

Investigation of Techniques for Accelerating the Construction of Bridge Deck Overlays



Final Report
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16. Abstract Use of bridge deck overlays is important in maximizing bridge service life. Overlays can replace the deteriorated part of the deck, thus extending the bridge life. Even though overlay construction avoids the construction of a whole new bridge deck, construction still takes significant time in re-opening the bridge to traffic. Current processes and practices are time-consuming and multiple opportunities may exist to reduce overall construction time by modifying construction requirements and/or materials utilized. Reducing the construction time could have an effect on reducing the socioeconomic costs associated with bridge deck rehabilitation and the inconvenience caused to travelers. This work included three major tasks with literature review, field investigation, and laboratory testing. Overlay concrete mix used for present construction takes long curing hours and therefore an investigation was carried out to find fast-curing concrete mixes that could reduce construction time. Several fast-curing concrete mixes were found and suggested for further evaluation. An on-going overlay construction project was observed and documented. Through these observations, several opportunities were suggested where small modifications in the process could lead to significant time savings. With current standards of the removal depth of substrate concrete in Iowa, it takes long hours for the removal process. Four different laboratory tests were performed with different loading conditions to determine the necessary substrate concrete removal depth for a proper bond between the substrate concrete and the new overlay concrete. Several parameters, such as failure load, bond stress, and stiffness, were compared for four different concrete removal depths. Through the results and observations of this investigation several conclusions were made, which could reduce bridge deck overlay construction time.					
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INVESTIGATION OF TECHNIQUES FOR ACCELERATING THE CONSTRUCTION OF BRIDGE DECK OVERLAYS

Final Report
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Principal Investigator
Brent Phares
Director, Bridge Engineering Center

Co-Principal Investigator
Travis Hosteng
Director, National Center for Wood Transportation Structures
Bridge Research Specialist, Bridge Engineering Center

Research Assistant
Anmol M. Pakhale

Authors
Brent Phares, Travis Hosteng, Lowell Greimann, and Anmol Pakhale

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A report from
Bridge Engineering Center
Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664
Phone: 515-294-8103 / Fax: 515-294-0467
www.bec.iastate.edu

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EXECUTIVE SUMMARY

Today's environment is becoming increasingly hostile to bridge decks by exposure to deicing salts and environmental factors such as large temperature swings and polluting chemicals. Decks being subjected to the most severe loading of all the bridge components, they undergo deterioration and cracking, which usually results in the deck service life being shorter than the other major bridge components. Overlays can replace the deteriorated part of the deck, thus extending the bridge life. Many states including Iowa have been using overlays to replace the damaged deck concrete.

Even though overlay construction avoids the construction of a whole new bridge deck, it takes significant time to re-open the bridge to traffic. Reducing the time required for the construction of the overlay could have an effect on reducing the socioeconomic costs associated with bridge deck rehabilitation and the inconvenience caused to travelers.

Therefore, in this project, various ways of accelerating the construction of the overlays were investigated. The study started with three tasks: finding the latest fast-curing concrete mixes that can be used for overlays, observing an ongoing overlay construction project to suggest time-saving changes, and finding the required depth for removal of the substrate concrete.

Generally, the Iowa Department of Transportation (DOT) uses high-performance concrete (HPC) Class HPC-O or Class O concrete mix for overlay construction, which takes at least three days after overlay placement to re-open the bridge to traffic. For the first task, literature on the latest fast-curing concrete mixes were studied and several concrete mixes were found that can reduce the curing time to as short as four hours.

During the second task, an ongoing overlay construction project was observed and documented. The goal of these observations was to identify if there were opportunities for increased efficiency.

According to current Iowa DOT practice, during the removal of old unsound concrete, if the unsound concrete is found to be present above half the diameter of the top reinforcing steel bar, there is no need for extra removal of any sound concrete. If the unsound concrete is present below half the diameter of the reinforcing steel bar, in addition to the unsound concrete, extra sound concrete needs to be removed until one-half to one inch below the reinforcing steel bar. This extra removal of the substrate concrete leads to additional construction time.

A major part of this project was the third task, which was comprised of four different laboratory tests with different loading conditions to determine if the additional sound concrete removal is necessary. The bond strength between the substrate concrete and the new overlay concrete was tested for four different concrete removal depths. Several parameters, like failure load, bond stress, and stiffness, were compared for the different removal depths.

The results from the tests indicated that removing the additional sound concrete below half the diameter of the reinforcing steel would not result in a significant difference in the bond strength.

1. INTRODUCTION

1.1 Background

Due to exposure to extreme environmental conditions, heavy-truck wheel loadings, and deicing salts that corrode reinforcement, bridge decks are subject to the most severe conditions of all bridge components. This usually results in deck service lives being less than the other major bridge components.

Rehabilitating damaged deck slab concrete with an overlay system can significantly increase the life of the reinforced concrete bridge deck and thus reducing the costs of constructing a new bridge (Ramey and Oliver 1998). Published literature reveals that many states use overlay systems to prolong bridge decks service lives.

Generally, the Iowa Department of Transportation (DOT) uses high-performance concrete (HPC) Class HPC-O or Class O concrete for overlay construction. For the bridge to be open to traffic after overlay construction, the overlay concrete must reach a flexural strength of 400 psi. HPC-O concrete generally takes about three days to reach the required strength.

The Ohio DOT (ODOT) Office of Materials and Management Cement and Concrete Section reported that CTS Cement Rapid Set mixes are able to achieve the flexural strength of 400 psi in just two hours (Ohio DOT 2007). Part of this project was to identify if any other types of concrete mixes could reduce the curing time by a marked amount.

One of the major concerns about the construction of an overlay is the time it takes to open the bridge to traffic. As with other construction activities, attempts to minimize construction time must not compromise the structural soundness or longevity of the bridge. However, reducing the construction time could have a great effect on reducing societal costs and inconvenience to travelers. In this research, various ways of accelerating the construction of overlays were investigated.

Additionally, according to standard practice for overlay construction in Iowa, during removal of existing concrete, if more than half of the reinforcing steel bar becomes exposed, additional concrete needs to be removed so that the entire bar is exposed (Iowa DOT 2012). This process of removing additional, possibly sound, existing concrete material can be a significant part of the construction process, particularly if the work is completed using handheld tools. Although this concrete removal approach has resulted in satisfactory performance for many years, questions exist as to how, when, and why this requirement was enacted.

Thus, questions remain regarding how much removal is actually needed while still maintaining adequate structural stability. Answers are particularly important if hydrodemolition is utilized to remove the deteriorated material, because hydrodemolition equipment can usually be “dialed in” to remove quite precise depths of concrete.

1.2 Objective and Approach

The primary objective of this project is to accelerate the construction of bridge deck overlays. This objective is divided into three parts as follows:

1. Investigation into faster curing concrete alternatives for overlays

The time required to cure traditional concrete is one aspect of the construction process that requires a notable amount of time. Current practice in Iowa requires three days of curing for HPC-O concrete. However, new types of concrete have been introduced that require far less curing time. Therefore, an investigation of other concrete mixes was completed by studying the available literature.

2. Observation of the overlay construction process to identify any opportunities for reducing construction time

In this activity, an ongoing overlay project was observed and documented. Throughout construction, the process was carefully observed and the time required for each process was noted. The goal of these observations was to identify if there were opportunities for increased efficiency. The intent was not to suggest that changes or mandates to contractor's means and methods should be made.

3. Laboratory testing to determine the required amount of existing concrete that must be removed

Removal of the substrate concrete to replace it with new overlay concrete requires a significant amount of time in the construction of an overlay. The standard practice in Iowa requires the contractor to remove the deteriorated substrate concrete, but if the removal depth exceeds half the diameter of the reinforcing bar, it is required that the contractor remove the concrete to 0.5 to 1 in. below the bar. To investigate the efficacy of this practice, laboratory testing was completed to determine the relationship between removal depth and the bond between the substrate concrete and the new overlay concrete.

1.3 Report Content

This report is divided into five chapters. After the introductory material provided in this chapter, the second chapter includes a literature review of different types of fast-curing concrete including information on properties. The third chapter contains a summary of a recently completed bridge deck overlay with suggestions on process changes that may reduce overall construction time.

The fourth chapter covers the laboratory testing completed to evaluate the needed amount of substrate concrete removal. The chapter summarizes the methodology that was utilized and

includes details about the test procedure, specimen configuration, and testing arrangement. This chapter also includes the results and discussion of the laboratory tests with the details on the failures of the specimens.

The fifth chapter summarizes the entire project and includes conclusions and recommendations for reducing the time associated with overlay construction.

2. OVERLAY SYSTEMS

2.1 Description of Different Types of Overlays

2.1.1 Class O Portland Cement Concrete

The Iowa DOT currently uses Class O Portland cement concrete (PCC) as an overlay concrete to replace the unsound, top-of-deck concrete during overlay construction. The water-to-cement (w/c) ratio is intended to be controlled by the slump specified when these mixtures are used. A water-reducing agent is typically required for this mix. Class O mixes require coarse aggregate specifically intended for repair and overlay.

2.1.2 Class HPC-O High Performance Concrete

Class HPC-O is also a highly used overlay concrete by the Iowa DOT for bridge deck overlay construction (Iowa DOT 2012). HPC is a concrete mix proportion that has been designed to provide several benefits that cannot always be achieved routinely using conventional ingredients, normal mixing, and normal curing practices.

HPC possesses high durability and high strength when compared to conventional concrete. This concrete contains one or more cementitious materials, such as fly ash, silica fume, or ground granulated blast furnace slag, and usually a super plasticizer. The use of some mineral and chemical admixtures like silica fume and super plasticizer enhance the strength, durability, and workability qualities to a very high extent. The maximum w/c ratio is 0.42 and, just like Class O mix, Class HPC-O mix is also specified as low slump concrete for overlay construction (Iowa DOT 2012).

Table 1 lists various HPC mix properties.

Table 1. Properties of HPC concrete mix

Property	Value	Curing time
Traffic return time	72 hrs	72 hrs
Compressive strength (psi)	3000 up to 10,000	as little as 3 hrs 28 days
Flexural strength (psi)	300 1000	as little as 3 hrs 28 days
Permeability (coulombs)	500-2000	
Chloride penetration	less than 0.07% Cl at 6 months	
Modulus of elastisity (psi)	5800000	
Abrasion resistance	0-1mm depth of wear	
Absorption	2% to 5%	
Freeze-thaw resistance (durability factor for 300 to 1000 cycles)	95 to 100	
Cost (\$/yd ³)	119	

Source: Kosmatka et al. 2003

Curing

The Iowa DOT *Standard Specifications for Highway and Bridge Construction* include the following curing instructions: Allow the surface to cure using wet burlap for at least 72 hours. The burlap should be wet at all times by means of an automatic sprinkling or wetting system. When Class HPC-O is used on projects with a deck overlay quantity greater than 1,800 square yards (1500 m²), allow the surface to cure for 168 hours (Iowa DOT 2012).

2.1.3 CTS Cement Rapid Set Low-P Mixes

CTS Cement launched a cement product called Rapid Set Low-P, that, when incorporated into a concrete, provides very low permeability, high durability, and corrosion resistance. These attributes are highly desirable for structural repairs and bonded overlays in exterior and harsh environments. Low-permeability concrete inhibits the passage of salt solution through the concrete, which in turn results in less corrosion of the internal reinforcing steel. Rapid Set Low-P Cement requires the addition of aggregates, water and, in some cases, a retarder such as citric acid. (CTS Cement 2016)

Due to the fast setting nature of Rapid Set Low-P cement, tensile strength development occurs very rapidly. This shortens the amount of time that vibrations from adjacent traffic lanes can be a factor in early-age stress cracking in the concrete.

Table 2 lists CTS Cement Rapid Set Low-P mix properties.

Table 2. Properties of CTS Cement Rapid Set Low-P mixes

Property	Value	Curing time
Traffic return time	4 hrs	4 hrs
Compressive strength (psi)	4000-4500	3 hrs
	5000-6000	6 hrs
	8000-9000	28 days
Tensile bond strength (psi)	200-250	24 hrs
	600	7 days
	700	28 days
Slant shear bond strength (psi)	1200	24 hrs
	1900	7 days
	2200	24 days
Initial set	30 min	
Final set	40 min	

Source: CTS Cement 2014

Other advantages (CTS Cement 2014):

- Single component cement – just add water and aggregates
- Provides corrosion protection
- High sulfate resistance
- Easy to place, high slump, non-segregating formula
- Hydraulic cement based formula – provides excellent long-life durability

Curing

The CTS Cement *Rapid Set*[®] *Low-P*[™] *Cement Datasheet* includes the following curing information: For overlays, the surface should be covered promptly after final finishing with a single, clean layer of wet burlap followed by a layer of clear polyethylene film. Patches can be water cured by maintaining a moist sheen on the surface. Curing should continue until the concrete has reached the strength desired. Depending on temperatures and specified strength, this will usually be within 1 to 3 hours after final finishing. During the entire period, apply more water, as needed, to keep the entire concrete surface continuously wet (CTS Cement 2014).

2.1.4 4×4 Concrete Mix

The Iowa DOT specifications for highway and bridge construction state that the overlay concrete needs to reach a minimum flexural strength of 400 psi to re-open the bridge (Iowa DOT 2012). “The name 4×4 concrete originates from a concrete that obtains at least 400 psi of flexural strength within 4 hours of placement... The flexibility of 4×4 concrete is such that it can be modified to meet many different specified strength conditions simply by adjusting the mixture proportions and admixture dosages.” (BASF 2016)

With 4×4 concrete, it is possible to proportion a mixture using locally available Portland cements, aggregates, and selected admixtures. With 4×4 concrete, a synthetic high-range water-reducing admixture is used to provide fluidity and strength, a hydration control admixture is used to provide workability control, and an accelerating admixture provides early strength (Meyers n.d.). Air-entraining admixtures can be used where the concrete has to be air-entrained (BASF 2011).

Smith, Alarcon, and Glauz mention that 4×4 concrete has met all of the technical and performance expectations of the California DOT (Caltrans) highway engineers (Smith et al. 2001). For example, no cracks have been observed four hours after placement of the material.

Table 3 lists 4×4 concrete mix properties.

Table 3. Properties of 4×4 concrete mix

Property	Value	Curing time
Traffic return time	4 hrs	4 hrs
Compressive Strength (psi)	4130	4 hrs
	7740	24 hrs
	8250	28 days
Flexural strength (psi)	480	4 hrs
	855	24 hrs
	1250	28 days

Source: Meyers n.d.

Other advantages (BASF 2011, Meyers n.d., Smith et al. 2001):

- Very user-friendly and easy to place and finish since it can be mixed on site
- Uses portable dispenser system for accelerating admixtures on site
- Exceptional high-early strength permits rapid opening to traffic minimizing lane closures
- No cracks observed 4 hours after placement when a loaded ready mix truck was driven onto the slab
- High abrasion resistance
- Uses DOT-approved admixtures and locally available cement and aggregates
- Mixed and delivered in ready-mixed concrete trucks

Curing

The researchers did not find any printed instructions readily available on curing 4×4 concrete mixes for overlays, but the manager/chief engineer with BASF Admixture Systems replied to our inquiry saying moist curing or curing compounds are used insulating blankets are used to retain heat resulting from the hydration process ((Nmai 2016).

2.1.5 Polyester Polymer Concrete

Polymer concrete is an expensive overlay material that can cost twice as much as conventional PCC and slightly more than latex-modified concrete. However, an increasing number of highway engineers are choosing polymer concrete for concrete bridge deck rehabilitation, finding that its advantages as an overlay material might justify its high cost.

Some benefits of polymer concrete include improvement in abrasion and skid resistance of the deck surface and also protection against corrosion of the internal steel reinforcement. Additionally, it is impermeable to water, deicing salts, and chemicals that can accelerate corrosion.

Polyester concrete is a composite of dry aggregate in an unsaturated or thermoset, polyester resin binder. Certain polymer content, well-graded aggregates, fibers, and coupling agents influence the various properties of polyester polymer concrete. When the liquid resin cures into a hardened, cross-linked state, a polyester concrete is formed.

Maggenti stated that Caltrans' use of polyester polymer concrete for 20 years has been successful and proved to be very effective in terms of durability, crack resistance, chloride ion intrusion resistance, bonding, ease of construction, and lane closure time (Maggenti 2001).

Table 4 lists polyester polymer concrete properties.

Table 4. Properties of polyester polymer concrete

Property	Value	Curing time
Traffic return time	2-4 hrs	2-4 hrs
Compressive strength (psi)	3982	24 hrs
	7000	7 days
	8030	28 days
Flexural strength (psi)	2200	28 days
Tensile strength (psi)	800	28 days
Chloride permeability (coulombs)	0-200	
Modulus of elasticity (psi)	$1 \times 10^6 - 2 \times 10^6$	
Abrasion (mm/year)	4 (8 to 10 times more than PCC)	
Cost (WSDOT- weighted avg \$/sq ft)	10.73	

Sources: Oberoi 2012, Anderson et al. 2013

Curing

The Washington State DOT (WSDOT) Materials Laboratory included the following instructions on curing in a 2013 report: Polyester polymer concrete shall be placed immediately after the prime coat is applied to the bridge deck. The prime coat shall cure for a minimum of 30 minutes before placing the polyester concrete overlay. After placement, a 30 to 90 minute set time will be

produced by implementing initiators. Depending on environmental conditions such as weather, accelerators or inhibitors may be added to the mix to help produce the specified cure time.

Traffic and construction equipment shall not be permitted on the polyester polymer concrete overlay for at least two hours and until the polyester polymer overlay has reached a minimum compressive strength of 3,000 psi as verified by the rebound number determined in accordance with ASTM C805. No vehicles or personnel will be allowed to travel on the finished polyester concrete overlay during the curing process.

The contractor will utilize a Schmidt hammer to determine the proper time to open the roadway to traffic. A 3,000 psi reading on the rebound hammer will be achieved in order to open the roadway to traffic (Anderson et al. 2013).

2.1.6 Very-Early-Strength LMC

Latex-modified concrete (LMC) is a PCC in which an admixture of styrene butadiene latex particles suspended in water is used to replace a portion of the mixing water. LMC has been used on highway bridges for overlay rehabilitation for more than 40 years (Sprinkel 1998).

Compared to concrete without latex, LMC is reported to be more resistant to intrusion of chloride ions, to have higher tensile, compressive, and flexural strength, and to have greater freeze-thaw resistance. The use of LMC overlays is one of the most popular ways to extend the time to corrosion initiation. The resistance to chloride intrusion is said to be attributable to the lower w/c ratio and a plastic film produced by the latex particles within the concrete (Sprinkel 1998).

Table 5 lists very-early-strength LMC properties.

Table 5. Properties of very-early-strength LMC

Property	Value	Curing time
Traffic return time	3 hrs	3 hrs
Compressive strength (psi)	3000	3 hrs
	4000	6 hrs
	6500	5 days
Chloride permeability (coulombs)	300-1400	28 days
	0-10	1 year
	0-60	9 years
Drying shrinkage (%)	0.02	170
Tensile adhesion bond strength (psi)	153-276	1-6 months
	176-301	9-10 years
Cost (\$/yd ³)	140	

Source: Sprinkel 2011

Curing

The overlay is to be quickly covered with wet burlap and polyethylene to provide a moist environment during the three-hour curing period (Sprinkel 1998).

3. INVESTIGATION OF ONGOING OVERLAY CONSTRUCTION PROJECT

The acceleration of the construction of bridge deck overlays may be achieved through management of time, labor, and materials. As part of this research, a team observed a portion of an ongoing overlay construction project to document the time required for different activities and to observe possible activities where construction time could be reduced. It should, again, be noted that the observations and comments are not intended to suggest that changes to contractor's means and methods associated with overlay construction are needed or should be required.

Overlay construction for the bridge on IA 163 over Fourmile Creek, 1.7 miles west of US 65 (FHWA No. 40941, overlay project number BRFN-163-1(87)--39-77), was observed. The bridge was 256 ft long and 56 ft wide. For this research, the team observed overlay construction of only the eastbound lanes. A summary of the team's investigation of the construction activities follows.

3.1 Removal of Temporary Bollards

Temporary bollards were installed on the bridge deck during construction of the westbound overlay. These bollards were installed between the eastbound and westbound lanes to direct traffic safely. The bollards that were used were bolted to the deck and had to be detached using a hand drill as shown in the Figure 1.



Figure 1. Temporary bollards being detached by workers

It took two hours for 10 workers to remove all of the bollards.

3.2 Removal of Top 2 to 3 in. Layer of Deck Concrete

After the temporary bollards were removed, a milling machine was lined up with the deck surface and prepared for operation. Preparing the road milling machine took about an hour.

One person operated the machine and four workers watched over the machine and guided the operator. The milled concrete was transferred to a dump truck by a conveyor connected to the milling machine as shown in Figure 2.



Figure 2. Milling machine removal of top layer of the deck

In one pass from one end of the bridge to the other, the milling machine was able to remove about 2 to 3 in. of concrete, so that there would be only 0.5 to 1 in. deep concrete on top of reinforcing steel. The milling required an hour to finish one pass and, once a pass was done, it took 15 to 20 minutes to turn around and start working on the next pass.

After half of the deck was milled, the cutting drum of the road milling machine was changed, which took 30 to 45 minutes. The overall time for the removal of the top layer of concrete was seven hours.

After doing five passes, all of the top layer of concrete on the deck was removed and the residual concrete was cleaned off. Alongside cleaning, the cleaned deck portion was inspected for unsound and damaged areas, which were marked for more in-depth removal as shown in Figure 3.



Figure 3. Area marked for more in-depth removal

Throughout the removal of the top layer of concrete, three dump trucks were used to take milled concrete from the construction site to the dump site. Even though three trucks were used, many times, after a truck was filled with concrete, a new truck was not ready to continue the road milling machine's operation. Access to the bridge site required long travel times and, as a result, a truck was not yet available at times and the milling operation had to be halted for several minutes. Providing one more dump truck could reduce that downtime.

3.3 Placing the Compressed Air Line

Jackhammers were used to further remove the unsound concrete after removal of the top 2 to 3 in. layer. To power the jackhammers along the length of the bridge, a pipeline for compressed air was installed on the outer side of the bridge railings. Five workers were working on the installation of the compressed air pipeline while the top layer of the deck was being removed using the milling machine.

3.4 Removal of Substrate Concrete using Jackhammers

The removal of substrate concrete using the jackhammers was completed by nine workers over the course of three days. On the first day, it took an hour to prepare for the task and then removal took about six hours. By the end of second day, all marked, unsound concrete was removed. On the third day, all areas were carefully inspected and marked for additional concrete removal. After the inspection, removal of the marked concrete took place for seven additional hours. Figure 4 shows a worker removing the marked patch of concrete using a jackhammer.



Figure 4. Removal of unsound concrete using jackhammer

Considering that it took three days for removal of the substrate concrete, utilizing additional workers could lead to shorter completion time. Also, according to standard practice for overlay construction in Iowa, if more than half of the bar becomes exposed during substrate removal, additional sound concrete needs to be removed such that the entire bar is exposed. Considering the large area of concrete needing removal, removing the additional sound concrete around the bar may have taken a significant amount of time.

On the third day, the deck was inspected for areas where the entire reinforcing steel bar needed to be exposed. According to the contractor, about 30% of the time, the damaged concrete level is between half the diameter to the full diameter of the bar and the workers need to expose the entire reinforcing steel bar. This extra removal may take many hours to complete depending on how deep the deteriorated concrete is and over how much area it extends. In a best case scenario, it may have been possible for the entire third day of concrete removal to have been almost entirely avoided if the deteriorated concrete was just barely below the half diameter point. It seems fair to say that this additional removal may have taken 4 to 8 hours. Figure 5 shows a deteriorated area of deck concrete after removal of the substrate concrete.



Figure 5. Deteriorated area of the deck after removal of the substrate concrete

In this figure, the concrete has been removed below the reinforcing steel for almost the entire area.

3.5 Sandblasting the Deck

The entire deck was then sandblasted to provide the roughness needed for a proper bond between the concrete and the new overlay concrete. Sandblasting also removed any corrosion on the exposed reinforcing steel. Six people were simultaneously working on the sandblasting process, either operating the sandblasting equipment or cleaning the sand off the deck. Preparing for sandblasting and sandblasting the whole deck took about nine hours. Two sandblasting crews working on the deck simultaneously would require less time, but would also require more workers.

3.6 Overlay Concrete Placement

Preparatory work for overlay placement took about five hours with 10 workers. Followed by the preparation work, the ready-mixed concrete was placed on the deck as shown in Figure 6.



Figure 6. Ready-mixed concrete being placed on the deck

About 20 workers worked on the overlay placement at the same time. Many tasks were carried out by workers including watching over the overlay concrete for proper placement, operating the machinery, laying wet burlap for curing, moving the machinery and equipment, and scooping extra concrete from one place and dumping it to another place. The whole process took about four hours. The concrete was cured for three days before opening to traffic.

3.7 Other Observations

During overlay installation on the westbound lanes prior to the research team's observations on the eastbound lanes, a fiber optic cable was found near the bridge. In addition, the contractor found a manhole at the approach to the westbound lanes, which was not shown in the plans, as shown in Figure 7. Although the true impact of these observations on the project schedule are not known, the contractor, when asked, did mention this as an unexpected factor.



Figure 7. Manhole discovered near the approach to the westbound lane

The as-built overlay construction schedule of the eastbound lanes observed by the researchers (64 hours over the course of 7 working days) is shown in Figure 8.

The schedule does not show curing time after overlay placement nor the time to actually open the eastbound lanes to traffic.

Removal of the substrate concrete on the deck and along the barrier rail using jackhammers took the most time (33 hours over the course of 4 working days). Based on the above mentioned observation regarding the amount of sound concrete removed below the one-half diameter point, it is possible that 4 to 8 hours may have been saved had this requirement not been in place. In bridges with more extensive areas of deteriorated concrete that is not as “deep,” it is possible that relaxing or eliminating this requirement could have notable time saving implications. Such a reduction could have an impact on the critical path for the entire project.

The contract proposal for the entire bridge deck overlay construction (eastbound and westbound lanes) shows a contract period of 40 working days. During this project, however, the research team only observed the overlay portion of the project, as the goal was to identify areas when traffic mobility was impacted. Collectively, the two most time-consuming operations were old concrete removal and overlay placement. If the rapid set alternatives briefly described in Chapter 2 were shown to provide the durability, permeability, abrasion resistance, freeze-thaw resistance, etc. that is needed, and if the additional concrete removal below the one-half bar diameter requirement was eliminated, it seems possible that up to 77 hours of the estimated 136 could have been saved.

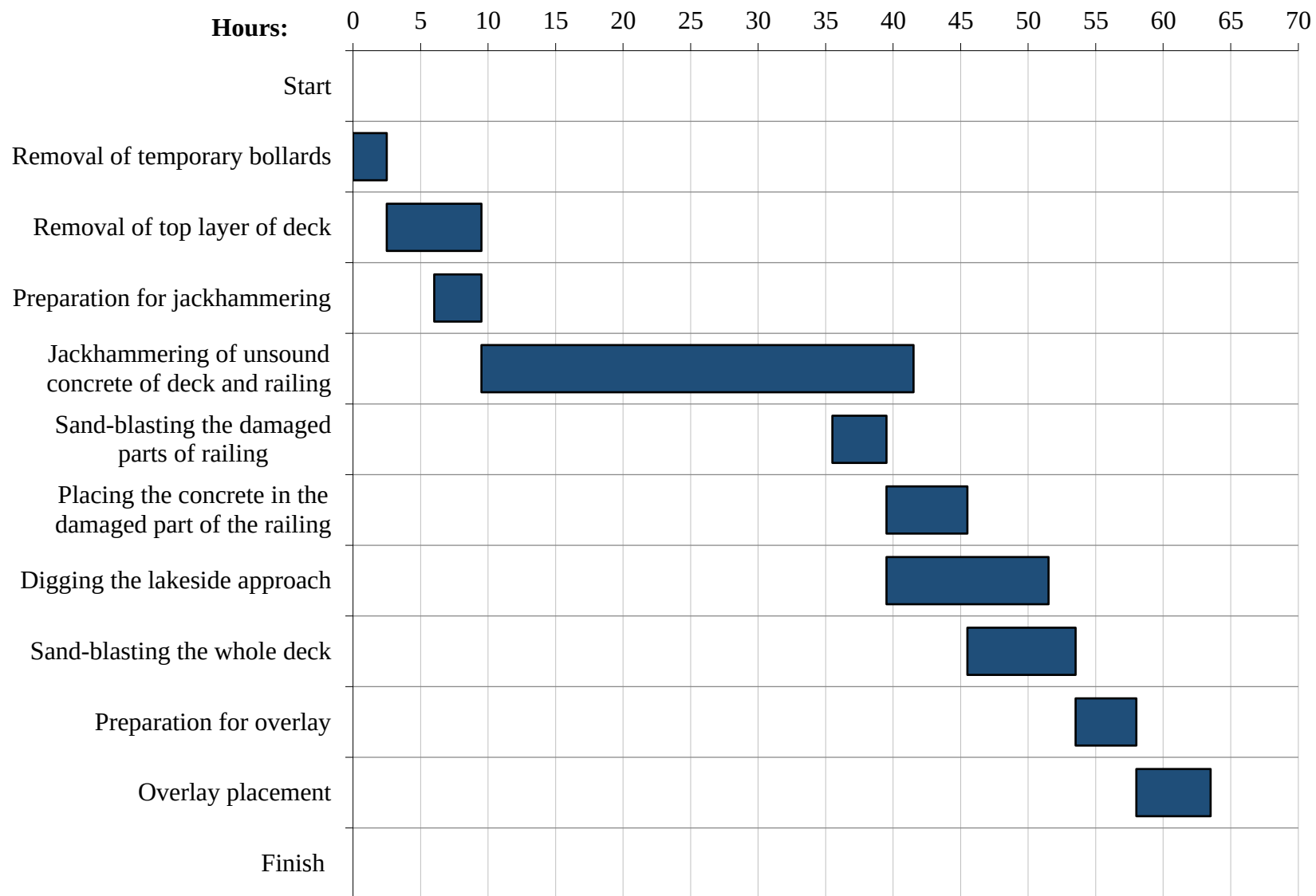


Figure 8. Eastbound overlay construction schedule as observed

4. LABORATORY TESTING

4.1 Methodology and Study Parameters

With this project, one of the approaches investigated for accelerating overlay construction was to determine if the change in depth of overlay concrete affects the bond strength between the substrate concrete and the new overlay concrete. Currently, if the concrete needs to be removed up to half of the diameter of the reinforcing steel, then it is not necessary to remove it any further; but, if there is a need to remove the concrete any deeper than half the diameter of the reinforcing steel, it is removed to expose all of the bar plus an extra 0.5 to 1 in. of concrete. This need for extra removal takes extra construction time.

Four different cases of reinforcing steel exposure were considered in four tests so that, the bond strength between the substrate and the overlay concrete could be studied. Three specimens were tested for every removal depth level.

The following four cases of removal depth levels were considered, as also shown in Figure 9.

Case 1. Concrete removed down to the upper surface of the reinforcing steel

In this case, the substrate concrete was removed down to the top surface of the reinforcing steel so that there would be virtually no exposure of the reinforcing steel to the new overlay concrete.

Case 2. Concrete removed down to half the diameter of the reinforcing steel

The substrate concrete was removed up to half the diameter of the reinforcing steel leaving the top half of the reinforcing steel exposed to the new overlay concrete.

Case 3. Concrete removed down to the full diameter of the reinforcing steel

In this third case, the substrate concrete was removed to the bottom of the reinforcing steel, so that the entire diameter of the reinforcing bar would be exposed to the new overlay concrete.

Case 4. Concrete removed down to the full diameter of the reinforcing steel plus an additional 0.5 to 1 in. below it

To get deeper, an additional 0.5 to 1 in. concrete was removed in addition to the full bar exposure condition.

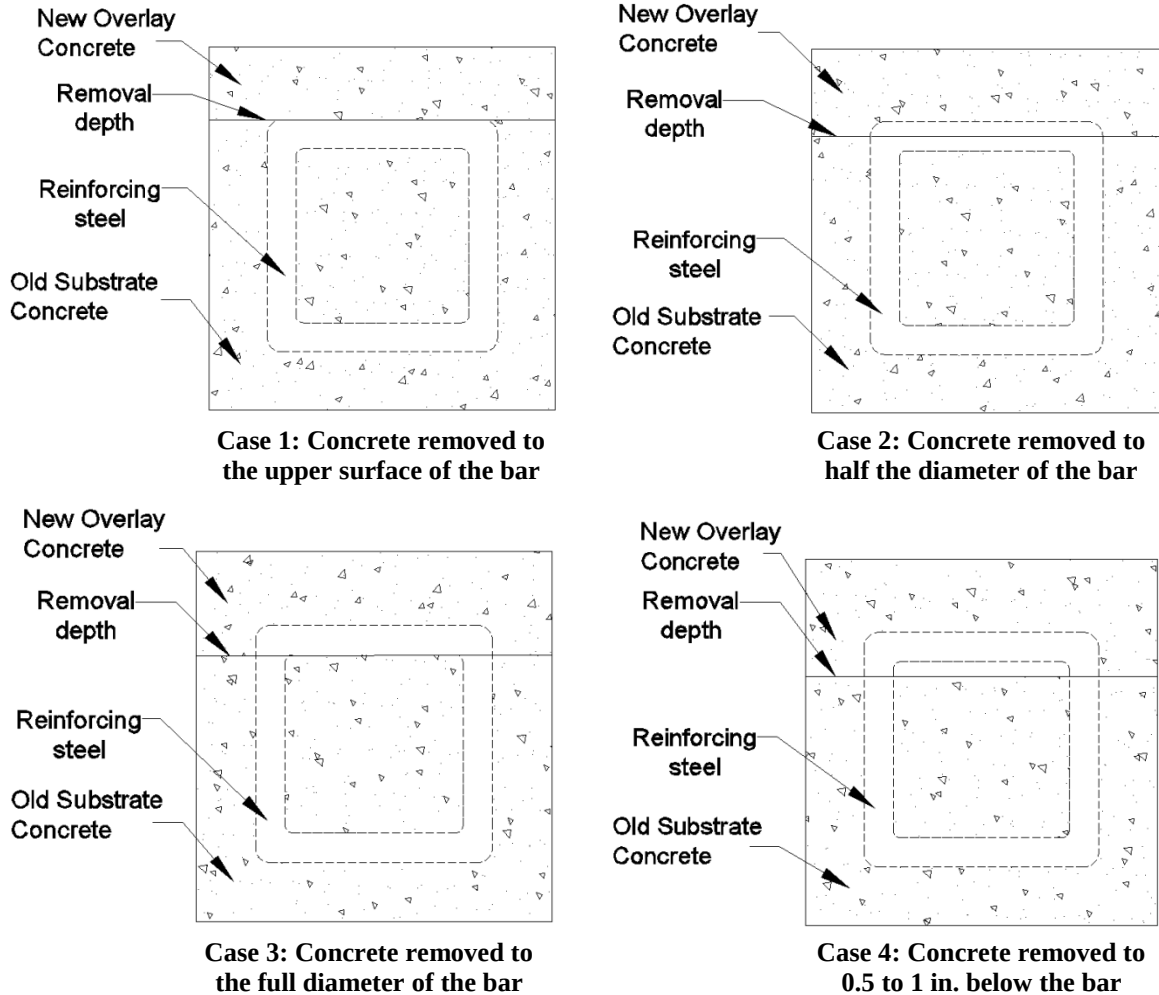


Figure 9. Different depths of concrete removal considered

For these four different cases of removal depth, the bond between the substrate concrete and the new overlay concrete was evaluated using four different tests:

- Pull-off test
- Push-out test
- Positive bending flexural test
- Negative bending flexural test

Factors that were taken into consideration for comparing the bond strength were load at stiffness changes, maximum load, shear stresses at stiffness change and at failure, and stiffnesses.

Two types of concrete mixes were used for all of the tests. For the substrate concrete, C4 concrete was used; and, for the new overlay concrete, HPC-O concrete was used. The strength values for these concrete mixes are shown in Table 6 and Table 7.

Table 6. C4 concrete mix strength values

Age (days)	Compressive strength (psi)	Splitting tensile strength (psi)
7	4767	495
21	4765	508
28	5190	515

Table 7. HPC-O concrete mix strength values

Age (days)	Compressive strength (psi)	Splitting tensile strength (psi)
3	3947	420
21	6008	549
28	6501	573

This chapter further describes the methodology that was followed for the four different tests. Each of the tests and their results are described in the following sections.

4.2 Pull-Off Test

The pull-off test was used to determine the tensile bond strength between the old concrete and the new overlay concrete with variable removal depth levels.

4.2.1 Specimen Details

The specimens were fabricated to resemble a bridge deck slab. The dimensions of each specimen, the reinforcing steel spacing, and the detailing are all similar to an actual deck slab and are shown in Figure 10 for Case 1 (concrete removed down to the upper surface of the reinforcing bar).

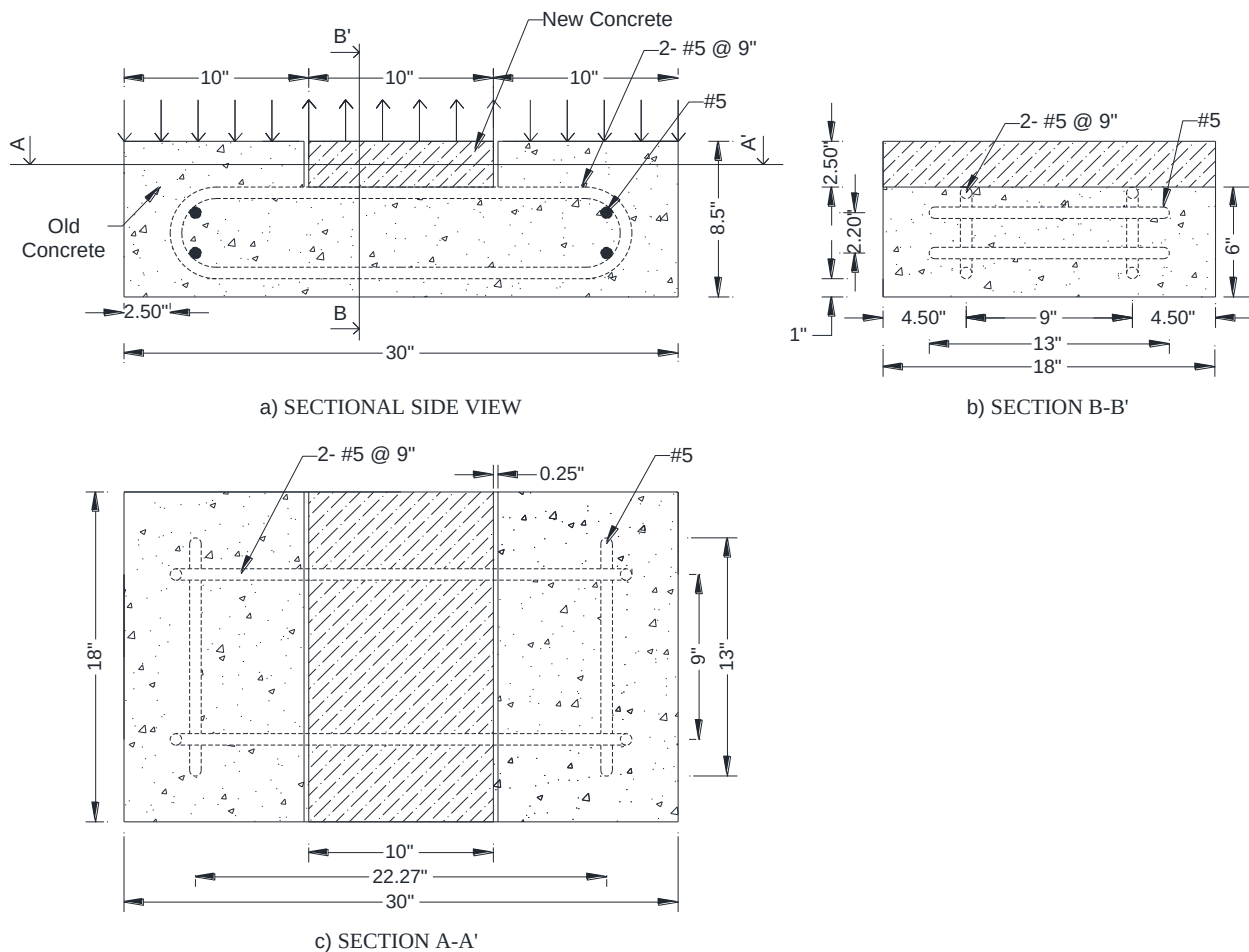


Figure 10. Pull-off test specimen schematic (Case 1)

Wooden formwork (as shown in Figure 11) was fabricated for the construction of the pull-off test specimens. The shaded part in Figure 10 was to be filled by the new overlay concrete after the concrete being used for the substrate concrete had cured. To create the voids to be filled later, foam was used to fill the shaded parts until the substrate concrete hardened and the overlay concrete could be placed. To keep the foam stable, the formwork was built upside down and the

reinforcing steel was placed on the foam. An extra reinforcing steel bar was used to keep the main reinforcing steel stable horizontally. The reinforcement arrangement can be seen in Figure 11.



a) Top view



b) Angle view

Figure 11. Pull-off test formwork for substrate concrete placement

C4 concrete was placed into the formwork and the specimens were vibrated appropriately. The specimens were covered with plastic and wetted periodically to maintain the moisture level inside. After curing the specimens for three days, the foam and formwork were removed. The depth of the foam was only up to the face of the reinforcing steel (i.e., 2.5 in.) deep. To achieve

the different depth conditions, the portions where foam was used were chipped below the face of the bar and the exposed C4 concrete was then roughened using a jackhammer (Case 1 specimens only needed to have the C4 concrete roughened).

As shown earlier in the Figure 10 schematic (upper left), a gap is needed between the substrate concrete and the new overlay concrete for pull-off test placement of the overlay concrete. Without the gap, at the time of pull-off test loading, the vertical bond between the substrate concrete and the new overlay concrete along the edges of the overlay concrete would provide shear bond strength to resist the load in addition to the tensile bond strength provided by the horizontal bond at the bottom of the overlay concrete. To get only the tensile strength resistance, foam with a 0.25 in. thickness was glued to the C4 concrete on each side to create the voids as shown in Figure 12.



Figure 12. Pull-off test formwork for overlay concrete placement (Case 4)

The most challenging aspect of this test was to figure out a method to apply the pull-off force to the new overlay concrete. After much discussion, shear studs welded to a steel plate, as shown in Figure 13, were used.

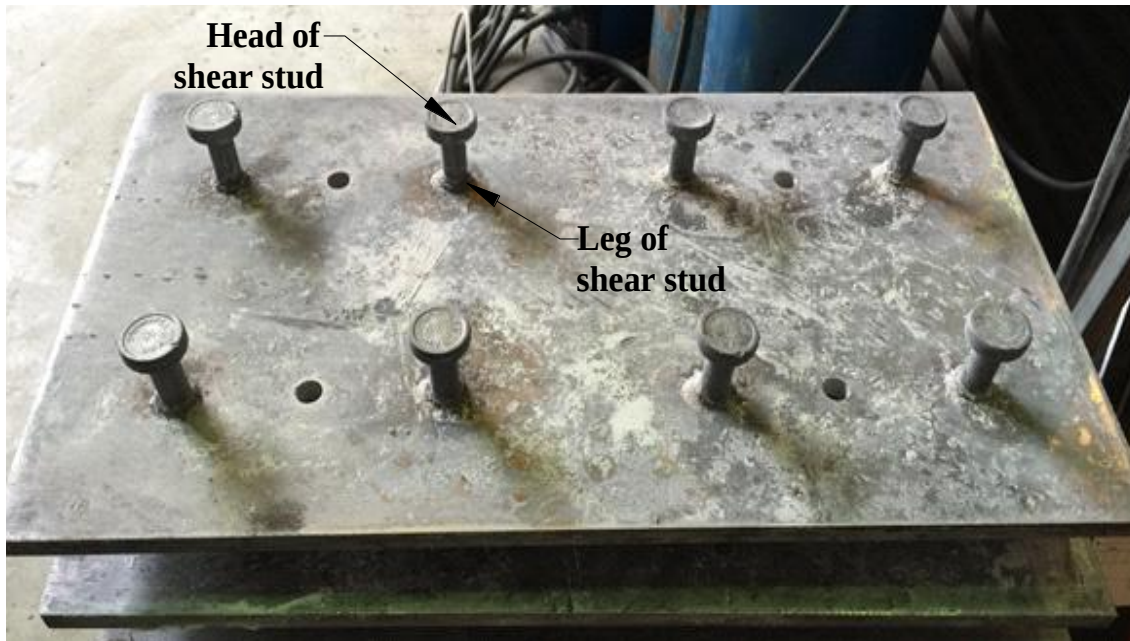


Figure 13. Pull-off test steel plate with welded shear studs

Eight shear studs were welded to each steel plate. The shear studs were 1.5 in. long and the diameter of the head was 1 in. The plate was 10 x 18 x 0.5 in. The steel plate also had four 3/8 in. threaded holes, in which four bolts were fastened to connect it to a thicker plate, which was used to apply the pull-off force. The shear studs of each steel plate were embedded in the overlay concrete of each pull-off test specimen at the time of concrete placement.

To bond the new overlay concrete to the previously placed concrete, a grout consisting of a mixture of about 5 to 6 gallons of water to each 94 lb bag of cement (12.5 to 13.8 in³ of water per lb of cement) was used. The grout material was applied to the chipped portion using a stiff hand brush, just prior to placing of the overlay concrete. As soon as the grout was applied, the overlay concrete was placed so that the applied grout would still be wet when the concrete was placed. After the concrete was placed, the steel plate studs were embedded in it by firmly tapping the plate using a rubber hammer as shown in Figure 14.



Figure 14. Tapping the steel plate to embed the shear studs on a pull-off test specimen

All specimens were covered with a plastic sheet to maintain the moisture level. The forms were removed after two days of curing so that the specimens would be ready for testing after the third day.

4.2.2 Testing Arrangement

The Iowa DOT cures the overlay concrete for 72 hours and then opens the bridge to traffic. To simulate the same conditions, each pull-off test started two hours prior to 72 hours of curing and each test continued for approximately four hours.

Figure 15 shows the testing arrangement for the pull-off test. Closer views of the specimens are shown in the next section.

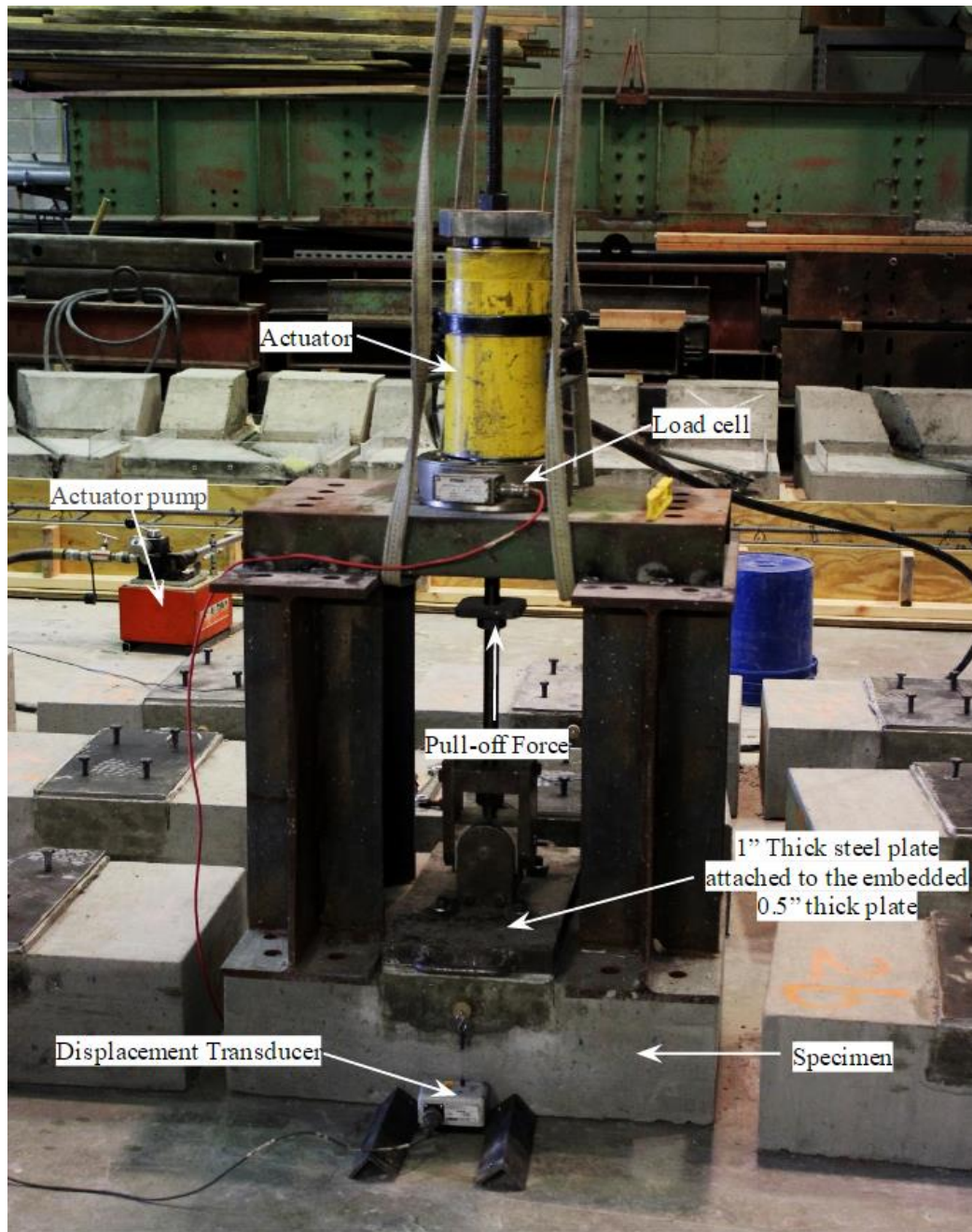


Figure 15. Testing arrangement for pull-off test

Each steel plate with the studs that were embedded in the overlay concrete of a specimen had four threaded holes for bolts. Using these bolts, the embedded steel plate was attached to a thicker steel plate to which the pulling force (upward) was applied.

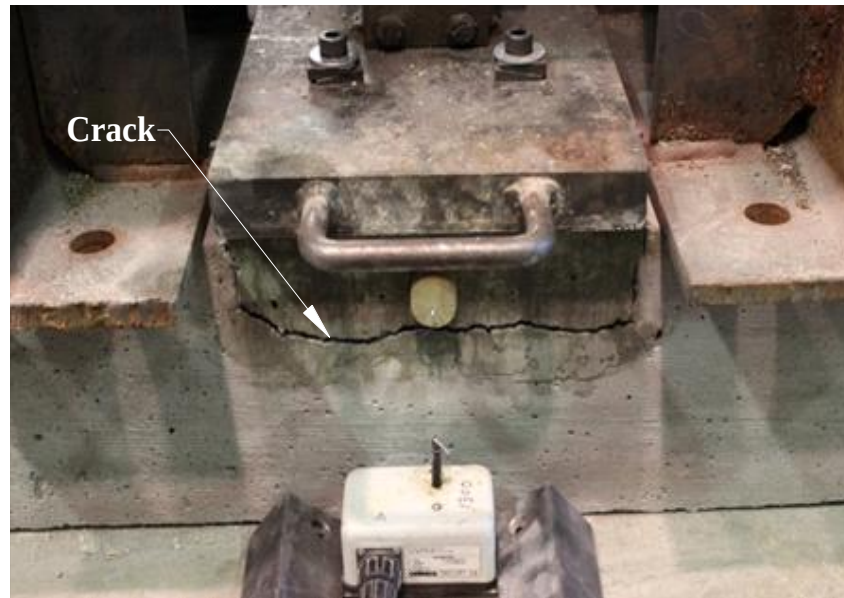
One displacement transducer was attached on each side of the overlay to measure the displacement. A hydraulic loading system was used to apply the pull-off load. The load was gradually increased up to a point where the specimen failed (i.e., the two concrete pieces separated either at the interface of the bond or in the overlay concrete material).

4.2.3 Results

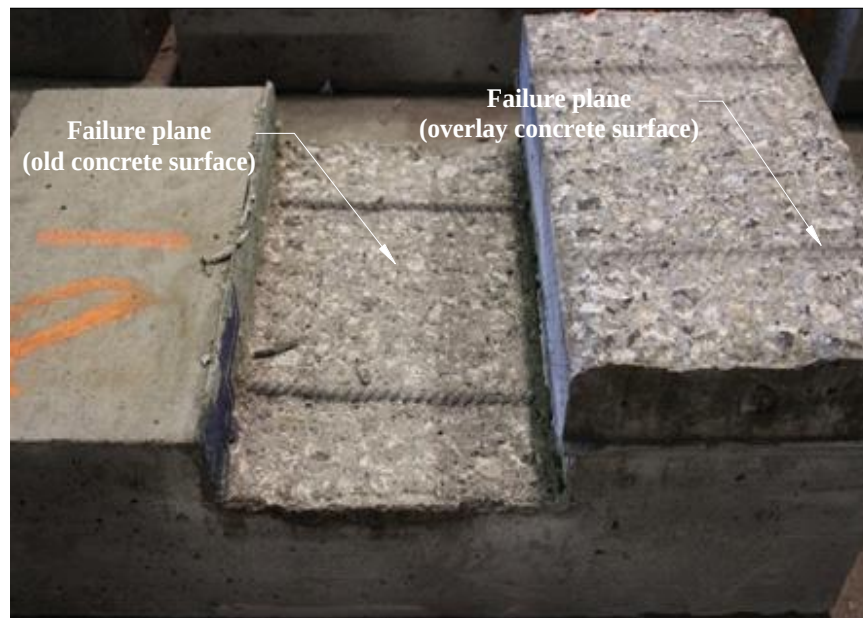
The results from the pull-off tests and the comparisons between different parameters are provided here. Observations of all tests made it clear that the shear studs created a potential failure plane at the head of the shear studs. In fact, some specimens failed at the heads of the shear studs in the overlay and some failed at the bond interface. In each case, a sudden failure was observed. Following are the results for the different concrete removal depth levels studied (Case 1 through 4).

Case 1– Concrete Removed to the Top of the Reinforcing Steel

For Case 1, two of the specimens failed at the bond interface and one specimen failed in the overlay. Figure 16 shows a side view of the failure (total separation of the bond) at the interface of the substrate and new overlay concrete and a top view of the interface surface after the failure.



Side view



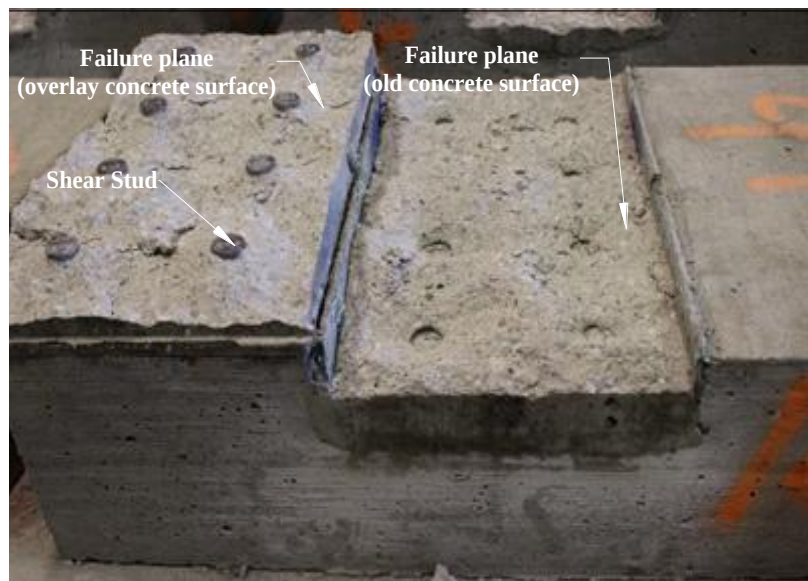
Top view

Figure 16. Case 1 pull-off test specimen failure at concrete bond interface

Figure 17 shows a side view of the failure of the specimen in the overlay concrete at the heads of the shear studs and a top view of the failure plane at the break in the bond.



Side view

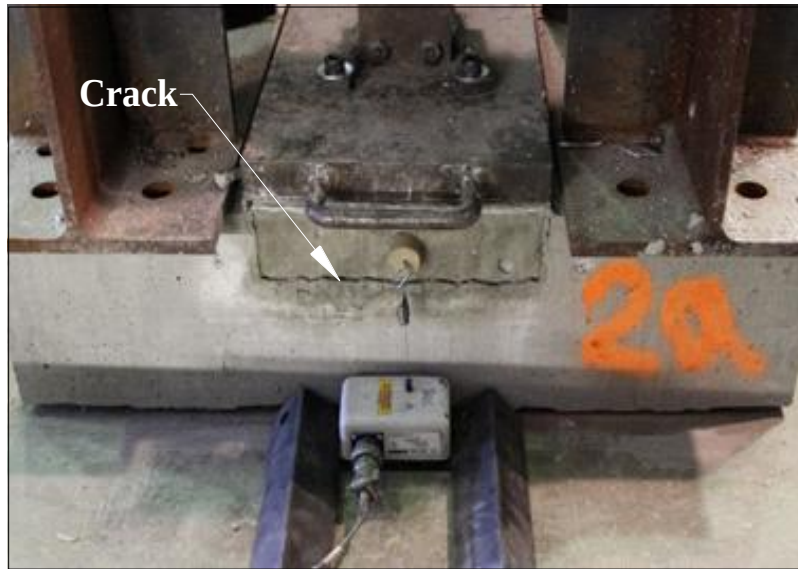


Top view

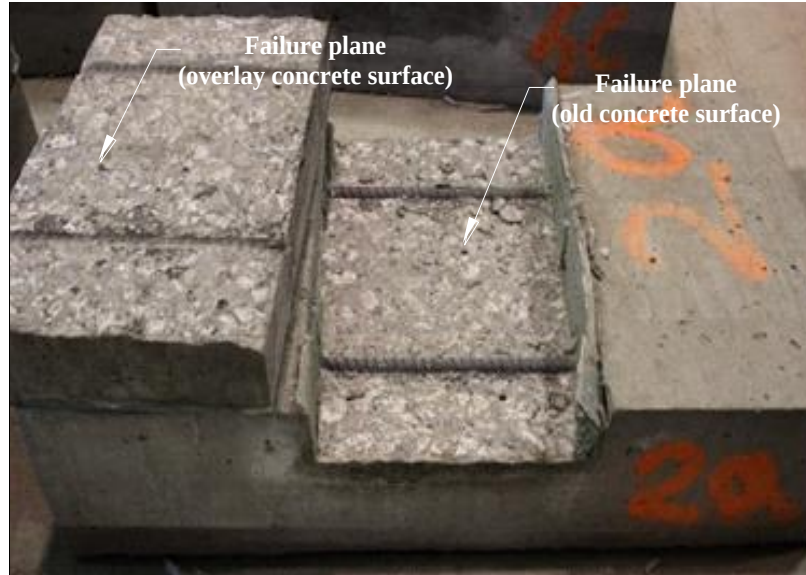
Figure 17. Case 1 pull-off test specimen failure in concrete overlay

Case 2– Concrete Removed to Half the Diameter of the Reinforcing Steel

In this case, two specimen failures were observed at the bond interface and one specimen failed in the overlay concrete at the heads of the shear studs. Figure 18 shows the failure of the specimen at the interface of the substrate and new overlay concrete.



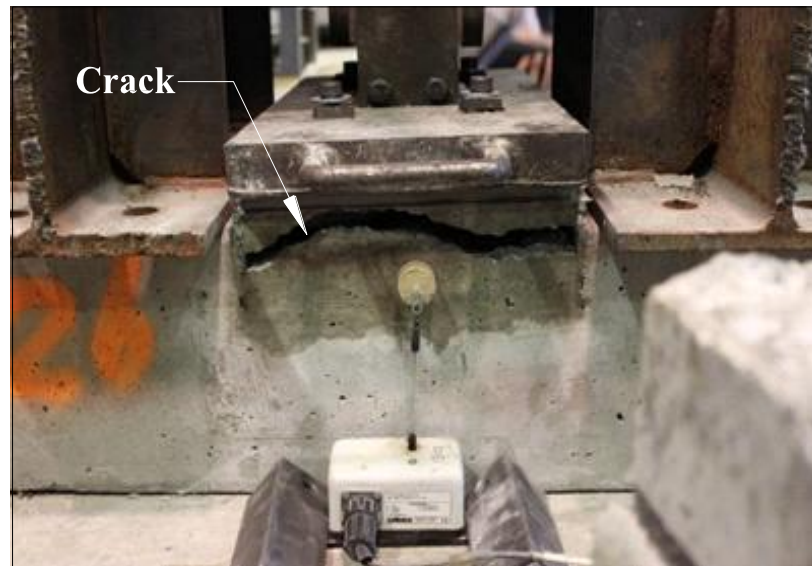
Side view



Top view

Figure 18. Case 2 pull-off test specimen failure at concrete bond interface

Figure 19 shows the failure of the specimen in the overlay concrete at the heads of the shear studs and the surface at which the break in the bond was observed.



Side view



Top view

Figure 19. Case 2 pull-off test specimen failure in concrete overlay

Case 3– Concrete Removed to the Full Diameter of the Reinforcing Steel

All of the specimens in this case failed at the interface level as shown in the Figure 20. The figure shows the pattern of the crack and the interface surface.



Side view

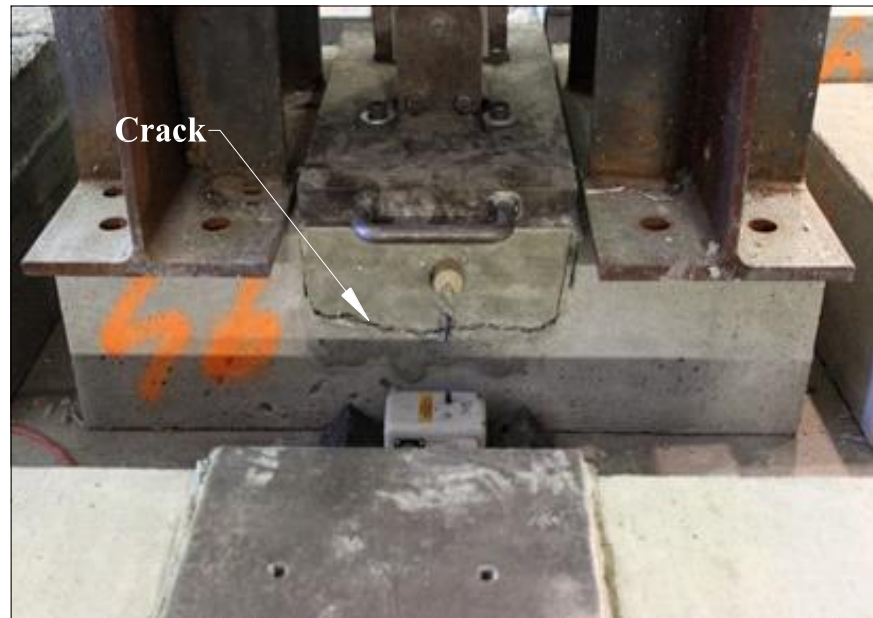


Top view

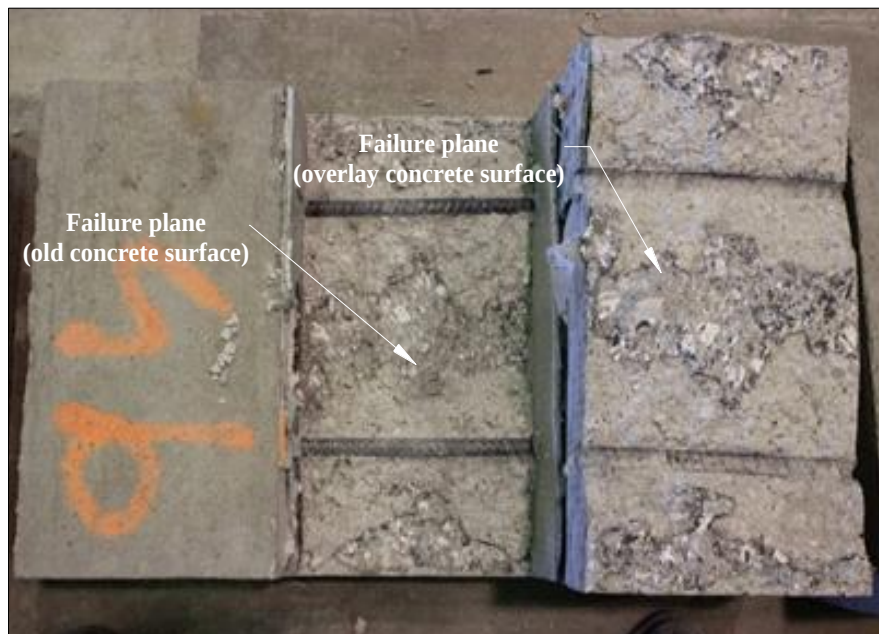
Figure 20. Case 3 pull-off test specimen failure at concrete bond interface

Case 4– Concrete Removed to the Full Diameter of the Reinforcing Steel Plus 0.5 to 1 in.

In this case, two of the specimens failed in the overlay and one specimen failed at the interface. Figure 21 shows the failure of the specimen at the interface of the substrate concrete and new overlay concrete.



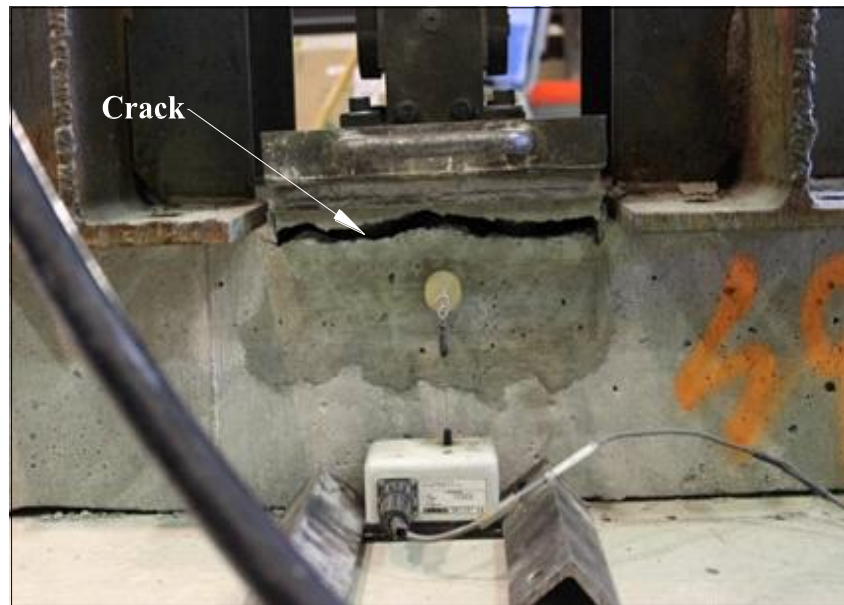
Side view



Top view

Figure 21. Case 4 pull-off test specimen failure at concrete bond interface

Figure 22 shows a side view of the failure of the specimen in the overlay concrete at the heads of the shear studs and a top view of the interface surface after the failure.



Side view



Top view

Figure 22. Case 4 pull-off test specimen failure in concrete overlay

All Removal Depths/Cases

Table 8 shows the peak tensile stresses for all specimens and the average values for each concrete removal depth (Case 1 through 4).

Table 8. Pull-off test results

Concrete Removal Depth/Case No.	Specimen No.	Load at Failure (kips)	Tensile Stress at failure (psi)	Failure plane location
1	1	15.1	84	Bond interface
1	2	16.9	94	At shear stud head
1	3	18.2	101	Bond interface
1	Average	16.8	93	
2	1	17.6	98	Bond interface
2	2	19.1	106	At shear stud head
2	3	15.0	83	Bond interface
2	Average	17	96	
3	1	14.5	81	Bond interface
3	2	15.8	88	Bond interface
3	3	19.1	106	Bond interface
3	Average	16	92	
4	1	19.8	110	At shear stud head
4	2	17.5	97	Bond interface
4	3	20.1	112	At shear stud head
4	Average	19	106	

Removal Depth/Case No.:

1 – To top of the reinforcing steel

2 - Half the diameter of the reinforcing steel

3 - Full diameter of the reinforcing steel

4 - Full diameter of the bar and 0.5 to 1 in. additional

Figure 23 shows the variation of the average load at failure versus the concrete removal depth level (Case 1 through 4).

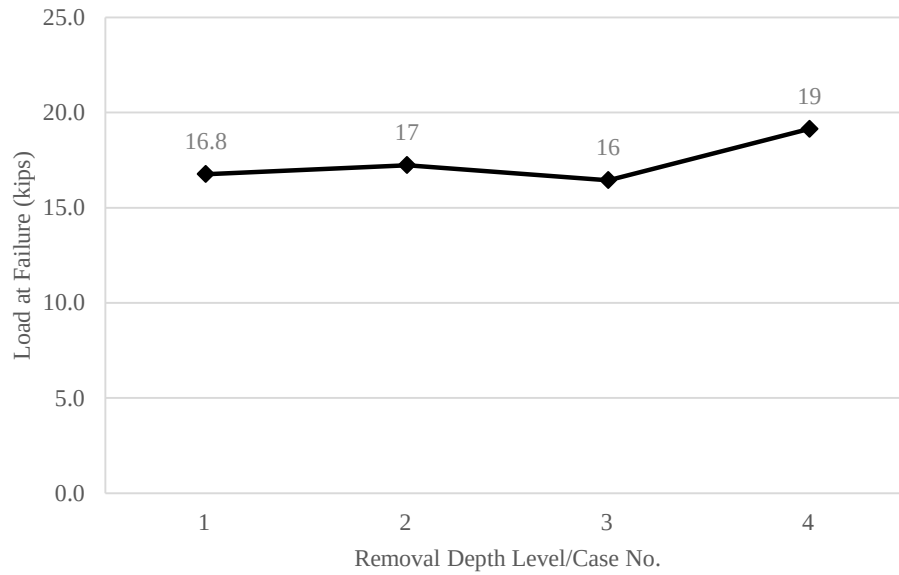


Figure 23. Average load at failure versus concrete removal depth (pull-off test)

Figure 24 shows the variation of the average tensile bond stress versus the concrete removal depth level (Case 1 through 4).

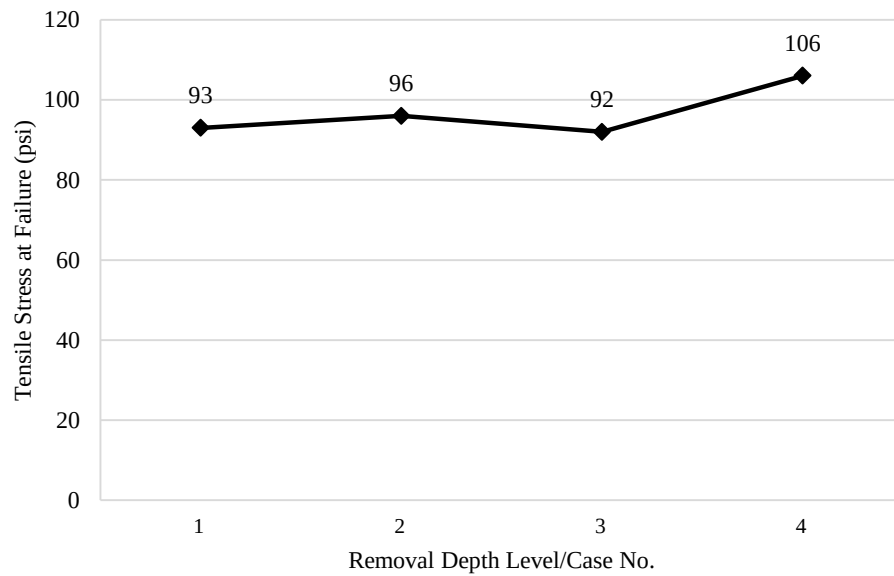


Figure 24. Average tensile stress at failure versus concrete removal depth (pull-off test)

4.2.4 Summary

Two failure plane locations were observed during pull-off testing. One failure plane was at the bond interface between the substrate concrete and the new overlay concrete and the other failure plane occurred at the shear studs in the overlay concrete. Even though a greater number of specimens failed at the bond interface, no criteria could predict the location of failure. It is possible that the load was not evenly distributed over the surface and perhaps the failure was caused by peeling. As the depth of concrete removal increased, the reinforcing steel held down more overlay concrete and retained that concrete upon the failure of the bond.

A very slight variation was seen in the peak load for the first three removal depth cases and the fourth case had a slightly greater failure load compared to other three. The variation in the tensile stress was similar to the variation of the peak load. Overall, the failure load and the stress at failure had a 13% increase from Case 1 to Case 4, but Case 2 values were closer to Case 4 values.

4.3 Push-Out Test

The push-out test was used to determine the shear bond strength between the substrate concrete and the overlay concrete for the four removal depths (Case 1 through 4). A shear load was applied to the bond on each of the specimens and the shear stress at failure was calculated for comparison between the four levels of concrete removal.

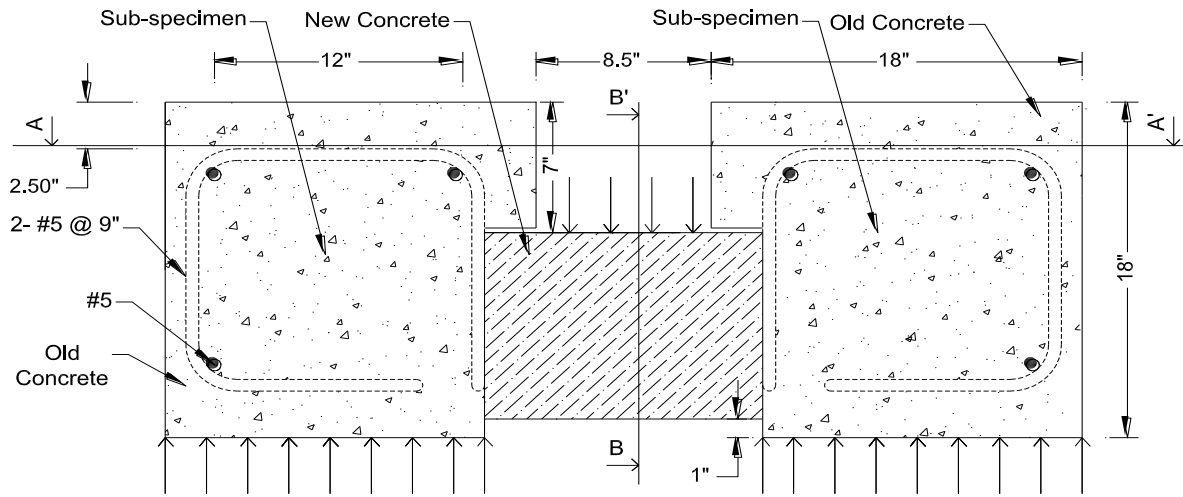
4.3.1 Specimen Details

The specimens for the push-out test were designed to determine shear strength. The bar spacing used was similar to that for a typical deck slab. The shape and dimensions of the specimens are shown in Figure 25 (Case 1) and Figure 26 (Case 4).

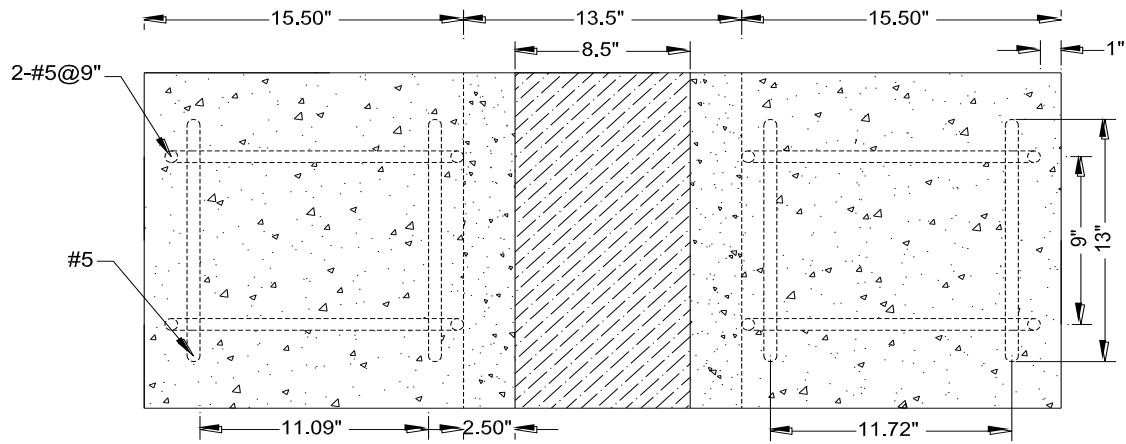
For each of the test specimens, two sub-specimens of substrate concrete (C4 mix) were prepared and then bonded to each other with the overlay concrete between them. The two bonds between the substrate concrete sub-specimens and the new overlay concrete (between them) were then subjected to shear stresses to determine the shear strength.

The shaded portions in Figure 25 and Figure 26 represent the portion where the overlay concrete was placed. Foam that was 2.5 in. thick, as shown in Figure 27, was used to create the voids in the substrate concrete for placement of the overlay concrete later.

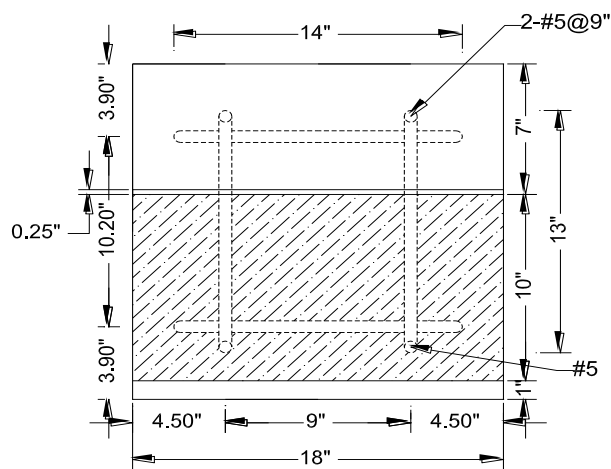
An additional steel bar was placed along the length on top of the reinforcement to prevent any horizontal movement during the concrete placement.



a) SECTIONAL SIDE VIEW



b) SECTION A-A'



c) SECTION B-B'

Figure 25. Push-out test specimen schematic (Case 1)



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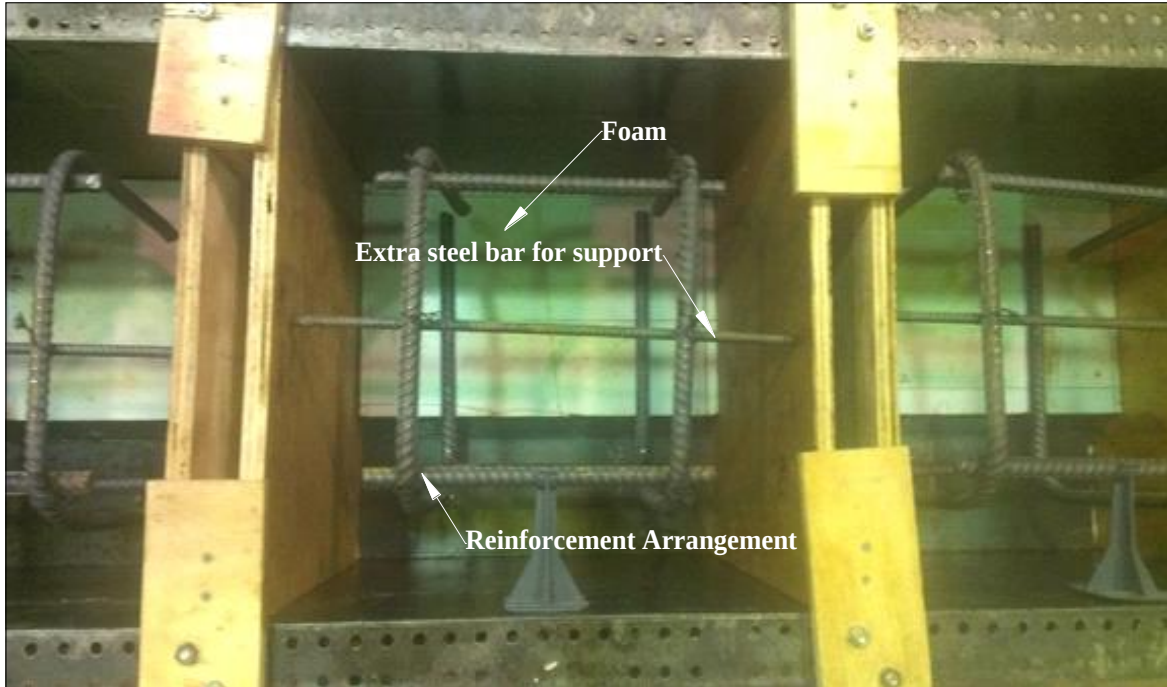


Figure 27. Push-out test formwork for substrate concrete placement

After curing the specimens for three days, the foam and the formwork were removed. The depth of the foam was only up to the face of the reinforcing steel (2.5 in.). Therefore, to achieve the different simulated concrete removal depths, additional concrete was removed and roughened using a jackhammer to the required depths, as shown in Figure 27 (Case 1 specimens only needed to have the concrete roughened).



Figure 28. Pair of push-out test sub-specimens after concrete removal (Case 4)

Note that a small (0.25 in.) gap was needed between the substrate concrete and the top of the overlay concrete (as shown in the schematic in Figure 25) to eliminate any tensile bond between the substrate concrete and the top of the overlay concrete. To create this gap, 0.25 in. thick foam was glued to the substrate concrete. Wooden forms were attached to the sides of each pair of specimens as shown in Figure 29 to create the space for the placement of the overlay concrete.



Figure 29. Push-out test formwork for overlay concrete placement

To fill the 1 in. gap below the overlay concrete, a 0.75 in. thick sheet of plywood coupled with 0.25 in. thick foam was used. To bond the overlay concrete to the previously placed substrate concrete, a grout consisting of a mixture of about 5 to 6 gallons of water to each 94 lb bag of cement (12.5 to 13.8 in³ of water per lb of cement) was used. The grout material was applied to the roughened concrete using a stiff hand brush just prior to placement the overlay concrete as shown in Figure 30.



Figure 30. Application of grout for push-out test specimen

The overlay concrete was placed until it touched the bottom of the foam, which was used to break the bond between the substrate concrete and the top of the overlay concrete on each specimen. The overlay concrete was vibrated and wet-cured on the top exposed surface. Figure 31 shows a specimen after placement of the overlay concrete.



Figure 31. Push-out test specimen after overlay concrete placement

4.3.2 Testing Arrangement

Each push-out test started 4 hours prior to 72 hours after overlay concrete placement. Figure 32 shows the testing arrangement.

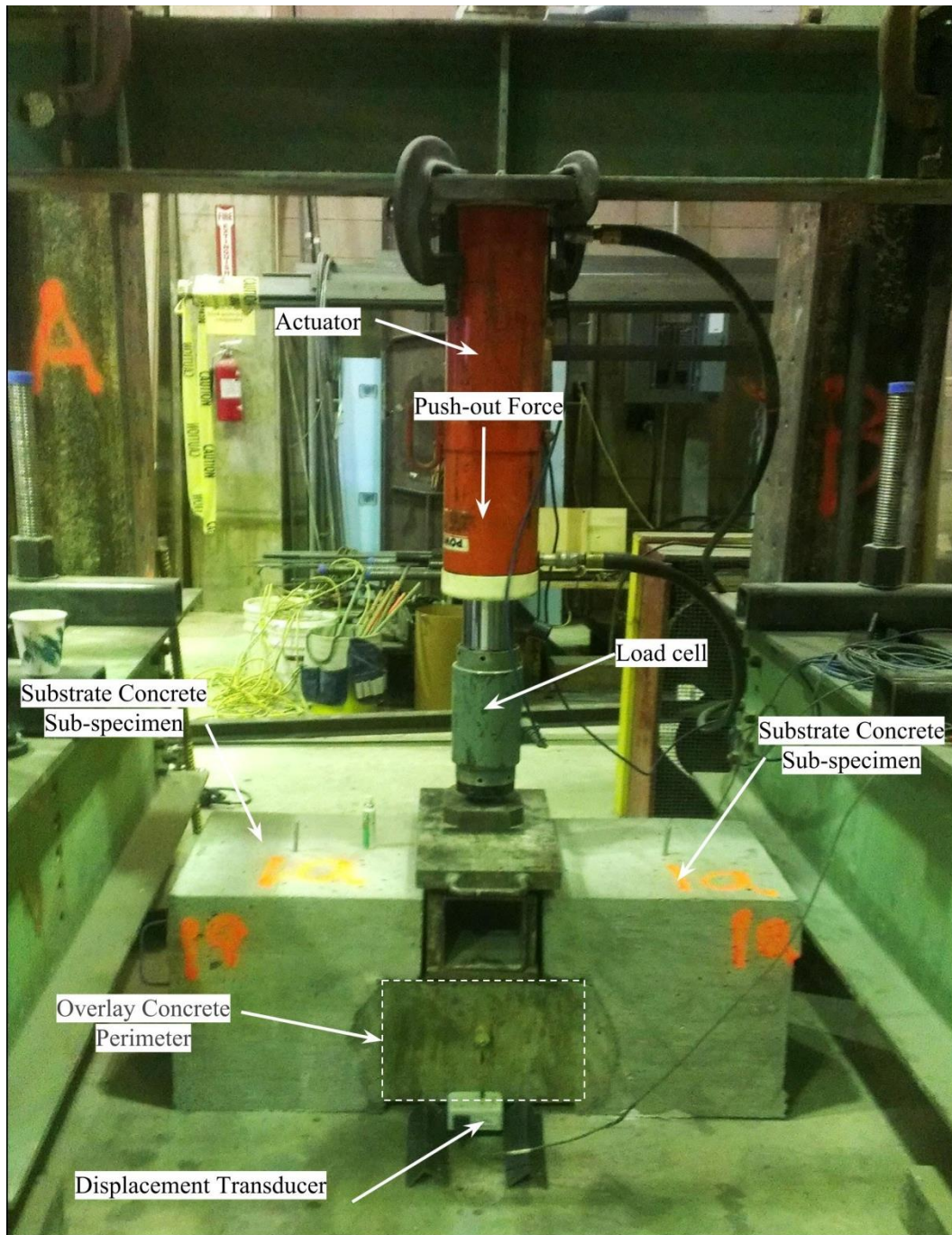


Figure 32. Testing arrangement for push-out test

The specimens were carefully moved to the testing area to be sure to not affect the shear bond of the substrate concrete and the overlay concrete. The specimens were set on the floor of the structural testing laboratory and the push-out load was applied to the overlay concrete from the top. Deflection transducers were mounted on both sides of the overlay concrete. A layer of neoprene was laid on top of the loading area to distribute the applied load.

4.3.3 Results

Each of the specimens had two bond interfaces, with one on each side of the overlay concrete. Only one bond failed in shear for all of the specimens. The results for the different concrete removal depths follow.

Case 1– Concrete Removed to the Top of the Reinforcing Steel

During application of the loads, sudden failures (a large drop in load and separation of one of the bonds) were observed. Figure 33(a) shows a failure surface with a crack and Figure 33(b) and (c) show an interface surface between the substrate concrete and the overlay concrete after failure.



a) Side view



b) Bond interface (substrate concrete)



c) Bond interface (overlay concrete)

Figure 33. Case 1 push-out test specimen failure at concrete bond interface

Given no exposure of the reinforcing steel to the overlay concrete for the Case 1 specimens, the entire bond broke after the crack formed.

Case 2– Concrete Removed to Half the Diameter of the Reinforcing Steel

The overlay concrete for Case 2 specimens was exposed to half the diameter of the reinforcing steel. After the first cracks were observed, as shown in Figure 34(a), the specimens had not completely failed.



a) Propagation of crack



b) Separation at interface



c) Bond interface (substrate concrete)



d) Bond interface (overlay concrete)

Figure 34. Case 2 push-out test specimen failure at concrete bond interface

The overlay concrete after the initial crack development was still bonded to the reinforcing steel. After further load application, a final break of the bond took place. Total separation of a bond and two interface surfaces after the separation are shown in Figure 34(b), (c), and (d).

Case 3– Concrete Removed to the Full Diameter of the Reinforcing Steel

Failures similar to Case 2 were observed for Case 3 specimens; but, due to the additional exposure of the reinforcing steel to the concrete, the bonds were stronger between the concrete and the reinforcing steel, withstanding a greater load after crack initiation. Figure 35 shows the failure of a specimen.



a) Propagation of crack



b) Separation at interface



c) Bond interface (substrate concrete)



d) Bond interface (overlay concrete)

Figure 35. Case 3 push-out test specimen failure at concrete bond interface

Case 4– Concrete Removed to the Full Diameter of the Reinforcing Steel Plus 0.5 to 1 in.

The loads for total separation of a bond were greatest for Case 4 specimens. Figure 36 shows a crack and total separation at a bond interface.

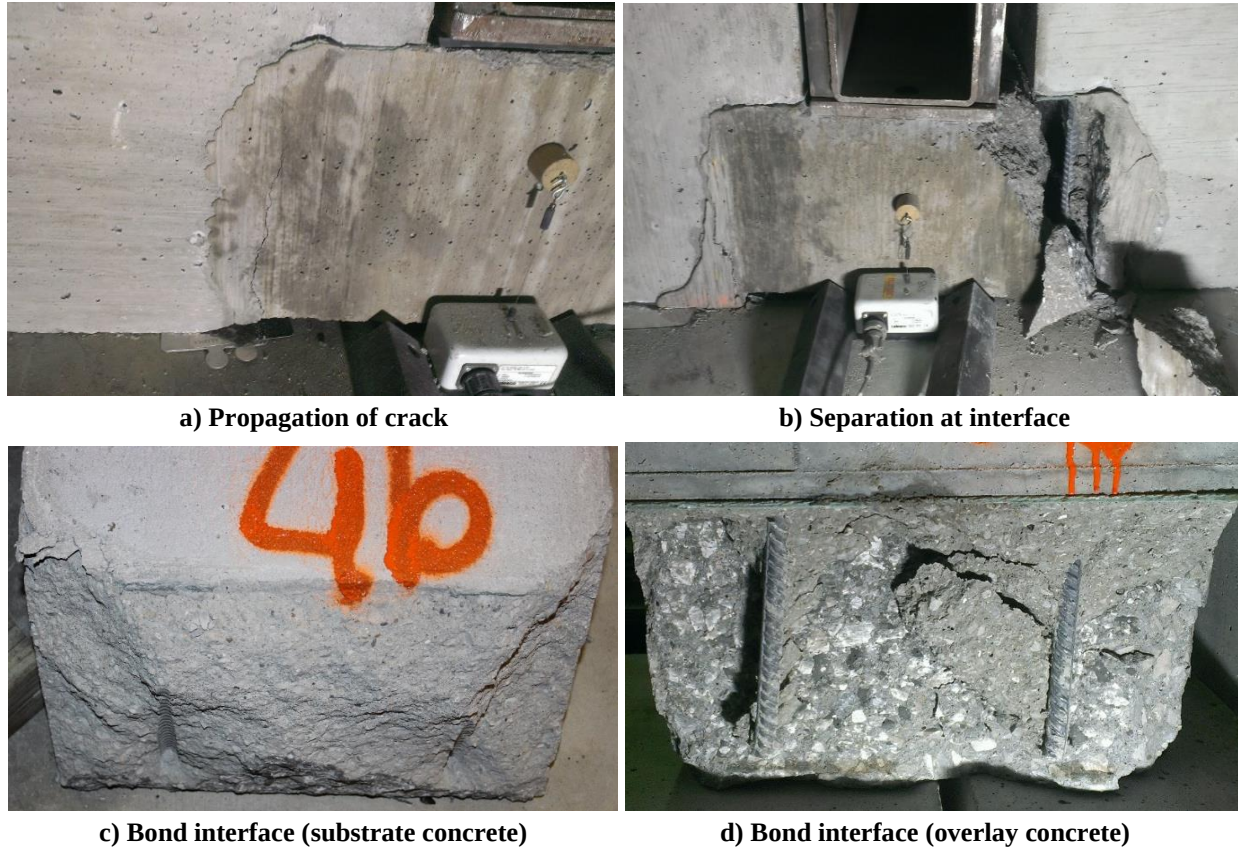


Figure 36. Case 4 push-out test specimen failure at concrete bond interface

Perhaps not surprising, the concrete bonded to more of the reinforcing steel on these specimens, as shown in Figure 36(d).

All Removal Depths/Cases

Table 9 shows the shear stresses at first stiffness change and at maximum load for all specimens and the average values for each concrete removal depth (Case 1 through 4).

Table 9. Push-out test results

Concrete Removal Depth/ Case No.	Specimen No.	Load at First Stiffness Change (kips)	Shear Stress at First Stiffness Change (psi)	Maximum Load (kips)	Shear Stress at Maximum Load (psi)	Stiffness (kips/in.)
1	1	17	48	17	48	2000
1	2	23	63	23	63	2000
1	3	17	48	17	48	3000
1	Average	19	53	19	53	2333
2	1	20	55	31	86	600
2	2	19	52	33	92	3000
2	3	22	62	27	75	4000
2	Average	20	57	30	84	2533
3	1	15	42	24	67	600
3	2	19	52	40	112	2000
3	3	21	58	39	108	4000
3	Average	18	51	34	96	2200
4	1	25	68	36	99	1000
4	2	18	49	40	110	3000
4	3	27	76	43	120	4000
4	Average	23	65	40	110	2667

Removal Depth/Case No.:

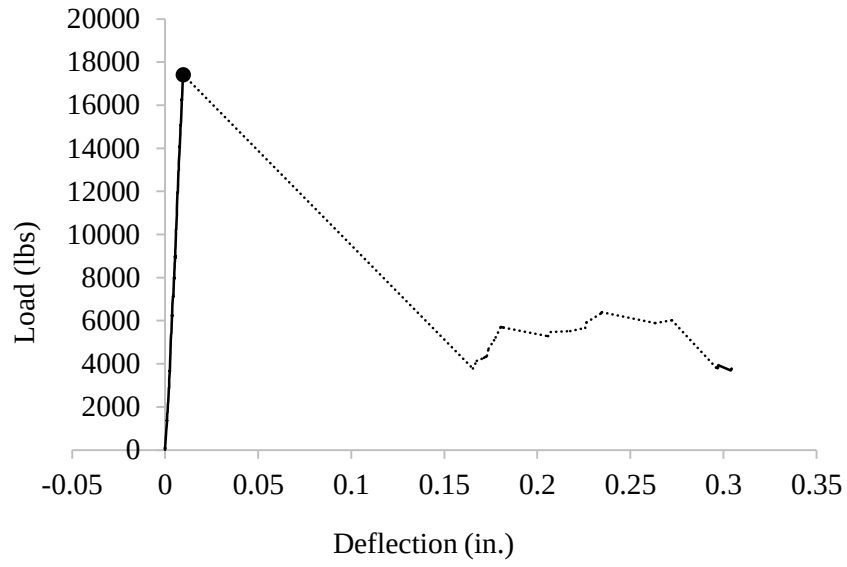
1 – To top of the reinforcing steel

2 - Half the diameter of the reinforcing steel

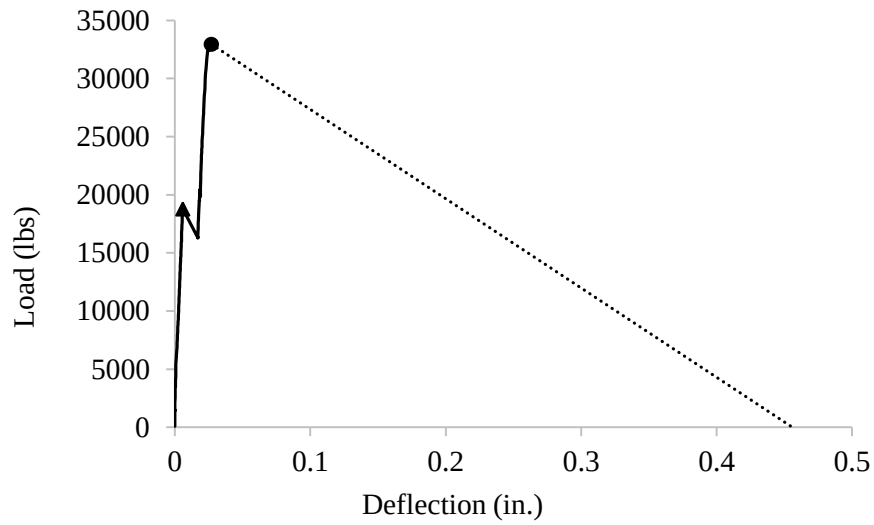
3 - Full diameter of the reinforcing steel

4 - Full diameter of the bar and 0.5 to 1 in. additional

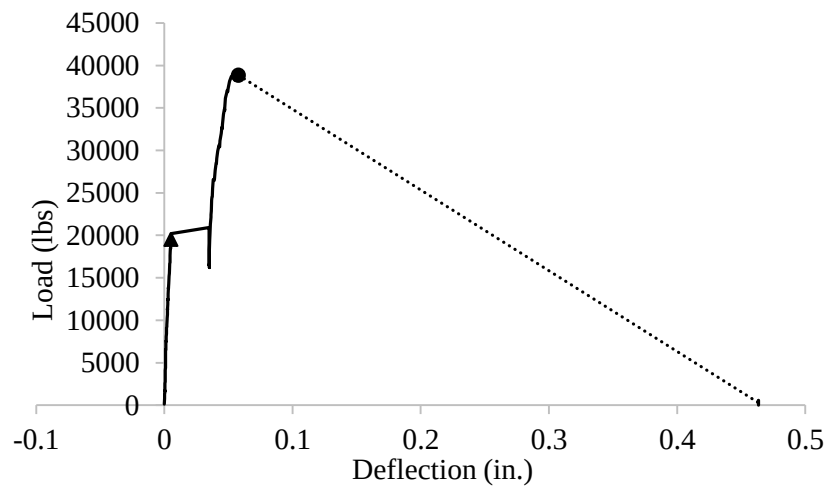
Figure 37 shows the load versus deflection graph for one specimen for each of the four concrete removal depth cases. The solid circular mark on each graph represents the maximum load value for that particular specimen and the solid triangular mark represents the point where first stiffness change was observed.



Case 1



Case 2



Case 3

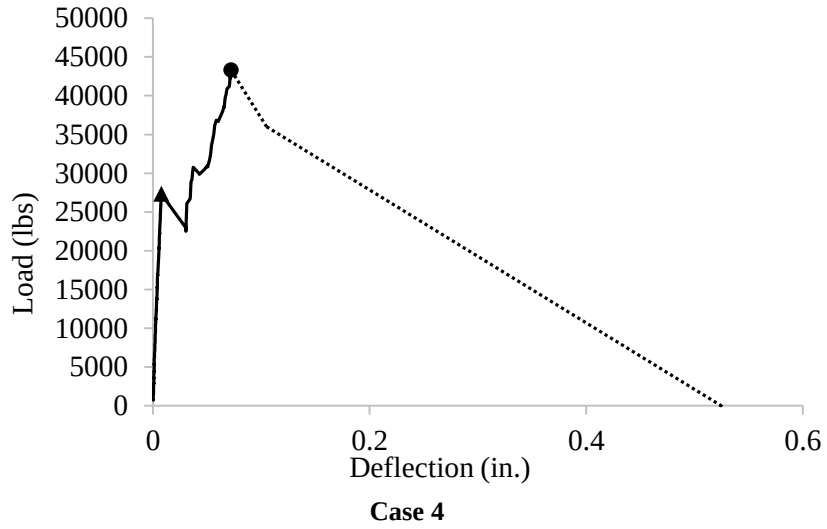


Figure 37. Load versus deflection (push-out test)

Figure 38 shows the average load at the stiffness change (triangles) and the maximum load (squares) versus the concrete removal depth case.

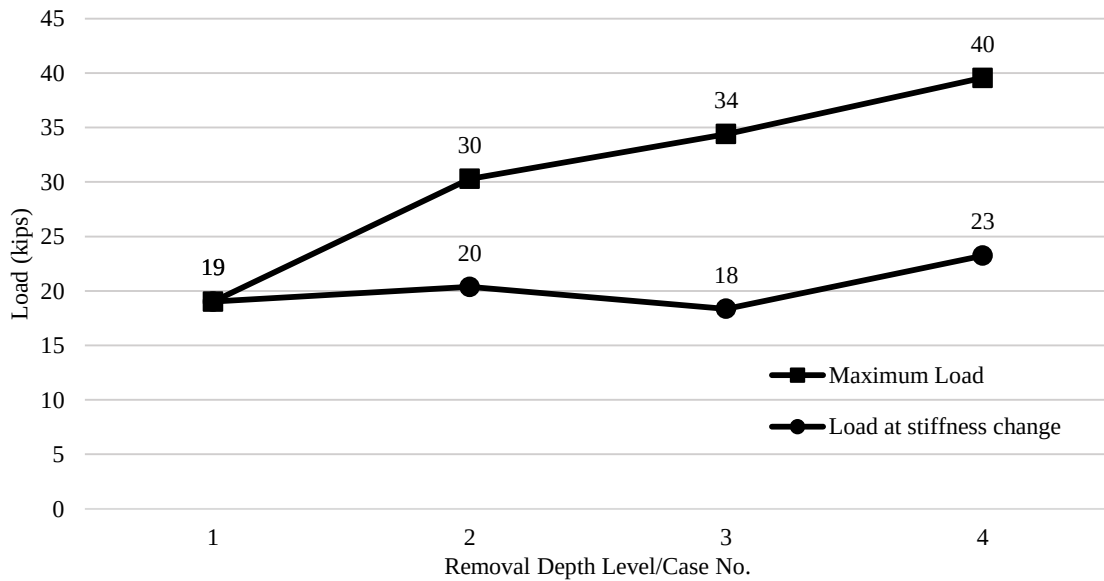


Figure 38. Average load versus concrete removal depth (push-out test)

Figure 39 shows the variation of the average shear stress at the stiffness change (triangles) and at the maximum load (squares) with change in the concrete removal depth level.

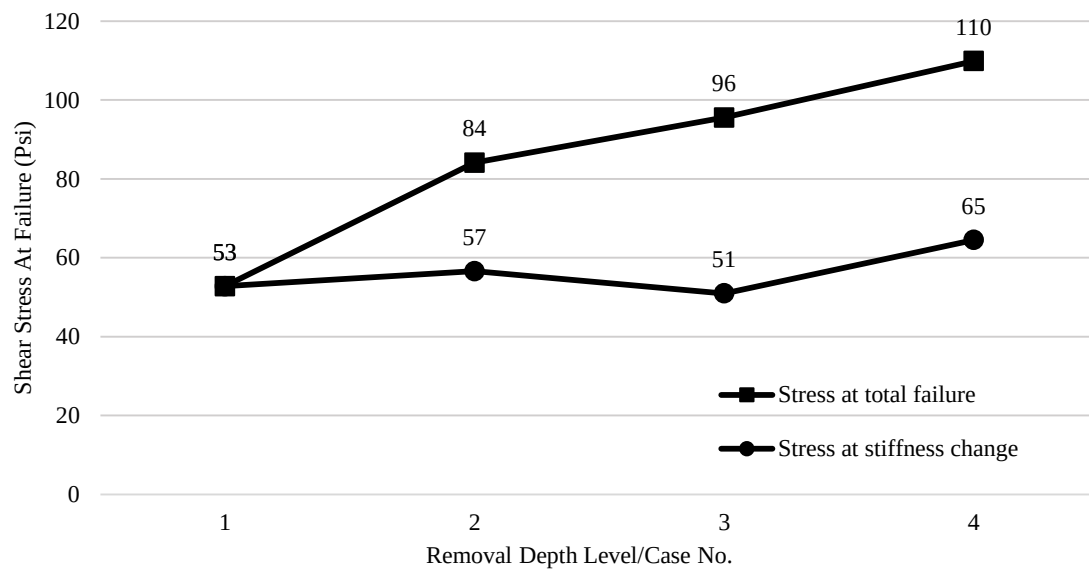


Figure 39. Average shear stress versus concrete removal depth (push-out test)

Figure 40 shows the variation of the average stiffness before the stiffness change with respect to the concrete removal depth level or case.

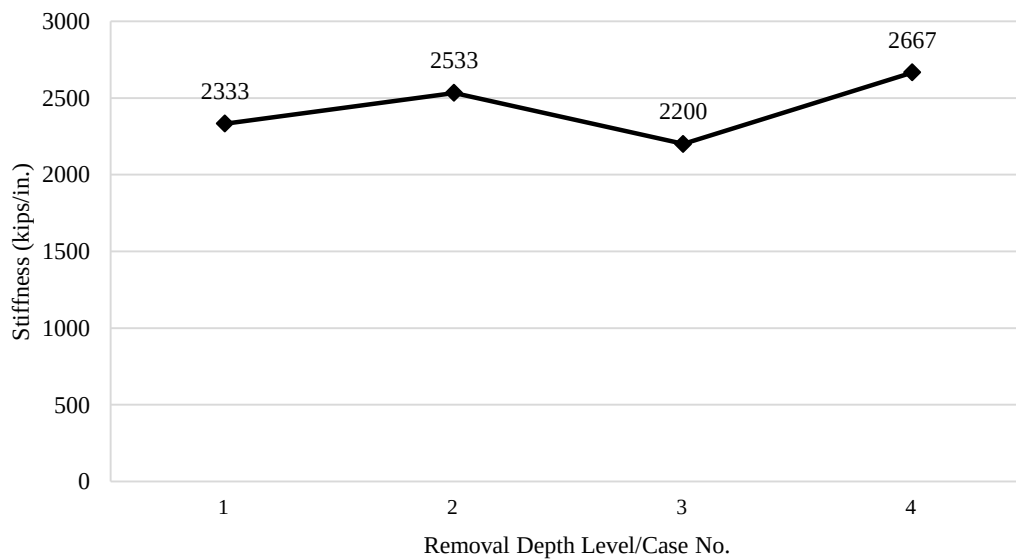


Figure 40. Average stiffness versus concrete removal depth (push-out test)

The stiffness was calculated as the initial slope of the load versus deflection from zero load to the point where the specimen started showing a non-linear behavior or a large stiffness change.

4.3.4 Summary

Case 1 specimens had a very small amount of exposure of the reinforcing steel to the overlay concrete, so a sudden failure was typically observed. As a result of this sudden failure, the load values at the stiffness change and the maximum value of the load are the same.

For Cases 2, 3, and 4, the overlay concrete had more bond with the reinforcing steel. The loading continued to increase after the initial crack (first change in stiffness) and, with a further increase in load, total separation was observed at the greater load. As the concrete removal depth increased, the maximum failure load increased slightly.

The maximum load values showed an increase with the increase in the concrete removal depth level. The variation in the load at the stiffness change also showed a slight increase with an increased concrete removal depth level.

Similar behavior was observed for the shear stress values at the stiffness change and at maximum load. The stiffness values had slight changes in values irrespective of the concrete removal depth level.

Overall, Case 1 specimens (with concrete removal down to the surface of the top reinforcing bars) showed significantly lower bond strength. The load at the stiffness change and the shear stress at the stiffness change showed insignificant variation from Case 2 to Case 4. The maximum load and the shear stress at failure had a 33% increase from Case 2 to Case 4. The stiffness values showed relatively insignificant changes, yet the increase in the value from Case 1 to Case 4 was observed to be 14%.

Even though a significant increase in the maximum load was observed, pure shear conditions never occur on an actual bridge deck, so the maximum load applied in this test may not be an appropriate measure of performance.

4.4 Positive Bending Flexural Test

A bridge deck under traffic loading undergoes positive bending between the girders. This bending of the deck can cause compression in the top fibers of the concrete deck where the overlay is placed. The compression in the top fibers leads to horizontal shear stress, which can affect the bond between the overlay and the substrate concrete.

4.4.1 Specimen Details

In this flexural test, beam specimens that resembled a bridge deck were constructed. The four concrete removal depth levels were evaluated using three specimens for each case. The details of the specimens including the reinforcing steel arrangement are shown in Figure 41.

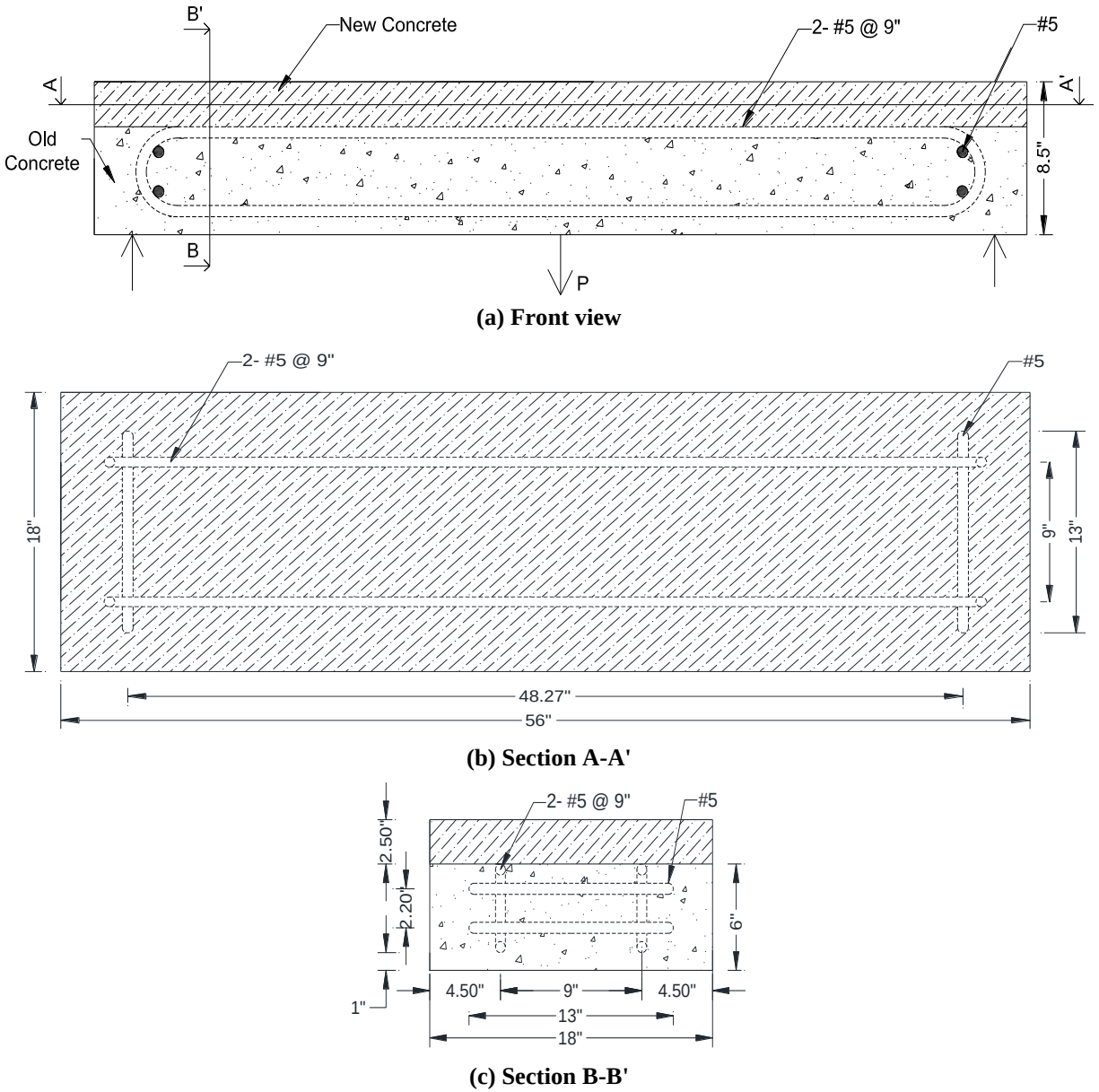


Figure 41. Positive bending flexural test specimen schematic (Case 1)

To apply the force on the bottom of the specimen (P as shown at the bottom of Figure 41(a)), the shear studs on a metal plate were embedded in each specimen. Note that a pull down force was used to avoid providing a clamping force between the new overlay concrete and the substrate concrete. The size of the plate was 10 x 18 x 0.5 in. and each plate had 12 shear studs on it as shown in Figure 42.

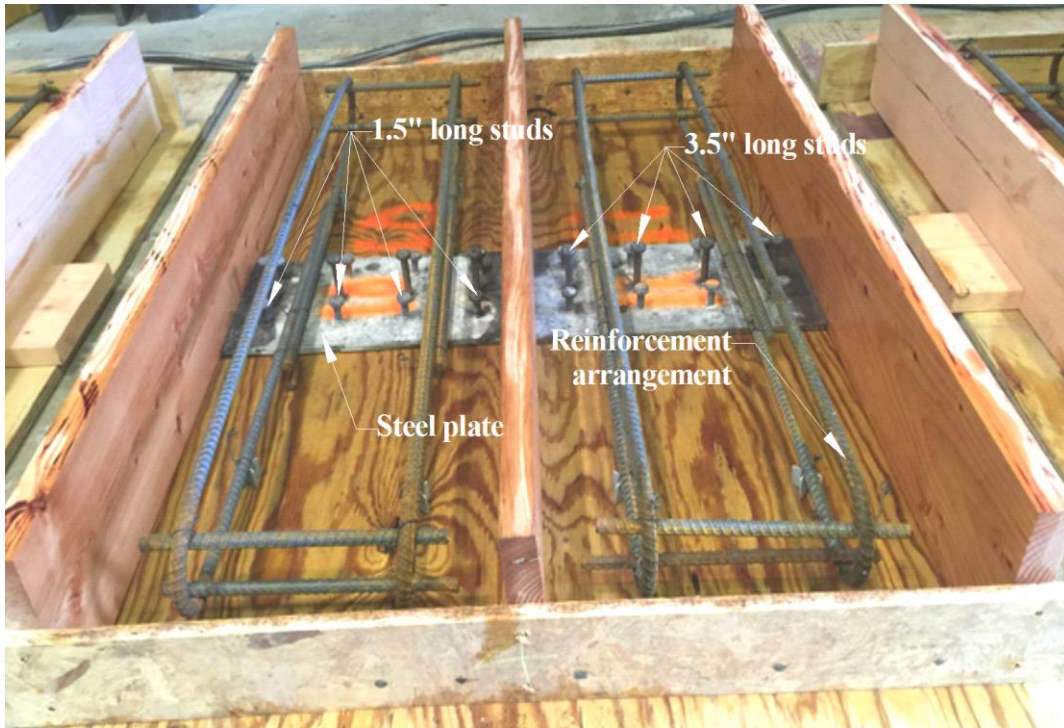


Figure 42. Positive bending flexural test formwork for substrate concrete placement

On each steel plate, the four studs in the middle were 3.5 in. long with 1 in. diameter head and the two sets of four shear studs on the sides were 1.5 in. long with 1 in. diameter heads. The plate also had four holes with threads, which were used to attach a 1 in. thick steel plate to which the force P was applied. This plate with the shear studs was placed below the reinforcement arrangement at the mid-span of the specimen before placement of the concrete as shown in Figure 42.

The substrate concrete was placed 0.5 in. above the required concrete removal depth level of each specimen so that a 0.5 in. of concrete could be chipped using a jackhammer to give it a proper roughened finish. Figure 43 shows a Case 4 specimen with the substrate concrete placed up to the bottom of the top reinforcing steel bars (i.e., 0.5 in. extra on top of the concrete removal depth level for Case 4).



Figure 43. Positive bending flexural test specimen after substrate concrete placement (Case 4)

This concrete was then cured with regular water application and covered with plastic. After two days of curing, the plastic cover was removed and the chipping process was started. Figure 44 shows the typical roughness of a substrate surface.



Figure 44. Positive bending flexural test specimen after roughening of substrate concrete (Case 1)

After curing the substrate concrete for 28 days, the specimens were prepared for the overlay concrete layer. The grout material as described in the previous tests was applied on the roughened surface with a brush as shown in Figure 45.



Figure 45. Application of grout to positive bending flexural test specimen (Case 1)

Immediately after applying the grout, the HPC-O mix overlay concrete was placed on top to create a 8.5 in. total specimen depth. After overlay placement, the specimens were covered with plastic to maintain the moisture level. These specimens were cured for three days.

4.4.2 Testing Arrangement

Each flexural test for positive bending started 1.5 hours prior to 72 hours after overlay placement. Figure 46 shows the load frame with a specimen mounted in it.

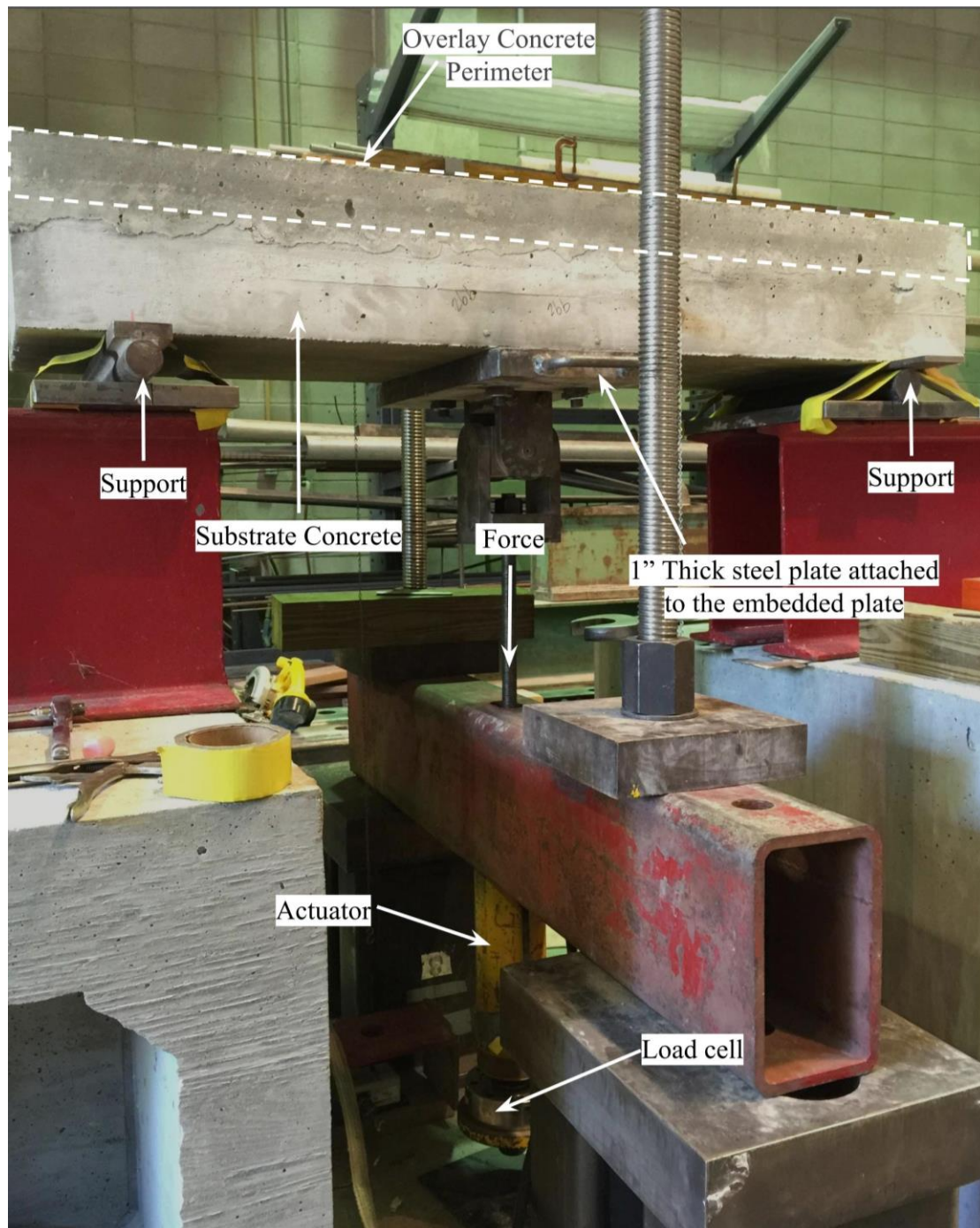


Figure 46. Testing arrangement for positive bending flexural test

The specimens were supported with pin and roller supports. A deflection transducer was attached on each side of the specimen to measure the deflection. The deflection transducers were mounted 2 to 3 in. right of center. The load was gradually applied to pull the steel plate down, thereby inducing positive bending in each specimen.

4.4.3 Results

The factors that were considered for comparison using this test were the maximum load attained, the elastic shear stress at the bond interface at the maximum load, and the stiffness.

During testing, two types of cracks were observed. Flexure cracks were formed at the bottom of the specimen near mid-span and shear cracks were formed at the interface of the concrete bond. These cracks were found in specimens for all four cases (concrete removal depth levels). When the loads were increased, failures of the bond between the substrate concrete and the new overlay concrete were in the form of a visible separation at the interface.

Figure 47 through Figure 50 show one specimen for each case after failure. All three failed specimens for each case were similar.

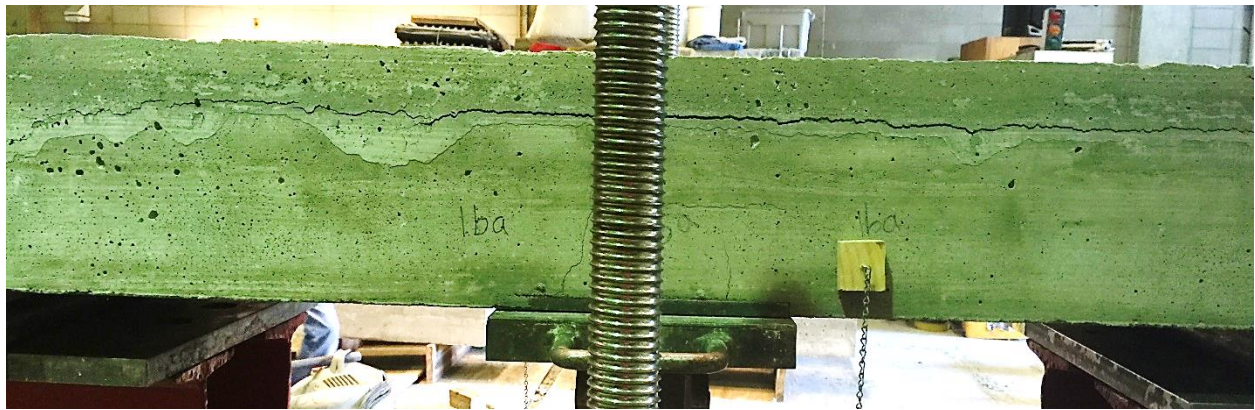


Figure 47. Case 1 positive bending flexural test specimen failure at concrete bond interface

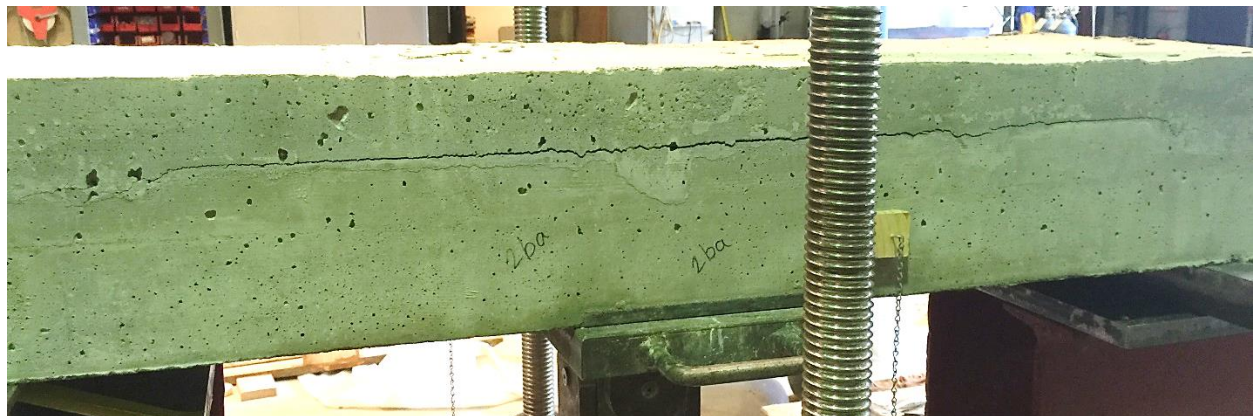


Figure 48. Case 2 positive bending flexural test specimen failure at concrete bond interface



Figure 49. Case 3 positive bending flexural test specimen failure at concrete bond interface



Figure 50. Case 4 positive bending flexural test specimen failure at concrete bond interface

Table 10 shows the test values for maximum load, elastic shear stress at the bond interface at maximum load, and stiffness as well as the average values for each concrete removal depth (Case 1 through 4).

Table 10. Positive bending flexural test results

Concrete Removal Depth/Case No.	Specimen No.	Maximum Load (kips)	Elastic* Shear Stress at Max. Load (psi)	Stiffness (kips/in.)
1	1	16.8	66	423
1	2	18.4	72	440
1	3	17.9	70	394
1	Average	17.7	70	419
2	1	16.6	70	376
2	2	16.6	70	497
2	3	18.9	79	417
2	Average	17.3	73	430
3	1	17.7	78	351
3	2	16.6	73	377
3	3	19.6	86	512
3	Average	18.0	79	413
4	1	16.6	78	437
4	2	16.2	77	399
4	3	16.8	79	412
4	Average	16.6	78	416

* All assumed section properties are for an un-cracked section

Removal Depth/Case No.:

1 – To top of the reinforcing steel

2 - Half the diameter of the reinforcing steel

3 - Full diameter of the reinforcing steel

4 - Full diameter of the bar and 0.5 to 1 in. additional

The elastic shear stress at maximum load was calculated on the basis of section properties of an un-cracked section. Note that the distance of the bond interface from the neutral axis was different for each case of the concrete removal depth level, which led to a different value of shear stress at the bond interface for each case, even though the value for the maximum load could be the same.

Figure 51 shows the variation of the maximum load with the change in the removal depth level (Case 1 through 4).

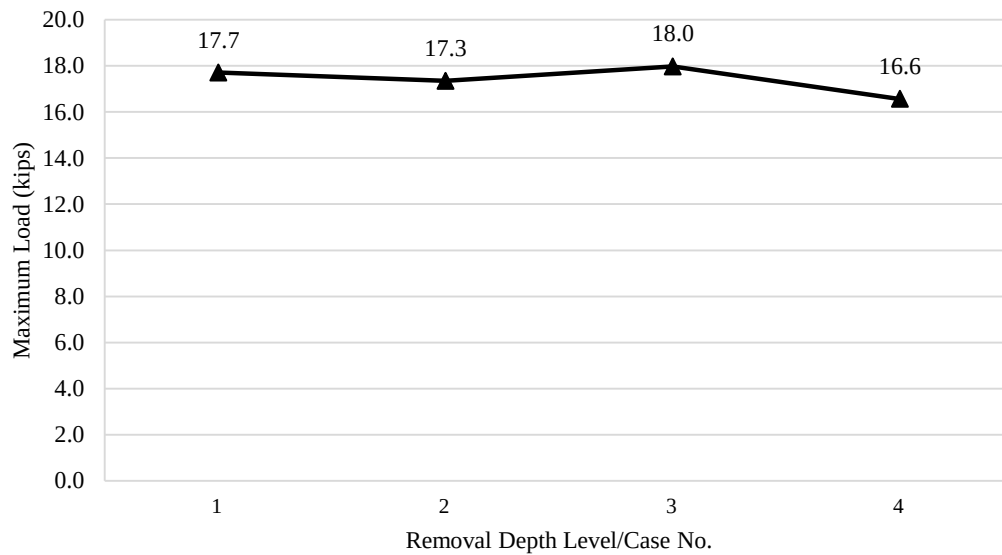


Figure 51. Average maximum load versus concrete removal depth (positive bending flexural test)

Figure 52 shows the variation of elastic shear stress at the interface at the maximum load relative to the concrete removal depth level.

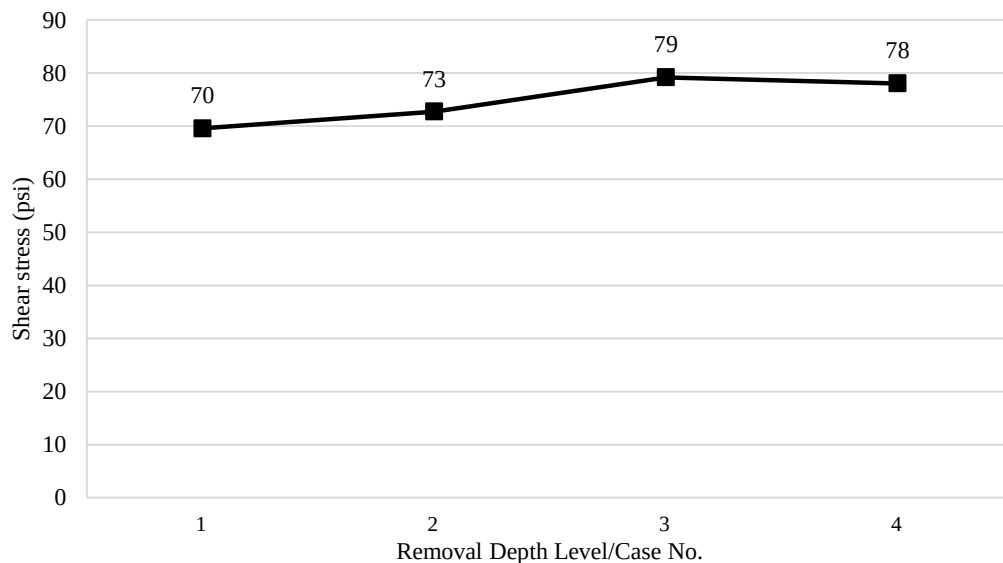


Figure 52. Average elastic shear stress at maximum load at interface versus concrete removal depth (positive bending flexural test)

Figure 53 shows the variation of average stiffness of the specimen depending on the change in concrete removal depth level.

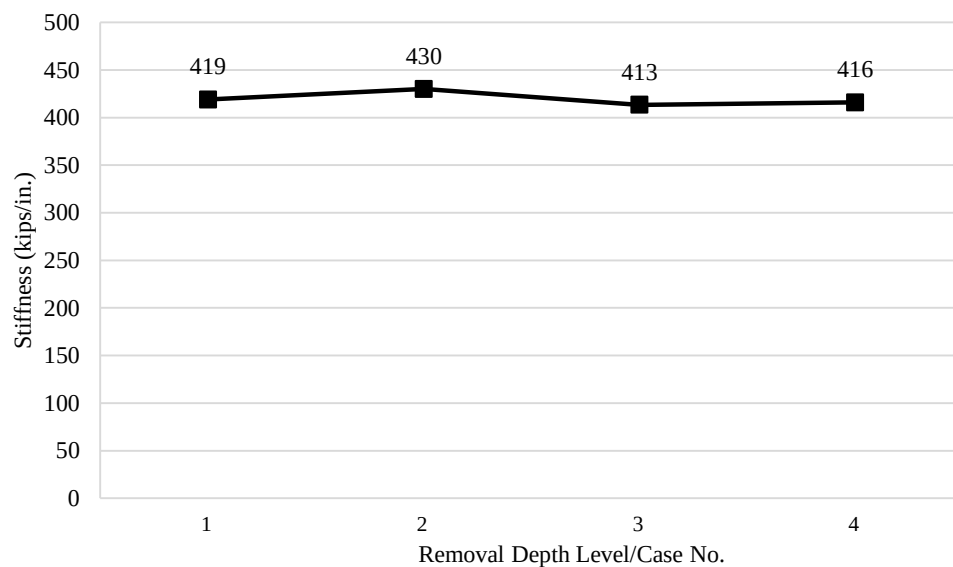


Figure 53. Average stiffness versus concrete removal depth (positive bending flexural test)

The stiffness was calculated as the slope of the load versus deflection data up to the point where the specimen started showing non-linear behavior or a large stiffness change.

4.4.4 Summary

For the flexural tests with positive bending, the gradual increase in the loading led to sudden failures where a large drop in the load and a shear crack at the bond interface was observed. Some flexure cracks were also observed near mid-span.

The variation in all of the parameters depending on the concrete removal depth level was small. The greatest values for maximum load and elastic shear stress were for Case 3 specimens, while the greatest value for stiffness was for Case 2 specimens.

The maximum load values showed a 6% decrease from Case 1 to Case 4; whereas, the elastic shear stress showed a 10% increase from Case 1 to Case 4. The stiffness of the specimens showed very slight changes in the values with less than a 1% decrease from Case 1 to Case 4.

4.5 Negative Bending Flexural Test

While the bridge deck experiences positive bending between the girders, negative bending is observed in the regions over the beams. This negative bending can cause tension in the top fibers of the bridge deck. The tension can induce horizontal shear stress in the top fibers, leading to damage to the bond between the overlay concrete and the substrate concrete.

With this test, specimens were tested for negative bending to further evaluate the effects of concrete removal depth.

4.5.1 Specimen Details

Specimens similar to those for the positive bending flexural tests were fabricated for the negative bending flexural tests; however, during the tests, the specimens were placed upside down while applying the load to simulate negative bending. Figure 54 shows the specimen dimensions and reinforcing steel details.

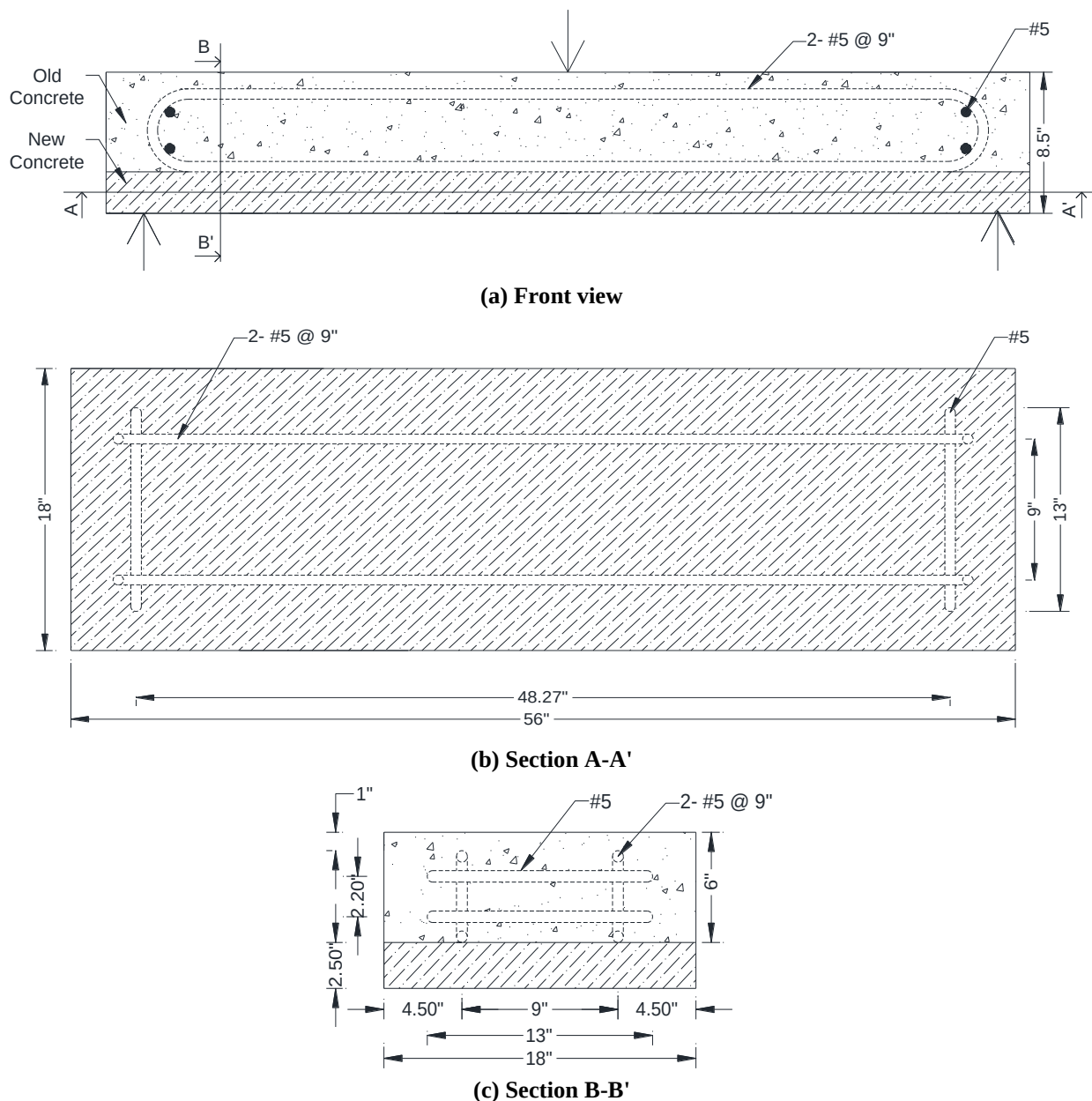


Figure 54. Negative bending flexural test specimen schematic

Figure 55 shows the formwork for the specimens.



Figure 55. Negative bending flexural test formwork for substrate concrete placement

The substrate concrete was placed into the formwork first. As with the other tests, C4 concrete was used. After curing the concrete for about two days, the concrete was removed by chipping it to its required depth with an electric demolition jackhammer, as shown in Figure 56, also giving the surfaces the proper roughness.



Figure 56. Chipping of substrate concrete for negative bending flexural tests

The typical roughness of the surface after chipping and roughening is shown in Figure 57.



Figure 57. Negative bending flexural test specimen after concrete removal to required depth (Case 3)

As described for the other tests, the same grout material was applied with a brush to the surface of the substrate concrete, as shown in Figure 58, before placement of the overlay concrete.



Figure 58. Application of grout to negative bending flexural test specimen

The overlay concrete was placed on the substrate concrete up to the total depth of the specimen.

4.5.2 Testing Arrangement

Each flexural test for negative bending started 3 hours prior to the typical 72 hour curing. Figure 59 shows the testing arrangement with the overlay concrete on the bottom.

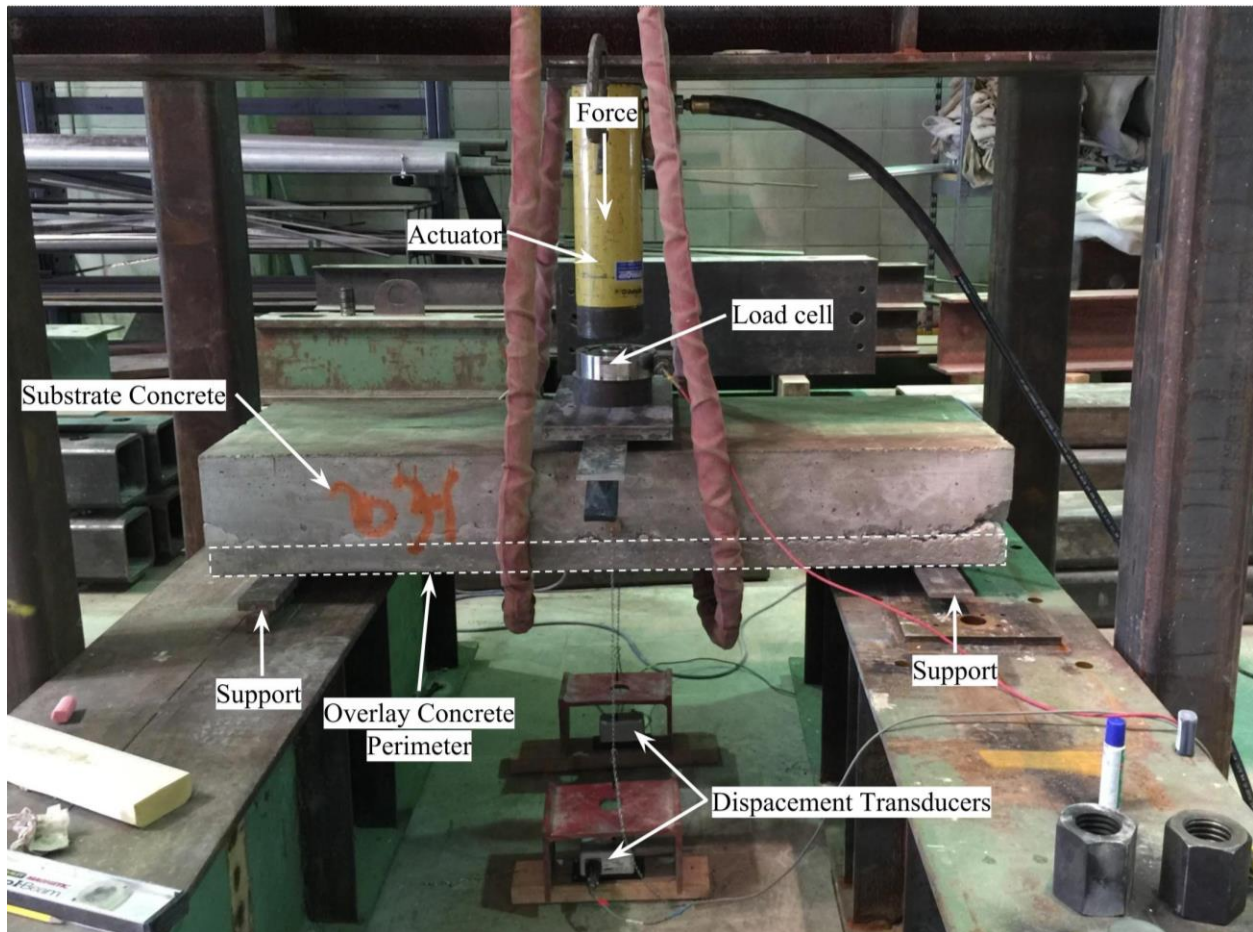


Figure 59. Testing arrangement for negative bending flexural test

The new overlay side of each specimen was supported on each end with a roller and a pin. A neoprene strip was placed at the center of the specimen and the load was applied with a hydraulic loading system. Displacement transducers were mounted on both sides of the specimen at the center to measure the vertical deflection of the specimen on both sides.

4.5.3 Results

In this flexural test, the specimens were subjected to loading that simulated negative bending. When the gradually increasing loads were applied to the specimens, shear cracks at the bond interface and some flexure cracks were observed on the specimens. Figure 60 through Figure 63 show specimens after testing.



Figure 60. Case 1 negative bending flexural test specimen failure at concrete bond interface

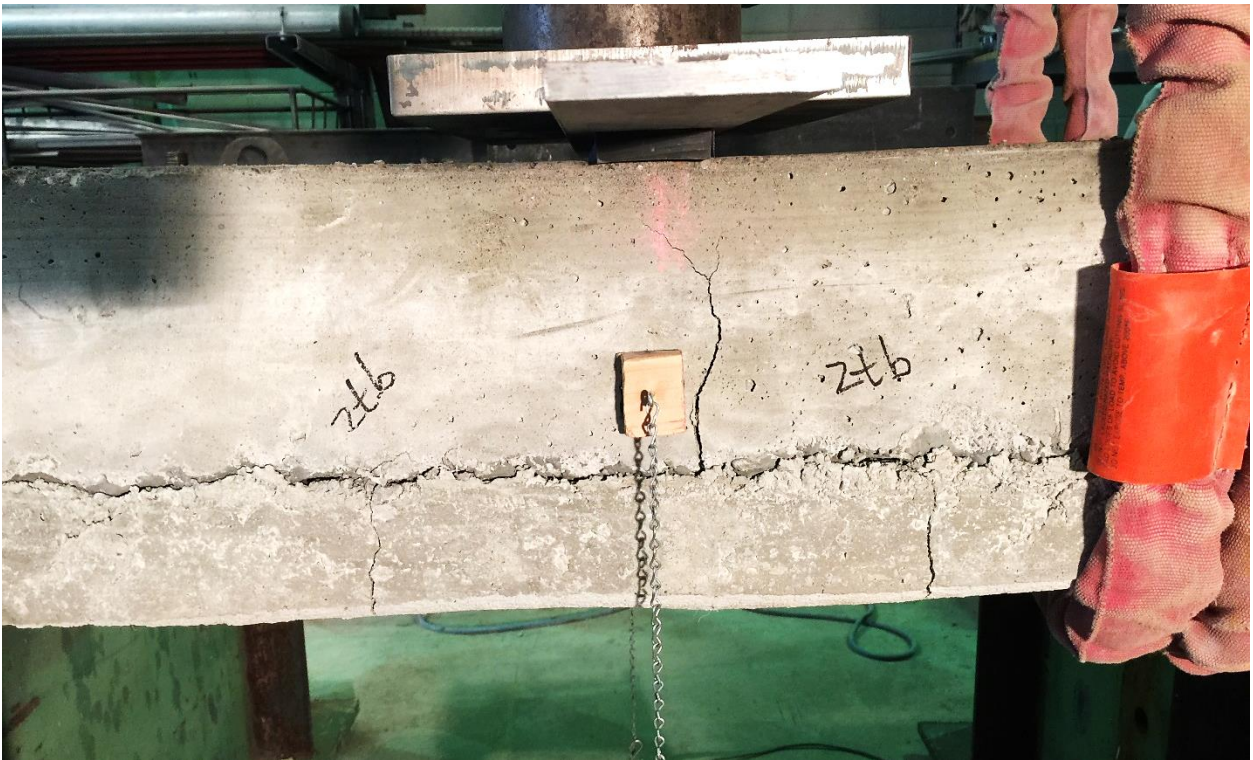


Figure 61. Case 2 negative bending flexural test specimen failure at concrete bond interface

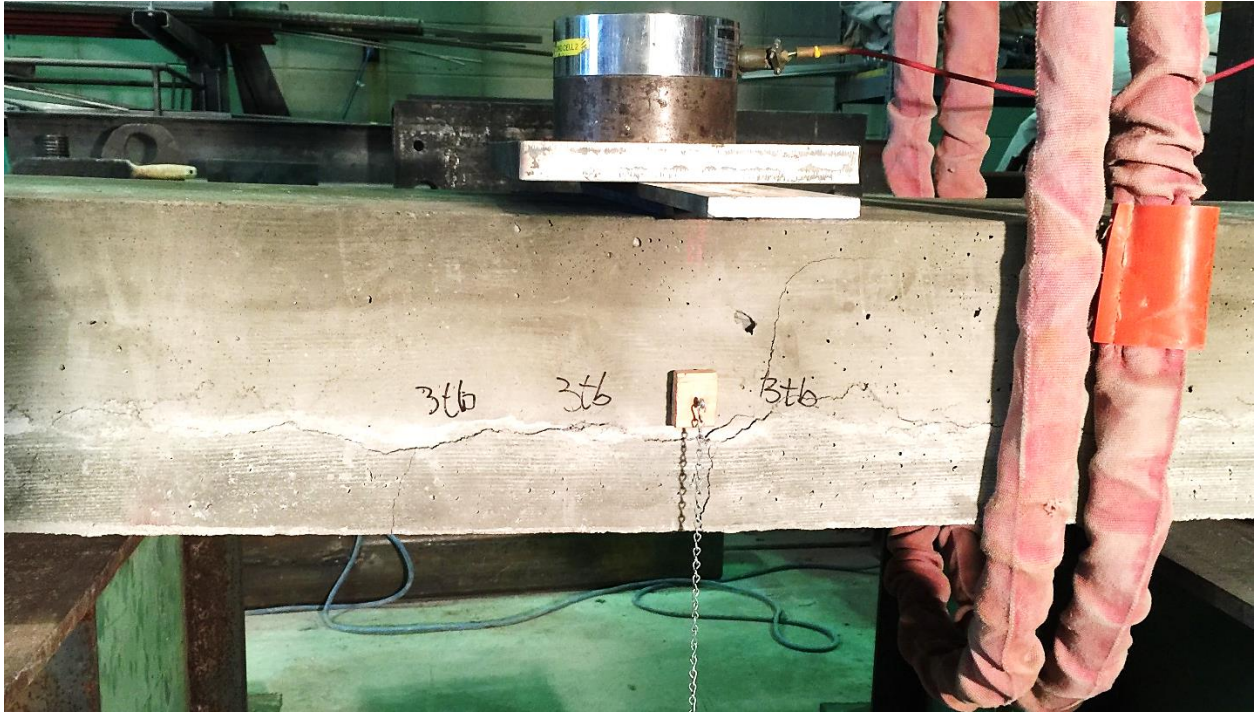


Figure 62. Case 3 negative bending flexural test specimen failure at concrete bond interface

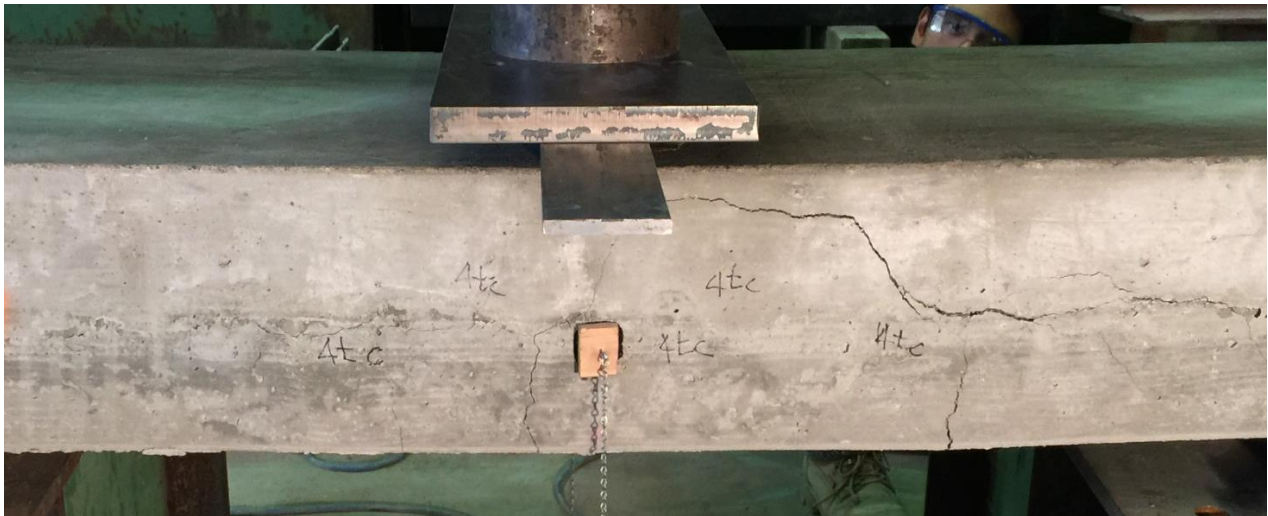


Figure 63. Case 4 negative bending flexural test specimen failure at concrete bond interface

The shear cracks and the flexure cracks are clearly visible in these images. Even though shear cracks were formed in the specimens at the bond interfaces, the cracks did not propagate all the way to the ends (i.e., the two layers of concrete on each specimen were not completely separated from each other). All three specimens for each concrete removal depth level (Case 1 through 4) showed similar failure patterns.

For the first three concrete removal depth level specimens (Cases 1 through 3), the stiffness change was observed only one time; but, for the Case 4 specimens, the change in the stiffness was observed twice. The first stiffness change for the Case 4 specimens was small and occurred at a lower load value of 6 kips, compared to 10 kips, which was the average stiffness change value for the for the other cases. However, the second change in stiffness for the Case 4 specimens was approximately 10 kips. Therefore, only the second stiffness change for Case 4 specimens were compared with the stiffness change from the other cases.

Table 11 shows the values for maximum load, elastic shear stress, and stiffness for all specimens along with the average values for each concrete removal depth (Case 1 through 4).

Table 11. Negative bending flexural test results

Concrete Removal Depth/ Case No.	Specimen No.	Load at Stiffness Change (kips)	Elastic* Shear Stress at Stiffness Change (psi)	Max. Load (kips)	Elastic* Shear Stress at Max. Load (psi)	Stiffness (kips/in.)
1	1	7	28	26	102	211
1	2	8	31	25	98	183
1	3	8	31	20	79	215
1	Average	8	30	24	93	203
2	1	10	42	25	105	210
2	2	9	38	25	105	181
2	3	11	46	24	101	243
2	Average	10	42	25	103	211
3	1	11	48	24	106	245
3	2	10	44	26	115	198
3	3	11	48	23	101	162
3	Average	11	47	24	107	202
4	1	10	47	21	99	204
4	2	9	42	21	99	169
4	3	10	47	22	104	219
4	Average	10	46	21	101	197

* All assumed section properties are for an un-cracked section

Removal Depth/Case No.:

1 – To top of the reinforcing steel

2 - Half the diameter of the reinforcing steel

3 - Full diameter of the reinforcing steel

4 - Full diameter of the bar and 0.5 to 1 in. additional

Due to the change in the section properties (depth of substrate concrete and overlay concrete) for each removal depth level case, the average elastic shear stress at the bond interface at the maximum load and the stiffness change showed a dissimilar pattern compared to the average load values.

Figure 64 shows the variation of the average load at the stiffness change and the maximum load with the change in the concrete removal depth level.

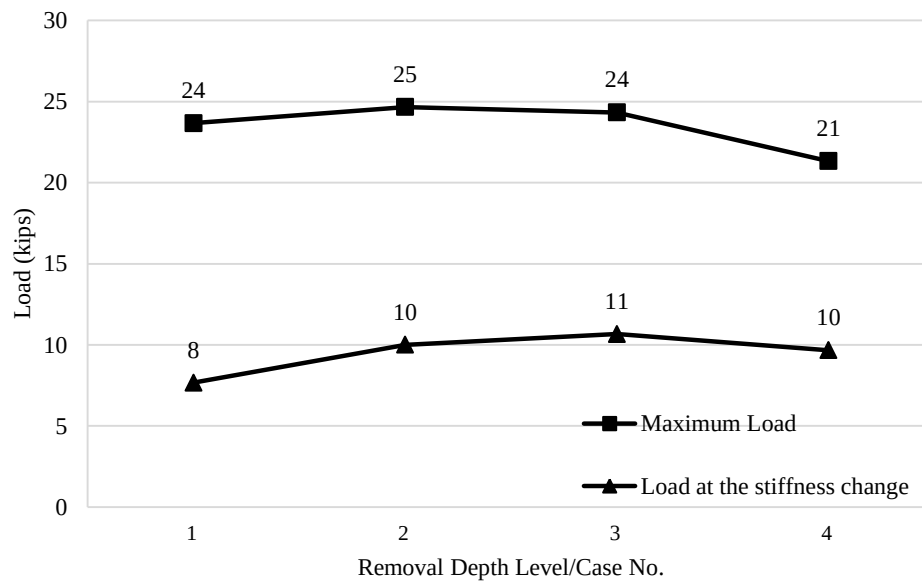


Figure 64. Average load versus concrete removal depth (negative bending flexural test)

Figure 65 shows the variation of the average elastic shear stress (at the bond interface) at the maximum load and at the stiffness change depending on the concrete removal depth level.

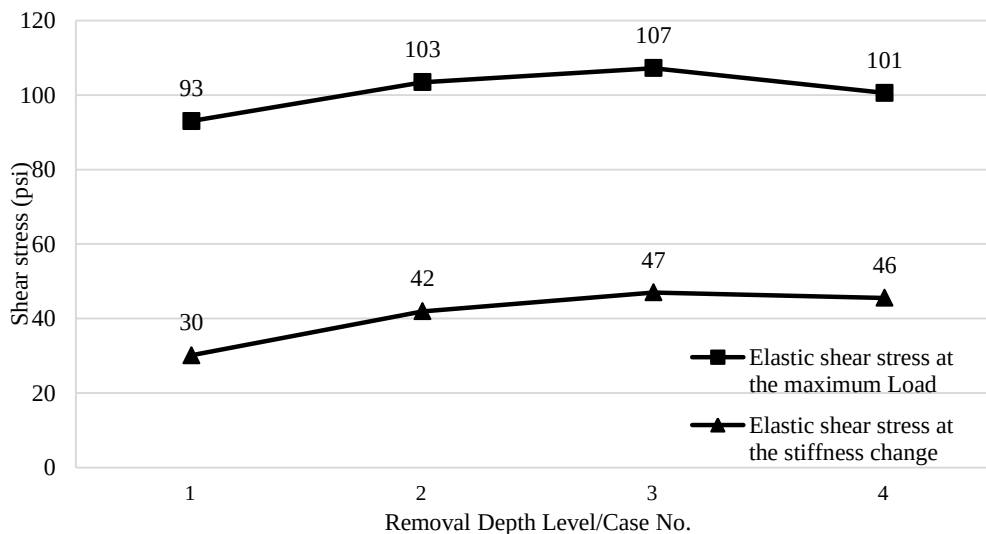


Figure 65. Average elastic shear stress versus concrete removal depth (negative bending flexural test)

Figure 66 shows the variation of the linear stiffness with the change in the concrete removal depth level.

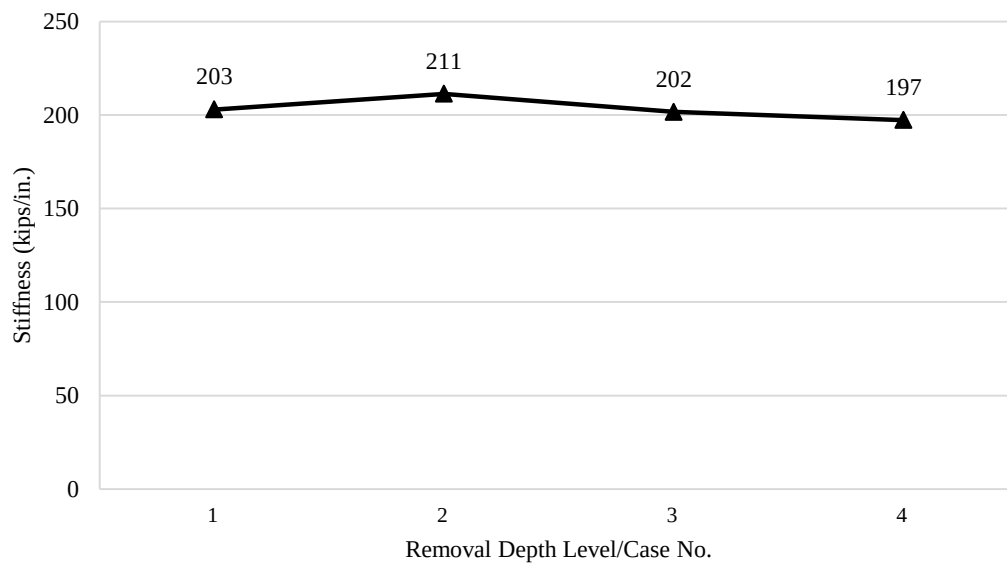


Figure 66. Average stiffness versus concrete removal depth (negative bending flexural test)

The stiffness was calculated as the slope of the linear portion of the load-deflection curve. For Case 4 specimens, the slope of the curve was taken from the starting point to the second change in the stiffness, given that the first stiffness change was small.

4.5.4 Summary

For the flexural tests with negative bending, the gradually increasing loads caused shear and flexural cracks in the specimens. Loading was stopped after it was clear that the steel in the specimens had started to yield.

The values for both the load at the stiffness change and the maximum load for each concrete removal depth level were not much different. Overall, the maximum load decreased 13% from Case 1 to Case 4, while the load at the stiffness change increased by 25%. The elastic shear stress at the maximum load and at the stiffness change increased by 9% and 53%, respectively, from Case 1 to Case 4. Stiffness of the specimens showed very little variation with concrete removal depth.

From Case 2 to Case 4, the difference in the values of all parameters was observed to be insignificant.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

Overlay construction is a vital part of bridge preservation and accelerating overlay construction is important in re-opening bridges to traffic as quickly as possible. To achieve the goal of providing information that might reduce overlay construction time, the researchers performed three major tasks.

Given that curing the overlay concrete consumes a major part of the overlay construction time, for the first task, a variety of the latest fast-curing concrete mixes were studied based on their performance for overlays and the curing time.

For the second task, the researchers observed and documented an ongoing overlay construction site. Upon investigation, various means were noticed that could lead to a reduction in construction time.

Finally, a vital part of this project was laboratory testing to study the influence of concrete removal on the overlay bond and performance. Four different laboratory tests were performed with four different concrete removal depth levels to determine if the change in depth of overlay concrete affects the bond strength between the substrate concrete and the new overlay concrete.

5.2 Results and Conclusions

The literature review on fast-curing concrete mixes led to a conclusion that CTS Rapid Set Low-P cement mixes, 4×4 concrete mix, polyester polymer concrete, and very-early-strength LMC may be possible substitutes for Class HPC-O and O concrete, and therefore could be used for overlay construction to reduce curing time without having any loss in the necessary strength requirements.

Investigation of the ongoing overlay construction project concluded that some minor improvements such as use of additional machinery like sandblasting setup, jackhammers (and the workers using them), and dump trucks could lead to time savings.

Based on the laboratory testing to determine the required removal depth level, the following results were found.

- For the pull-off test, the load at failure and the tensile bond stress at failure showed slight variation with respect to the concrete removal depth. This suggests that the removal of the additional sound substrate concrete beyond half the diameter of the reinforcing steel bar would not have a significant effect on the bond strength.

- Push-out test results showed that the concrete removal depth Case 1 showed significantly lower bond strength than the other removal depths. The load and the shear stress values at the stiffness change for the concrete removal depths Case 2 through 4 showed insignificant variation. The stiffness values for all cases showed very small variation. The load and the shear stress at a stiffness change (i.e., crack development) are important parameters when it comes to ensuring long-lasting structural performance of a bridge deck. The push-out test indicates that the removal of the additional sound concrete below half the diameter of the reinforcing steel bar would not result in a significant difference in the bond strength.
- Results from flexural tests with positive bending showed that the maximum load, stiffness, and elastic shear stress at the bond interface were slightly different for different concrete removal depths. The results show that Case 2 provides sufficient bond strength and no additional bond strength is achieved with additional sound concrete removal.
- For the flexural tests with negative bending, the load at stiffness change, maximum load, and elastic shear stresses showed relatively small change in values with changes in concrete removal depths. This shows that the removal of sound concrete below half the diameter of the reinforcing steel bar would not lead to a significant increase in bond strength.

Overall, from all of the laboratory tests, it can be concluded that the removal of the substrate concrete to half the diameter of the reinforcing steel bar provides as much bond strength as removing additional sound concrete. If unsound substrate concrete exists below half the diameter of the reinforcing steel bar, removing only the unsound concrete would likely be sufficient.

5.3 Recommendations

The following recommendations are suggested based on the observations and results of this project:

- CTS Rapid Set Low-P cement mixes, 4×4 concrete mix, polyester polymer concrete, and very-early-strength LMC should be further evaluated for use as overlay materials.
- During overlay construction, additional machinery like sandblasting equipment, jackhammers (and the workers using them), and dump trucks could be provided at times when it would lead to time savings. Contractors could possibly look at potential means and methods to help minimize closure time.
- During the removal of the unsound substrate concrete on an actual bridge, a trial attempt should be made with the following removal conditions:
 - If unsound concrete exists to or above half the diameter of the reinforcing steel bar, all concrete should be removed to half the diameter of the reinforcing steel bar.

- If unsound concrete exists below half the diameter of the reinforcing steel bar, all the unsound concrete should be removed until the depth to which it exists, but no additional sound concrete should be removed.
- The performance of overlays should be evaluated over a period of years following installation.

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