

EXPERIMENTAL INVESTIGATION OF HIGH PERFORMING PROTECTIVE SHELL USED FOR RETROFITTING BRIDGE ELEMENTS

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Abstract

The bridge structure elements are exposed to severe environmental conditions which causes reduction in service life and durability that may require repair and retrofit. In this project, thin shells of Ultra High Performance Concrete (UHPC) are used to retrofit damaged portions of bridge elements. UHPC shells are beneficial for protection against deleterious environmental conditions. The application of these shells is suited for retrofitting due to easy installation, design for variety of shapes, increasing the strength of element, and reducing time and cost.

In this project, thirteen beam specimens were tested under three-point flexure tests for verification of the proposed retrofitting method. These test beams included an undamaged, damaged and retrofitted beams in different configurations. The damage scenarios in beam are simulated by varying concrete and steel area loss. The test variables include shell thickness, configuration and interface between UHPC and regular concrete. The configuration of additional UHPC shell was either applied flushed or an unflushed surface. The preparation of interface was done by sand blasting and use of mechanical connectors.

The results show that the UHPC shell concept to repair damaged bridge element is a promising concept. A comparison of retrofitted beams shows an increase in the flexure capacity of the beam compared to damaged beams. Retrofitting of beams prepared with sand blasting provided adequate bond between UHPC shell and regular concrete. Based on experimental results, a numerical and analytical study will be used to find the most feasible detail for UHPC shell. Additional testing is required to validate and develop methodologies for real life application and provision of design recommendations for retrofitting with UHPC shells.

Keywords: Concrete Bridge, Retrofit, UHPC, shell, Accelerated Bridge Construction

Introduction

The American Association of State Highway and Transportation Officials (AASHTO) estimates that repairing of 67,000 structurally deficient bridges will cost roughly \$76 billion (1) (2) (3). Many bridge elements are exposed to severe environment. The structural damages in concrete can occur from different sources such as atmospheric effect, corrosion, overloading, construction joint fatigue effects, shrinkage, error in design and detailing, chemical reaction, traffic loading and errors in construction. Chlorides from natural sources (salt water) or the application of deicing salts can ingress through cracks in concrete and result in corrosion of steel reinforcement (1) (4) (5) (6) (7). Development of a system for easy and quick repair of damaged areas can provide bridge owners with alternatives for extending the use of existing bridge inventories (1).

One of the outstanding properties of the UHPC is its low permeability which can make it a suitable material for hardening and protecting the existing and new reinforced concrete structures subjected to severe environment and mechanical stresses (8) (9)(10). A thin shell of the UHPC can be made in variety of shapes, by applying new technologies such as 3-D printing for making of formwork. The formworks could then be attached to the damaged elements and the UHPC could be poured at site. The thin shell of UHPC can protect the bridge elements against chloride intrusion and other damages. Studies have shown that the layer of UHPC retrofitted beams can increase the strength of reinforced concrete beams (1).

This study was performed as a part of an overall program to investigate the potential of retrofitting the bridge elements by attaching a thin layer of UHPC shell to damaged areas. The study includes thirteen tests constructed at the Structures Laboratory at Florida International University. This preliminary investigation was used as proof of concept. Additional tests are underway to implement the concept in practice. Materials presented in this report should be viewed as introduction of the idea (1).

Background

Rehabilitating damaged concrete elements can be called a more attractive alternative to rebuilding and demolishing existing structures based on the present national economic climate (11) (12). In certain projects retrofitting is the only option because of budgetary restrictions that bridge owners are facing (1).

Up to now based on availability of materials, cost, level of damage and environmental condition several methods of repair have been developed. These methods include attaching external plate by using bolting or epoxy, bonding external reinforcement, chemical grouting, Portland cement grouting (5) (13), resin based repair mortar, high flow concrete, jacketing technique, patch repair, low slump dense concrete, Fiber Reinforced Polymer (FRP) and fiber shotcrete (11) (14) (15).

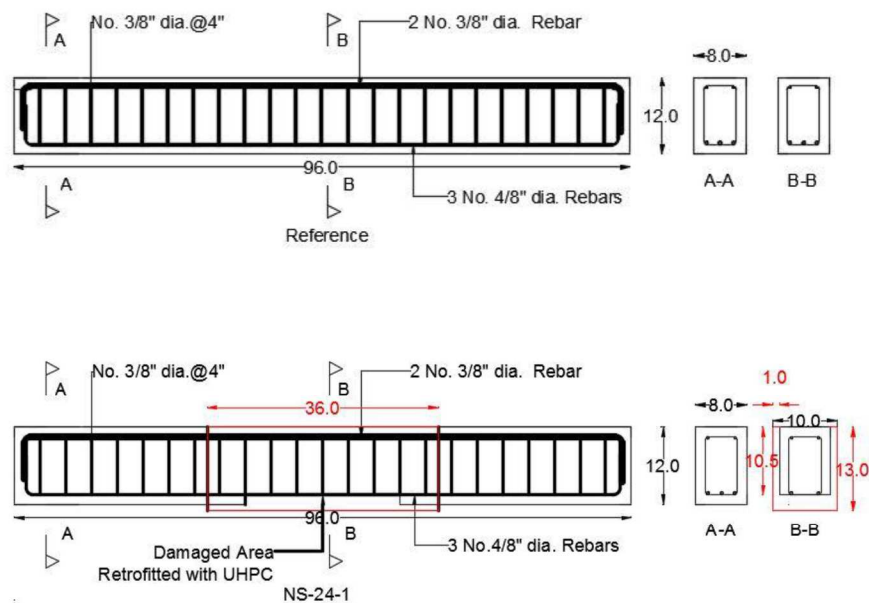
Retrofitting methods generally includes the removal of existing demolished concrete; surface preparation, can be done by, water demolition, sandblasting, hand chipping and iron brushing, etc. (1) (16) (17) (18) (19) (20). Selecting the right method, details related to severity and location of existing damage and right material are critical steps (13) (1). In FRP retrofitting the challenges are cited as brittle failure related to mismatching of strength and stiffness with substratum (1) (13) resin cost, toxic fumes, shear resistance capacity, flammability of the resins, non-applicability on wet surfaces and lack of vapor permeability and recycling. (1) (21) (22). In external plate bonding technique, the challenges are brittle failure of the beams which are strengthened for flexural failure related to debonding of the plate, corrosion of plate, interface

shear stresses between the concrete and plate surface (23), difficulty in handling the plate for long span beams and butt joint systems (1) (24) (13) in reinforcement jacketing the time that it takes to do the construction and in steel jacketing corrosion of the steel are the main concern (23). In patch repair, which involves applying mortar to the spalled, deboning failure is the major problem (25).

Some of the advantages of using UHPC shell in retrofitting include very low permeability, high durability and service life, reducing time of retrofitting, fluidity of UHPC, possibility of using the shell in different shapes and sizes and good bonding between UHPC and substratum (1) (26).

Experimental Investigation

As part of an ongoing research project to develop retrofitting techniques to rapidly retrofit damaged sections of bridge elements, thirteen test specimens were constructed and tested. Results of test specimens are provided in this paper. These tests are used to draw conclusions and develop a set of recommendations that will be used in design and construction of additional specimens to be tested within this project. The thirteen test specimens consisted of rectangular beams, 8 x 12-in., and 96-in. long. Figure 1 shows the details of the test specimens. Reference specimen is without any damage and is used as a reference point. Other specimens simulate various types of damages.



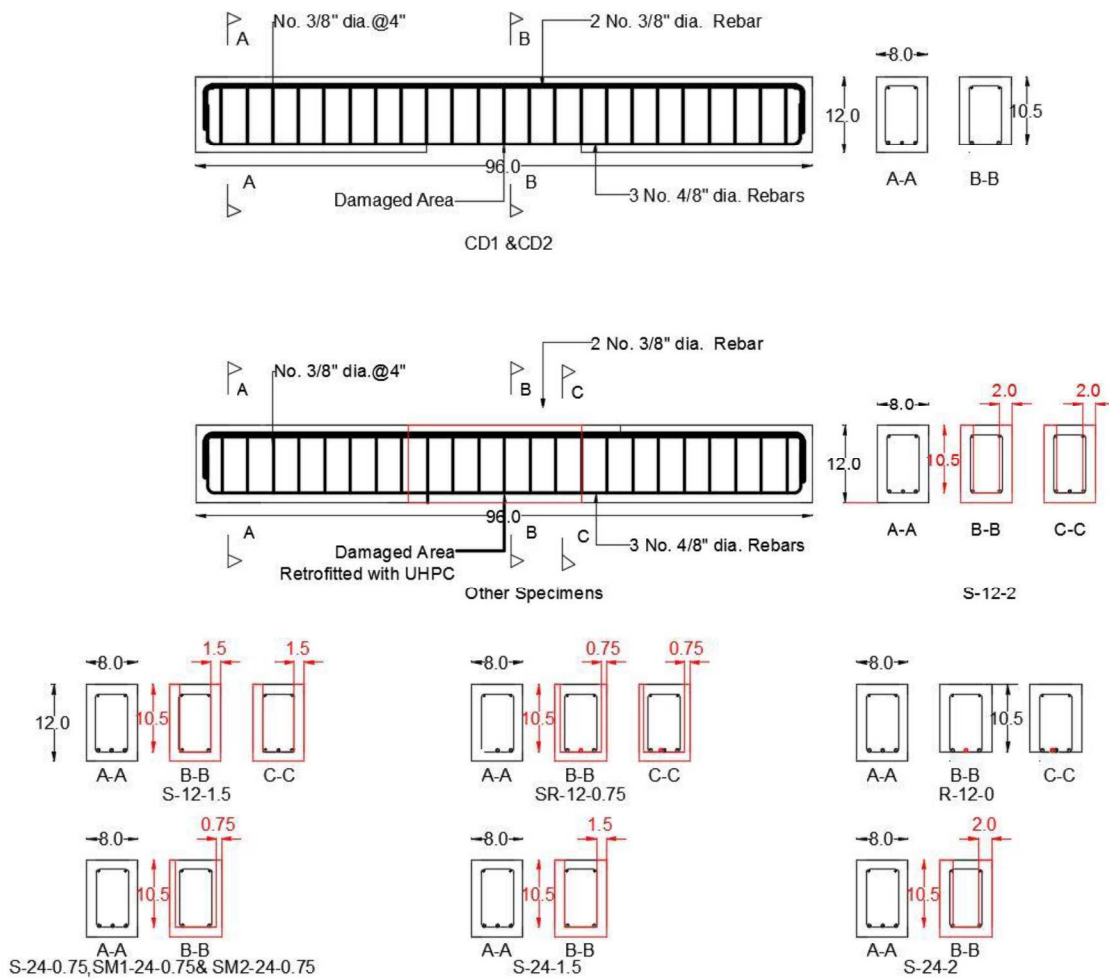


FIGURE 1 Test specimens details.

These damages are in the form of removing cover concrete in the bottom of the beam and removing some of the longitudinal tension reinforcement. Specimens CD1, CD2 and NS-24-1 were identical, except that the simulated damage area in specimen NS-24-1 was repaired using thin layer of UHPC shell.

TABLE 2 Test Specimens Matrix

Specimen ID	Cover loss At Sides (in)	Added UHPC length (in)	Added UHPC Thickness At bottom (in)	Added UHPC Thickness At Sides (in)	Rebar Cut length (in)	Rebar Added Length (in)	Sand blast	Nail Added
Reference	0	0	0	0	0	0	NO	NO
CD1	0	0	0	0	24	0	NO	NO
CD2	0	0	1.5	0	24	0	NO	NO

NS-24-1	0	36	1.5	1	24	0	NO	NO
S-24-0.75	0.75	24	1.5	0.75	24	0	YES	NO
SM1-24-0.75	0.75	24	1.5	0.75	24	0	YES	YES
SM2-24-0.75	0.75	24	1.5	0.75	24	0	YES	YES
S-24-1.5	1.5	24	1.5	1.5	24	0	YES	NO
S-24-2	2	24	1.5	2	12	0	YES	NO
R-12-0	0	24	1.5	0	12	22	NO	NO
SR-12-0.75	0.75	24	1.5	0.75	12	22	YES	NO
S-12-1.5	1.5	24	1.5	1.5	12	0	YES	NO
S-12-2	2	24	1.5	2	12	0	YES	NO

SMR-X-Y

S: Sandblast, M: Mechanical connection, R: Reinforcement added, X: length of rebar cut, Y: thickness of UHPC in sides, CD: Control Damage.

As shown in Figure 1, in all damaged specimens, part of the bottom concrete cover was removed, exposing the longitudinal tensile reinforcements. The discontinuity in concrete is 8 x 1.5-in., and 24-in. long in the middle of the beam. Each specimen included three number 4 reinforcing bars. In damaged specimens, in the middle of the beam, one of longitudinal reinforcements was cut.

For specimen NS-24-1, the UHPC was poured from one side of formwork to ensure a uniform shell around the damaged area Figure 2. It should be noted that the UHPC shell placed on sides of test specimen NS-24-1 was firmly attached to the bottom side of the beam, while the vertical sides did not incorporate any mechanism for positive attachment. Further, the surface of the beam was not prepared in any way prior to placing the UHPC. For the rest of test specimens, the selected strategies include mechanical connections and having the entire shell element being flushed with surface of existing concrete and sand blasting the damaged surface before retrofitting with UHPC as shown in Figure 2.

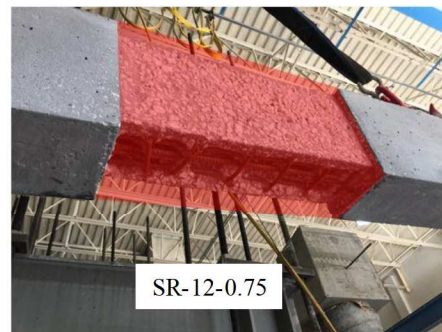




FIGURE 2 UHPC shell detail.

Specimens S-24-0.75, FSM1-24-0.75 and SM2-24-0.75 were identical, except that the simulated damage area in specimen S-24-0.75 was repaired using only thin layer of UHPC and specimen



FIGURE 3 Detail of the test specimens surface before sand blasting.





FIGURE 4 Detail test specimens surface after sand blasting.

SM1-24-0.75 and SM2-24-0.75 were repaired using thin layer of UHPC shell and using mechanical connections between the UHPC shell and regular concrete with different patterns. Specimens S-24-1.5 and S-24-2 were identical as specimen S-24-0.75 in concept of using only UHPC in the damaged area without any mechanical connections and their difference is the thickness of UHPC shell in the sides. As shown in Figure 1.

For most of damaged test specimens, surfaces were prepared with the sand blasting and making the surfaces coarse for making better bonding between the UHPC shell and the regular concrete Figure 3 and Figure 4 show the surfaces before and after preparation. For rest of test specimens, the cut length of rebar was 12 inches long and for SR-12-0 and SR-12-0.75 a rebar with length of 22 inches was added to the damaged area.

Material properties

Normal-strength concrete, provided by a local supplier, was used in the construction of all beam specimens. The average compressive strength of the concrete at the day of tests was 7.1 ksi (49 MPa). ASTM A615 Grade 60, No.4 (12.7-mm diameter) and No.3 (9.525-mm diameter) steel reinforcing bars were used for longitudinal reinforcement and stirrups. The yield and ultimate strength of the longitudinal reinforcement were 68 ksi (468 MPa) and 113 ksi (780 MPa) respectively.

The UHPC used in this research was provided by Ductal. It was a low water/cement fine powder mixed with fiber reinforcement (Table 2). The average compressive strength of the UHPC on the day of the test was 18 Ksi.

TABLE 2 UHPC Composition (24)

Material	Amount (lb/yr ³)	Percent by Weight
Portland cement	1200	28.5
Silica Fume	390	9.3
Steel Fibers	263	6.2
Fine Sand	1720	40.8
Ground Quartz	355	8.4
Accelerator	50.5	1.2
Water	184	4.4
Superplasticizer	51.8	1.2

Test setup and testing procedure

Flexure testing using three-point loading was used. Testing of specimen was achieved by placing the beams over roller type supports and loading each specimen using single hydraulic jacks, as shown in Figure 5.

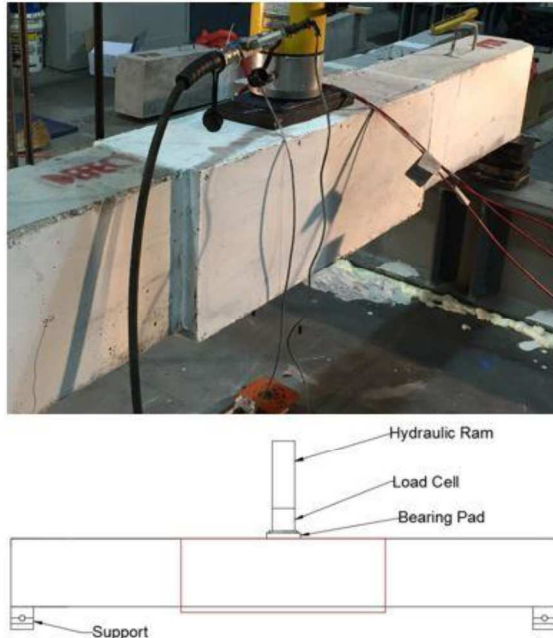


FIGURE 5 Test set up detail.

Deflections of the test specimens were measured by using three linear string potentiometers which were located at supports and mid-span. Each specimen was loaded until failure load and deflection was observed continuously during the tests.

Test results and observations

Reference specimen was loaded at a rate of 0.4 kips/min. The first flexural cracks were observed at the load of $P = 5$ kips, $\Delta = 0.07$ in. By increasing the loads the flexural cracks increased in the length and the height of the beam and the beams failed when applied load reached 23 kips with corresponding deflection, $\Delta = 0.14$ in (Figure 7).

Specimen CD1 was loaded with the rate of 0.62 Kips/min. The first crack was observed at the load of $P=5$ kips, $\Delta = 0.04$ in. and by applying more load more flexural cracks were observed at the bottom of the beam in tension area. Crushing of concrete in compression side was first observed at the load of $P=16.89$ kips, $\Delta = 1.55$ in. The final failure occurred at the load of $P = 17.5$ kips, $\Delta=3.2$ in. (Figure 6).

Specimen CD2 had its first crack at load of 4.2 kips, and the next crack was observed at load of 6 kips, and by increasing the loads the specimen crushed at load of 17.5 kips.

Specimen NS-24-1 was loaded at the rate of 0.5 Kips/min. The first crack was observed at a load of $P = 7.7$ kips, $\Delta = 0.06$ in. at the bottom of the boundary of the shell and regular concrete. At load $P = 10$ kips, $\Delta = 0.11$ in., the first crack became wider and one flexural crack was observed at a distance of 8 in from the edge of the UHPC shell on the regular concrete. At the

load $P = 13$ Kips, $\Delta = 0.22$ in., the cracks between the regular concrete and the UHPC shell at the top and the side were observed. At the load $P = 15.5$ Kips, $\Delta = 3$ in. it was observed that the crack inside the regular concrete close to the boundary became wider than the crack in the connection of regular concrete and the UHPC, indicating that the beam with regular concrete was failing sooner than the connection in the joint.

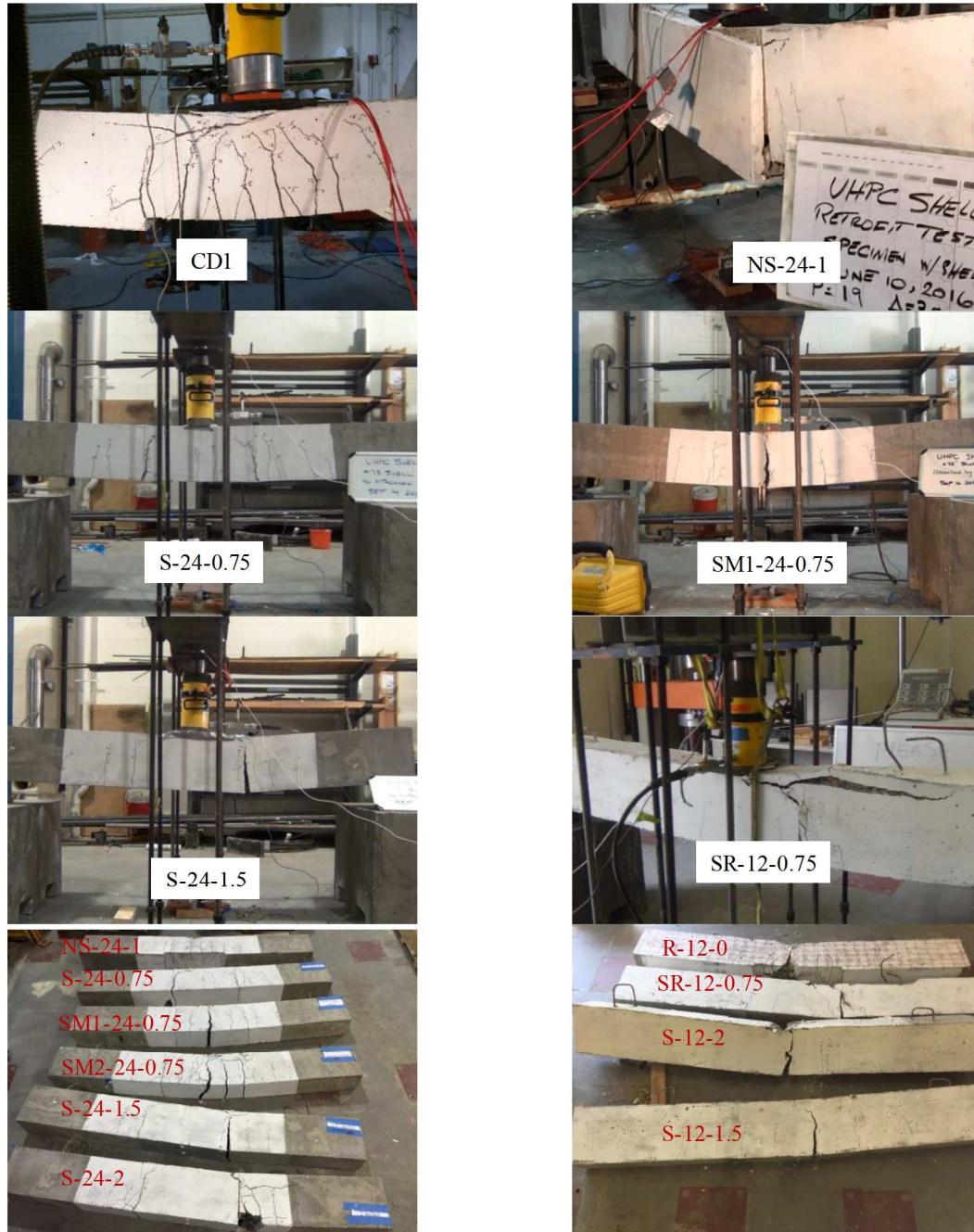


FIGURE 6 Failure of test specimen.

By increasing the load up to $P = 17$ Kips, $\Delta = 1.6$ in., a uniform crack was observed around the boundary of the UHPC and the regular concrete and at the load $P = 18.3$ Kips, $\Delta =$

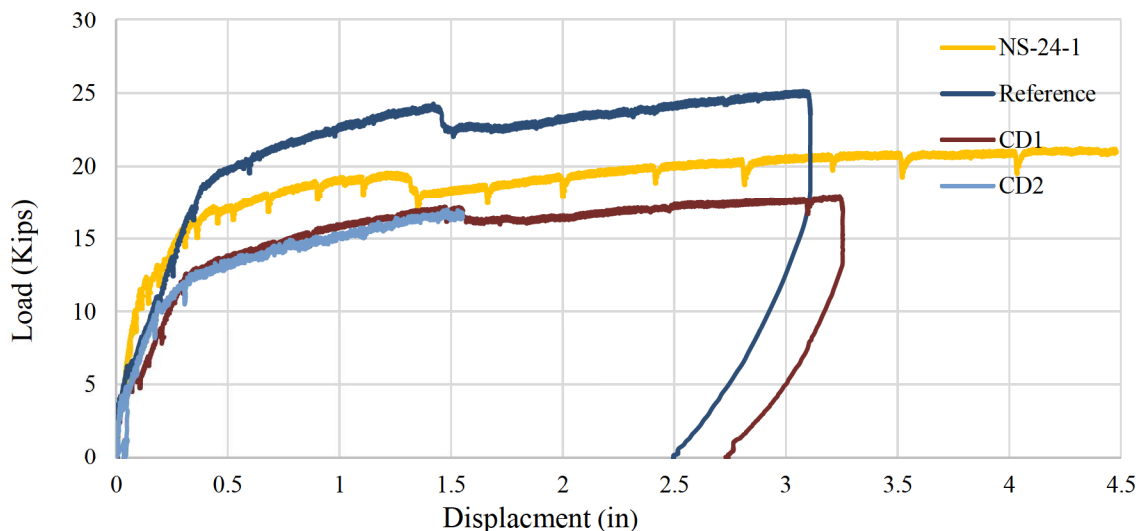
1.96 the separation of UHPC shell from regular concrete on sides of the beam was very apparent. (Figure 6).

This preliminary test result indicated that there is a need to have a mechanism to prevent separation of UHPC shell from repaired areas. Test specimen S-24-0.75 had its first crack at loads of 6 kips, at load 20 kips the loads drop but no crack was observed so may it was because of slippage between the shell and regular concrete. From the test result the shell hold on but the concrete inside crushed.

Test specimen SM1-24-0.75 had a minor crack at 2 kips outside the UHPC shell, and at load 3.8 kips some cracks were observed at UHPC edges and the middle of UHPC shell at load of 18 kips, $\Delta = 1.05$ in we had a big crack in middle of UHPC shell that it may be caused by increasing shear and concentrated stress at two nails. at this point the test was stopped and load was dropped. At the end of the test big cracks in the middle of UHPC and also between connection of UHPC shell and regular concrete was observed. This test showed better durability compared to previous specimens.

Test specimen SM2-24-0.75 had its first crack at load of 6 kips at joint of regular concrete and UHPC shell. At load of 7 kips the first crack was observed on the surface of UHPC shell. At load of 9 kips the first crack was observed in the middle of UHPC shell and at load of 10 kips the first flexural crack outside of UHPC shell was observed. By increasing the load, the crack in the middle of the beam become larger and the same as previous good deflection was observed. For specimen S-24-1.5, the first crack appeared at load 3 kips on surface of UHPC shell at load of 6 kips two edges of shell boundary had cracks. at load of 8 kips the first flexural crack appeared outside of UHPC area. In this case less crack compering to case S-24-0.75 was observed. At load 18 kips a big crack and gap at the connection of UHPC and regular concrete was observed that may cause by pop out of the rebar from the boundary. At the end of the test deflection measured as 2 inches.

Test specimen S-24-1.5, had its first crack on the surface of UHPC at load of 5.7 kips and at the load of 8 kips the first crack appeared outside of UHPC. For this case even at load of 14 kips no more cracks were observed in load of 15.5 kips the stiffness increases. At a load of 15.5 kips and deflection of $\Delta = 0.3$ in two large cracks were observed between connection of UHPC shell and regular concrete. At the end of the test the regular concrete was crushed Figure 6.



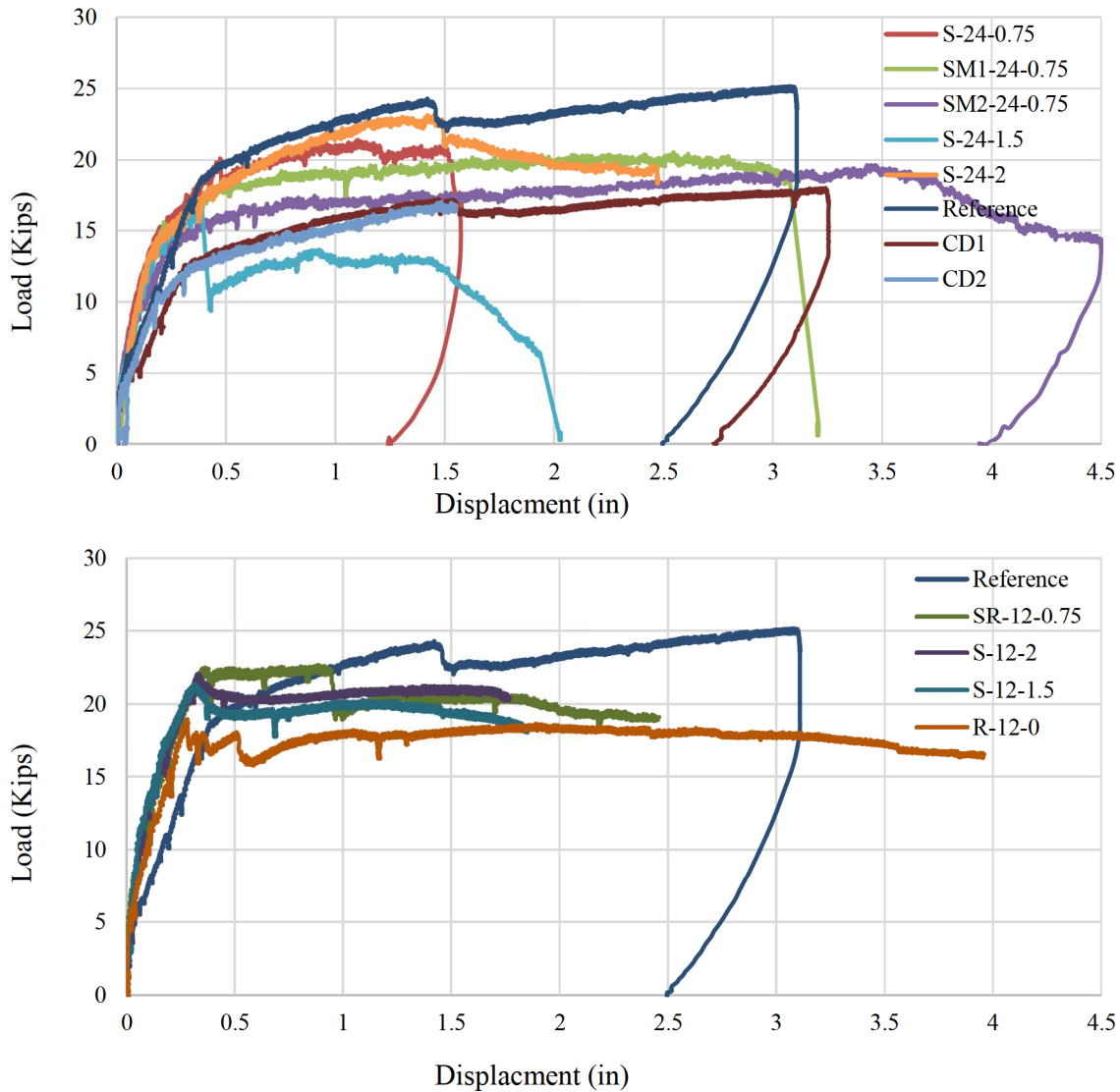


FIGURE 7 Test specimens results.

Test specimen R-12-0 developed first crack at 9 kips, and next crack was observed at load 11 kips, by increasing the load the specimen crushed at load of 17 kips and $\Delta = 1.16$ in.

For test specimen SR-12-0.75, the first crack appeared at load of 11.5 kips and $\Delta = 0.11$ in. At load 22 kips UHPC started to detaching from the beam and load dropped. at load 20 kips, $\Delta = 0.17$ in the load started to increasing but at the end the beam failed in compression at load of 19.5 kips, $\Delta = 1.7$ in. Even until load 18 kips and $\Delta = 2.2$ in No damaged was observed on the UHPC surface and all the damages were observed in the bond of UHPC and regular concrete in boundary of one sides and also as crush of regular concrete at the tops side of regular concrete Figure 6.

For specimen S-12.1.5 the first crack appeared at load of 12.3 Kips, $\Delta = 0.1$ in. At load of 20.3 Kips, $\Delta=0.4$ a wide crack in the middle of the beam was observed when there were no other cracks on the surface of the UHPC. At the End the beam started to crush at the load of 21 kips, $\Delta = 1.7$ in.

For test specimen S-12-2, at load of 14.7 kips, $\Delta = 0.14$ in, some cracks were observed in

the middle of UHPC and outside of the UHPC on the regular concrete. By increasing the load up to 20 kips, $\Delta = 0.37$ in, the flexural cracks increased in the middle of UHPC shell and at the end test specimen crushed at load of 19.5 Kips, $\Delta = 1.4$ in. The resulting load displacement responses of all thirteen specimens are provided in Figure 7. The results of retrofitted beams show an increase of almost 35% capacity in the flexure capacity of the beam compared to damaged beams.

Conclusions

This report provides an alternative method to repair damaged portions of bridge elements using thin UHPC shell.

In this study, thirteen beam specimens were tested. Based on the results of these tests, the following preliminary conclusions can be made:

- The UHPC shell concept to repair damaged bridge element is a promising concept. For the next step, some numerical analysis based on test results will be conducted to find out the most feasible detail of the shell.
- By comparing the results, sand blasting produced an acceptable bonding between the regular concrete and the UHPC.
- As expected, combination of adding rebar and using UHPC (SR-12-0.75), and using 2 inches UHPC in sides (S-24-2 and S-12-2) could give the best results based on increasing the strength.
- Having 1.5 inches UHPC in each sides and touching the core of the stirrups (S-25-1.5, S-24-2, S-12-1.5 and S-12-2) can guarantee a good bonding between regular concrete and UHPC shell.

Many additional aspects of the proposed techniques need to be researched before implementation in the field. These include construction techniques for the shell, transportation of the shell to the site, if pre-fabricated shell elements are to be constructed and then attached to damaged elements of the structures, effective ways of attaching UHPC shell to damaged portion, durability and long term performance of the retrofitted areas. Additionally, preventing further advancement of the corrosion in damaged area and covered by UHPC shell is an issue that warrants investigation.

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