types of non-road engines, equipment, and vehicles.

Regulated non-road construction equipment either has engines that meet U.S. EPA Tier emission standards or have diesel retrofit devices for after-treatment pollution control verified by EPA or the California Air Resource Board (CARB).

Requirements for each level of achievement

☐ Meet minimum requirements. Conventional level = 1 point

- Establish a fuel usage baseline.
- Reduce non-road construction equipment emissions.

☐ Improved level = 2 points

- *Conventional level activities AND one of following*
- Reduce baseline fuel usage by 10%.
- Use regulated non-road construction equipment for 50% of the operation hours.

☐ Advanced level = 3 points

- *Improved level activities AND one of following*
- Reduce baseline fuel usage by 20%.
- Use regulated non-road construction equipment for 75% of the operation hours.

☐ Exceptional level = 4 points

- *Advanced level activities AND one of following*

- Reduce baseline fuel usage by 30%.
- Use regulated non-road construction equipment for 100% of the operation hours.

Related criteria

- Noise abatement.
- Vibration mitigation.

Demolition waste diversion

Target: Reduce demolition waste (e.g., concrete, reinforcing steel) by recycling or repurposing.

Description

Diverting demolition waste reduces the impact of the project on the environment and saves money for bridge owners and taxpayers. The Federal Leadership in Environmental, Energy, and Economic Performance specifies a 50% diversion of construction and demolition materials, and debris rate by fiscal year 2015 (FedCenter 2009).

Requirements for each level of achievement

☐ Meet minimum requirements. Conventional level = 1 point

- Collect and store recyclables.
- Calculate the total baseline amount of recyclable concrete and steel.

☐ Improved level = 2 points

- *Conventional level activities AND*
- Reuse and recycle 30% of the baseline concrete and steel.

☐ Advanced level = 3 points

- *Improved levels activities AND*
- Reuse and recycle 60% of the baseline concrete and steel.

☐ Exceptional level = 4 points

- *Advanced level activities AND*
- Reuse and recycle 90% of the baseline concrete and steel.

Related criteria

- Preservation of existing superstructure.
- Bridge deck removal plan.

Results and Discussion

Current sustainable infrastructure rating systems do not specifically address sustainability concerns for deck removal projects. The proposed scorecard and criteria are based on a review of the current sustainable infrastructure rating systems that include bridges in their rating categories. The deck removal scorecard is intended to improve sustainability practices in bridge deck removal projects. The deck removal section would be integrated with the section that covers the entire project and deck reconstruction.

CHAPTER 8. CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the conclusions developed based on interviews, surveys, and workshops; provides conclusions based on results of small-scale trials and shear strength evaluations; and presents a sustainability scorecard. The limitations of this study are discussed, and then recommendations for future research and practice are provided.

Conclusions

This research explored methods for removing concrete decks from steel girder bridges. Interviews with bridge owners and contractors indicated that concrete deck replacement was more economical than replacing the entire superstructure under the assumption that salvaged superstructures have adequate remaining service life and capacity. Surveys and workshops discussed the advantages and disadvantages of various deck removal methods. Small-scale trials explored three promising deck removal methods: (1) hydrodemolition, (2) chemical splitting, and (3) peeling. Push-out tests validated that removing all concrete around shear connectors may not in some cases unnecessary from a shear strength perspective. Finally, a sustainability scorecard and criteria were proposed to incorporate sustainable practices into bridge deck removal projects. Key findings are summarized in four sections.

Interviews, surveys and workshops key findings

- Sawing, use of percussive tools (e.g., jackhammers and rig-mounted breakers), and hydrodemolition are three commonly used deck removal methods identified through interviews, surveys, and workshops.
- Damage caused by deck removal methods and equipment is not considered in cost estimates or other decisions because the damage is typically minimal.
- Hydrodemolition has the unique advantage that it does not damage steel girders.
- Contractors usually have equipment that can be used for peeling.

- Grinding, welding, heat-straightening, flange build-up or replacement is currently used to repair damaged superstructures.
- Ten of the 28 state DOTs responding to the project survey reported that they specify deck removal methods and equipment in special provisions.
- Removing bridge decks takes approximately the same amount of time as removing entire superstructures when bridges are over waterways.
- Bridge deck removal takes longer and is more delicate work than removing the entire superstructure or bridge.
- Concrete deck replacement has not been widely used.
- Concrete deck replacement is more economical than replacing the entire superstructure under the assumption that salvaged superstructures have adequate remaining service life and capacity.

Small-scale trials key findings

- Hydrodemolition is well suited for both partial and full-depth concrete removals.
- Hydrodemolition did not damage the steel elements in the trial, which validated the survey results.
- Hydrodemolition consumes a large quantity of water and produces wastewater, slurries, and debris.
- Hydrodemolition might be cost prohibitive, depending upon the cost of water sources, wastewater treatment, and disposal.
- Chemical splitting was found to not be an effective deck removal method.
- Peeling is a simple, economical deck removal method.

Shear strength evaluation key findings

- The shear strength of the stud shear connector is insensitive to the quantity of concrete removed.
- The shear strength of the channel connector is sensitive to the amount of concrete removed.
- Some difference in the shear strength of the angle-plus-bar connector was observed in a lower percentage of concrete removed.

Sustainability scorecard key findings

- There are no sustainability tools that specifically address bridge projects.
- Current deck removal activities should implement more sustainable practices.
- The proposed sustainability scorecard, when implemented with sections that address the entire project and the bridge reconstruction, can help contractors and bridge owners incorporate sustainable practices into bridge deck removal projects.

Limitations

The analysis of cost-effective replacement alternatives is based on two components: (1) three interviews from a Midwest DOT estimator and two bridge contractors and (2) the assumption that superstructures have adequate service life and capacity. The survey results were based on 28 responses, and its design did not adequately capture sufficient responses to many of the questions. The low response rate for many questions limited the validity of the data. Six of 27 shear test results were not obtained because of technical difficulties. Finally, the proposed sustainability scorecard has not been tested.

Recommendations for Future Research

- Evaluate the fatigue performance of shear connectors with partial concrete removal.

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APPENDIX A. SURVEY OF DOTS ON CURRENT PRACTICE

1. Please indicate which state you completing this survey?

Alabama	Alaska	Arizona	Arkansas	California
Colorado	Connecticut	Delaware	Florida	Georgia
Hawaii	Idaho	Illinois	Indiana	Iowa
Kansas	Kentucky	Louisiana	Maine	Maryland
Massachusetts	Michigan	Minnesota	Mississippi	Missouri
Montana	Nebraska	Nevada	New Hampshire	New Jersey
New Mexico	New York	North Carolina	North Dakota	Ohio
Oklahoma	Oregon	Pennsylvania	Rhode Island	South Carolina
South Dakota	Tennessee	Texas	Utah	Vermont
Virginia	Washington	West Virginia	Wisconsin	Wyoming

Other Agency (please specify) ____________

2. For the steel and precast concrete girder type bridges indicated below, does your state have provisions and/or guidelines for full-depth concrete deck removal (re-decking)?
3. Which removal methods have previously been used and are currently allowed within your state for decks placed on steel and precast concrete girders?
4. Using the drop down menus, please describe the typical cost, duration, safety, and noise of each method you previously indicated.
5. Please describe how likely the methods you have indicated will cause damage to the girder flange?
6. In your experience, have you witnessed the methods indicated cause damage to the shear connectors? If so, please describe.
7. If a steel I-girder's top flange is damaged during deck removal, what actions are taken for varying degrees of damage?
8. If a Standard AASHTO girder's top flange is damaged during deck removal, what action are taken for varying degrees of damage?

9. If a Bulb-T girder's top flange is damaged during deck removal, what actions are taken for varying degrees of damage?
10. In the event where stay-in-place forms were used for deck construction, how is the deck removed?
11. What new deck removal approaches or innovative ideas would you recommend if the project was not restricted by time and cost?
12. May we at the Bridge Engineering Center contact you directly with any further questions we may have? If so, please provide your direct contact information.

Name:	Agency:
Address:	City/Town:
State:	ZIP:
Email Address:	Phone Number:

APPENDIX B. INTERVIEW QUESTIONNAIRE ON DECK REMOVAL

States are looking for cost-effective methods of removing bridge deck from steel girders to extend the service life of bridge. The cost analysis is comparing the bridge deck removal with promising methods versus complete removal of bridge deck and steel girder. Actual cost data analysis will provide foundation for making future cost-based replacement decisions.

Purpose of Interview:

- Understand estimate of bridge deck removal from contractor's perspective.
- Discuss cost associate factors in concrete deck removal (Evaluate factor's sensitivity)
- Identify cost-factor related relationship.

General Questions

1. Name:
2. Current Title and position description:
3. Duration with Estimating and experience at different titles:
4. Past bridge deck replacement projects:

Specific Questions:

Methods

1. What are the conventional methods of removing concrete deck from steel girders?
    A. Saw cutting, Percussive tools (Jackhammer, Whip-hammer, and breaker), Drilling, Splitting, Blasting, Ball and Crane.
    B. New methods (Hydrodemolition, Chemical Splitting, Peeling off, Milling, Crusher, Thermal cut)
2. When selecting methods, what factors do you consider?
    A. Project type, size, location, traffic, environment impact and sustainability.
    B. Cost, Damage, Safety,

C. Vibration, Dust, Noise, Falling material,

D. Time/Duration (Efficiency), Length of Concrete Deck (Quantity), Equipment,

3. Do you consider damage when selecting different deck removing methods?

Damages

1. What are the typical damages to steel girder?

    A. Shear connector damages, Saw cut top flange, indentation, local damages (distortion, deformation), Fatigue, Crack,

    B. Other damage?

2. How do you assess the damages?

    A. Level of damage? Damage rating?

3. What are the repairing means and methods?

    A. Heat-straightening

4. Based on what criteria the damages would be more restricted in a project? How does it affect method selections and cost?

    A. DOT provision

    B. Project details

    C. Contractor's means and methods

    D. Repairing cost

Cost and Estimate

1. How do you estimate the cost of a bridge deck removal project?

    A. Unit price, unit labor, crew and equipment

2. What would be the typical duration range of a bridge deck removal project?

    A. Duration of removing concrete deck

B. Duration of new concrete deck

C. Formwork and placement of concrete

D. Installation of precast concrete

3. What are the cost for repairing damages? How does damage level play into estimate?

A. How to estimate?

B. What are historical values?

4. Which would be more cost-effective when comparing extra days of removing concrete deck carefully and extra cost of repairing damages to steel girders versus the cost of new steel girders?

A. Is the comparison sensitive to any other factor?

B. Bridge Length? Damages (amount and level)? Steel price?

5. As you know, cost is very dependent on the removing methods and methods. How would you determine the most cost-effective means and methods to removing concrete decks from steel girder?

A. Start from preliminary consideration to the end of construction.

B. Does it ever change? Lessons learn?

6. Is the current practice still very cost-effective or the new methods are taking over?

A. Why it would be that way?

7. How would you provide water source for hydrodemolition and manage the wastewater?

A. What are those additional items' cost? Still cost-effective than conventional methods?

8. Did you remove concrete deck by peeling off or chemical splitting methods before?

A. If so, how well does it work? Is it cost-effective? What are costs?

9. How to get the unit price data on bridge deck removal project from State DOT websites?
    A. Can you provide a guidance?
10. Can you provide itemized cost data for past projects on three methods?
    A. Conventional methods (i.e., saw cutting + Jack hammering)
    B. New methods (i.e., hydrodemolition)
    C. Replacement of both concrete deck and steel girder
    D. Cost of removing
    E. Cost of new girder
11. Within the projects experience, do you see any relationship between the length of the bridge and the unit cost?
    A. Concrete Deck Quantity (length, Width, Thickness)